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Intelligent Transport Systems

Connectivity in C-ITS

Investigating pathways to accelerate the uptake of road safety and efficiency technologies

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Putting the Connectivity in C-ITS – Investigating pathways to accelerate the uptake of road safety and efficiency technologies

Executive Report

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Executive summary

NOTE: As this report is being published, the coronavirus pandemic continues to alter the deployment of many technologies mentioned within it. Although the pandemic's ultimate impact on transportation remains unclear, continued development and deployment of these technologies as well as the expansion of new vehicles will be impacted. While little can be projected with any real certainty the research suggests that the pandemic impacts will only increase the need to consider interim interventions such as after-market devices to improve safety and efficiency outcomes.

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Project Overview

There are considerable national and international efforts in accelerating and incentivising the uptake of innovative technologies that can improve road safety as well as the overall performance of transport systems. Communication technologies are enabling the introduction of connected vehicles, which have the potential to both reduce roadway crashes and improve traffic flows. At the same time, global companies are developing automated vehicles, many of which will also incorporate connected technology. This project aims to deliver a systematic understanding, classification, and evaluation of available communication technologies for roadway safety by combining the results of four lines of research inquiry: 1) literature review of existing communication technologies, pilot experiments, and trial implementations, 2) expert panel interviews and literature review to investigate the challenges and opportunities for technology implementation in the Australian context, 3) analysis of Victorian motor vehicle crash types with respect to their being addressed by currently available connected safety applications, and 4) traffic simulation study to estimate the minimum penetration rate of connected vehicle technology required for mobility and environmental benefits to be realised.

Executive Summary

C-ITS technologies offer short-range and long-range communications, where the nature of applications enabled governs the type of communication employed. Two dominant short-range communication technologies exist (Dedicated Short Range Communication, DSRC; and Cellular Vehicle-to-Everything, C-V2X) which have enabled three types of C-ITS implementation: 1) DSRC short-range direct communication, 2) C-V2X short-range direct communication (PC5) combined with long-range cellular communication (Uu); and 3) Hybrid: DSRC short-range direct communication combined with cellular long-range communication.

Performance comparisons show both short-range C-ITS technologies are able to host the connected safety applications needed to provide significant positive outcomes in roadway crash reduction, as well as applications for reducing traffic congestion. These benefits have been assessed in multiple trials and simulations around the world, with most large-scale real-world trials testing DSRC for communications, while field testing involving C-V2X technology is limited. Connected technology is expected to augment currently-available advanced driver assistance systems (ADAS), with clear safety benefits created by messages between vehicles and infrastructure. Benefits have been identified for all classes of motor vehicle (cars, trucks, and buses) but are less clear for vulnerable road users, although safety solutions are urgently needed for pedestrians, motorcycles, cyclists, and various modes of micromobility.

Expert and stakeholder interviews provided valuable insight into current informed viewpoints and the future direction for C-ITS technology implementation in Australia and worldwide. Many stakeholders were agnostic towards the uptake and use of DSRC and/or C-V2X and were more interested in the potential for connectivity to provide road safety and traffic efficiency benefits. Several challenges in C-ITS deployment were identified, including user acceptance, and achieving penetration rates that would enable safety and traffic benefits to be realised. The cost associated with investments in infrastructure, and the need for interoperability were also of concern. Penetration rates in the Australian vehicle fleet will be influenced by early and consistent OEM fitment, and by the availability and use of retrofit devices. Overall, stakeholders viewed C-ITS technology as a singular opportunity to improve road safety outcomes, with potential benefits to

reduction of crash rates an order of magnitude higher than other known safety technologies (such as existing ADAS).

Connected applications, or use cases, represent a vast field; a useful classification scheme has been presented by the US DOT. In addition, the framework presented by the European Roadmap to Deployment presents a broader view of the field, with added information on likely sequencing and progression of the technologies. Both frameworks make an important distinction between use cases that i) promote awareness of potential safety issues in the vicinity of the host vehicle and ii) generate warnings of specific crash-related risks. Under such schemes, awareness messaging benefits can be realised at low penetration rates, while sensing and cooperative driving applications require higher rates of penetration for benefits to be realised. Additional factors associated with technology deployment include network coverage, where rural and remote areas may require significant infrastructure investment in order to provide adequate coverage for cellular connectivity applications.

A comprehensive analysis of Victorian Road Safety data, covering a fifteen-year period with approximately 190,000 recorded crashes indicated that eight major connected safety use cases: Lane Keep Assist (LKA), Curve Speed Warning (CSW), Cooperative Forward Collision Warning (CFCW), Do Not Pass Warning (DNPW), Intersection Movement Assist (IMA), Right Turn Assist (RTA), Cooperative Blind Spot Warning (CBSW/LCW), and Pedestrian Safety Messages (PSM), have the capability to address approximately 80% of crashes on Victorian roads, specifically 78% of fatal crashes, 82% of serious injury crashes, and 84% of other injury crashes. These cases have also been studied in other literature, trials, and simulations. However, use case benefits are not evenly distributed among different cohorts of road users and across different driving environments. Additionally, the cases studied represent varying levels of assumed connectivity relative to the European Roadmap to Deployment. While use cases at lower levels of connectivity and penetration (i.e. ADAS-only and Day 1) have the potential to address a significant share of crashes, these applications are more suited to addressing crashes in medium to sparsely populated environments and not applicable/beneficial to all modes. There is clearly a need to consider pathways towards to implementing Day 2 to 3+ use cases given that benefits are expected to be seen across all geographic regions and modes.

To understand the potential of connected vehicles in providing mobility and environmental benefits in the network, traffic microsimulation experiments were conducted comparing the integration of connected vehicle data with traffic control systems to existing methods. Traffic microsimulation experiments in arterial corridors indicated that connected vehicles at penetration rates of 30% (V2V and V2I) can reduce peak congestion by up to 11%. Meanwhile, network microsimulation in Melbourne City during peak hour indicated that average travel speeds of vehicles can be improved by 10% with connected vehicle penetration rates above 20%.

Even at low levels of penetration, it is clear that there are benefits to be reaped from successful deployment of C-ITS technology. Both stakeholders and literature agree that there are many challenges that need to be addressed. Despite these issues, C-ITS technology, deployed in vehicles at both the OEM and aftermarket levels, presents an exciting opportunity to improve road safety outcomes, both in the state-level Victorian data investigated, as well as at a national and global scale.

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1 Introduction

Co-operative intelligent transport systems (C-ITS) involve emerging technologies for vehicle connectivity and communications with other vehicles (V2V), infrastructure (V2I), and other entities such as motorcycles, cyclists, and pedestrians (V2X). These communications will enable connected and automated vehicles (CAVs) to potentially deliver a range of benefits, particularly in road safety and traffic network performance, as well as greenhouse gas reduction, energy efficiency, and emissions reduction. These technologies offer both short-range and long-range communications, where the scenario or nature of application governs the type of communication employed. Two C-ITS geopolitically-differentiated communication technologies are discussed: Cellular Vehicle-to-Everything (C-V2X) and Dedicated Short Range Communication (DSRC). We consider the potential for implementing DSRC as a short-range communication method, C-V2X for both short- and long-range communications, and a hybrid method consisting of DSRC for short-range with a cellular long-range communication capability. These implementation methods are based on the approaches to testing and simulating C-ITS communication observed in the USA (where DSRC has been subjected to in-depth testing and model deployment) and Europe (where the hybrid model is being considered).

There are numerous use cases for connected vehicles which have been trialled and simulated by government endorsed agencies, industry, and in academia. These trials aim to test and demonstrate the safety, environmental, and mobility benefits which CVs can provide. The safety functions of C-ITS communication technology are divided into two categories: awareness messages and warning messages. Awareness messages are defined as non-critical communications which act to provide an increased knowledge of the driver's surrounding infrastructure and environment. These include advisory warnings for speed, red light signals ahead, or other hazards. Warning messages, on the other hand, are considered critical, where the driver is warned of an imminent threat where reactions to such messages are time sensitive. These include warnings about potential conflicts or collision paths with other vehicles and imminent requirements for corrective action (such as emergency braking). Other benefits from connected vehicles, including mobility and environmental benefits, are also investigated for their ability to provide reduced fuel consumption, and travel-time savings.

The safety benefits of C-ITS can be assessed by examining the proportion of crashes which each specific use cases have the potential to address. Victoria's Road Safety database contains a comprehensive record of crashes over the last fifteen years, with attributes for each crash occurrence including severity of injury, specific crash classifications, geographic location, road geometry, lighting conditions, and modes involved. These parameters allow for investigation into factors and variables that make certain crashes more common and presents an opportunity to target development and deployment C-ITS use cases that have the ability to address a higher proportion of crashes. Meanwhile, the potential for network mobility improvement and environmental benefits can be measured through traffic simulations comparing different penetration rates of connected vehicles to existing and academic traffic signal control methods.

The deployment of connectivity technology requires several decisions to be made, including the type of technology chosen and the method of deployment in vehicles; we present opinions from a panel of experts to support the identification of challenges that C-ITS deployment face in the Australian environment. The necessary decisions for technology are also considered based on the framework presented in the European Roadmap to Deployment. Some of the challenges and opportunities in the deployment of C-ITS technology considered include performance requirements, penetration rates required for benefits to be realised, use of aftermarket and original equipment manufacturer (OEM) hardware, network coverage requirements, interference and congestion issues, human machine interaction factors, and security, privacy, and user acceptance.

This report summarises the findings from four lines of research inquiry: 1) literature review of the state of C-ITS technology, 2) expert panel interviews with predominantly Australian-based stakeholders, 3) analysis of Victorian Road Safety data to understand potential for C-ITS safety use case benefits, and 4) traffic simulation study to estimate the penetration rates required for mobility and environmental benefits to be realised. Each of these pieces of research have also been produced as standalone documents.

2 Literature Review

C-ITS platforms are being developed in an effort to deliver cross-cutting benefits, including safety and traffic efficiency, to road users and the wider transport network globally. This section provides a summary of the status of the two technologies, DSRC and C-V2X in the market, a summary of how C-ITS supports connected and automated vehicles, and highlights trials and the specific use cases which have been assessed for road safety purposes.

2.1 Technology and Terminology

C-ITS technologies offer short-range and long-range communications, where the nature of application governs the type of communication employed. Two dominant communication technologies exist (Dedicated Short Range Communication, DSRC; and Cellular Vehicle-to-Everything, C-V2X) which have enabled three types of C-ITS implementation:

1. ***DSRC short-range direct communication:*** There have been a significant number of large-scale and real-world trials that test the ability of DSRC for C-ITS communication use cases. Volkswagen is noted to have deployed a chipset that operates with DSRC for V2X communication in Golf models across Europe. The USA has dedicated the ITS spectrum specifically for this method of communication. However, some changes have been proposed recently (FCC proposal, December 2019) to introduce the segmentation of 5.9 GHz spectrum to allow for Vehicular and Unlicensed Applications.
2. ***C-V2X short-range direct communication (PC5) and long-range cellular communication (Uu):*** This implementation method is a proposed alternative to short-range communication provided by DSRC. This technology currently lacks large-scale and real-world testing to support its deployment but is supported by a number of industries. Ford has announced deployment of C-V2X for vehicles in China in 2021, and Telstra and Lexus are testing this implementation within the Victorian Towards Zero program.
3. ***Hybrid – DSRC short-range direct communication with cellular long-range communication:*** This approach is currently adopted by the directives for C-ITS communications in Europe and being tested in multiple trials including the CAVI project in Queensland, Australia.

These implementation methods provide the following main functionalities:

- ***Device-to-device connections***: V2V, V2I, and V2P direct communication without the need for reliance on network involvement for scheduling. Both DSRC and C-V2X (PC5) enable this method of communication.
- ***Device-to-network connections***: V2N solution using traditional cellular links to enable cloud services for an end-to-end solution. This communication is provided by either C-V2X Uu or a hybrid technology implementation.

2.1.1 DSRC short-range

Dedicated short range communication (DSRC) is a one- or two-way wireless communication, also known as ETSI ITS-G5 or IEEE 802.11p (initially approved in 2010) and provides V2X communication (i.e. V2V and V2I). This communication method is based on the IEEE Wireless Access in Vehicular Environments (WAVE) protocol. DSRC operates in the 5GHz frequency band and uses dedicated channels between 5.850 to 5.925 GHz for communications.

The evolution of DSRC was announced by IEEE and the IEEE Standards Association in May 2018, with the study named 802.11bd Next Generation V2X (NGV). This future development is backwards compatible with 802.11p and aims to increase the throughput and transmission range with modifications at the physical (PHY) layer of the existing technology.

2.1.2 C-V2X short-range and long-range communication

Cellular-V2X is a communication technology based on cellular 4G/long-term evolution (LTE). The technology standards are defined by the 3rd Generation Partnership Project (3GPP), a consortium of seven telecommunications standard development organisations: ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, and TTC. C-V2X is defined by 3GPP Release 14 as LTE-V2X (or LTE-V) has two radio interfaces Uu and PC5.

1. **Uu** is the ***cellular network communication*** interface which supports network V2N communications in the traditional mobile broadband licensed spectrum.
2. **PC5** is a ***direct communication method*** which refers to a reference point where the User Equipment (UE) directly communicates with another UE over the direct channel. Communication with the base station is not required for this method of communication. The PC5 interface supports V2V, V2I, and V2P communications based on direct LTE sidelink.

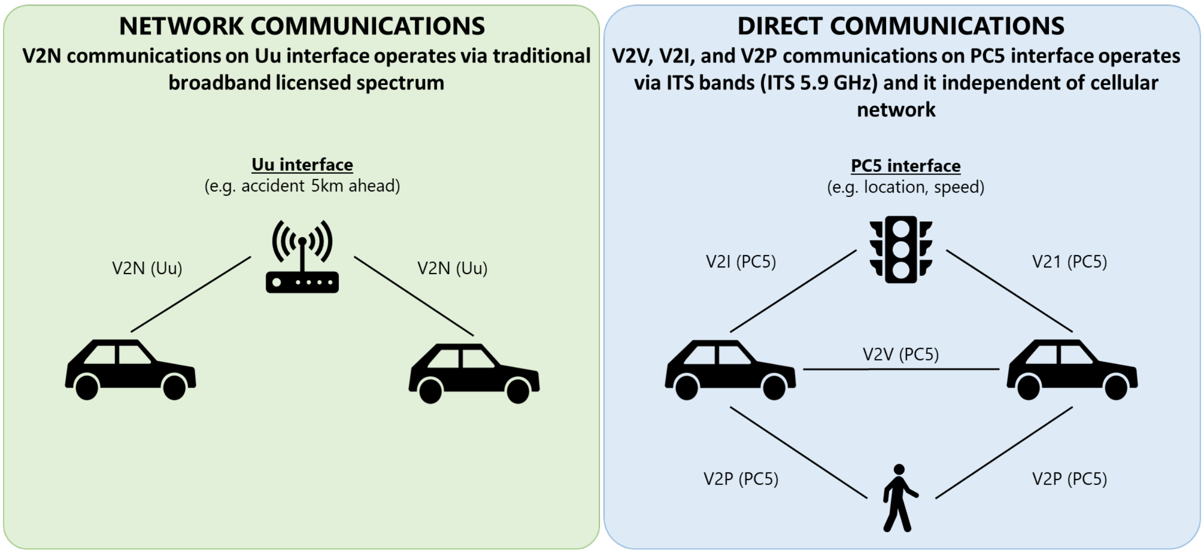


Figure 2.1 C-V2X interfaces for communication

The next generation of C-V2X technology (3GPP Release 15 and Release 16) will encompass the 5G radio interface known as 5G New Radio (NR).

2.1.3 Hybrid: DSRC short-range and cellular long-range

A hybrid combination of DSRC and cellular technologies has also proven effective in multiple trials around the world. In the hybrid implementation method, direct and short range communication is delivered by DSRC, and cellular connectivity delivers the V2N connectivity for longer range communications. This approach has been endorsed in Europe in the short- and long-range provisions in the supplement to ITS Directive 2010/40/EU.

Both the C-V2X and Hybrid technology implementation methods will rely on traditional cellular links to enable device-to-network communication. Cellular provides the ability for long-range vehicle communications.

2.2 Pilots and Trials

There are few large-scale real-world trials for either technology (DSRC, C-V2X, and Hybrid), limiting the number of definitive conclusions which can be drawn for estimated road safety and traffic efficiency benefits. All real-world trials have been designed to address safety benefits; fewer studies have addressed traffic efficiency benefits, and simulation has been used, rather than actual field testing. These current and historical trials contribute to the assessment of C-ITS communication performance and deployment for specific use cases. Trials in Australia are of particular interest as they are conducted in Australian environments within the existing infrastructure and network. Significant trials and past/present projects influencing policy and deployment of C-ITS technology are summarised in Table 1.1.

Table 1.1 C-ITS Trials and Simulations

Trial/Simulation	Country/ Region
Safety Pilot Model Deployment, 2012	***United States***
The Safety Pilot Model Deployment (SPMD) led by the University of Michigan was launched in August 2012 in Ann Arbor, Michigan. The SPMD tested six safety use cases for vehicle-to-vehicle communication and two vehicle-to-infrastructure road safety use cases. Following the SPMD and analysis of an unprecedented V2X database, the USDOT confirmed that use cases tested were capable of avoiding target sets of crash types, and this would occur on a sufficiently robust national scale as to justify federal rulemaking.	
ITS V2X Spectrum Testing, USDOT, 2020	***United States***
Following the proposed FCC segmentation of the 5.9GHz bank, the US Department of Transport announced "ITS V2X Spectrum Testing" in February (2020) which will see the procurement of V2X communication devices including LTE-C-V2X devices, dual mode DSRC and C-V2X devices, and 5G NR devices to evaluate the safety performance and capabilities of the devices through both small- and large-scale testing, including scalability and congestion, interoperability, and complex transportation scenarios.	
Driving Implementation and Evaluation of C2X Communication Technology in Europe, DRIVE C2X, 2014	***Europe***
Drive C2X is a project which aimed to create and harmonize a European testing environment for C-ITS, test the compatibility of emerging cooperative systems and evaluate the impacts which these technologies have on improving safety and mobility. The Drive C2X tests were carried out across seven countries in Europe to capture a wide range of climates and environmental conditions. Several use cases were tested: Approaching Emergency Vehicle Warning (AEVW), Traffic Jam Ahead Warning (TJAW), In-Vehicle Signage (IVS), Road Works Warning (RWW), Obstacle Warning (OW), Car Breakdown Warning (CBW), Weather Warning (WW), and Green Light Optimal Speed Advisory (GLOSA). The study found that in-vehicle warnings for the IVS and WW use cases showed the highest potential in their ability to reduce the number of fatalities.	
Livorno, IT: ETSI Plug Test, 2016	***Europe***
The ETSI ITS Plug test conducted in 2016 involved more than 20 vendors and simulated real-world large-scale DSRC technology use. Eight use cases were tested, three of which are focused on communication between infrastructure services: (1) communicating to surrounding vehicles that there is a hazard/pedestrian on the road, (2) notifying ITS stations of the location of a vehicle carrying dangerous goods, and (3) notifying ITS stations and surrounding vehicles	

Trial/Simulation	Country/ Region
of the position of an available parking space. These test cases simulate integration of the motorways network (1,2) and integration with IoT technologies (3). This trial successfully demonstrated that DSRC (ITS-G5) conformed to ETSI ITS Release 1 standards and verified the interoperability between OBU providers and RSU vendors involved in the trial.	
Safety Benefits of Cooperative ITS and Automated Driving in Australia and New Zealand, Austroads, 2017	***Australia***
Austroads' research into C-ITS and Automated Driving identified six application fields for C-ITS: collision avoidance and hazard detection, vulnerable road user safety, in-vehicle signage, road weather alert systems, post-crash notification systems, and mobility and eco-driving. Safety benefits of four C-ITS crash-avoidance use cases: Cooperative Forward Collision Warning (CFCW), Curve Speed Warning (CSW), Intersection Movement Assist (IMA), and Right Turn Assist (RTA) were estimated for the Australian road environment. The estimations provided in this report were based on the assessment of a combination of real-world crash data from Australia, and operating parameters that would affect the likelihood of technology application and assumed a 100% penetration rate for vehicles as well as an adequate amount of roadside infrastructure to support communication use cases.	
Cooperative Intelligent Transport Initiative (CITI)	***NSW, Australia***
The Cooperative Intelligent Transport Initiative began in 2012 and is one of Australia's largest C-ITS projects. This $1.65M trial of V2V and V2I deployment in heavy vehicles is conducted along a 42km freight corridor in Illawarra, New South Wales. C-ITS communication was provided by DSRC devices used to convey intersection collision warnings, forward collision warnings, braking ahead messages, advance warning of red lights, and in-cab messages for truck and bus speed limits at a particular location.	
Cooperative and Automated Vehicle Initiative (CAVI)	***QLD, Australia***
Queensland's Cooperative and Automated Vehicle Initiative consists of three pilots: Cooperative Intelligent Transport Systems (C-ITS) Pilot, Connected and Highly Automated Driving (CHAD) Pilot, and the Vulnerable Road User Pilot. The C-ITS pilot will trial retrofitted equipment on approximately 500 vehicles and infrastructure for a number of V2V and V2I safety use cases including: emergency brake warning, in-vehicle speed warning, turning warning for bicycles and pedestrians, red light warning, road works warning, stopped or slow vehicle warning, back of queue warning, and hazard warning. The estimated benefits of these trials include a 20% reduction in road collisions, 2% reduction in crash related grid lock, and 3% reduction in overall fuel emissions.	
Australian Integrated Multimodal Ecosystem (AIMES)	***VIC, Australia***
The Australian Integrated Multimodal Ecosystem (AIMES) is a real-world connected test bed area located at the edge of Melbourne's CBD incorporating approximately 100 kilometres of roads and intersections. The test bed included hundreds of sensors to collect data on vehicle and pedestrian movement, and public transport use. Three trials have recently been completed by AIMES in conjunction with a number of industry partners: 1) use of edge and fog computing for interactions between vehicles and vulnerable road users, 2) use of Video Analytics and Artificial Intelligence technology to provide insights into road user behaviour, and 3) use of WiFi detectors and edge and fog computing to determine the accuracy and latency of positional information transmission in real-time.	

Trial/Simulation	Country/ Region
Towards Zero CAV Trials	***VIC, Australia***
Telstra and Lexus Australia to conducted Australia's first connected vehicle field trial using advanced 4G mobile networks (C-V2X) rather than Wi-Fi DSRC technology (DSRC). Use cases including emergency braking alerts, in-vehicle speed limit compliance warnings, curve speed warnings, right-turn assist for vulnerable road users, and warnings when surrounding vehicles are likely to violate a red light were tested. Lexus vehicles in this trial were fitted with C-V2X technology, as well as advanced driver assist features including crash warning systems and lane keeping assist.	

2.3 Road Safety Applications and Use Cases

While safety has been the main driver of the deployment of connected technologies, four types of Connected Vehicle Applications: Safety, Environmental, Mobility, and Support have been classified by US DOT *Connected Vehicle Reference Implementation Architecture*, where each type is comprised of application fields that further contain specific use cases. The list of use cases presented is not exhaustive and will focus predominantly on the application field of Safety and Mobility.

Table 1.2 Applications fields and use cases for Road Safety Applications

Application	Application Field	Use Case
Safety applications (Warnings)	*Warnings for conflicts between vehicles*	Intersection Movement Assist (IMA) Red Light Violator Warning Right Turn Assist (RTA)/ US: Left Turn Assist (LTA) Cooperative Forward Collision Warning (CFCW) Cooperative Blind Spot Warning (BSW) and Lane Change Warning (LCW) Do Not Pass Warning (DNPW) Approaching Emergency Vehicle Warning (AEVW)
	Warnings for conflicts involving vulnerable road users	Detecting vulnerable road users Alerting vulnerable road users
Safety applications (Awareness)	*Infrastructure and environment awareness*	Curve Speed Warning (CSW) Intersection Awareness Hazard Awareness In-Vehicle Signage
Mobility and Environmental applications	*Traffic Network and Signalling*	Cooperative Adaptive Cruise Control (CACC) Variable Speed Limit (VSL) Connected Signal Optimisation and Traffic Routing

Assessment of C-ITS should include comparing and identifying the efficacy of individual use cases. For this review, use cases in the safety application fields were classified according to their proximity to the crash, as follows.

- ***Safety awareness messages***: non-critical communications which act to provide an increased knowledge of the driver's surrounding infrastructure and environment. Generally, these awareness messages convey a static hazard, for example, upcoming work zones or red lights signals. Depending on the latency requirements of the use case, cellular long-range communication methods are expected to be able to provide the necessary communication.
- ***Safety warning messages***: time-critical communications where the driver is warned of an imminent threat and reactions to messages are time-sensitive. This involves situations where other road users may be moving and require an additional level of prediction based on the driver's movements and the movements of the other road user, for example, warnings for potential collision paths with another vehicle or a vulnerable road user. For these cases, short-range direct communication methods, usually DSRC, are tested in real-world trials. The content of the safety communication between vehicles, and between vehicle and infrastructure, has been standardised in the Basic Safety Message (SAE J2735).

2.4 Roadmap to Deployment

Given that Australia is expected to follow the European standards for C-ITS deployment, the European Roadmap to Deployment assists in considering the many stages of deployment despite the differing policy environments. This framework is summarised in Table 1.3.

The model assumes that the level of automation increases with time. That is, Day 1 C-ITS applications are provided for low levels of automation (and potentially low penetration), but are still effective for increasing awareness of risks and for the dissemination of information to drivers, while, Day 3+ activities assume that there are mid to high levels of technology penetration, as well as high, if not fully automated vehicles available for cooperative use cases. This roadmap is intended to demonstrate a potential model for achieving cooperative automated driving with the objective of accident free road transport and optimal traffic flow.

Table 1.3 European Roadmap to Deployment: Expected Services and Use Cases

Timeframe	Expected Services	Message Types	Potential Use Cases
Day 1 Awareness driving via status data	Cooperative awareness and decentralised notification; and Basic infrastructure support	Cooperative Awareness Message; Decentralised Environmental Notification; Basic Safety Message; Signal Phase and Time; Road/lane topology and traffic manoeuvre; In-vehicle-Information Message; and VRU Awareness	In-vehicle signage Hazard Awareness Intersection Awareness Curve Speed Warning

Timeframe	Expected Services	Message Types	Potential Use Cases
Day 2 Sensing Driving via sensor data	Improved cooperative awareness and decentralised notification; Collective Perception; and Improved Infrastructure Support	Collective Perception Message (CPM)	Intersection Movement Assist Red Light Violator Warning Right Turn Assist
			Cooperative Forward Collision Warning Cooperative Blind Spot Warning/ Lane Change Warning Do Not Pass Warning
Day 3+ Cooperative Driving via intention and coordination data	Trajectory/ manoeuvre sharing; Coordination/ negotiation; and VRU active advertisement	Manoeuvre Coordination Message; and Platooning Control Message	Vulnerable Road user protection Pedestrian Safety Messages Cooperative Adaptive Cruise Control Connected Signal Optimisation and Traffic Routing

3 Stakeholder Interviews

In addition to the review of literature and global C-ITS trials, eighteen expert panel and stakeholder interviews were conducted in order to gain an understanding of the existing research and development of V2X (Vehicle-to-Everything communication) technologies, expert opinions on penetration and uptake of these technologies, and the challenges faced by different stakeholders. Participants included transport agencies, associations, and operators, specialised technology providers, mobile network providers, state level government (Australia), policy agencies, insurance agencies, and academics. Stakeholders represented expert opinions in areas related specifically to transport operations efficiency or transport network safety, while others had involvement with mobile network communications, equipment manufacturers, or policy activities. This diversity of roles and perspectives allowed for a comprehensive overview of the current mindsets and future direction for C-ITS technology implementation in Australia and worldwide. Specifically, specialised technology providers and mobile network providers brought valuable knowledge of the performance and functional aspects of V2X technology as well as the current state of infrastructure and further improvement requirements. Government agencies provided insights into regulatory and standardisation challenges, while also reflecting on current initiatives and large-scale implementation. Overall, the variety of stakeholders interviewed provided valuable insight on significant issues surrounding connected vehicle deployment that were also reflected in the literature reviewed. The topics discussed in this section include Perceptions of C-ITS technology, deployment and penetration benefits, the use of aftermarket or OEM technology, and human-machine interaction factors.

3.1 Perceptions of C-ITS Technology

Many stakeholders noted the potential for connectivity to act as an augmentation to traditional ADAS applications and automated vehicle functionality. Stakeholders were largely in agreement with regard to the potential for connectivity to improve safety and productivity outcomes for traffic networks. Interviewees who focused on safety outcomes assert that connectivity will not only reduce the likelihood of crashes but also reduce the severity of crash outcomes. Stakeholders also acknowledged that benefits become increasingly significant at higher levels of penetration. However, a number of interviewees who viewed C-ITS as a support to ADAS functions stated that the benefits provided by the additional connectivity element may be outweighed by the costs of implementation and deployment, especially during the transition period. Furthermore, upgrading the necessary infrastructure to accommodate connectivity in rural areas has been identified as a major challenge by stakeholders, due to the sheer cost and scale of such a task. Some stakeholders also raised concerns over the immaturity of the technology, claiming issues such as reliability and cybersecurity may threaten to subvert the initial intentions of the application and even exacerbate existing traffic problems.

While DSRC and C-V2X technologies were noted to operate on different “systems of systems” in wireless connectivity by stakeholders, many were agnostic towards the uptake and use of DSRC and/or C-V2X in road safety and productivity and acknowledged that the hybrid DSRC short-range direct communication with cellular long-range communication would likely become the norm. V2X, in general, was noted to be an additional form of data acquisition and seen as an augmentation to existing in-car sensors, which can allow the improvement of current ADAS.

A difference between cellular and DSRC technologies that was identified in the interviews was that the DSRC standards base may be more stable given that the technology has existed for a longer period and has been tested more extensively. Regarding performance, DSRC can provide an advantage in road safety use cases because of its low latencies, although some stakeholders have noted that with human factors involved, this benefit may be less significant. Discussion of cellular technology and its future with 5G noted that this form of communication may provide a broader range of applications for road safety and efficiency, although this is scenario dependent, especially when adequate coverage and reception are required. In this sense, specialised technology providers indicated that they are likely to produce hardware that can operate with both technologies, either simultaneously or alternatively. Some interviewees representing agencies noted that different regions may have pushed for the uptake of one or the other technology, but again, all recognised that there is the potential for both technologies to operate concurrently to support different road safety and productivity functions. Stakeholders were also aware that significant standardisation and regulation is required, as well as a unified national approach toward C-ITS communications.

3.2 Penetration and benefits

The technology penetration rates required for safety and efficiency benefits is heavily dependent on the type of message being communicated. When considering Day 1 applications, awareness messages do not require significant penetration. However, higher penetrations are crucial in sensing and warning messages and present a major challenge in the deployment of C-ITS technologies where the realisation of safety and mobility benefits requires a minimum percentage of connected vehicles and infrastructure.

Stakeholders have noted that along with user acceptance, achieving penetration rates that will enable safety and traffic benefits to be fully realised is expected to depend heavily on investment in infrastructure. The costs of implementing road-side units to support connectivity functions is expected to be significant, along with the costs of upgrading existing cellular infrastructure. Several stakeholders have contemplated the “chicken and egg” scenario, and are of the view that no one wants to be the first to invest as benefits will not be seen until after the uptake of technology is significant. On the vehicle implementation side, the type of technology integration must be appealing to users so that they will invest their time and money into using the connectivity features. This is a particularly important consideration when attempting to achieve critical mass in uptake.

In Victoria, ANCAP estimates the existing fleet to have an average age of approximately 10 years, with penetration of connectivity technologies in the market currently limited. Taking into account the fact that fleet age and rate of change are highly variable, as are the number of manufacturers and models of vehicles available to Australian consumers, stakeholders have provided estimates for significant fleet penetration range from a few years, to a few decades for the technology to be commonplace. However, interviewees have noted that benefits to traffic flow and productivity may be seen at penetration rates below 50% which may be achieved in a reduced amount of time.

The Queensland Department of Transport and Main Roads predicts that delay in implementation of C-ITS technologies in Southern Queensland would result in a reduction of benefits with net economic loss of approximately $200 million[1] under an optimistic scenario, and approximately $60 million if the moderate scenario is considered. The reduction in benefits arising from a delay in deployment is supported by the University of Michigan Transportation Research Institute who have identified a significant loss of opportunity associated with lives lost when waiting to deploy C-ITS crash reduction measures (do nothing scenario). Therefore, uncertainty surrounding the type of communication technology (i.e. DSRC or C-V2X) results in negative consequences as the ability to prevent two-vehicle crashes, injuries, and fatalities is delayed.

3.3 Aftermarket vs. OEM

Technology for C-ITS communications may be integrated by the original equipment automotive manufacturer or purchased and fitted in the automotive aftermarket. The following distinctions are made between aftermarket (retrofitted) and OEM (machine integrated) solutions:

- ***Aftermarket solution:*** aftermarket equipment may allow V2V, V2I or V2X communications via DSRC and/or C-V2X. The equipment is retrofitted into an existing vehicle or operated independently from the vehicle’s controller network.
- ***OEM solution:*** communication equipment (DSRC, C-V2X, or both) is integrated into vehicles during production and integrated to the newly produced vehicle’s controller network. This type of device is capable of providing highly accurate information using the in-vehicle information to generate basic safety messages (BSMs).

When considering the equipment that can be deployed for C-ITS communications, we must consider how the OEM and aftermarket options compare relative to the previously-discussed

[1] 2015 dollars, 7% discount rate

roadmap for deployment, and what functions the equipment is required to perform. For awareness communications (i.e. Day 1 applications from the European Roadmap), the technology deployed must be able to transmit awareness messages and provide basic infrastructure support. Services provided on Day 1 are aimed at enhancing the driver's understanding of their surrounding infrastructure and environment, and do not necessarily require large amounts of information to be communicated. Beyond Day 1 applications, the amount of information communicated increases for sensing and warning functions. For use cases on Day 2 and Day 3+, a high level of accuracy is required as positional information is often conveyed; additional factors such as security must now also be considered given the time-critical nature of the communication. The delivery of precise information is crucial for cooperative use cases to function effectively and provide expected road safety and productivity benefits.

3.3.1 Hardware

In order for the benefits of connected vehicles to be recognised, a number of hardware requirements must be satisfied. Some of the vehicle equipment configurations used in C-ITS communication trials include Integrated Safety Devices (ISD), Aftermarket Safety Devices (ASD), Retrofit Safety Devices (RSD), and Vehicle Awareness Devices (VAD). These devices offer varying levels of integration with the vehicles, and hence, have different levels of functionality as well as installation requirements. The three aftermarket safety devices (RSD, ASD, VAD) have limitations when compared to an ISD:

- ***Integrated Safety Device (ISD):*** When used in trials, these devices most accurately reflect an OEM installed device.
- ***Retrofit Safety Device (RSD):*** The level of integration with the vehicle decreases when retrofitting RSDs compared to ISDs, although the device is still connected to the vehicle's data bus. This allows for basic safety messages and vehicle to vehicle safety applications to be communicated. This device requires a certified installer for the placement of antennas and security certification.
- ***Aftermarket Safety Device (ASD):*** This retrofit device requires power from the vehicle and has the ability to communicate BSM and V2V safety applications, although the safety applications which can be conveyed using this technology are limited when compared to those which RSDs can potentially achieve. Again, this device requires a certified installer for the placement of antennas and security certification.
- ***Vehicle Awareness Device (VAD):*** This device can only provide an outbound BSM which alerts surrounding or nearby vehicles of the vehicle's presence; no safety applications or use cases can be performed in the host vehicle. This device still requires a certified installer for the placement of antennas and security certification.

The following hardware contributes to providing vehicles with the necessary information for vehicle awareness: Cameras, Radars, Lidar, Ultrasonic sensors, V2X wireless sensors, antennas, 3D HD Map, Global Navigation Satellite System (GNSS). This hardware builds a virtual image of the surrounding environment which vehicles can communicate to other road users. It is necessary for at least some of these elements to be present in connected vehicles in order for any C-ITS communication technology to realise safety benefits.

3.3.2 Strategies

There has been some debate surrounding the use of aftermarket solutions versus OEM technology. Some stakeholders note that aftermarket penetration will be difficult to achieve with challenges arising in retrofitting vehicles, including the need for powering the devices and fitting antennas, as well as integrating into the vehicle's data systems. This may not be an economical solution for deployment in large volumes. For aftermarket devices used in real-world trials, the installation of antennas requires time whereas OEM equipment is factory fitted into vehicles.

A number of stakeholders believe that aftermarket devices may be a viable option for penetrating the market, particularly given the age of the existing fleet. OEM fitment is generally the preferred option. On the other hand, tests have found that there is currently no significant difference between choosing an aftermarket solution or OEM solution. However, looking towards the future with 5G networks, there may well be a difference between aftermarket devices and OEMs in terms of quality, liability and operability. Specifically, the quality of the aftermarket solution cannot be guaranteed and may present a challenge for the insurance industry. Stakeholders also noted that OEMs have previously experienced the unsuccessful installation of aftermarket solutions in their vehicles.

3.4 Human factors

The human-machine interface (HMI) is an important factor to maximise the effectiveness of C-ITS communication technologies in increasing road safety and traffic efficiency. Some researchers are concerned over human factors issues which may threaten the intent of CVs. It is suspected that some application systems may change driver behaviour or reactions, a product of the new technology that may not have been originally intended. A number of potentially concerning human machine interaction issues were identified by stakeholders and in literature including lack of trust resulting in limited benefits realised, driver overreliance on technology leading to loss of skill, adoption of risky driving behaviour, driver distraction, and false positives eroding trust and altering driver behaviour.

4 Victorian Road Safety Data Analysis

To gain a quantitative understanding of the potential safety benefits of the C-ITS communication technologies in the Australian context, we conducted a comprehensive data analysis with the crash record open database from the Victorian Department of Transport. The crash dataset used in this analysis includes information from all crashes in the state of Victoria, from January 2006 to August 2019, where at least one person was injured. We analysed basic statistics for crashes in the state of Victoria, including statistics on crash severity by different crash types, modes, and regions. Selecting a set of dominant C-ITS communication technologies use cases that have been trialled for crash reduction benefits, both nationally and internationally, we estimated the addressable market for each use case to understand the scale of potential impacts associated with each use case of the technology.

In the preliminary road safety analysis, data suggested that each type of road user is prone to a certain set of crash type classifications which were not necessarily similar across modes of transport involved and geographic location. As a result, a diverse set of C-ITS communication use cases can potentially lead to most extensive crash reductions with distributed benefits over all transport modes and both in Melbourne Metropolitan area and rural/remote regions.

We investigated eight use cases noted in the European Roadmap to Deployment (Section 2.4 Table 1.3). The first use cases assessed was Lane Keep Assist, an advanced driver assistance system (ADAS). This an ADAS-only application – all following use cases are an improvement on ADAS functionalities and are assumed to require communication technologies. That is, use cases such as forward collision warning and intersection movement assist amongst others require some level of ADAS or similar sensing hardware to function effectively. The other seven cases considered are: Curve Speed Warning (CSW), Cooperative Forward Collision Warning (CFCW), Do Not Pass Warning (DNPW), Intersection Movement Assist (IMA), Right Turn Assist (RTA), Cooperative Blind Spot Warning (CBSW/LCW), Pedestrian Safety Messages (PSM). Table 3.1 details the specific Victorian road safety incident classifications (DCA codes) that can be addressed with each use case considered and notes the expected timeframe for deployment.

Table 3.1 Types of incidents (DCA codes) that can be addressed by road safety use cases

Deployment and Use Case		Type of crash addressed (DCA codes)
ADAS	Lane Keep Assist (LKA)	133, 160, 170, 171, 172, 173
Day 1	Curve Speed Warning (CSW)	180, 181, 182, 183, 184, 189
2	Cooperative Forward Collision Warning	130, 131, 132
2	Do Not Pass Warning (DNPW)	150, 151, 152, 153, 159
2	Intersection Movement Assist (IMA)	110, 111, 112, 113, 114, 115, 116, 117, 118, 119
2	Right Turn Assist (RTA)	121, 123, 124
2/3	Cooperative Blind Spot Warning	134, 135, 136, 137, 142, 147, 154
3+	Pedestrian Safety Messages (PSM)	100, 101, 102, 103, 104, 105, 106, 107, 108, 109

Assuming the crashes classified above are addressed by the use cases presented, we examined the expected proportion of road safety incidents that could be reduced based on several factors including the severity of injury, geographic region, and type of vehicle involved.

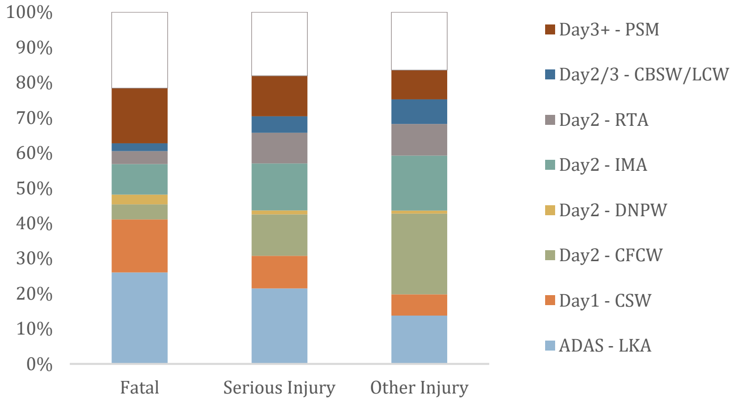


Figure 3.1 Proportion of crashes that specific use cases can address by severity

Approximately 80% of all crashes, for all levels of injury can be addressed by the eight use cases presented. The deployment of vehicles equipped with ADAS functions along with the connectivity required for Day 1 applications accounts for a little over 40% of all fatal injury crashes. Interestingly, lane keep assist functions have the potential to prevent the highest proportion of fatal incidents.

When C-ITS deployment reaches Day 2, more than 60% of all incidents have the potential to be avoided. The ability for vehicles to provide intersection movement assist and cooperative forward collision warning will help in preventing a significant portion of the serious and other injury crashes on Victorian roads. Meanwhile, the Day 1 use case, curve speed warning, is expected to have the potential to prevent approximately 10% of fatal crashes.

We note that these percentages are only a proportion of crashes that could potentially be addressed, and the measures provided are only indicative of the scale to which C-ITS applications can improve safety across the network. With this in mind, understanding the potential of Day 3+ applications is of particular interest given the ability for pedestrian safety messages to address crashes involving the most vulnerable road users. Pedestrian safety messages have the potential to address approximately 20% of fatal injuries; this use case has been underexplored in global trials, although some Australian trials have investigated such messages. Fatal pedestrian injuries were observed to be most prevalent in higher density metropolitan areas, thus, use cases addressing crashes involving pedestrians are an important avenue of investigation.

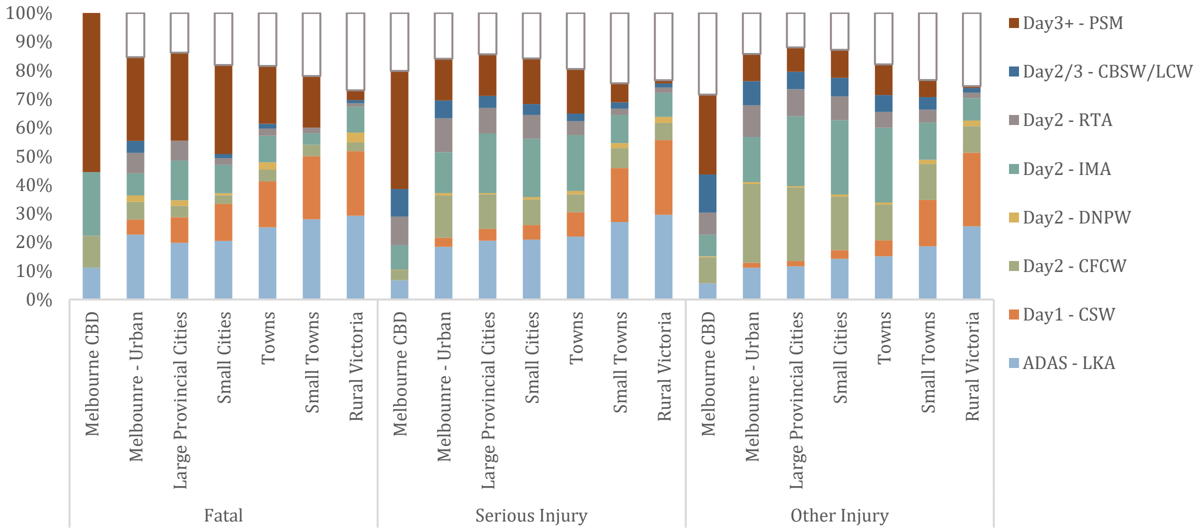


Figure 3.2 Proportion of crashes that specific use cases can address by severity and geographic region

The uptake of ADAS-only technology, specifically lane keep assist functions, has significant potential in addressing road incidents across all areas; this potential increases with decreasing density for all injury types. That is, high density areas like Melbourne CBD are recorded a small proportion of crash-types that could be addressed by LKA, while towns and rural Victoria are likely to see a greater impact. This trend is also observed in curve speed warning applications – locations with decreased urban density have the greatest potential to benefit from this use case.

We observe the reverse trend for the use of intersection movement assist (Day 2) and pedestrian safety messages (Day 3+), with an increase in capability to crashes in more urban environments. A significant proportion of fatal and serious injury crashes occur in increasingly dense and urban environments. Notably, pedestrian safety messages have the potential to address more than half of the fatal crashes that occur in Melbourne CBD, and approximately 30% to 40% of other and serious injury crashes in the same area. Additionally, CFCW is expected to have the greatest potential to address serious and other injury crashes in medium to sparse density environments, although have limited potential in addressing fatal crashes.

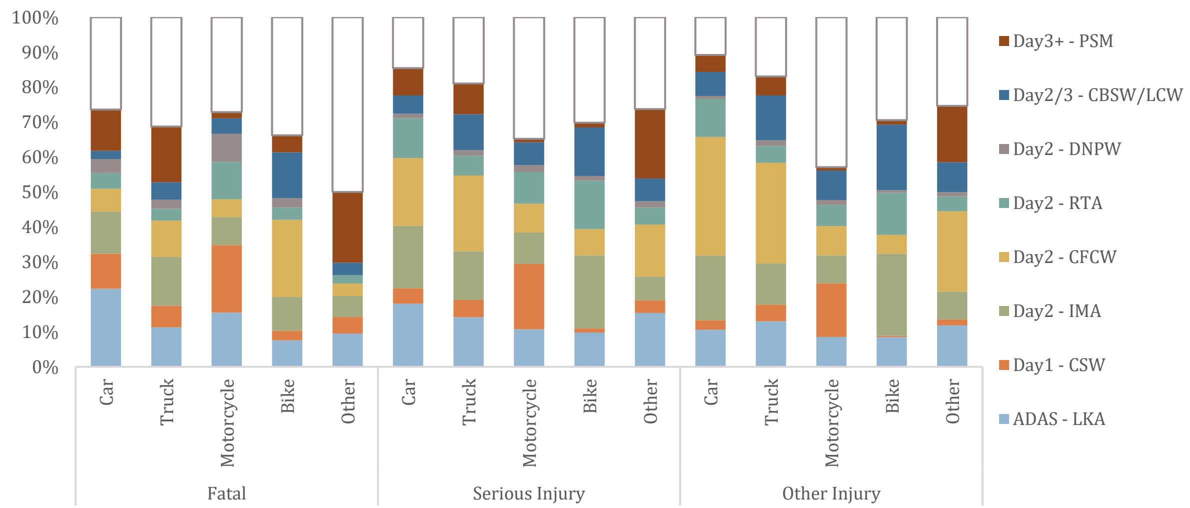


Figure 3.3 Proportion of vehicles involved in crashes that specific use cases can reduce by severity and vehicle type

As previously noted, Lane Keep Assist has significant potential to address crashes in all geographic areas, particularly for incidents involving cars. This use case has diminished potential in addressing crashes involving bikes or other vehicles. In fact, all used cases considered have a greater potential in addressing crashes involving cars and trucks than other modes with the exception of pedestrian safety messages. CFCW is still expected to have the greatest potential in addressing serious and other injury crashes; this use case is also considered more likely to reduce the number of crashes that involve cars and trucks. However, approximately 20% of fatal incidents involving bikes could also be addressed by cooperative forward collision warning – this is consistent with the preliminary data analysis finding that the leading deadly crash type for bikes is “Rear end”.

On Day 1, curve speed warning is most applicable for motorcycle crashes for all severities. As the deployment timeline progresses to Day 2, we observe intersection movement assist to have a similar potential as curve speed warning to reduce the number of crashes across all vehicle types and injury levels. A similar trend is also observed for right turn assist, although for a smaller percentage of incidents. Day 2/3 cooperative blind spot warning and lane change warning is more relevant in addressing incidents involving bikes and trucks. For Day 3+ applications, pedestrian safety messages are observed to have the greatest potential for incidents involving cars, trucks and “other” vehicles.

While there is capability for ADAS-only lane keep assist and Day 1 curve speed warning to address a large proportion of crashes in Victoria, our analysis shows that these use cases are more applicable to medium to sparse environments such as small towns and rural regions. Given most of the population lives in denser and more urban regions, there is a need to consider pathways towards to implementing Day 2 to 3+ use cases as they are more likely to provide benefits across all geographic regions and vehicle types. Perhaps most importantly, these cases will address road safety cases involving the most vulnerable road users. Overall, the eight use cases were found to have the capability to address approximately 80% of all crashes on Victorian roads (78% of fatal crashes, 82% of serious injury crashes, and 84% of other injury crashes) and have also been studied in other literature, trials, and simulations.

5 Traffic Simulation

The emergence of connected vehicle (CV) technology is promising for traffic control and can provide benefits for traffic circulation. CVs are a rich data source that can be collected and used for smart, pre-emptive, and proactive traffic control schemes. Traffic signals (installed at intersections) are critical points in any traffic control system. Generally speaking, a traffic signal control scheme (TSCS) consists of two components: i) an optimisation framework to minimise vehicles' delay behind the signals or to increase the throughput (number of vehicles that signals can process), and ii) loop detector models to estimate or measure number of vehicles entering the signals and those stuck behind the queue as input to the optimisation framework. The total number of CVs compared to the total number of vehicles in a network/fleet (i.e. CVs and ordinary vehicles combined) is called the "penetration rate" (PR). We tested the addition of CV data into a traffic signal control scheme (TSCS) over varying levels of penetration, called TSCS+CV, to evaluate the minimum level of penetration at which benefit of the CV data could be observed. CV data (such as speed and position) was added to the inputs to increase TSCS awareness of traffic conditions; we expect that the additional information to such systems achieves a reduced delay at intersections and allows for a higher number of vehicles to pass through the signals. We compared the performance of the TSCS+CV with actuated technology (a TSCS without CV) and an advanced academic method (Balance[2]) over several PRs.

5.1 Corridor Management

Existing signal control strategies are known to be effective when dealing with a series of intersections along a specific corridor. This test was carried out with data from three intersections from the AIMES testbed in Victoria, along the intersection of Queensberry Street with Lygon Street, Drummond Street, and Rathdowne Street. Comparison of results was made to the Balance method to show the effectiveness of incorporating CV data into traffic control schemes. From the simulations, it was found that CV data, when used in traffic control, increased the total number of vehicles processed by an intersection, and improved environmental factors of emission and fuel consumption. Overall, a CV penetration rate of 30% was found to improve mobility and environmental factors by almost 11% compared to the Balance method.

5.2 Network Management

Unlike corridor management, traffic signal coordination for a network of intersections can be challenging. We tested the TSCS+CV over a network of 17 intersections near Melbourne City and compared this with the best of the available technology in place, an actuated system based on the inductive loop detector sensors. This simulation found a CV penetration rate of 20% increased intersection throughput and reduced density of traffic when compared to the Actuated method.

Across the corridor and network simulations, CV data was found to increase efficiency in traffic control, minimise delays at traffic signals, increase average vehicle speeds, and reduce pollution when used in a robust framework. The TSCS+CV is a suitable alternative to the best of available

[2] Based on a traffic simulation model (more precisely a dynamic traffic assignment) to find the traffic state (i.e. traffic volume, speed, etc.) for a prolonged period in the future. Data is then fused with an optimisation algorithm (the Genetic Algorithm) to set traffic signals (i.e., phase structure, green/red time, etc.).

technology and the state of the art of methods proposed in academic literature. With a relatively low PR of 30%, a significant improvement in traffic efficiency (up to 10%) can be achieved.

6 Conclusion

This document provides an overview of C-ITS communication technology and the state of development and deployment. The potential safety benefits associated with eight specific use cases have been shown through analysis of Victorian Road Safety data, while mobility and environmental benefits at varying levels of technology penetration were estimated in traffic simulations. Additionally, expert panel opinions identifying potential challenges and opportunities of C-ITS deployment, both in the Australian market and worldwide, have been discussed.

Connected technology covers both short-range and long-range messaging, and a full suite of connected applications - addressing safety and traffic efficiency - probably requires both of these messaging capabilities. The following three connected solutions have been proposed:

1. **DSRC short-range direct communication**
   Most field operational tests, model deployments and data analytics have been carried out using DSRC alone. All truck platooning trials use DSRC.
2. **C-V2X short-range direct communication (PC5) and long-range cellular communication (Uu)**
   This all-cellular implementation method is a proposed alternative to short-range communication provided by DSRC. The C-V2X short-range technology currently lacks large-scale and real-world testing to support its deployment but is supported by a substantial group of key companies. The lack of testing of long-range cellular is less critical.
3. **Hybrid: DSRC short-range direct communication with cellular long-range communication**
   This approach is currently adopted by the directives for C-ITS communications in Europe, and probably represents a stepping stone towards Option 2, once the technical performance of C-V2X for time-sensitive safety warnings has been fully tested.

There is currently limited deployment in the market, with few original equipment manufacturers committing to implementing connected technology (using DSRC or C-V2X) in new vehicles. A review of literature finds that there is an unnecessary divide between stakeholders of C-ITS communication technologies with regard to their apparent technology preferences (DSRC or C-V2X); these stakeholders include Original Equipment Manufacturers and Mobile Network Operators. We note that stakeholders may have vested interests with one or other connected technology.

Performance comparisons show C-ITS technology has the potential to provide significant positive outcomes in roadway crash reduction and in alleviating traffic congestion. These benefits have been assessed in multiple trials and simulations around the world, with most large-scale real-world trials testing the safety potential of DSRC. A review of the expected road safety and traffic benefits finds that connectivity can also augment the existing advanced driver assistance systems, with clear safety benefits for V2V and V2I applications. However, the benefits of V2P applications are less understood at this stage.

The framework presented by the European Roadmap to Deployment demonstrates that awareness messaging benefits can be realised at low penetration rates, while safety warnings and cooperative driving applications require higher rates of penetration for benefits to be realised. Analysis of eight use case that are expected to be achieved at varying times in the deployment roadmap indicated that there is capability for the use cases to address approximately 80% of all crashes in Victoria. ADAS-only Lane Keep Assist and Day 1 Curve Speed Warning alone can address a large proportion of crashes, although these use cases are more applicable to medium to sparse environments such as small towns and rural regions. Given most of the population lives in denser and more urban regions, there is a need to consider pathways towards to implementing Day 2 to 3+ use cases (e.g. Cooperative Forward Collision Warning, Do Not Pass Warning, Intersection Movement Assist, Right Turn Assist, Cooperative Blind Spot Warning, and Pedestrian Safety Messages) as they are more likely to provide benefits across all geographic regions and vehicle types. Perhaps most importantly, these cases will address road safety cases involving the most vulnerable road users. Along with the potential safety benefits, there are considerable mobility and environmental improvements that can be realised with C-ITS deployment. Traffic simulations indicated that penetration rates as low as 30% can reduce peak congestion by up to 11%, while the average travel speed of vehicles can be improved by 10% with connected vehicle penetration rates above 20%.

Additional factors associated with technology deployment include network coverage, where rural and remote areas may require significant infrastructure investment in order to provide adequate coverage for cellular connectivity applications. Considering the significant potential benefits in terms of crash reductions and congestion alleviation reported in the literature, a comprehensive benefit cost analysis with a specific focus on safety outcomes for Australia is recommended. Timely action is needed, with studies in the US indicating a significant loss of opportunity associated with lives lost when waiting to deploy C-ITS crash reduction measures (do nothing scenario).

The stakeholder interviews conducted reflected findings in literature and provided valuable insight into current expert thinking and the future direction for C-ITS technology implementation in Australia and worldwide. It was found that many stakeholders were agnostic towards the uptake and use of DSRC and/or C-V2X and were more interested in the potential for connectivity to provide road safety and traffic efficiency benefits. Several challenges in C-ITS deployment were identified, including user acceptance, and achieving penetration rates that would enable safety and productivity benefits to be realised. Specifically, the availability of infrastructure investment, difficulty in achieving sufficient penetration rates from retrofitting vehicles, and the need for interoperability were of concern. Despite these issues, stakeholders viewed C-ITS technology, deployed in vehicles at both the OEM and aftermarket levels, as an exciting opportunity to improve road safety outcomes.

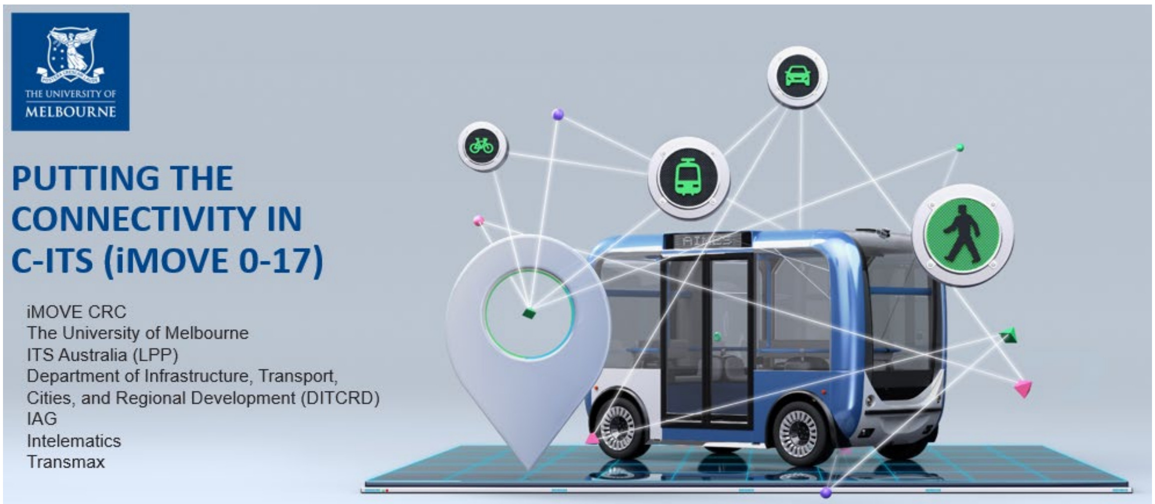
Literature review

Putting the Connectivity in C-ITS - Investigating pathways to accelerate the uptake of road safety and efficiency technologies

Literature Review

University of Melbourne
Majid Sarvi
Jessica Tong, Neema Nassir, Patricia Lavieri,
Saeed Asadi, Peter Sweatman

ITS Australia
Stacey Ryan, Susan Harris



October 2020

The University of Melbourne

Summary

There are considerable national and international efforts in accelerating and incentivising the uptake of innovative technologies that can improve road safety as well as the overall performance of transport systems. Communication technologies are enabling the introduction of connected vehicles, which have the potential to both reduce roadway accidents and improve traffic flows. This report provides an overview of some of the trials and simulations that have been conducted for DSRC and Cellular-V2X technology, and notes the benefits which are expected for safety and mobility applications; these include vehicle awareness and warning messaging, as well as sensing and cooperative driving applications. This investigation finds that benefits for awareness applications can be realised at low penetration rates, while other warning and cooperative functions require increasing levels of technology penetration to be effective. To achieve the estimated benefits, several factors must be considered, including the technology deployed, method of deployment (i.e. through aftermarket or original equipment manufacturer technology), and infrastructure deployment requirements for adequate network coverage. In addition to these considerations, some challenges and opportunities faced by key stakeholders in the deployment of Cooperative Intelligent Transport Systems (C-ITS) technologies include regulation and standardisation, human machine interaction factors, and security and privacy issues.

Abbreviations and Acronyms

3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G PPP	5G Private Public Partnership
5GAA	5G Automotive Association
5GCAR	Fifth Generation Communication Automotive Research and Innovation
AD	Autonomous Driving
ADAS	Advanced Drive Assistance System
AEB	Autonomous Emergency Braking
AI	Artificial Intelligence
ARIB	Association of Radio Industries and Businesses
B5G	Beyond 5G
BSM	Basic Safety Message
CAM	Cooperative Awareness Message
CAV	Connected and Automated Vehicle
C-ITS	Cooperative Intelligent Transport System
CPM	Collective Perception Message
CV	Connected Vehicle
C-V2X	C-ITS technology – Cellular- V2X (Vehicle-to-Everything)
CVLLA	Connected Vehicle Lower Level Automation
DCC	Decentralised Congestion Control
DEN	Decentralised Environmental Notification
DSRC	C-ITS technology – Dedicated Short Range Communication also known as ITS-G5
ECU	Embedded Control Unit
ER	Effective Range
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
FCW	Forward Collision Warning
FDM	Frequency Division Multiplexing
FMVSS	Federal Motor Vehicle Safety Standard
GNSS	Global Navigation Satellite System
HARQ	Hybrid Automatic Repeat Request HV Home Vehicle
HMI	Human-Machine Interface
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
IMA	Intersection Movement Assist

IoT	Internet of Things
IP	Internet Protocol
IPG	Interpacket Gap
ISO	International Organisation for Standardisation
ITS	Intelligent Transport System
ITS-G5	C-ITS technology, also known as DSRC
KPI	Key Performance Indicator
LCW	Lane Change Warning
LDW	Lane Departure Warning
LIDAR	Light Detecting and Ranging
LOS	Line of Sight
LTE	Long Term Evolution
LTE-V2X	C-ITS technology – a short distance protocol, also known as PC5
MAC	Media Access Control Layer
MAPEM	Map (Road/lane topology and traffic manoeuvre) Message
MCM	Manoeuvre Coordination Message
MCS	Modulation and coding scheme
MIMO	Multiple-Input Multiple-Output
MNO	Mobile Network Operator
MPR	Market Penetration Rate
MR	Maximum Range
MV	Moving Vehicle
NHTSA	National Highway Traffic Safety Administration
NLOS	Non-line of sight
NPRM	Notice of Proposed Rule Making
NR	New Radio
OBU	Onboard Unit
OEM	Original Equipment Manufacturer
OFDM	Orthogonal frequency-division multiplexing
PCM	Platooning Control Message
PDR	Packet Delivery Ratio
PHY	Physical Layer
PRR	Packet reception ratio
PSM	Personal Safety Message
Rel	Release
RSU	Roadside Unit
RTTT	Road Traffic and Transport Telematics
SAE	Society of Automotive Engineers
SPaT	Signal Phase and Timing

SV	Stationary Vehicle
TDM	Time-division multiplexing
TTA	Telecommunications Technology Association
UE	User Equipment
U-NII	Unlicensed-National Information Infrastructure
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2N2I	Vehicle-to-Network-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VAM	VRU Awareness Message
VRU	Vulnerable Road User
VSL	Variable Speed Limit
WAN	Wide Area Network
WAVE	Wireless access in vehicular environments
WiFi	IEEE 802.11x
WLAN	Wireless Local Area Networks

Glossary

C-V2X	Refers to a mix of cellular short-range communication, including either the 3GPP Release 14 and 15 (LTE-V2X) specifications, or 3GPP Release 16 (5G related short-range communication) specifications, and cellular long-range communications.
DSRC	DSRC in Europe refers to the European CEN DSRC tolling standards that operate on a specified frequency. In the US, DSRC refers Wi-Fi communication in the 5.9 GHz band licensed by the FCC.
ETSI ITS-G5	The European Standard for Vehicular Communication; IEEE 802.11p telecommunications (Wi-Fi) standard in the 5.9 GHz band; also known in the USA as DSRC
IEEE 802.11p	An approved amendment to the IEEE 802.11 standard to add wireless access in vehicular environments.
IEEE 802.11	The set of standards that define communication for WLANs.
LTE Sidelink	Direct communication over PC5 interface.
PC5 interface	Sidelink technology - the direct channel between which one UE communicates with another UE (i.e. V2V or V2I) where communication with the base station is not required.
U-NII-3 band	Unlicensed-National Information Infrastructure transmitting at the 5.725-5.850 MHz band
Uu interface	The logical interface between the user equipment and the base station (i.e. V2N) for cellular communication.

Contents

1 Introduction

Co-operative intelligent transport systems (C-ITS) involve emerging technologies for vehicle connectivity and communications with other vehicles (V2V), infrastructure (V2I), and other entities such as motorcycles, cyclists, and pedestrians (V2X). These communications, will enable connected and automated vehicles (CAVs) to potentially deliver a range of benefits, including increased road safety and traffic network performance, as well as greenhouse gas reduction, energy efficiency, and emissions reduction. C-ITS technologies offer short-range and long-range communications, where the scenario or nature of application governs the type of communication employed. Two C-ITS geopolitically-differentiated communication technologies are discussed: Cellular Vehicle-to-Everything (C-V2X) and Dedicated Short Range Communication (DSRC). This review will consider the potential for implementing DSRC as a short-range communication method, C-V2X for both short- and long-range communications, and a hybrid method consisting of DSRC for short-range with a cellular long-range communication capability. These implementation methods are based on the approaches to testing and simulating C-ITS communication observed in the USA (where DSRC has been subjected to in-depth testing and model deployment) and Europe (where the hybrid model is being considered).

There are numerous use cases for connected vehicles which have been trialled and simulated by government endorsed agencies, industry, and in academia. These trials aim to test and demonstrate the safety, environmental, and mobility benefits which CVs can provide. The safety functions of C-ITS communication technology are divided into two categories: awareness messages and warning messages. Awareness messages are defined as non-critical communications which act to provide an increased knowledge of the driver's surrounding infrastructure and environment. These include advisory warnings for speed, red light signals ahead, or other hazards. Warning messages, on the other hand, are considered critical, where the driver is warned of an imminent threat where reactions to such messages are time sensitive. These include warnings about potential conflicts or collision paths with other vehicles and imminent requirements for corrective action (such as emergency braking). Other benefits from connected vehicles, including mobility and environmental benefits, are also investigated for their ability to provide reduced fuel consumption, and travel-time savings.

The deployment of connectivity technology requires several decisions to be made, including the type of technology chosen and the method of deployment in vehicles. These decisions are considered based on the framework presented in the European Roadmap to Deployment. Other challenges and opportunities in the deployment of C-ITS technology include performance requirements, penetration rates required for benefits to be realised, network coverage requirements, interference and congestion issues, human machine interaction factors, and security, privacy, and user acceptance.

2 C-ITS Communication Technology

2.1 C-ITS Communications: A Global Perspective

C-ITS platforms are being developed in an effort to deliver cross-cutting benefits, including safety and traffic efficiency, to road users and the wider transport network in countries and regions such as Europe, the USA, Japan, and South Korea.

In the US, the Federal Communications Commission (FCC) allocated a 75 MHz bandwidth in the 5.9 GHz band dedicated for DSRC use in transport and vehicular applications in 1999. Europe followed with the allocation of the 5.9GHz bandwidth in 2008. The allocations for both these regions were originally aimed at facilitating DSRC development and deployment but have since been amended to include unlicensed applications (e.g. WiFi, Infotainment, etc) and C-V2X.

C-ITS standards and operation in Europe are based on the ITS Directive 2010/40/EU (European Parliament and of the Council, 2010), a policy and legal framework created to accelerate the deployment of innovative transport solutions. This policy requires that there is ***interoperability*** (i.e. every vehicle can communicate with any other vehicle or roadside unit) between technologies, as well as a maintaining capability for backwards ***compatibility*** between versions of the same technology.

ITS communication occurs in a spectrum that has previously been defined by the European Union and has been widely adopted by other regions/countries. In 2008, the Electronic Communications Committee (ECC) issued recommendation ECC/REC(08)01 and decision ECC/DEC/(08)01 for intelligent transport systems operation in the 5.9GHz band. Alongside this decision, the European Union designated a 30 MHz frequency band between 5875 – 5905 MHz in commission decision 2008/671/EC for ITS.

In March 2019, the European Commission issued a delegated act supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to the deployment and operation use of cooperative intelligent transport systems. This act endorses a "hybrid communication approach" (European Parliament and of the Council, 2019) with:

- Short-range communication technologies operating in the 5.9 GHz frequency band and are most relevant for time-critical services. ITS-G5 (i.e. DSRC), which is now considered mature, tested, and already deployed, is a candidate for this service. C-V2X technologies including LTE-V2X and 5G NR are also being considered.
- Longer-range communication technologies that leverage the coverage of existing networks to connect larger areas and are most relevant for less time critical V2I services. Existing cellular 3G and 4G technologies can provide this service.

In the US, the recent FCC proposal (December 2019) introduces the segmentation of 5.9 GHz spectrum to allow for Vehicular and Unlicensed Applications:

- 5.850 - 5.895 GHz to Unlicensed Applications: this includes Wi-Fi devices such as routers and their associated connected devices to provide high data rate local area network connections for smartphones, tablets, computers, television and other devices inside and outside the home to interconnect with and access to Internet), as well as C-V2X operation.
- 5.895-5.925 GHz to Vehicular Applications: this allocation is dedicated to utility for transport and vehicle safety technologies and includes a proposal to allow C-V2X operation specifically in a 20 megahertz subsection of this band (5.905-5.925 GHz).

This proposal seeks to reduce the number of channels available for safety applications from seven to three (ITS America, 2020) and is opposed by the US Department of Transport (USDOT), along with state DOTs and other automakers and safety groups (ITS America, 2020). Testing of V2X technology to determine whether unlicensed devices interfere with V2X technology, and whether there are benefits in expanding the spectrum available for Wi-Fi and other unlicensed devices is ongoing.

Australia is expected to follow the European standards for C-ITS deployment, given that the country's existing automotive standards and radio spectrum allocation closely resemble those of Europe (European Comission and Ricardo Energy & Environment, 2016). However, deployment and standardisation activities in both the US and Europe are being monitored. In Australia, the ACMA released the discussion paper *Proposed regulatory measures for the introduction of cooperative intelligent transport systems in Australia* on 5 August 2016, which proposed the allocation for ITS services in the 5.9GHz band to coexist with fixed-satellite services among other services.

A timeline of the main events for the evolution of C-ITS communication technology development and studies in Europe and the United States is shown in Table 2.1. The current global regulations for V2X deployment are shown in Table 2.2.

Table 2.1 Main events for C-ITS technology development in Europe and the US

Date	**Event**	**Technology**
October 1999	Frequencies allocated in the US for DSRC technology	DSRC
2004	IEEE 802.11p Task Group formed	DSRC
2008	Frequencies allocated in Europe for ITS communications	General
2010	IEEE 802.11p is approved	DSRC
2012	US Safety Pilot Model Deployment lead by the University of Michigan	DSRC
October 2016	3GPP Release 14 (first part) is published	C-V2X
November 2016	Europe ETSI ITS Plug Test in Livorno – ITS-G5 is declared ready	DSRC
January 2017	US NHTSA (National Highway Traffic Safety Administration, 2017) proposed rule to mandate DSRC technology	DSRC
March 2017	3GPP Release 14 is frozen	C-V2X
May 2018	IEEE 802.11 Next Generation V2X is announced (IEEE 802.11bd)	DSRC
March 2019	3GPP Release 15 is frozen	C-V2X
March 2019	European Commission endorses a "hybrid communication approach"	General
October 2019	Volkswagen deploys Wi-Fi (DSRC) V2X technology in 2019 model Golfs across Europe with chipset from NXP (expected to be the largest deployment of DSRC)	DSRC
December 2019	US FCC proposes segmentation of 5.9GHz spectrum for Vehicular and Unlicensed Applications	General
March 2020	3GPP Release 16 is frozen (included Enhancement of Ultra-Reliable (UR) Low Latency Communications (URLLC))	C-V2X

Source: NHTSA (2017), Bazzi et al. (2019), NXP (2019), European Parliament and of the Council (2019), USDOT (2020), 3GPP (n.d.)

Table 2.2 Regulatory frameworks for V2X deployment globally

Country/ Region	Standard/ Framework followed	Spectrum for ITS communication/purpose	Comments and requirements
Australia	ETSI Standard EN 302 571	5855 – 5925 MHz	• Class license required for stations; • Vehicle OBUs and RSUs do not need to register for the license.
China		5905 – 5925 MHz	• This 20MHz band has been allocated for LTE-V2X technology use; • A radio frequency license must be obtained from the national radio regulatory administration; • A radio station license must also be obtained from the local region's/ municipality's radio regulatory administration.
Europe	ETSI; ITS Directive 2010/40/EU	5.9 GHz (5875 – 5905 MHz)	• A supplementary document to ITS Directive 2010/40/EU (European Parliament and of the Council, 2019) outlines a hybrid deployment approach for short- and long-range communication technologies such as DSRC and C-V2X.
Japan	ARIB Development	5.770-5.850 GHz 755.5-764.5 MHz	• Two spectrum bands allocated for ITS use.
Korea	Advanced ITS	5855 – 5925 MHz	• All ITS services can be operated in this technology neutral spectrum regulation.
Singapore	IEEE 802.11p; IEEE 1609	5855 – 5875 MHz	• Spectrum established based on DSRC requirements; • Non-vehicular units require either a localised radio-communication station license, or wide area private network license; • Vehicle OBUs are license exempt.
United States	IEEE 802.11p; FCC	5.9 GHz (5.850-5.925 GHz)	• This spectrum was dedicated specifically to DSRC technology use by the FCC on October 21, 1999; • In December 2019, the FCC proposed segmentation of 5.9GHz spectrum for Vehicular and Unlicensed Applications (i.e. to allow the spectrum to be used by C-V2X and other emerging technologies).

Source: 5GAA (2019b), Kawser et al. (2019)

2.2 Technologies discussed in this paper

Three communication implementation methods will be discussed in this paper:

1. ***DSRC short-range direct communication***
   Noting that while it may not be a feasible C-ITS implementation method to provide short-range only communication, there have been a significant number of large-scale and real-world trials that test the ability of DSRC. Volkswagen is noted to have deployed an NXP chipset (2019) that operates with DSRC for V2X communication in Golf models across Europe. In the past, the USA has dedicated the ITS spectrum specifically for this method of communication although changes have been proposed.
2. ***C-V2X short-range direct communication (PC5) and long-range cellular communication (Uu)***
   This implementation method is a proposed alternative to short-range communication provided by DSRC. This technology currently lacks large-scale and real-world testing to support its deployment but is supported by a number of industries. Ford (2019) has announced deployment of C-V2X for vehicles in China in 2021.
3. ***Hybrid: DSRC short-range direct communication with cellular long-range communication***
   This approach is currently adopted by the directives for C-ITS communications in Europe.

These methods will provide the following communication modes:

- ***Device-to-device:*** V2V, V2I, and V2P direct communication without the need for reliance on network involvement for scheduling. Both DSRC and C-V2X (PC5 Mode 4) enable this method of communication.
- ***Device-to-network:*** V2N solution using traditional cellular links to enable cloud services for an end-to-end solution. This communication is provided by either C-V2X Uu or a hybrid technology implementation.

2.2.1 DSRC Short-Range

Dedicated short range communication (DSRC) is a one- or two-way wireless communication, also known as ETSI ITS-G5[1] or IEEE 802.11p (initially approved in 2010) and provides V2X communication (i.e. V2V and V2I). This communication method is based on the IEEE Wireless Access in Vehicular Environments (WAVE) protocol. DSRC operates in the 5GHz frequency band and uses dedicated channels between 5.850 to 5.925 GHz for communications (Kawser, Fahad, Ahmed, Sajjad, & Rafi, 2019).

2.2.1.1 *Next Generation DSRC*

The evolution of DSRC was announced by IEEE and the IEEE Standards Association in May 2018, with the study named *802.11bd Next Generation V2X (NGV)*. This future development is backwards compatible with 802.11p and aims to increase the throughput and transmission range with modifications at the physical (PHY) layer of the existing technology (Bazzi, Cecchini, Menarini, Masini, & Zanella, 2019).

2.2.2 C-V2X Short-Range and Long Range Communication

Cellular-V2X is a communication technology based on cellular 4G/long-term evolution (LTE). The technology standards are defined by the 3rd Generation Partnership Project (3GPP), a consortium of seven telecommunications standards development organisations: ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, and TTC (3GPP, n.d.). C-V2X is defined by 3GPP Release 14 as LTE-V2X (or LTE-V) has two radio interfaces Uu and PC5 (Molina-Masegosa & Gozalvez, 2017):

i. **Uu** is the ***cellular network communication*** interface which supports network V2N communications in the traditional mobile broadband licensed spectrum.
ii. **PC5** is a ***direct communication*** method which refers to a reference point where the User Equipment (UE) directly communicates with another UE over the direct channel. Communication

[1] G5 refers to the 5 GHz frequency, while 5G refers to the 5th Generation waves which includes high frequencies (see Figure 2.2)

with the base station is not required for this method of communication. The PC5 interface supports V2V, V2I, and V2P communications based on direct LTE sidelink. LTE sidelink (or device-to-device communication) consists of two modes of V2V operation:

a) ***Mode 3:*** Cellular-assisted V2V
   - Requires that vehicles are in coverage of a base station.
   - The cellular network selects and manages the radio resources used by vehicles for their direct V2V communications.

b) ***Mode 4:*** Ad-hoc V2V (also known as autonomous or out of coverage)
   - This is considered the baseline mode providing short-range communication and represents an alternative to DSRC.
   - Vehicles can select the radio resources for their direct V2V communications.
   - Can operate without cellular coverage.
   - Includes a distributed scheduling scheme for vehicles to select their radio resources.
   - Includes the support for distributed congestion control.

The two interfaces for C-V2X communication are depicted below.

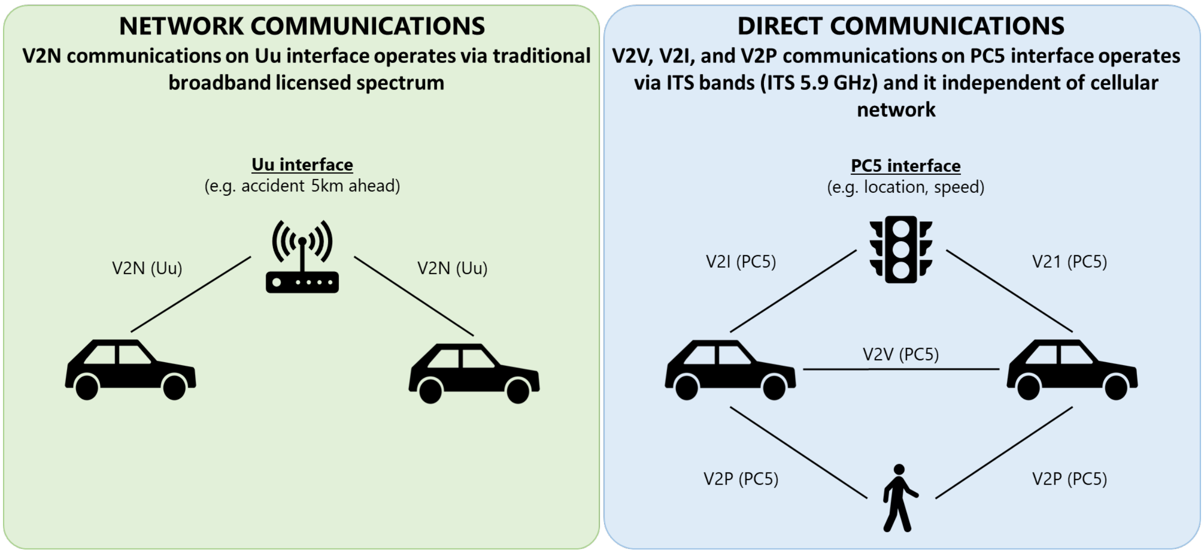


Figure 2.1 C-V2X interfaces for communication

2.2.2.1 *Next Generation C-V2X*

The next generation of C-V2X technology (3GPP Release 15 and Release 16) will encompass the 5G radio interface known as 5G New Radio (NR). A brief overview of the generations of mobile systems is shown in Table 2.3 with the spectrum of operation for each generation shown in Figure 2.2. 3GPP Releases 15 and 16 will introduce more V2X services by providing the ability to deal with high relative vehicle speeds up to 500 km/h, allowing for longer range communications, increasing efficiency of resource allocation, and providing enhanced services. These services include higher density, throughput, reliability, precise positioning, and most importantly reduced latency (Kawser, Fahad, Ahmed, Sajjad, & Rafi, 2019).

Release 16 operates on a different channel to Release 14 and Release 15 (Autotalks, 2019) and does *not have backwards compatibility* with previous versions. This fails to deliver the ***compatibility*** required by the ITS Directive 2010/40/EU (European Parliament and of the Council, 2010). Instead, an optional second interface is added to improve the performance of sidelink PC5 (Bazzi, Cecchini, Menarini, Masini, & Zanella, 2019).

Along with Release 16, Prospective standard SAE J3161 is currently being developed by the C-V2X Technical Committee. This document is an adaptation of SAE J2945 and will define the on-board system requirements for LTE-V2X-V2V safety communications (SAE International, 2012).

2.2.3 Hybrid: DSRC Short-Range and Cellular Long-Range

This review will also consider a hybrid communication method of direct communication with the use of DSRC for direct communication and cellular V2N for longer range communications. Cellular in this scenario acts as a complement to DSRC, supporting V2N services which DSRC alone cannot offer. This approach has been endorsed in Europe in the short- and long-range provisions in the supplement to ITS Directive 2010/40/EU.

2.3 Cellular Enabled Device-to-Network Communications

Both the C-V2X and Hybrid technology implementation methods will rely on traditional cellular links to enable device to network communication. Cellular provides the ability for long-range vehicle communications; the generations of cellular networks and spectrum of operation for each are shown in Table 2.3 and Figure 2.2 respectively.

Table 2.3 Generations of Mobile Systems

Generation	Description and major milestones
1G	• From 1980s; • First generation of cell phone technology; • Radio signals are analogue.
2G	• From 1990s; • First digital systems introducing voice, SMS and data services.
3G	• From 2000s; • Operates at frequencies up to 2.1GHz; • Facilitates greater voice capacity, greater data capacity, and increased data transmission; • Includes multimedia services support.
4G	• From 2010s; • Operates at frequencies up to 2.5GHz; • Provides high speed, high quality, and high capacity; • Achieves this with Multiple Input Multiple Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) technology; • Backwards compatible with 2G and 3G;
5G	• Operates at higher frequencies than previous generations; • Expected to improve data rates, enable higher connection density, and reduce latency; • Massive MIMO, Li-Fi, and other technologies will provide lower latencies and increase the number of connections available.

Source: 3GPP (n.d.), Net-informations (n.d.), Thales (n.d.)

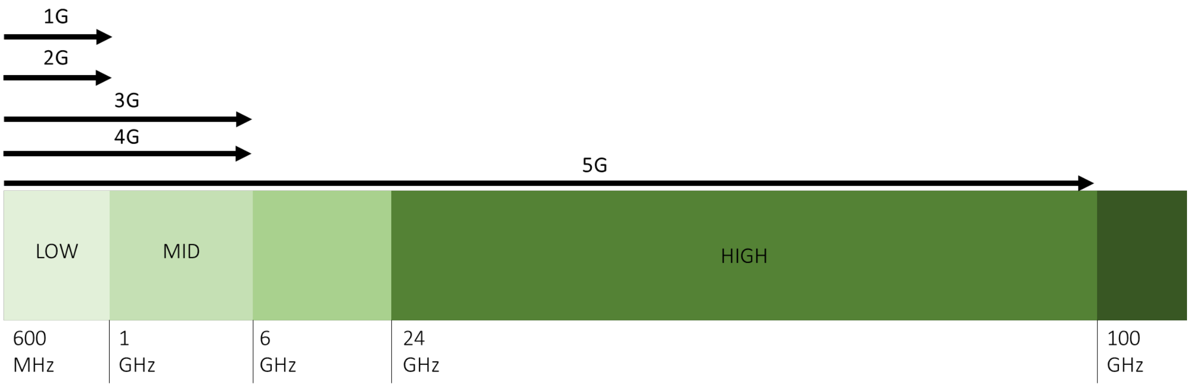


Figure 2.2 Spectrum of operation frequencies for each mobile generation (Thales, n.d.)

2.4 System Architecture

Connected and automated vehicles are continually developing. The integration of C-ITS technologies with other automation features is essential in contributing to increases in the safety and efficiency of transportation networks. Figure 2.3 illustrates the role of C-ITS technology in connecting vehicles at all levels of automation to other vehicles, infrastructure, road users, and the environment.

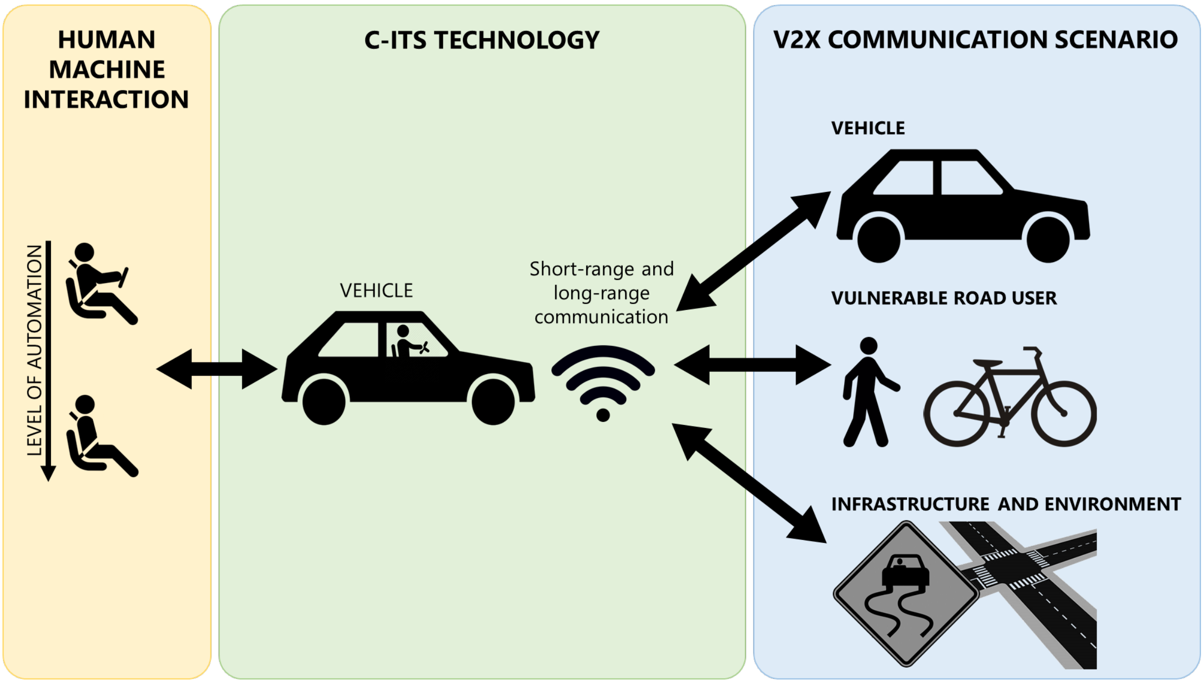


Figure 2.3 Connected and automated vehicle system architecture

For human and machine interaction factors, two distinct levels of automation are considered when determining whether the C-ITS communication is affected:

- ***Human driver***: defined in this study as a level zero to level three, and sometimes level four of automated driving (SAE International, 2018) where the vehicle requires supervision and input from a human occupant to a certain extent. For these levels of automation, a human driver is at the receiving end of the communication and ultimately determines the appropriate response.
- ***Machine driver:*** defined in this study as a level four or level five automated driving vehicle which is fully automated and requires no human input or attention. For this level of automation, the V2X communication will be relayed only to the vehicle/machine, and the intervention will be automatic.

Section 4 discusses the benefits which C-ITS communications are expected to bring for different scenarios. CVs are expected to augment traditional Advanced Driver-Assistance Systems (ADAS):

- ***ADAS:*** are systems that help the vehicle operator and provide warnings while driving or during parking and are designed with a safe human-machine interface. ADAS is intended to increase car safety and more generally, road safety. These systems do not require a communication method with other road users.
- ***Connectivity:*** is provided when there is communication between the vehicle and other road users to obtain information which can then be used in road safety applications. ADAS can be enhanced with connectivity to improve overall network safety.

In summary, realising the benefits of connected vehicles will depend on a number of factors including driver responses to communications, penetration, and the type and method of communication.

3 Trials and Projects

There are few large-scale real-world trials for either technology (DSRC, C-V2X, and Hybrid), limiting the number of definitive conclusions which can be drawn for estimated road safety and traffic efficiency benefits. All of the real-world trials have been designed to address safety benefits; fewer studies have addressed traffic efficiency benefits, and simulation has been used, rather than actual field testing. The trials taking place, both globally and in Australia, contribute to the assessment of C-ITS communication performance and deployment for specific use cases. Trials in Australia are of particular interest as they are conducted in Australian environments within the existing infrastructure and network and support the estimated benefits for road safety and mobility discussed in Section 4.

Significant trials and past/present projects influencing policy and deployment of C-ITS technology are discussed below.

3.1 United States

3.1.1 Safety Pilot Model Deployment, 2012

The Safety Pilot Model Deployment (SPMD) led by the University of Michigan was launched in August 2012 in Ann Arbor, Michigan. This trial consisted of more than 2,800 vehicles (cars, trucks and buses) equipped with a mix of integrated, retrofitted, and aftermarket connected vehicle devices along with 29 connected infrastructure sites. The SPMD cost over $30 million dollars and tested six distinct safety use cases for vehicle-to-vehicle (V2V) communication: Forward Collision Warning (FCW), Emergency Electronic Brake Lights (EEBL), Do Not Pass Warning (DNPW), Left Turn Assist (LTA), Intersection Movement Assist (IMA), and Blind Spot Warning and Lane Change Warning (BSW and LCW). Two vehicle-to-infrastructure road safety use cases: Curve Speed Warning (CSW) and Pedestrian in Signalised Crosswalk Warning (PCW) were also tested.

Following the SPMD and analysis of an unprecedented V2X database, the USDOT confirmed that use cases tested were capable of avoiding target sets of crash types, and this would occur on a sufficiently robust national scale as to justify federal rulemaking. The generalised and broad safety benefit of DSRC then underpinned a rulemaking that proposed the creation of a new Federal Motor Vehicle Safety Standard (FMVSS) which requires that all light vehicles (passenger cars and light truck vehicles) have a vehicle-to-vehicle communication capability and meet minimum performance requirements for V2V devices and messages. While all federal requirements for safety rulemaking were met, the current Administration has not proceeded to release the rule, amid its preferred stance of removing, rather than adding to, federal regulations imposed on industry, including the automotive industry.

3.1.2 ITS V2X Spectrum Testing, USDOT, 2020

Following the proposed FCC segmentation of the 5.9GHz bank, the US Department of Transport announced "ITS V2X Spectrum Testing" in February (2020) which will see the procurement of V2X communication devices including LTE-C-V2X devices, dual mode DSRC and C-V2X devices, and 5G NR devices to evaluate the safety performance and capabilities of the devices through both small- and large-scale testing, including scalability and congestion, interoperability, and complex transportation scenarios.

3.2 Europe

3.2.1 Driving Implementation and Evaluation of C2X Communication Technology in Europe, DRIVE C2X, 2014

Drive C2X is a project that aimed to create and harmonize a European testing environment for C-ITS, test the compatibility of emerging cooperative systems and evaluate the impacts which these technologies have on improving safety and mobility. The Drive C2X tests were carried out across seven countries in Europe to capture a wide range of climates and environmental conditions. Several use cases were tested: Approaching Emergency Vehicle Warning (AEVW), Traffic Jam Ahead Warning (TJAW), In-Vehicle Signage (IVS), Road Works Warning (RWW), Obstacle Warning (OW), Car Breakdown Warning (CBW), Weather Warning (WW), and Green Light Optimal Speed Advisory (GLOSA). Note that these use cases are all less crash-specific than the US use cases, and can only be associated with improvements to the safety environment, but not the avoidance of specific crashes or types of crashes. The study found that in-vehicle warnings for the IVS and WW use cases showed the highest potential in their ability to reduce the number of fatalities. Other warnings that demonstrated potential for reducing the number of safety incidents included RWW, EEBL, and TJAW.

3.2.2 Livorno, IT: ETSI Plug Test, 2016

The ETSI ITS Plug test conducted in 2016 involved more than 20 vendors and simulated real-world large-scale DSRC technology use. Eight use cases were tested, three of which are focused on communication between infrastructure services: (1) communicating to surrounding vehicles that there is a hazard/pedestrian on the road, (2) notifying ITS stations of the location of a vehicle carrying dangerous goods, and (3) notifying ITS stations and surrounding vehicles of the position of an available parking space. These test cases simulate integration of the motorways network (1,2) and integration with IoT technologies (3). This trial successfully demonstrated that DSRC (ITS-G5) conformed to ETSI ITS Release 1 standards and verified the interoperability between OBU providers and RSU vendors involved in the trial. Again, the use cases tested support a generalised safety environment rather than the avoidance of crashes precipitated by human error.

3.3 Australia

3.3.1 Safety Benefits of Cooperative ITS and Automated Driving in Australia and New Zealand, Austroads, 2017

Austroads' research into C-ITS and Automated Driving identified six application fields for C-ITS: collision avoidance and hazard detection, vulnerable road user safety, in-vehicle signage, road weather alert systems, post-crash notification systems, and mobility and eco-driving. Safety benefits of four C-ITS crash-avoidance use cases: Cooperative Forward Collision Warning (CFCW), Curve Speed Warning (CSW), Intersection Movement Assist (IMA), and Right Turn Assist (RTA) were estimated for the Australian road environment. The estimations provided in this report were based on the assessment of a combination of real-world crash data from Australia, and operating parameters that would affect the likelihood of technology application and assumed a 100% penetration rate for vehicles as well as an adequate amount of roadside infrastructure to support communication use cases. This report also found a range of limitations of C-ITS applications, including performance issues, security and privacy concerns, and human factors issues.

3.3.2 NSW: Cooperative Intelligent Transport Initiative (CITI)

The Cooperative Intelligent Transport Initiative began in 2012 and is one of Australia's largest C-ITS projects. This $1.65M trial of V2V and V2I deployment in heavy vehicles is conducted along a 42km freight corridor in Illawarra, New South Wales. This project consisted of two phases:

- Phase 1: the initial setup of the testbed and implementation of connectivity devices to 60 trucks and three intersections.
- Phase 2: the addition of C-ITS technology to 11 buses, 50 light vehicles, and at an additional four intersections.

C-ITS communication was provided by DSRC devices fitted onto trucks, buses, light vehicles, motorcycles, traffic signal units, RSUs, and a railway level crossing. These were used to convey intersection collision warnings, forward collision warnings, braking ahead messages, advance warning of red lights, and in-cab messages for truck and bus speed limits at a particular location (Transport for NSW, n.d.).

3.3.3 QLD: Cooperative and Automated Vehicle Initiative (CAVI)

Queensland's Cooperative and Automated Vehicle Initiative consists of three pilots: Cooperative Intelligent Transport Systems (C-ITS) Pilot, Connected and Highly Automated Driving (CHAD) Pilot, and the Vulnerable Road User Pilot.

The C-ITS pilot will trial retrofitted equipment on approximately 500 vehicles and infrastructure for a number of V2V and V2I safety use cases including: emergency brake warning, in-vehicle speed warning, turning warning for bicycles and pedestrians, red light warning, road works warning, stopped or slow vehicle warning, back of queue warning, and hazard warning. The estimated benefits of these trials include a 20% reduction in road collisions, 2% reduction in crash related grid lock, and 3% reduction in overall fuel emissions. C-ITS technologies in use are estimated to save $2 billion over 30 years with a cost benefit ratio of 1:3.4 over a 30-year period with moderate penetration (Queensland Department of Transport and Main Roads, 2017).

3.3.4 VIC: Australian Integrated Multimodal Ecosystem (AIMES)

The Australian Integrated Multimodal Ecosystem (AIMES) is a real-world connected test bed area located at the edge of Melbourne's CBD incorporating approximately 100 kilometres of roads and intersections. The test bed included hundreds of sensors to collect data on vehicle and pedestrian movement, and public transport use. Three trials have recently been completed by AIMES in conjunction with a number of industry partners.

AIMES (2019) tested the use of edge and fog computing for interactions between vehicles and vulnerable road users. Four use cases of V2X technology were conducted in this study with the use of retrofitted DSRC OBUs, Cohda Wireless MK5 Roadside Unit, and Cisco IR829 router. The trials concluded that the use of edge computing and edge fog fabric technology to transmit the road safety message accounts for approximately 10ms of the total 210ms it takes for the detection and transmission of the message to the vehicle. AIMES states that the use of cloud-based computing instead of the edge and fog computing would increase the latency of the message transmission, adding up to two seconds to the transmission. It is estimated that an investment into "smarter connected infrastructure" will allow V2X technology such as edge and fog computing to provide an accelerated response to threats to VRUs.

Another trial conducted in the AIMES testbed, led by Cisco, set out to determine whether Video Analytics and Artificial Intelligence technology was able to provide insights into road user behaviour, including the possibility for predictive capability. The equipment used for these trials was physically mounted on poles/roadside cabinets at the intersection and included Cisco Intelligent Edge Video Analytics (CIEVA), Cisco IP Cameras, and IC3000 with edge computing capability and fog compute node. Cisco identified a number of following possible use cases for the technology on intersections that are intended to increase road safety including: automatic adjustment of pedestrian crossing lights to allow groups to safely cross the intersection, priority treatment at intersections to direct heavy vehicles off local roads and away from areas of high pedestrian activity, evaluation of risks at intersections based on analysis of traffic and road user types, alteration of traffic signals based on observed volumes, and identification of near-miss incidents to improve machine learning capabilities and provide valuable information for improving safety at the intersection in future. Cisco (2019a) expects that Video Analytics and AI technology will, in future, allow for more immediate response to road safety incidents identified at intersections.

Cisco (2019b) also trialled the use of WiFi detectors and edge and fog computing to determine the accuracy and latency of positional information transmission in real-time. This technology is expected to be used to improve monitoring of road-user interactions. Based on the tests, Cisco identified the following possible use cases for the technology on intersections that will increase road safety: provision of priority for emergency vehicles via routing and real-time navigation, alerting drivers of predicted threats such as collision, informing traffic signal timing and distribution, and providing safety assessments at key intersections.

3.3.5 VIC: Towards Zero CAV Trials

A $3.5 million grant was awarded by the Victorian Government to Telstra and Lexus Australia to conduct Australia's first connected vehicle field trial using advanced 4G mobile networks (C-V2X) rather than Wi-Fi DSRC technology (DSRC). Use cases including emergency braking alerts, in-vehicle speed limit compliance warnings, curve speed warnings, right-turn assist for vulnerable road users, and warnings when surrounding vehicles are likely to violate a red light were tested at the Lexus test track in the Melbourne suburb of Altona. Lexus vehicles in this trial were fitted with C-V2X technology, as well as advanced driver assist features including crash warning systems and lane keeping assist. The trials involved the use of an optimised version of 4G designed by Telstra for connected vehicle technology and Ericsson's C-V2X technology, which was observed to achieve end-to-end latencies less than 50ms for 95 percent of the trials conducted (Ericsson, 2020).

4 Application Fields and Use Cases for C-ITS

Planners and policy makers are placing a greater emphasis on understanding the potential of connected technology to act as a new solution to modern safety issues, alongside a multitude of more traditional approaches. This has led to a surge in research efforts which aim to estimate the benefits of existing and emerging C-ITS use cases in an attempt to measure the impacts of wider adoption and deployment of connected technologies.

While safety has been the main driver of the deployment of connected technologies, four types of Connected Vehicle Applications: Safety, Environmental, Mobility, and Support have been classified by USDOT (2016), where each type is comprised of application fields that further contain specific use cases. The list of use cases presented in this review is not exhaustive and will focus predominantly on the application fields of Safety, Environmental, and Mobility. Other use cases can be found in the USDOT *Connected Vehicle Reference Implementation Architecture* (2016).

The benefits of notable use cases for Safety, Environmental, and Mobility applications that have been defined and trialled by connected vehicle programs endorsed by government authorities (including those presented in section 3) will be the focus of this review (outlined in Table 4.1). To support the findings from the programs endorsed by government authorities, results from industry trials (if available) and smaller-scale trials and simulations described in academic journals will also be analysed.

Table 4.1 Applications fields and use cases considered in this review

Application	Application Field	Use Case
Safety applications (Warnings)	*Warnings for conflicts between vehicles*	Intersection Movement Assist (IMA)
		Red Light Violator Warning
		Right Turn Assist (RTA)/ US: Left Turn Assist (LTA)
		Cooperative Forward Collision Warning (CFCW)
		Cooperative Blind Spot Warning (BSW) and Lane Change Warning (LCW)
		Do Not Pass Warning (DNPW)
		Approaching Emergency Vehicle Warning (AEVW)
	Warnings for conflicts involving vulnerable road users	Detecting vulnerable road users
		Alerting vulnerable road users
Safety applications (Awareness)	*Infrastructure and environment awareness*	Curve Speed Warning (CSW)
		Intersection Awareness
		Hazard Awareness
		In-Vehicle Signage
Mobility and Environmental applications	*Traffic Network and Signalling*	Cooperative Adaptive Cruise Control (CACC)
		Variable Speed Limit (VSL)
		Connected Signal Optimisation and Traffic Routing

4.1 Safety Applications

Connected vehicle (CV) applications promise to reduce crashes that cause fatalities and serious injuries, primarily by minimising the occurrence of driver errors, a predominant factor in 94% of traffic crashes (Yue, Abdel-Aty, Wu, & Wang, 2018). NHTSA (2010) demonstrates this capability through the analysis of its IntelliDrive safety systems program, which consisted of various connected vehicle applications. By sourcing crash data from the 2005-2008 General Estimates System, NHTSA estimated that connected vehicle applications have the potential to address over 4.5 million or 81% of all police reported vehicle crashes in the United States. Assessment of C-ITS should include comparing and identifying the efficacy of individual use cases. For this review, use cases in the safety application field are classified according to their proximity to the crash, as follows.

- ***Safety awareness messages***: non-critical communications which act to provide an increased knowledge of the driver's surrounding infrastructure and environment. Generally, these awareness messages convey a static hazard, for example, upcoming work zones or red lights signals. Depending on the latency requirements of the use case, cellular long-range communication methods are expected to be able to provide the necessary communication.
- ***Safety warning messages***: time-critical communications where the driver is warned of an imminent threat and reactions to messages are time-sensitive. This involves situations where other road users may be moving and require an additional level of prediction based on the driver's movements and the movements of the other road user, for example, warnings for potential collision paths with another vehicle or a vulnerable road user. For these cases, short-range direct communication methods, usually DSRC, are tested in real-world trials. The content of the safety communication between vehicles, and between vehicle and infrastructure has been standardised in the Basic Safety Message (SAE J2735) which includes instantaneous position, speed and heading, and is broadcast 10 times per second.

A recurring issue alluded to by researchers is the efficacy of CV at different market penetration rates. Although it is well understood and agreed upon that as CV penetration rates increase safety benefits (Zhang & Cassandras, 2018), a 100% Market Penetration Rate (MPR) should not be regarded as a realistic goal. However, Olia et al. (2014) found the greatest marginal decrease in incident probability occurred within the first 10% of CV penetration. Ma & Wang (2019) presented a solution to maximise safety benefits according to varying levels of market penetration. By introducing exclusive CV lanes on freeways and arterials, the drawback of low penetration levels is effectively mitigated by segregating connected vehicles and non-connected vehicles. The authors determined that, at penetration rates between 10-40%, one exclusive lane should be introduced, and two exclusive lanes for 50-90% penetration rate.

4.1.1 Warnings for Conflicts Between Vehicles

4.1.1.1 *Intersection Movement Assist (IMA)*

Intersection Movement Assist (IMA) is an application designed to address common crash types at intersections. IMA acts to warn the driver that entering an intersection is unsafe due to another vehicle approaching from a lateral direction. This V2V communication exchanges BSMs that contain information that can be translated into the distance between two vehicles and the time to collision.

The efficacy of IMA has been identified for heavy vehicles in simulations conducted by the NHTSA (2016b). The experiment involved 40 simulations of two heavy trucks approaching an intersection at identical speeds and at the same time, half of which had a heavy truck equipped with IMA and the other half without. Whilst only approximately half the trucks equipped with IMA managed to avoid a collision, they also found that the trucks without IMA collided in every scenario. This study concluded that IMA has a 43-56% effectiveness for crash avoidance. It is noted that IMA was tested and found to be effective in the SPMD, and similarly, intersection collision warnings were tested in the CITI project.

In support of this estimate provided by the NHTSA, Austroads (2017) predicted an estimated 33-51% effectiveness range for IMA with human intervention, equating to approximately 940-1470 fatal and serious injury (FSI) crashes in Australia. Their estimations were conducted based on the assessment of a combination of real-world crash data from Australia, and operating parameters that would affect the likelihood of technology application. The researchers also found that if, hypothetically, an automated intervention system was integrated into the IMA system, overall effectiveness of crash elimination would rise to 56-88%. The estimate provided in this study assumed a 100% technology penetration rate. Wu, Ardiansyah and Ye (2017) also conducted a field experiment to model the effects of IMA, in which 40 participants were randomly selected to engage in seven different scenarios at four different intersections. Their methodology resulted in 15-26% fewer collisions, supporting a significant benefit to intersection safety.

4.1.1.2 *Red Light Violator Warning*

Another intersection specific warning, red light violator warning, has been trialled by CAVI and in the Towards Zero CAV trials. In this case, a warning of a potential collision is communicated to the driver where another vehicle in the opposite direction (oncoming vehicle) is at risk of running a red light at the intersection ahead. This message can be communicated either by another cooperative vehicle (V2V), or by the intersection (V2I). This specific use case has the potential to be coupled with traffic signal logic and used to extend a red-light phase at the intersection if a potential collision is detected. There are currently no published quantitative results to demonstrate the effectiveness of this case.

4.1.1.3 *Right Turn Assist (RTA)/ US: Left Turn Assist (LTA)*

Right Turn Assist (RTA) is another intersection-specific collision avoidance warning which alerts the driver of potential collision with an oncoming vehicle from opposing direction while making a turn at both signalised and unsignalised intersections using V2V communication. This case is discussed specifically due to the safety benefits which are expected, and significant amount of testing and simulation which has been completed. This use case is expected to provide the highest benefit in situations where the driver's line of sight is obscured by other vehicles, road curvature, or road infrastructure.

NHTSA (2016b) estimated the crash avoidance system effectiveness of left turn assist (LTA) functions to range between 37 to 63%. This estimate is based on simulations conducted, where the LTA was activated only when the left turn signal was used. Similarly, Austroads' (2017) assessment of Australian crash data estimated RTA had an effectiveness range between 27-42% for human intervention cases, equating to a maximum 525-825 savings in FSI crashes in Australia. While this estimate is somewhat lower than that provided by the NHTSA simulation, Austroads predicts a significantly higher range of 54-85% when assuming automated intervention is present. This use case was tested and found to be effective in the SPMD.

4.1.1.4 *Cooperative Forward Collision Warning (CFCW)*

Cooperative Forward Collision Warning (CFCW), also known as stopped or slow vehicle warning, acts to warn drivers of a threat ahead (e.g. stopped, or slowed vehicle), based on information provided by neighbouring vehicles and operates without the need for the ranging sensors used in traditional FCW Advanced Driver Assistance Systems (ADAS). The lead vehicle is able to convey a message to following vehicles (V2V communication), mitigating or reducing the outcome of rear-end collisions for vehicles travelling in the same lane.

Austroads' research report estimated a 20-32% crash avoidance effectiveness when the warning was acted upon by a human driver, and a 44-69% effectiveness when intervention following the warning was automated. Overall, the study projected 515-805 savings in FSI crashes in Australia with the use of CFCW. This use case was tested and found to be effective in the SPMD.

A specific CFCW case, Emergency Electronic Brake Light (EEBL), warns the driver that vehicle ahead (potentially not in the driver's LOS) is decelerating rapidly. This communication is provided by the decelerating vehicles (V2V) with the warning increasing the amount of time for a driver to respond. This use case was tested by the SPMD and was found to provide relatively frequent value from the driver's perspective. It was also tested by the Towards Zero CAV trials, CAVI (called emergency braking warning), and CITI (called harsh braking vehicles ahead alert). No quantitative results are currently available for any of these specific use cases trialled. Three specific CFCW use cases, emergency brake light warning, traffic jam ahead warning, and car breakdown warning were tested in the Drive C2X trials (2014) which estimated a 2% reduction in overall fatalities assuming 100% penetration. While the field results from these trials were noted to be partially inconclusive resulting in a reduced effectiveness estimation, the trials demonstrate that these use cases do have the potential to provide safety benefits in providing some level of reduction in the number of road safety incidents.

4.1.1.5 *Blind Spot Warning (BSW) and Lane Change Warning (LCW)*

Blind Spot Warning (BSW) and Lane Change Warning (LCW) are ADAS functions which warn the driver when a potentially dangerous lane change manoeuvre is detected. With the use of connected vehicle technology, these functions can be enhanced to allow lane change warnings to operate at greater ranges, eliminating a key drawback of lane change warning and allowing for the development of similar applications like Overtake Assistance. Cooperative BSW/LCW removes the need for sensors within the vehicle to detect the lane change movement, instead, the vehicles performing these manoeuvres are able to broadcast their movements to surrounding vehicles (V2V communication). BSW and LCW were trialled successfully in the SPMD.

When analysing the effects of V2V blind spot warning systems at MPR's of 0%, 25%, 50%, 75% and 100%, Theriot et al (2017) found that a penetration of 50% was necessary to notice any significant safety benefits. Rahman et al. (2019) analysed the effects of a combined FCW and LCW system which utilised V2V communication and noticed that benefits were realised at a minimum of 30% MPR, with maximum benefits at 100% MPR.

4.1.1.6 *Do Not Pass Warning (DNPW)*

An Overtake or Do Not Pass Warning (DNPW) operates with V2V communication and alerts the driver that it is unsafe to perform an overtaking manoeuvre as there is an oncoming vehicle. This feature is expected only to operate when the driver has activated their turn signal and therefore does not have the ability to address situations when the drive unintentionally drifts into the oncoming lane. The Texas Department of Transportation supported research by Motro et al. (2016) who simulated DSRC-based V2V warnings for overtaking manoeuvres on two-lane rural highways. Motro et al. (2019) furthered these simulations with 153 trials for overtaking warnings, with varying configurations for oncoming and overtaking vehicles speeds, which ranged between 40 to 60 mph. These trials and simulations found that an overtaking warning was successfully sent and received in 77-96% of trials depending on the specific configurations. This use case was also successfully trialled in the SPMD.

4.1.1.7 *Approaching Emergency Vehicle Warning (AEVW)*

Approaching Emergency Vehicle Warning (AEVW) is a time-critical use case where drivers are alerted to the presence of an approaching emergency vehicle. This warning aims to provide drivers with additional time to pull over and stop – as required under US traffic law – and generally allow the emergency vehicle to reach its target destination as soon as possible. This warning also acts to reduce the potential for collisions with emergency vehicles. Drive C2X (2014) estimated that AEVW would contribute to a reduction of at least 0.8% of all fatalities with a high penetration rate. The authors also note that this very practical use case may be particularly attractive for user acceptance of connected technology.

4.1.2 Warnings for Conflicts Involving Vulnerable Road Users

Connectivity has also opened up gateways to novel vulnerable road user (VRU) safety applications. VRUs are often considered as non-motorised road users, including pedestrians and pedal cyclists, and may also include motorcyclists and various electrified machines for micromobility. Vehicle to pedestrian collisions usually lead to severe injury or fatality on the pedestrian's part, accentuating the need to protect non-motorised vulnerable road users as a priority. There is a lack of worldwide trials targeting warnings of conflict between a vehicle and vulnerable road users. However, Australian trials including AIMES, CAVI, and the Towards Zero CAV, are investigating these use cases; currently, only qualitative results for expected benefits of connectivity for VRUs have been reported.

4.1.2.1 *Detection of vulnerable road users*

A trial conducted by AIMES (2019) assessed the ability to detect and warn a driver on a collision course with a VRU at an intersection. This detection method passively located the VRU mobile wi-fi signal and presents a significant benefit as minimal roadside infrastructure is required in order to provide this road safety enhancement.

4.1.2.2 *Alerting vulnerable road users*

An application of V2P communication at the forefront of discussion is a smart phone application which alerts vulnerable road users when crossing an intersection. Tahmasbi-Sarvestani et al. (2017) developed and analysed a DSRC-enabled smart phone application which acted to alert vehicles when a potential collision may occur. The application functioned effectively as a beacon, communicating the location, direction and speed of the vulnerable road user to the vehicle, and warning the driver if collision was likely. Their evaluation found that whilst the technology theoretically functioned correctly, there were many challenges and drawbacks which may hinder the overall effectiveness of the application such as network congestion, energy (battery) use and security.

Rahimian et al. (2016) analysed a similar application that sent the warning alert to the pedestrian instead of the vehicle. The target of this application was to act as an automatic protection for pedestrians who may be in the habit of using their phones in hazardous situations. Their analysis involved an immersive simulation to test how participants would react to alerts whilst texting and crossing the road and found that there was a clear difference between the reaction rate of those who received an alert from the application and those who did not have the application. However, they also detected an unhealthy reliance on alerts by those users who paid less attention to the roads when crossing, an unintended consequence of the application.

4.1.3 Infrastructure and Environment Awareness

4.1.3.1 *Road Geometry Awareness*

Curve Speed Warning (CSW) aims to address *single vehicle crashes* associated with excessive speed in the negotiation of highway curves. The application compares the car's speed with a safe speed for the curve in question and warns the driver to slow down.

Austroads (2017) estimated a 19-29% effectiveness range for the use of CSW with human intervention which is projected to prevent 75-115 fatal and serious injury (FSI) crashes in Australia. These estimates were based on the assessment of a combination of real-world crash data from Australia, and operating parameters that would affect the likelihood of technology application. CSW was also trialled in the SPMD and found to be effective.

Monsere et al. (2005) attempted to measure the impacts of CSW by installing the systems near predetermined curve which would measure the speed of traffic both north and southbound and warning vehicles using a variable message sign. It was found that the system yielded positive results, with a clear reduction in speed for most vehicles entering the curve in the study area. Biral et al. (2010) found a similar trend when applying personal CSW systems to motorcycles, where they determined that riders with the system would respond faster and more effectively to sudden changes in road curvature. Based on these simulations and the estimation provided by Austroads (2017), it is expected that CVs with the ability to communicate CSW will have a positive effect on increasing the road safety.

4.1.3.2 *Intersection Awareness*

Signalised crosswalk awareness messages alert drivers of the potential presence of a pedestrian at an upcoming intersection/crosswalk. Such awareness has the potential to reduce the number of road safety incidents involving vulnerable road users at crossings and was tested by the SPMD as well as CAVI. Similarly, the Towards Zero CAV trials conducted by Telstra successfully demonstrated the ability for road infrastructure to communicate to vehicles concerning the presence of crossing pedestrians or bicycles at an upcoming intersection.

Drive C2X trialled Green Light Optimal Speed Advisory (GLOSA), an intersection awareness application, where the driver receives a speed recommendation which will enable them to comfortably pass through a green traffic light, or series of green lights (a "green wave"). This communication will only occur if it is determined that the driver is able to pass through the intersection within the given speed limit before the lights turn red. While this application was developed for traffic optimisation, trials showed GLOSA to marginally reduce the total number of fatalities by 0.2%.

4.1.3.3 *Hazard Awareness*
Hazard awareness messages are targeted at increasing the information available to the driver about their surroundings, including static factors which have the potential to cause road safety incidents. Examples of this include roadworks ahead warnings, level crossing ahead warnings, and weather warnings. These warnings are communicated by surrounding infrastructure or other vehicles to the driver, and have been tested in the CAVI, CITI and Drive C2X trials.

4.1.3.4 *In-Vehicle Signage*
An additional capability for C-ITS communications is enhancement to existing driver assist in-vehicle signage. Traditionally, in-vehicle signage relies on in-vehicle database and GPS information to inform drivers about excessive speed, or upcoming hazards (see Hazard Awareness above). With vehicle connectivity, this function can be enhanced by providing drivers with real-time and up to date information about active, static, and variable speed limits as well as an alert if they are exceeding the limit. In-vehicle speed indicators have been tested in CAVI and Drive C2X trials.

4.2 Mobility and Environmental Applications
Apart from their safety potential, connected vehicles have the potential to greatly advance vehicle mobility, diminish environmental damage and enhance the overall productivity of traffic networks as a whole. Increased urban agglomeration and over-reliance on cars has created insurmountable challenges for road planners, designers and managers, with resultant congestion costs rising not only directly from delays, but also indirectly from emissions and inefficient use of energy. In 2011, the United States estimated that the economic cost of increased travel time and fuel consumption alone due to congestion was approximately $121 billion, with excess carbon dioxide emitted at around 56 billion pounds (Lu, Cheng, Zhang, Shen, & Mark, 2014). Similarly, Infrastructure Australia (2019) estimates that congestion costs will double in most capital cities around Australia by 2031. With congestion levels reaching historical highs around the world and urban environments limiting land use for infrastructure development, connected vehicle technology has become valued for its potential to act as a new and disruptive solution.

4.2.1 Traffic Controls and Networks

4.2.1.1 *Vehicle Platooning*
Vehicle platooning is a method of joining multiple vehicles together in order to reduce reliance on human drivers, reduce road space requirements and increase roadway capacity. V2V communication in the form of DSRC is the preferred method for creating vehicle platoons. Platooning has mainly been applied to freight vehicles.

As with many other connected technology applications, the benefits of platooning are noticed at moderate to higher levels of penetration (Schladover, Su, & Lu, 2012), with negligible effects at penetration levels lower than 40% (Arem, van Driel, & Visser, 2006). Lioris et al. (2017) simulated the impact of platooning on freeway throughput, noticing a potential doubling of throughput. This is in line with the findings of Talebpour and Mahmassani (2016a) who also found a doubling of throughput at a 100% penetration rate and diminishing returns as penetration rate decreased. They also found that overall traffic stability and safety increased as connectivity increased. The potential to allow heavy vehicle platooning is promising as heavy trucks are more likely to suffer from acceleration deceleration lag effects both from a productivity loss and safety perspective. Ploeg, Serrarens and Heijenk (2011) found that platooning systems allowed for headways between trucks to reach times of less than one second, contending that such a reduction in headway would have significant improvements to throughput and decreases in fuel consumption and emissions. Lu et al. (2018) elaborates on this by finding that in a three truck platoon, the first truck would not experience any fuel consumption reduction, whereas the second truck would reduce fuel consumption by between 6% and 7% and the third truck would experience a 9% to 11% fuel reduction. This demonstrates how platooning can have environmental benefits and how these are likely to increase benefits when more vehicles employ connected technology.

4.2.1.2 *Cooperative Adaptive Cruise Control (CACC)*
Advancing traditional Adaptive Cruise Control (ACC) technology, Cooperative Adaptive Cruise Control (CACC) employs V2V communication to apply the same technology to multiple vehicles in the same traffic

lane. CV technology used for platooning involves the driving of vehicles together in synchronisation, minimising vehicle to vehicle related collisions through communication and harmonization of movement. CACC works by using feed-forward and feedback loops to transmit messages of acceleration and deceleration between the lead vehicle and those connected vehicles trailing behind. This allows for smooth and concurrent movements, reducing stop start lag effects resulting from human reactions and improving overall driving efficiency. Rahman and Abdel-aty (2017) applied connected vehicle technology to improve upon theoretical lane keep assist (LKA) and FCW systems, allowing a lead vehicle to effectively platoon following vehicles and as such, maintaining lane keeping and safe gap distance for connected vehicles. They found that a dedicated CV lane reduced surrogate safety measures by 26-28% compared to a case of no connected vehicles, demonstrating a reduced crash risk when platooning vehicles. More recently, Rahman et al. (2019) elaborated on their earlier research by analysing the effects of different CV market penetration rates on safety benefit realisation. They found that at least 30% connected vehicle market penetration was necessary before benefits were noticed, with maximum benefit of approximately 21% noticed at 100% MPR.

4.2.1.3 *Variable Speed Limit (VSL)*

V2I Variable Speed Limit (VSL) is a connected technology system that allows for adaptive and dynamic adjustments to speed limits to maximise throughput whilst also accounting for traffic, weather and other hazards. The system relies on input from connected vehicles and infrastructure and uses an algorithm to react appropriately, changing the posted speed limit to reflect safe but efficient driving conditions at that time. Van De Weg (2014) found that by introducing CV-based VSL to a congested freeway ramp scenario, moving traffic jams near off ramps were able to be resolved, increasing vehicle throughput and decreasing travel times. Khondaker and Kattan (2015) attempted to further VSL research by simulating the effects of VSL systems on traffic congestion and fuel consumption reduction at different connectivity penetration rates. Their predictive model allowed for the optimisation of the VSL system to maximise benefits in minimising total travel time and fuel consumption. They found that, at a 100% penetration level, average travel time for vehicles would reduce by 18-20% whilst fuel consumption may decrease in parallel by 15-16%. However, at 50% connectivity, the results became unpredictable and unreliable, indicating that higher penetration levels are key to realising the benefits of connectivity.

4.2.1.4 *Connected Signal Optimisation and Traffic Routing*

Effective control and operations of signalised intersections can also play a significant role in reducing traffic congestion and its negative impacts on transport costs and the environment. Connected vehicles can communicate their real-time speed and location information to intersection control systems for an optimal green time allocation. Traffic signals in a connected environment can communicate with platoons of vehicles and increase the intersection throughput for conflicting traffic movements. Liu at al. (2019) demonstrate that in a mixed traffic situation with 40% market penetration of connected vehicles, intersection delays and fuel consumption can be reduced by up to 30% through signal green time optimisation. In addition, a connected V2I system can also allow traffic signal times to be optimised, not only based on observed traffic volumes locally, but also based on real-time traffic flow distribution at the network level. Simulated experiments in oversaturated traffic networks indicated that a V2I centralised traffic control system can reduce total travel time by between 17% to 48% (depending on the level of congestion) as compared to individually optimized traffic signals (Al Islam & Hajbabaie, 2017).

With V2I connectivity, additional traffic management ideals have also been discussed for more efficient utilisation of existing roadway capacity. For example, a connected centralised traffic control system could help avoid the onset and propagation of traffic congestion in the network by communicating, monitoring, incentivising, and enforcing advanced traffic routing directions to drivers. Optimal traffic assignment models have been extensively studied for optimizing traffic routing advisory information and other applications in traffic management (Tajtehranifard, Bhaskar, Haque, Chung, & Nassir, 2016; Nassir, Hickman, Zheng, & Chiu, 2014a). These applications range from traffic management practices, such as congestion pricing (Hearn & Ramana, 1998) and incentive schemes (Yang & Wang, 2011), to non-recurrent traffic management practices, such as incident traffic management (Sawaya, Ziliaskopoulos, Mouskos, & Kamaryiannis, 2005; Tajtehranifard, Bhaskar, Haque, Chung, & Nassir, 2016) and evacuation scenarios (Nassir, Zheng, & Hickman, 2014b).

5 Deployment of Technology: Challenges and Opportunities

5.1 Roadmap to Deployment

Given that Australia is expected to follow the European standards for C-ITS deployment (European Comission and Ricardo Energy & Environment, 2016), the European Roadmap to Deployment assists in contemplating the many stages of deployment, despite our differing policy environments. This framework is summarised in Table 5.1; indicative timeframes of possible applications and reference to potential use cases are given in Section 4.

The safety use cases presented in Section 4 note the difference between awareness and warning messages; specifically, awareness messages are not time-critical and act to provide infrastructure- and location-related safety awareness, while warning messages are time-critical due to the presence of an imminent threat. These two types of safety messages are reflected in the timeframe of the deployment model shown in Table 5.1, where the types of potential use cases on "Day 1" are expected to be for awareness purposes, while the use cases in "Day 2" and "3+" provide more time-critical and safety-specific warnings.

The model assumes that the level of automation increases with the time-period. That is, Day 1 C-ITS applications are provided for low levels of automation (and potentially low penetration), but are still effective for increasing awareness of risks and for the dissemination of information to drivers, while, Day 3+ activities assume that there are mid to high levels of technology penetration, as well as high, if not fully automated vehicles available for cooperative use cases.

Table 5.1 European Roadmap to Deployment: Expected Services and Use Cases

Timeframe	Expected Services	Message Types	Potential Use Cases
Day 1 Awareness driving via status data	• Cooperative awareness and decentralised notification • Basic infrastructure support	• Cooperative Awareness Message (CAM) • Decentralised Environmental Notification (DENM) • Basic Safety Message (BSM) • Signal Phase and Time (SPaT) • Road/lane topology and traffic manoeuvre (MAPEM) • In-vehicle-Information Message (IVI) • VRU Awareness Message (VAM)	• In-vehicle signage • Hazard Awareness • Intersection Awareness • Curve Speed Warning

Timeframe	Expected Services	Message Types	Potential Use Cases
Day 2 Sensing Driving via sensor data	• Improved cooperative awareness and decentralised notification • Collective Perception • Improved Infrastructure Support	• Collective Perception Message (CPM)	• Intersection Movement Assist • Red Light Violator Warning • Right Turn Assist • Cooperative Forward Collision Warning • Cooperative Blind Spot Warning/Lane Change Warning • Do Not Pass Warning
Day 3+ Cooperative Driving via intention and coordination data	• Trajectory/ manoeuvre sharing • Coordination/ negotiation • VRU active advertisement	• Manoeuvre Coordination Message (MCM) • Platooning Control Message (PCM)	• Vulnerable Road user protection • Pedestrian safety Messages • Cooperative Adaptive Cruise Control • Connected Signal Optimisation and Traffic Routing

Source: Car 2 Car Communication Consortium (2019)

This roadmap is intended to demonstrate a potential model for achieving cooperative automated driving with the objective of accident free road transport and optimal traffic flow (Car 2 Car Communication Consortium, 2019). The authors of the roadmap recognise that, to achieve this target, a large number of complex issues must be considered; we consider the following issues and questions in the sections below:

- ***Technology Deployment Options*** – Which implementation method should be used, and is it suitable for the use cases and scenarios where C-ITS is expected to provide benefits?
- ***Aftermarket and OEMs*** – Is deployment limited by the speed which OEMs can introduce technology? Is retrofitting a suitable alternative for all applications?
- ***Infrastructure Deployment*** – What type of infrastructure must be deployed?
- ***Penetration*** – What level of penetration must be achieved to realise benefits?
- ***Coverage*** – Are there potential issues which may arise from areas of low coverage?
- ***Standards and Regulation*** – What type of standards and regulation exist, and is harmonisation required?
- ***Human and Machine Interaction Factors*** – Before full automation and penetration is reached, what factors affect human reactions to information provided by C-ITS applications?
- ***Security, Privacy and User Concerns*** – What challenges are faced with security, credential management, and privacy?

5.2 Technology Deployment Options

This report notes that the method of deployment of C-ITS communication technologies can be achieved in a number of ways, with:

1. DSRC short-range direct communication
2. C-V2X short-range direct communication via PC5 interface, and long-range cellular communication via Uu
3. Hybrid DSRC short-range direct communication with cellular long-range communication

In assessing the challenges and opportunities presented, the short-range direct communication methods presented are investigated for their suitability in delivering adequate communication for some of the application fields and use cases presented in Section 4. Highly-specific safety applications where warnings are time critical and require accurate, high-quality messages to be transmitted to allow drivers/vehicles to react appropriately need to be included. There are two important options for short-range communications for short-range communication: DSRC and C-V2X PC5. Note that, while there are some large-scale trials of C-ITS technology, the *direct* performance comparisons between DSRC and C-V2X presented in this review are based on small-scale trials and simulations.

5.2.1 Performance Capacity Requirements

There are several metrics on which DSRC and C-V2X PC5 direct communication (sidelink LTE-V2X) are assessed in studies to determine whether performance is adequate for carrying out road safety and efficiency communications. Some of the metrics which have been assessed in both empirical studies and smaller-scale industrial field tests are:

- **Packet Delivery Ratio (PDR):** the ratio of successful communication events to the total number of transmission attempts at a given distance between two units/vehicles.
- **Packet Reception Ratio (PRR):** the average ratio between the number of significant neighbours correctly decoding a message and the number of significant neighbours.
- **Latency:** the delay before a transfer of data begins following instruction for transfer.
- **Maximum Range (MR):** the maximum distance at which the vehicle or roadside unit (RSU) can receive packets from another vehicle with a larger-than-zero packet delivery ratio.
- **Effective Range (ER):** the distance within which the vehicle or RSU can receive packets from other vehicles with a packet delivery ratio larger than a defined threshold.
- **Update Delay (UD):** the time difference between a message being sent and correctly received for all significant neighbours.
- **Inter-Packet Gap (IPG):** the time between successive packets.

Kawser et al. (2019) note three important capacity requirements that C-ITS communication technologies must satisfy:

1. ***Low latency:*** End-to-end delays in communications due to data gathering, processing, transmission and addition of security mechanisms all add to latency within the system. These delays should be kept to a minimum of at least 300ms (as defined by ETSI TS 102 539-1) for general V2X applications.
2. ***Data load control:*** This is necessary to maintain uniform flow of data in the frequency spectrum allocated. Decentralised Congestion Control (DCC) functions are required in order to allow for communication to be effectively transmitted and received.
3. ***High message rate:*** Automated driving systems and driver assist functions require large amounts of data at low latencies in order to build an accurate, real-time model of the surrounding environment and subsequently, coordinate and perform road safety manoeuvres. Currently, the data flow is controlled by the generating vehicle/infrastructure/device and the communication channel.

These capacity requirements and metrics have been simulated and field tested in a handful of scenarios, both in industry white papers and in peer-reviewed journals. Scenarios include urban and highway environments, with varying traffic congestion to simulate interference, and line-of-sight (LOS) and non-line-of-sight (NLOS) conditions.

5.2.2 Performance-based Trials and Experiments

Given that the technology for DSRC has existed for a longer period than C-V2X, there are a greater number of trials and simulations for this technology. Notable DSRC trials include the 2012 Safety Pilot Model Deployment led by the University of Michigan (Bezzina & Sayer, 2015), and the 2016 ITS Plug Test in Livorno, Italy (European Telecommunications Standards Institute, 2016).

The University of Michigan Safety Pilot Model Deployment involved measuring the maximum range and packet delivery ratios for V2I communication between 1,050 vehicles with RSUs for over 1,000 days. This study aimed to simulate the use of DSRC in real-world situations and found that the metrics assessed were significantly affected by NLOS static obstructions (i.e. buildings), moving objects (i.e. other vehicles), and the location of the antenna for communication on the vehicles. Huang, Zhao, and Peng (2017) found that the road elevation/altitude has a noticeable effect on the MR for DSRC communication. It is hypothesised that results from trials show variation in PDRs due to reflection of communication from other vehicles, reflection inside the vehicle where antennas are mounted within the vehicle, and blockages and reflection from other vehicles using the road corridors. Buildings were the most significant cause of NLOS blockage which has adverse effects on the range and PDR of DSRC. Tree foliage also reduces the effective range of DSRC by approximately 20 meters and reduces the PDR by up to 10 percentage points. However, varying weather conditions are not observed to influence the MR or PDR in DSRC.

The ETSI ITS Plug test conducted in 2016 involved more than 20 vendors and simulated real-world large-scale DSRC technology use. Use-cases tested in this trial simulated the integration of the motorways network and integration with IoT technologies. The trial successfully demonstrated that DSRC (ITS-G5) conformed to ETSI ITS Release 1 standards and verified the interoperability between OBU providers and RSU vendors.

Since C-V2X was defined in 3GPP Release 14, some comparative trials have been conducted by industry to compare DSRC to C-V2X operation. However, it is important to reiterate that large scale field tests have been conducted for DSRC only, and there are few trials testing C-V2X. The Towards Zero CAV trial in Victoria is one of the notable large-scale C-V2X deployment tests. These trials found C-V2X to have end-to-end latencies below 50ms for 95% of tests conducted using Ericsson's C-V2X platform and an optimised 4G network provided by Telstra (Ericsson, 2020).

Small scale trials and simulations described in industry white papers and academic journals generally draw similar conclusions when comparing the performance of the short-range component of DSRC and C-V2X (PC5) technologies. Four notable comparison experiments and simulations are discussed: an industry white paper from 5GAA (2018), and three journal articles. While these papers provide direct performance comparisons, it is noted that these results are mostly simulations and have not been sufficiently tested and thus, should not be solely relied upon to inform final technology deployment decisions.

5GAA (2018) conducted both laboratory and field testing on both technologies to determine their reliability, end-to-end latency, operation with channel congestion, and resilience to interference. Overall, 5GAA testing showed that C-V2X (PC5) and DSRC perform similarly. In laboratory testing, latencies within 10ms were observed for both technologies in non-congested conditions. Overall, both C-V2X (PC5) and DSRC were found to be relatively reliable under interference testing. In field testing, 5GAA (2018) compared DSRC and C-V2X (PC5) on measures of range and IPG by controlling the factors that affect radio frequency propagation: antenna characteristics and placement, vehicle geometry and cabling, location and environmental conditions, power and interference settings, and vehicle speed. The field tests were designed and conducted to address two major questions: (1) What is the range of the system and reliability communication as a function of distance in scenarios with LOS/NLOS? and (2) What is the impact of out-of-band interference from the U-NII-3-band/an adjacent DSRC channel? Results from field tests demonstrated that C-V2X (PC5) has 1.3 to 2.9 times the range advantage over DSRC. Specifically, C-V2X (PC5) has 1.7 times the range in LOS scenario, and 2.2 times advantage in NLOS scenarios with signal obstruction.

Bazzi et al. (2019) tested the performance metrics of PRR and UD for three traffic scenarios simulated in MATLAB. These scenarios are Cologne (an urban and moderately dense environment), Bologna (an urban and congested environment with queues at intersections), and Highway (where traffic is highly congested). Five different configurations of DSRC and C-V2X (PC5) technology were simulated: C-V2X PC5 in Mode 3 (with cellular network assistance) and Mode 4 (with two difference probabilities to maintain allocations), standard DSRC, and an enhanced version of DSRC (Next Generation 802.11bd) where the PHY layer is assumed to have the same data rate and reliability as C-V2X PC5. The simulations found that in all scenarios C-V2X had a wider range than DSRC but presents higher delays. Results from PRR and UD measurements indicated that C-V2X in Mode 3 has improved performance over both C-V2X Mode 4 and DSRC in terms of packet reception ratio, but DSRC demonstrated a shorter update delay in the Bologna scenario. Bazzi et al. concluded C-V2X Mode 4 operation presents some advantages over DSRC in the urban and highway cases examined, but has a higher update delay, and thus, higher probability of producing multiple consecutive errors in message delivery. Simulation with the enhanced DSRC configuration demonstrated a PDR similar to C-V2X in Mode 4, and slightly lower update delay for the Cologne and Bologna scenarios.

Shi et al. (2019) tested the latency and packet delivery rate of the two technologies to evaluate whether the performance supports necessary road safety communication scenarios. These experiments were conducted at the National Intelligent Connected Vehicle (Shanghai) Pilot Zone using Mk5 Cohda Wireless devices for DSRC communication, and an LTE-V device from DTT for C-V2X communication. The latency of DSRC in all scenarios tested was found to be approximately 5ms on average, and lower that of C-V2X (on average, approximately 10ms). Additionally, latency was found to remain quite stable for both technologies as the range varied in tests. The PDR for both technologies was relatively similar and found to be strongly correlated with distance.

5.2.3 Performance in Road Safety and Productivity Simulations

Using the performance measurements obtained from trials and simulations comparing the use of DSRC and C-V2X (PC5) for direct communication, road safety and traffic efficiency applications have been simulated. Real-world trials for these applications are discussed in Section 4. This section will focus on results for simulations which have directly compared the two technologies.

5.2.3.1 *Safety Applications: Warnings for conflicts between vehicles*

Shi et al. (2019) conducted an application-oriented evaluation to test whether performance satisfied the communication needs for several scenarios and determined the required minimum “safe distance” for the communication to adequately warn drivers of an imminent road safety threat. This analysis was conducted based on the PDR correlation with range and simulated application in three real-world safety use cases: rear-end collisions, frontal collisions, and intersection collisions. These cases were simulated for both DSRC and C-V2X. Shi et al. found the success of the message transmission and subsequent reaction to avoid the collision depended heavily on the relative speeds between the two conflicting vehicles. Ranges are provided for situations when both technologies performed adequately, and the collision was avoided. This simulation is supported by real-world trials discussed in Section 4.1.1 where IMA, RTA/LTA, CFCW, and DNPW scenarios have been tested with DSRC technology.

Motro et al. (2019) also tested IMA scenarios, with the objective of capturing interference of built environment and geometric design features on DSRC performance, although the results were inconclusive due to GPS inaccuracy.

5.2.3.2 *Safety and Mobility Applications: Vehicle Platooning*

Vukadinovic et al. (2018) simulates the application of C-ITS communication technology for platooning of trucks in a high-density highway environment. This performance simulation was analysed for DSRC and C-V2X Mode 3 and Mode 4 and measured the message latency and reception rates assuming a platoon of 10 vehicles. Vukadinovic et al. found C-V2X Mode 3 effectively communicated platoon messages and was successful at providing collision avoidance under the conditions tested. C-V2X Mode 4 was affected by interference, but still marginally outperformed DSRC. Vukadinovic et al. (2018) expects that a combination of C-V2X Mode 3 in areas with supporting infrastructure, and Mode 4 in areas of poor cellular coverage is more suited for platooning applications than DSRC. Note that truck platooning as we know it is generally limited to a maximum of three vehicles and is universally carried out using DSRC.

5.2.3.3 *Mobility Applications: Traffic Management*

A traffic management technique using DSRC beacons to provide variable speed advisories was simulated by Andrews et al. (2018). This technique aimed to smooth traffic flow and minimise start-stop congestion by dynamically changing speed limits based on the latest traffic, weather, and road conditions. The author noted that while this trial was conducted with DSRC technology, this could be substituted with C-V2X. Andrews et al. found the maximum range in traditional display signs for variable speed limits (VSLs) was similar for both DSRC and C-V2X. The authors assumed that at 50% penetration, the benefits of speed harmonisation through CV-enabled VSL are expected to be realised. The use of DSRC beacons to provide VSL advice rather than existing signage is estimated to provide 35 times the savings in the state of Texas for initial implementation as connected vehicles (CVs) are able to perform the function of multiple existing VSL display signs at once. Andrews et al. also estimated that annual electricity expenses could be up to 220 times lower with the use of DSRC beacons for VSL messages. Based on this simulation, implementation of either DSRC or C-V2X technology could provide a more economical solution to traffic management than traditional variable message signs.

5.2.4 Performance and Application Results and Discussion

The small-scale trials and simulations conducted by 5GAA (2018) and Bazzi et al. (2019) concluded that while C-V2X PC5 presents range advantages, DSRC offers reduced delays in transmission. The Towards Zero CAV trials in Victoria indicated that the end-to-end latencies achieved in testing are adequate for "life-saving use cases" (Ericsson, 2020). In this sense, it is expected that C-V2X PC5 will be suitable in providing direct communication in a variety of ideal and adversarial environment scenarios although some time critical cases may be better served by DSRC technology. As we have noted, truck platooning always uses DSRC.

While there are a number of recent and ongoing trials for both the technologies (discussed in Section 3), it is noted that there are limited number of large-scale real-world trials which adequately test the performance and application of C-V2X technologies for road safety and productivity. Four road-safety use case simulations for C-ITS communications are presented in Shi et al. (2019) and Vukadinovic et al. (2018), while a traffic management and road productivity case for speed harmonisation is simulated by Andrews et al. (2018). For the use cases where both technologies are simulated, C-V2X (PC5) presents marginal or no gains when compared to DSRC. This result generally supports the findings of papers comparing the performance metrics of the two technologies. Simulation and field testing for a wider range of use cases is required in order to determine the communication technology most suited for carrying out specific safety critical functions and their effectiveness at reducing safety incidents and increasing efficiency in urban and rural scenarios. Nevertheless, based on current evidence, it should be expected that both technologies produce similar results to users, and thus, the decision to rely on one or the other, or both, may be geo-political, business-strategic, or financial (investment costs) rather than technical (technology performance).

Table 5.2 presents a summary of the results from a review of works comparing the *direct* communication provided by DSRC and C-V2X (PC5) technology performance. The comparisons demonstrate that C-V2X (PC5) provides a greater range and reliability than DSRC, while satisfying the requirements for latency and IPG. However, the presented results cannot be considered conclusive due to limited field testing. Real world testing in scenarios where traffic is highly congested, such as during peak hour in larger CBD's are required to validate vendor statements as to how well the respective standards fair, as traffic density may affect their performance and operation. This table is also based on a comparison of the short-range components of the two technologies by industry and academia which have not be formally peer-reviewed and should not ultimately determine the final technology deployment decision.

Table 5.2 Performance results and comparison of DSRC and C-V2X (PC5) for direct communication based on limited testing and simulations

Metric	DSRC	C-V2X (PC5) (LTE Rel 14/15)	Comparison
Maximum range **(condition dependant)**	100 m to 2km, typically 800m in LOS	450 m to > 2 km	C-V2X generally has a 1.3x to 2.9x greater range
Latency **(independent of condition; relatively stable)**	~ 2ms-5ms	~ 4ms-10ms (lab testing) < 100ms	DSRC presents lower latency than C-V2X. Even though C-V2X can meet requirements, in many cases the latency reaches the maximum, as defined in SAE J2945/1.
Packet Delivery Rate (PDR)/ Packet Reception Ratio (PRR)	In simulations, C-V2X found to have marginally higher PRR than DSRC in moderately dense, congested, and highway scenarios; this difference increases with range.		
Average end-to-end delay	~ 230ms	~ 50ms	C-V2X enables faster communication than DSRC in congested environments
Update delay	In simulations, DSCR found to have a shorter update delay in urban and congested environments, and highway scenarios than C-V2X PC5 Mode 3 and Mode 4.		
Reliability **(tests with interference)**	In simulations, both C-V2X and DSRC found to be susceptible to interference in non-ideal communication scenarios		

Source: 5GAA (2018), Bazzi et al. (2019), Southwest Research Institute (2018), Kawser et al. (2019), Shi et al. (2019), Andrews et al. (2018), Ericsson (2020)

5.3 Aftermarket and OEM Technology

Technology for C-ITS communications may be integrated by the original equipment automotive manufacturer, or purchased and fitted in the automotive aftermarket. The following distinctions are made between aftermarket (retrofitted) and OEM (machine integrated) solutions:

- ***Aftermarket solution:*** aftermarket equipment may allow V2V, V2I or V2X communications via DSRC and/or C-V2X. The equipment is retrofitted into an existing vehicle or operated independently from the vehicle's controller network.
- ***OEM solution:*** communication equipment (DSRC, C-V2X, or both) is integrated into vehicles during production and integrated to the newly produced vehicle's controller network. This type of device is capable of providing highly accurate information using the in-vehicle information to generate basic safety messages (BSMs).

Some alternative aftermarket applications which operate outside of the C-ITS environment through smart phone applications such as "Addinsight" (Adelaide) and "Speed Advisor" (Transport for New South Wales) are also being developed to deliver awareness messaging and offer improved safety for users (Austroads, 2017).

How do the OEM and aftermarket options compare relative to the previously-discussed roadmap for deployment? What functions will the equipment be required to perform? For awareness communications (i.e. Day 1 applications from the European Roadmap (Car 2 Car Communication Consortium, 2019)), the technology deployed must be able to transmit awareness messages and provide basic infrastructure support. Services provided on Day 1 are aimed at enhancing the driver's understanding of their surrounding infrastructure and environment, and do not necessarily require large amounts of information to be communicated. Beyond Day 1 applications, the amount of information communicated increases for sensing and warning functions. For use cases on Day 2 and Day 3+, a high level of accuracy is required as positional information is often conveyed; additional factors such as security must now also be considered given the time-critical nature of the communication. The delivery of precise information is crucial for cooperative use cases to function effectively and provide expected road safety and productivity benefits.

5.3.1 Hardware

In order for the benefits of connected vehicles to be recognised, a number of hardware requirements must be satisfied. Some of the vehicle equipment configurations used in C-ITS communication trials include Integrated Safety Devices (ISD), Aftermarket Safety Devices (ASD), Retrofit Safety Devices (RSD), and Vehicle Awareness Devices (VAD) (Bezzina & Sayer, 2015). These devices offer varying levels of integration with the vehicles, and hence, have different levels of functionality as well as installation requirements as noted by NHTSA (2016a). The three aftermarket safety devices (RSD, ASD, VAD) have limitations when compared to an ISD:

- ***Integrated Safety Device (ISD):*** When used in trials, these devices most accurately reflect an OEM installed device.
- ***Retrofit Safety Device (RSD):*** The level of integration with the vehicle decreases when retrofitting RSDs compared to ISDs, although the device is still connected to the vehicle's data bus. This allows for basic safety messages and vehicle to vehicle safety applications to be communicated. This device requires a certified installer for the placement of antennas and security certification.
- ***Aftermarket Safety Device (ASD):*** This retrofit device requires power from the vehicle and has the ability to communicate BSM and V2V safety applications, although the safety applications which can be conveyed using this technology are limited when compared to those which RSDs can potentially achieve. Again, this device requires a certified installer for the placement of antennas and security certification.
- ***Vehicle Awareness Device (VAD):*** This device can only provide an outbound BSM which alerts surrounding or nearby vehicles of the vehicle's presence; no safety applications or use cases can be performed in the host vehicle. This device still requires a certified installer for the placement of antennas and security certification.

Kawser et al. (2019) noted the following hardware contributes to providing vehicles with the necessary information for vehicle awareness: Cameras, Radars, Lidar, Ultrasonic sensors, V2X wireless sensors, antennas, 3D HD Map, Global Navigation Satellite System (GNSS). This hardware builds a virtual image of the surrounding environment which vehicles can communicate to other road users. It is necessary for at least some of these elements to be present in connected vehicles in order for any C-ITS communication technology to realise the safety and efficiency benefits discussed in Section 4.

In addition to such sensor hardware, vehicles must be equipped or retrofitted with an antenna for direct communications, in order to communicate with other road users and infrastructure. For both technologies, roadside units (RSUs) are also required in order to provide a communication platform between the vehicle and surrounding infrastructure/environment. For cellular network communication, C-V2X technology can operate utilising embedded modems that provide a means for connectivity; these modems are available in the vast majority of new vehicles according to Qualcomm (2017). However, C-V2X (PC5) will likely require the same equipment as DSRC for short-range direct communications.

5.3.2 Strategies

Whilst most deployment strategies aim to implement V2X communication via OEMs and the release of capabilities through new vehicles alone, some researchers raise concerns over the speed of such a strategy, inferring that deployment through new vehicles alone will not provide the penetration necessary to effectively realise the benefits of the technology (Chan, 2012). The long standing automotive aftermarket represents a USD 400 billion market in Europe alone (Breitschwerdt, Cornet, Kempf, Michor, & Schmidt, 2017). As such, the automotive aftermarket has been considered as a potential secondary pathway to expedite deployment of devices and tools necessary for vehicle communication in older fleets. NHTSA (2016c) concluded that even if a strategy which focused solely on connectivity in new motor vehicles were to be implemented, investment into DSRC-based aftermarket solutions which revolve around applications targeting safety, mobility or convenience would still occur.

NHTSA (2016c) modelled the likely deployment timelines under two scenarios: one where aftermarket products were available, and one where aftermarket products were not available. The model was built under guidance and direction of various stakeholder interviews. They found that previous models estimated that deployment under a “no aftermarket introduction” assumption would take a number of decades before the majority of vehicles were equipped with communication technology. NHSTA’s model, which included aftermarket options, found that it would take approximately 7 years for 60% of vehicles to be connected, with aftermarket solutions outpacing OEM products within 5 to 6 years of strategy implementation. Using this model, NHTSA evaluated and highlighted the positive impact of the automotive aftermarket on the speed of communication deployment. Although aftermarket alternatives present an interesting opportunity for deployment, policy makers note the difficulty of regulating and integrating aftermarket products, a challenge which may hinder the progress of deployment (Austroads, 2017).

5.3.3 Global Deployment

There are several OEMs who have begun or announced deployment of C-ITS communication solutions within their vehicles:

- Toyota introduced V2X enabled automobiles with DSRC technology in Japan in 2016 (Toyota, 2016) and had plans to deploy similar equipped vehicles in the U.S. although this has since been halted.
- General Motors introduced DSRC equipped Cadillac CTS sedans to the US market which have been sold since 2017. GM has announced its plan to introduce a DSRC-based V2X Cadillac crossover in higher volumes by 2023 (GM Authority, 2019).
- Ford announced support for C-V2X deployment and has been working with Qualcomm on testing and development of C-V2X for deployment in 2022 (Qualcomm, 2018).
- Volkswagen deployed Wi-Fi (DSRC) V2X technology in 2019 Golf models across Europe with a chipset from NXP; this is expected to be the largest OEM deployment of DSRC (NXP, 2019).

5.4 Infrastructure Deployment Model and Coverage

5.4.1 Cellular Coverage

Infrastructure must be deployed along with the in-vehicle equipment and technology in order for connectivity to function. Some connectivity applications require network coverage while some shorter-range, direct communications operate without network coverage. However, communication infrastructure for short-range V2I communication scenarios is still required. For applications requiring network coverage, urban areas that are well developed with high population density and infrastructure are likely to be covered by the existing network, although upgrades may be required. When considering regional and remote environments, which are located far from metropolitan or urban centres with limited infrastructure (including regional centres), coverage is expected to be limited. In order for safety benefits to be realised in regional and remote environments, new infrastructure must be deployed. Additional factors that require consideration for network coverage include security credential management systems (SCMS). It is expected that these systems can operate through cellular communication and will not operate via the direct communication method as these systems are not time critical. However, issues arise in situations when there is no, or limited coverage, and vehicles cannot verify the security certificates of the communication. Other issues may involve vehicles in areas of limited or no coverage presenting old security certificates that are not up to date (due to lack of cellular coverage) causing other vehicles to ignore or reject safety messages. Deployment of cellular towers to cover as much of the road network as possible and to reduce the number of limited and low coverage areas will aid in mitigating these security issues.

Infrastructure Victoria and WSP (2018) estimated that the required investment for the state-wide deployment of CAVs in Victoria through the provision of cellular towers for network (4G and planned 5G) coverage would be in the order 1.1 to 1.7 billion dollars[2]. This estimate is based on providing, at minimum, network coverage for all trips on sealed roads to ensure that a ‘network breadth of coverage’ (Infrastructure Victoria and WSP, 2018) exists. It is worth noting that planned future release 16 of C-V2X specifications will allow a certain level of connectivity without the requirement for cell towers to provide coverage, allowing certain use cases to be sustained without the need for central data processing in the cloud.

5.4.2 Infrastructure Deployment Costs and Benefits

The requirement for investment into supporting infrastructure to enable CV communications exists regardless of whether aftermarket or OEM technologies are deployed, or whether DSRC or C-V2X technology is implemented. This was considered by Infrastructure Victoria and WSP (2018), who noted roadside V2I devices represented a potential risk to overinvestment in ICT infrastructure due to competing technologies (i.e. DSRC and C-V2X) and suggested that the focus should be on cooperative data exchange and not the underlying technology and forms of communication. The European Commission and Ricardo Energy and Environment (2016) found that there is a significant benefit from spreading initial investment costs across numerous services including in-vehicle hardware and aftermarket devices alongside roadside infrastructure rather than investment into one type of service. Analysis also indicated that the more rapid the initial deployment, the earlier the network ‘breaks even’. The European Commission and Ricardo Energy and Environment recommend the deployment of a cellular connectivity communication (long-range communication) for V2I services as soon as possible so benefits can be realised immediately.

Queensland Department of Transport and Main Roads (2016) undertook a rapid cost-benefit analysis of deploying C-ITS infrastructure in Southern Queensland for three cases of new vehicle market penetration: pessimistic, moderate, and optimistic. The forecast model assumed three broad cost categories for infrastructure deployment:

- Vehicle ITS system: C-ITS communication technology fitted by the vehicle manufacturer.
- Roadside ITS system: C-ITS stations fitted to signs, signal gantries, poles, and cabinets.

[2] 2018 dollars

- Central ITS systems: data, tools, and services to enable C-ITS and associated use-cases, including positioning data and a security credential management system (SCMS).

Using a 7% discount rate, Queensland Department of Transport and Main Roads found that in-vehicle ITS systems made up majority of both the capital and operating expenditures (for deployment in Southern Queensland). In the moderate scenario, this accounted for approximately 84% of the upfront costs at $329 million dollars[3], and 74% of the ongoing costs at $296 million dollars[4].

Andrews et al. (2018) estimated the deployment cost of establishing DSRC infrastructure in Texas, USA, and compared this to an estimated C-V2X deployment cost. In their estimate, DSRC deployment costs excluded the cost of retrofitting DSRC to vehicles, and only included the cost of: RSU equipment, RSU installation, network planning for RSU sites and construction logistics, backhaul connections, operational costs (e.g. electricity, maintenance), and rental fees. C-V2X was assumed to not include an infrastructure as the LTE network required for C-V2X operation already covers the nation. Based on these assumptions, the authors found that coverage for the whole state was marginally cheaper if C-V2X was deployed. Note that the Queensland cost analysis confirmed a long-standing transport value chain skewed to the vehicles using the road, rather than infrastructure itself.

5.5 Penetration and Benefits

The technology penetration rates required for safety and efficiency benefits is heavily dependent on the type of message being communicated. When considering Day 1 applications, awareness messages do not require significant penetration. However, higher penetrations are crucial in sensing and warning messages and present a major challenge in the deployment of C-ITS technologies where the realisation of safety and mobility benefits requires a minimum percentage of connected vehicles and infrastructure. Given that there is currently limited penetration of C-ITS technology, it is unknown what the actual penetration is for the estimated safety and mobility benefits from the literature reviewed to be realised. Generally, the literature assumes operation in ideal conditions with full reliability of technology at high rates of penetration (often 100%). In safety and productivity simulations, Rahman et al. (2019) find that at least 60% connected vehicle market penetration is necessary before benefits can be noticed, a result supported by Khondaker and Kattan (2015).

The cost-benefit analysis for C-ITS deployment in Southern Queensland undertaken by Queensland Department of Transport and Main Roads (2016) assumed vehicle market penetration (with no aftermarket penetration) as a percentage of the new car sales with C-ITS in three scenarios:

- Pessimistic: 20% in 2020, 35% in 2030, and 0% in 2040
- Moderate: 40% in 2020, 70% in 2030, and 100% in 2040
- Optimistic: 100% in 2020, 100% in 2030, and 100% in 2040

Focusing on benefits of crash savings, crash delay reduction, fuel savings, and emission reductions, their forecast model found that in all penetration rate scenarios, the benefit-cost ratio was positive, indicating that the benefits realised from deployment of C-ITS technology, even at low penetration rates, outweigh the costs. Even under the pessimistic scenario, a benefit-cost ratio of 2.1 was achieved using a 7% discount rate. Queensland Department of Transport and Main Roads (2016) predicts that delay in implementation of C-ITS technologies would result in a reduction of benefits with net economic loss of approximately $200 million[5] under an optimistic scenario, and approximately $60 million if the moderate scenario is considered.

The reduction in benefits arising from a delay in deployment is supported by the University of Michigan Transportation Research Institute who have identified a significant loss of opportunity associated with lives lost when waiting to deploy C-ITS crash reduction measures (do nothing scenario) (Sayer, Flannagan,

[3] 2015 dollars
[4] 2015 dollars
[5] 2015 dollars, 7% discount rate

& Leslie, 2018). Therefore, uncertainty surrounding the *type* of communication technology (i.e. DSRC or C-V2X) results in negative consequences as the ability to prevent two-vehicle crashes, injuries, and fatalities is delayed. On U.S. roadways assuming a 100% penetration rate is reached in 15 years from initial deployment, Sayer, Flannagan and Leslie (2018) estimate that within three years of deployment there is the opportunity to prevent approximately 7,374,065 to 8,115,790 light vehicle crashes, 2,788,922 to 3,052,040 injuries, and 40,717 to 44,558 fatalities.

Another quantitative estimate of the benefits of C-ITS assuming a 100% penetration rate by 2060 in the US is provided by 5G Americas (2018). This penetration may have been feasible by 2060 if the NHTSA proposed mandate which required V2V technology to be installed in all new cars had been implemented. 5G Americas anticipated that the full deployment of V2V communication technology in the US would have saved approximately 5,631 to 7,613 fatalities annually by 2060. Reduction in infrastructure damage and congestion is expected to contribute $7.7 billion to $10.6 billion of the total annual expected savings.

5.6 Interference and Congestion

The Car 2 Car Communication Consortium (2020) notes that for all C-ITS message types to enable applications presented in the European Roadmap, a minimum of seven 10 MHz channels within the 5.9GHz safety band is required to support all message types. A challenge identified is the interference which DSRC and C-V2X present to each other when operated on the same frequency. The ETSI has made significant efforts to develop a method where both communication technologies are able to coexist. Qualcomm (2017) states C-V2X and 802.11p can co-exist by being placed on different channels in the ITS band. This recommendation has been supported in the US by the FCC with the proposed segmented reallocation of the 5.9GHz spectrum in late 2019. However, channel congestion may still occur in large-scale deployment of C-ITS infrastructure, although further testing, especially real-world large-scale testing, is required to verify this.

In the allocated spectrum for ITS, interference on wavelengths in the 5.9GHz band is experienced when objects larger than approximately 5 cm are present. The European Automobile Manufacturers Association (2018) notes that radio waves that are smaller than 9 cm also have difficulties in penetrating buildings and rugged terrain and conclude that best performance is achieved when there is LOS between the antennas of the sender and receiver. This interference challenge is particularly prevalent in urban scenarios, where the LOS path for V2V communication is often blocked by buildings at intersections (Lu, Cheng, Zhang, Shen, & Mark, 2014). Lu, Cheng, Zhang, Shen and Mark (2014) also suggest that in highway situations, trucks may also contribute to interference and cause significant signal attenuation and packet loss. Another consideration is the installation of antennas onto automobiles; this is crucial for ensuring there is adequate radio coverage, but the curved rooves of vehicles for retrofitting antennas to facilitate communication have the potential for interference problems from poor reception, an issue experienced by Huang, Zhao, and Peng (2017) in the Michigan Safety Pilot Model Deployment.

An additional challenge is the use of lower carrier frequencies, such as the 700 MHz band designated for V2V communication in Japan, which causes signals to travel further than required and creates additional interference. The European Automobile Manufacturers Association (2018) suggests the 3.4-3.8 GHz and 3.4-4.2 GHz bands would be more beneficial for V2X communication, particularly in cases where one or both communicating parties are moving and the LOS component may be missing. However, this carrier frequency requires larger antennas that may prove to be impractical for installation on vehicles. The operation of V2X communication on multiple carrier frequencies such as the 3GHz band along with the 5.9GHz band would add redundancy to the system, thereby increasing overall robustness (e.g. against jamming). The recommendation to add an additional band for ITS operation would require regulators to pass new standards and may prove to add more complexity to the system without solving any of the existing issues.

5.7 Regulation and Standardisation

In order to reach a successful deployment and adoption of C-ITS services, all stakeholders must be involved in the deployment process. The ITS Directive 2010/40/EU states that interoperability and compatibility between communication and equipment services is necessary. Ensuring interoperability of services between regions and within and between states will be essential for a successful rollout of C-ITS (European

Comission and Ricardo Energy & Environment, 2016). Worldwide interoperability and compatibility are ideal, although regulators from different regions currently have varying standards. The spectrum for 5G must be allocated keeping in mind that V2X communications require high quality mobile broadband to ensure that communication services, especially for road safety cases, meet minimum requirements. The recent decisions and movement in the US and Europe, two of the biggest influencers of C-ITS communication development, have indicated that there may be convergence of regulation in the future, although we are still a long way from harmonisation of regulation globally.

Industry cooperation, including formation of public-private partnerships is advised by Andrews et al. (2018). In particular, MNOs are advised to explore network sharing alternatives (5GCAR, 2019) when 5G services arrive. Network sharing can occur through passive infrastructure sharing, active infrastructure sharing, and core network sharing. This sharing will ultimately depend on regulators allowing network sharing practices, and MNO's willingness to share, but can reduce overall infrastructure costs to deliver connected and automated services. Further investigation into the viability and benefits of network sharing needs to be conducted.

5GCAR (2019) suggest that OEMs consider futureproofing the connectivity as an "off-board sensor" to enable information exchange. It is expected that ADAS applications in future will be developed with on- and off-board vision, and with off-board connectivity to play a significant role in enhancing and delivering communication in NLOS conditions.

In short, full integration of C-ITS technology will require coordination with numerous stakeholders and requires regulators to oversee and allow the technology to develop, while ensuring that the security and privacy of users is maintained.

5.8 HMI

The human-machine interface (HMI) is an important factor to maximise the effectiveness of C-ITS communication technologies in increasing road safety and traffic efficiency. This is particularly true under the following conditions:

1. The connectivity is provided through retrofitting an aftermarket devices. In that scenario, it is not possible or practical to re-certify the control system as "fit for purpose".
2. The automated driving system is Level 3 or less, requiring the human driver to be at the receiving end of the connected system and to ultimately determine the appropriate response.

In order for the benefits of C-ITS to be realised, messages from the vehicle to the driver must be conveyed effectively, and this remains difficult to examine and measure. This section aims to identify key equipment used for communication, and human factors issues to be considered for effective messaging and response.

The mode of messaging will determine the type of equipment required. In the case of full automation, no additional equipment is necessary as the machine processes warnings and makes decision. However, the adoption of V2X connected technology should not be linked to the arrival of fully automated vehicles (5GCAR, 2019), and human drivers are still expected to have a level of control in most vehicles. OEMs will likely provide the equipment needed to facilitate the communication between occupants and their vehicles although some aftermarket devices (i.e. retrofitted OBUs) are currently available for this purpose. Aftermarket devices can be retrofitted to the existing fleet, and provide a valuable option for increasing the penetration of technology, as discussed further in Section 5.3. Aftermarket devices which have been tested and are available include:

- *Q-free* (n.d.) *Vehicle ITS Station:* a hardware unit which is retrofitted to the vehicle via magnetic mounting to the roof, attachment to vehicle power through supplied PoE adapter, and connection to the vehicle network via WiFi or Bluetooth OBD-II interface. This device provides visual and audio warnings from a tablet mounted for driver interaction or integrated smartphone. The Q-free solution is able to communicate via 3G/4G, G5/M5/WAVE DSRC protocols, Bluetooth, WiFi, and Ethernet.
- *Savari* (2019) *MobiWAVE® 2000 OBU:* provides both DSRC and C-V2X, and provides driver alerts in real time via a built-in speaker and microphone. This aftermarket solution also has the

capability for smartphone integration and leverages the existing HMI interface on mobile devices (i.e. visual, audio, and haptic warnings).

- *Danlaw* (2019) *AutoLink - V2X Aftermarket Safety Device*: collects real-time information via either DSRC or C-V2X radios and designed to generate predictive insights and situational warnings via integration with existing LED displays, head-up displays, infotainment systems, and audio output on vehicles.
- *eTrans Systems* (2018) *DSRC OBU:* communicates via DSRC and interacts with vehicle drivers via integration with a smartphone application and has the ability to provide visual on-screen warnings.

Experiments conducted by Lerner et al. (2014) made use of visual displays with OEM display screens, portable displays, response touchpads, LED lights, and audio communication (e.g. through headphones or in-vehicle voice navigation) and tactile stimuli (C2 tactor and a RadioShack amplifier attached to the driver's wrist) to warn drivers. The necessary equipment for HMI depends heavily on the type of warnings which are being conveyed but will also depend on the cost of retrofitting the equipment to existing vehicles.

5.8.1 Message Conveyance and Effectiveness

The effectiveness of communication between machines and humans depends heavily on the mode of message conveyance. NHTSA (2014) supported four experiments with the aim of determining the most appropriate and safe way to communicate important information from the vehicle to the human.

1. ***User-Based Structure for Message Coding***
   Users were asked to rate the importance of receiving messages in approximately 78 different scenarios which ranged from different levels of safety, speeds, types of roadway and more. It was found that alerts related to safety were of the highest level of urgency and priority whereas alerts related to convenience or sustainability were at the opposite end of the spectrum. Situations on rural roads were also deemed to be more urgent than situations on urban arterials and freeways by those surveyed.
2. ***Urgency Coding Within and Across Modes***
   Several sub-experiments aimed to determine which communication mode was most effective at delivering an urgent message: visual, auditory or tactile. Results indicated that the tactile mode may be most suitable for displaying and communicating a range of critical messages to human drivers.
3. ***Multiple Warning Events***
   The aim of this experiment was to determine whether multiple concurrent warning events were reacted to positively by drivers. A scenario which involved a potential forward collision threat and dangerous lane change environment was experienced by participants. Half of the participants were given an initial forward collision warning before being given a dangerous lane change warning after reacting to the initial danger, whilst the other half were only given the initial FCW. It was observed that those who were given multiple concurrent warnings reacted significantly faster to the subsequent dangerous lane change than those who were not. Participants also responded positively when asked how they felt about multiple warnings.
4. ***Portable Device Pairing***
   In an attempt to determine how messages are displayed to drivers, this experiment randomly assigned participants to experience different message display conditions. It was found that participants were more likely to respond quickly to messages when only one display was present.

NHTSA concluded that the message urgency must be adequately defined and conveyed in order to elicit a reasonable response from human drivers. There are multiple factors that must be assessed when deciding on the most effective type of communication between vehicles/machines and humans, including the frequency and level of warnings communicated.

5.8.2 Human Factor Issues

Some researchers are concerned over human factors issues which may threaten the intent of CVs. It is suspected that some application systems may change driver behaviour or reactions, a product of the new technology that may not have been originally intended. Austroads (2017) identified a number of potentially concerning human machine interaction issues, some of which are summarised below:

- ***Driver Overreliance:*** Driver-Overreliance can be defined as drivers delegating too much responsibility to, or incorrectly assuming the functions of, an application. This could be a case of forgetting to apply the brakes at curves when using CSW or failing to visually check when changing lanes with LCW active.
- ***Adoption of Risky Driving Behaviour:*** There is a tendency for humans to increase their tolerance for risk in tandem with improvements to safety. Drivers may adopt riskier driving styles and or speeds to compensate for their perception of reduced crash risk brought about by the subject technology.
- ***Driver Distraction:*** The presentation of confusing, ambiguous or false alerts may distract drivers and shift their attention away from the driving task.

5.9 Security, Privacy, and User Acceptance

A major challenge with V2X technology is the threat of malicious attacks. Wang, Shao, Ge & Yu (2019) find the data on the V2X network to be more open and susceptible to loss of privacy when compared to traditional networks. These threats can be carried out on the following security attributes of C-ITS communication:

- Authentication e.g. Sybil attack, GPS spoofing/position faking attack, Node impersonation attack
- Availability e.g. DoS attack, DDoS attack, Jamming attack, black hole attack
- Data Integrity e.g. Masquerading attack, Replay attack, etc.
- Confidentiality e.g. Eavesdropping attack, Traffic analysis attack
- Non-repudiation e.g. Loss of event traceability
- Real-time constraints e.g. Timing attack

NHTSA (2016a) expects that security attacks may directly impact user safety and indirectly impact system acceptance. Meanwhile, privacy attacks on the communication system could involve either tracking the location of a vehicle or causing a vehicle to falsely be reported for misbehaviour resulting in removal of a valid driver from the CV communication system.

Jamming and spoofing attacks are expected to present the highest security risks as there is a high or moderate potential for major consequences associated with this type of threat (Yeh, Choi, Prelcic, Bhat, & Heath Jr, 2018). NGNM (2018) notes that there are risks with tracking vehicles through monitoring of messages transmitted in the system from the implementation of C-ITS technologies. These risks can reduce consumer acceptance and trust in C-ITS technology, as there is the chance of user data being disclosed outside the V2X system without the user's consent and being retained in the V2X systems for longer than necessary.

These security threats are expected to be addressed with V2X services operating under regional regulatory law and policy (Kawser, Fahad, Ahmed, Sajjad, & Rafi, 2019). Privacy of users may also be supported through the use of credentials and identifiers which are not linked to the specific user's equipment, and through periodic refreshment of credentials. While this may limit risk of privacy invasion and cybersecurity threats, there is still a requirement for policymakers to enforce periodic update of connectivity technology. In the US, the FCC notice of proposed rulemaking (December 2019) notes that the technology may not function adequately if the certificates are out of date. As noted by Competitive Enterprise Institute (2020), this approach fails to address situations where users have not updated the technology; this neglect may present an issue in terms of cybersecurity, as well as adequate V2X operation.

6 Assumptions and Limitations

When considering deployment of C-ITS technology and infrastructure, this report observes that both DSRC and C-V2X technologies are fit for purpose and neither presents any significant “show stoppers”. However, at present there are differences in terms of the level of readiness for deployment between these two technologies. DSRC technology is more mature and widely tested in several trial deployments around the world. It is noted that the performance evaluations reported for C-V2X technology are affected by the lack of extensive and large-scale field testing and rely heavily on simulations and models.

The estimated effectiveness and associated safety benefits of use cases involving C-ITS technologies is limited by the assumptions made in the literature assessed. Some estimated benefits assume that there are no technical limitations in the technology, and that the C-ITS deployment will be fully accepted by users. Additionally, some of these estimations may be more specific to the country or region of assessment, for instance, crash reductions are based on the common types of collisions which are present in that region.

Assumptions regarding infrastructure or other deployment cost estimates may also vary between countries or regions. A gap in the literature exists in the testing of C-ITS communications in rural and remote environments. Without a complete understanding of the effectiveness of both the short- and long-range communications in these situations, reported infrastructure deployment cost estimates were provided on the assumption that investment into, at minimum, network coverage of all sealed roads is required for connectivity benefits to be realised. However, there is no guarantee that the technology will be effective in these environments without further testing.

7 Conclusions

This document provides an overview of C-ITS communication technology and the state of development and deployment. Connected technology covers both short-range and long-range messaging, and a full suite of connected applications - addressing safety and traffic efficiency - probably requires both of these messaging capabilities. The following three connected solutions have been proposed:

1. **DSRC short-range direct communication**
   Most field operational tests, model deployments and data analytics have been carried out using DSRC alone. All truck platooning trials use DSRC.
2. **C-V2X short-range direct communication (PC5) and long-range cellular communication (Uu)**
   This all-cellular implementation method is a proposed alternative to short-range communication provided by DSRC. The C-V2X short-range technology currently lacks large-scale and real-world testing to support its deployment but is supported by a substantial group of key companies. The lack of testing of long-range cellular is less critical.
3. **Hybrid: DSRC short-range direct communication with cellular long-range communication**
   This approach is currently adopted by the directives for C-ITS communications in Europe, and probably represents a stepping stone towards Option 2, once the technical performance of C-V2X for time-sensitive safety warnings has been fully tested.

There is currently limited deployment in the market, with few original equipment manufacturers committing to implementing connected technology (using DSRC or C-V2X) in new vehicles. A review of literature finds that there is an unnecessary divide between stakeholders of C-ITS communication technologies with regard to their apparent technology preferences (DSRC or C-V2X); these stakeholders include Original Equipment Manufacturers and Mobile Network Operators. We note that stakeholders may have vested interests with one or other connected technology.

Performance comparisons show C-ITS technology has the potential to provide significant positive outcomes in roadway crash reduction and in alleviating traffic congestion. These benefits have been assessed in multiple trials and simulations around the world, with most large-scale real-world trials testing the safety potential of DSRC. A review of the expected road safety and traffic benefits finds that connectivity can also augment the existing advanced driver assistance systems, with clear safety benefits for V2V and V2I applications. However, the benefits of V2P applications are less understood at this stage.

The framework presented by the European Roadmap to Deployment demonstrates that awareness messaging benefits can be realised at low penetration rates, while safety warnings and cooperative driving applications require higher rates of penetration for benefits to be realised. Additional factors associated with technology deployment include network coverage, where rural and remote areas may require significant infrastructure investment in order to provide adequate coverage for cellular connectivity applications. Considering the significant potential benefits in terms of crash reductions and congestion alleviation reported in the literature, a comprehensive benefit cost analysis with a specific focus on safety outcomes for Australia is recommended. Timely action is needed, with studies in the US indicating a significant loss of opportunity associated with lives lost when waiting to deploy C-ITS crash reduction measures (do nothing scenario). Regardless of the deployment technology or method, certain challenges are expected to arise from interference and congestion issues, human machine interface issues, security, privacy, and user acceptance.

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Stakeholder interviews

Putting the Connectivity in C-ITS - Investigating pathways to accelerate the uptake of road safety and efficiency technologies

Stakeholder Interviews

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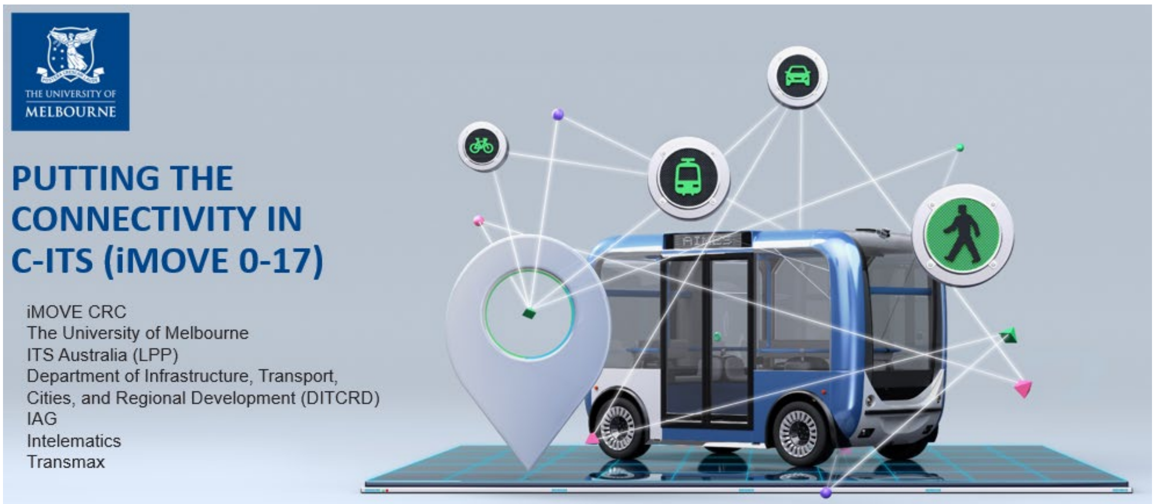

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The University of Melbourne

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ITS Australia led this project with research partner The University of Melbourne through iMOVE to better understand how connectivity and intelligent transport systems can improve safety and productivity outcomes for our communities and networks. We would like to thank our project partners and participants:

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Stakeholder Interviews

Eighteen stakeholder interviews were conducted in order to gain an understanding of the existing research and development of V2X (Vehicle-to-Everything communication) technologies, use cases being trialled, expert opinions on penetration and uptake of these technologies, and the challenges faced by different stakeholder groups. Participants included transport agencies, associations, and operators, specialised technology providers, mobile network providers, state level government, policy agencies, insurance agencies, and academics. A portion of the stakeholders interviewed are active in areas related to transport operations efficiency, others were concerned with transport safety, while some were involved in a more wholistic sphere of activities. This diversity of roles and perspectives allowed for a comprehensive overview of the current mindsets and future direction for C-ITS technology implementation in Australia and worldwide. Specifically, specialised technology providers and mobile network providers brought valuable knowledge of the performance and functional aspects of V2X technology as well as the current state of infrastructure and further improvement requirements. Government agencies provided insights into regulatory and standardisation challenges, while also reflecting on current initiatives and large-scale implementation.

1 V2X Technologies

The two predominant technologies discussed in the stakeholder interviews were DSRC (Dedicated Short-Range Communication) and C-V2X (Cellular network based V2X). While the two technologies were noted to operate on different "systems of systems" in wireless connectivity by stakeholders, many were agnostic towards the uptake and use of DSRC and/or C-V2X in road safety and productivity and acknowledged that the hybrid DSRC short-range direct communication with cellular long-range communication will likely become the norm. V2X, in general, was noted to be an additional form of data acquisition and seen as an augmentation to existing in-car sensors, which can allow the improvement of current ADAS (Advanced Driver Assistance Systems). This view is reflected in the use cases which have been identified and trialled by key stakeholders.

A difference between cellular and DSRC technologies that was identified in the discussions was that the DSRC standards base may be more stable given that the technology has existed for a longer period and has been tested more extensively. Regarding performance, DSRC can provide an advantage in road safety use cases because of its low latencies, although some stakeholders have noted that with human factors involved, this benefit may be less significant. Discussion of cellular technology and its future with 5G noted that this form of communication may provide a broader range of applications for road safety and efficiency, although this is scenario dependent, especially when adequate coverage and reception are required. In this sense, specialised technology providers indicate that they are likely to produce hardware that can operate with both technologies, either simultaneously or alternatively. Some interviewees representing agencies note that different regions may have pushed for the uptake of one or the other technology, but again, all recognise that there is the potential for both technologies to operate concurrently to support different road safety and productivity functions. Stakeholders are also aware that significant standardisation and regulation is required, as well as a unified national approach toward C-ITS communications.

Another V2X communication technology discussed in these interviews is RDS-TMC (Radio Data System Traffic Message Channel), a traffic message channel which has historically been used to allow vehicles to receive safety and traffic information. However, only a limited number of vehicles have access to this service, and those that have access are not required to use and subscribe to it.

2 Road Safety and Traffic Efficiency

2.1 Use Cases and Benefits

Interviewees identified a number of key cases where connectivity may act to improve upon safety and traffic efficiency (productivity) outcomes for road users. Some of the major recurring use cases identified include:

- Connected Signal Phasing/Intelligent Signal Optimisation
- Freeway On and Off Ramp Metering
- Variable Speed Limits
- Emergency Vehicle Prioritisation
- Vehicle Platooning, particularly of heavy vehicles
- Work-zone Safety
- Cross Traffic Alerts
- Rail Crossing Safety
- Road and Infrastructure Management
- Curve Ahead Warning
- Overhead Bridge Warning, particularly for large vehicles
- Extreme Weather Event Warning
- Driver Fatigue Warning for fleet operations

Many stakeholders noted the potential for connectivity to act as an augmentation to traditional ADAS applications and automated vehicle (AV) functionality. Stakeholders were largely in agreement in regard to the potential for connectivity to improve safety and productivity outcomes for traffic networks. Whilst no specific numbers were used, most stakeholders agreed that connectivity may improve safety and mobility by creating opportunities to address issues and implement transport policies which are currently impractical. Interviewees who focused on safety outcomes assert that connectivity will not only reduce the likelihood of crashes but also reduce the severity of crash outcomes. These stakeholders also acknowledge that benefits become increasingly significant at higher levels of penetration. However, a number of interviewees who viewed C-ITS as a support to ADAS functions stated that the benefits provided by the additional connectivity element may be outweighed by the costs of implementation and deployment, especially during the transition period. Furthermore, upgrading the necessary infrastructure to accommodate connectivity in rural areas has been identified as a major challenge by stakeholders, due to the sheer cost and scale of such a task. Some stakeholders also raised concerns over the immaturity of the technology, claiming issues such as reliability and cybersecurity may threaten to subvert the initial intentions of the application and even exacerbate existing traffic problems.

2.2 Trade-off between Road Safety and Efficiency

A common theme brought up by interviewees when asked about the impact of connectivity on road safety and productivity was the likely trade-off between the two outcomes. This is due to the relative novelty of the technology and the lack of accurate data available to make informed and effective policy decisions. A lack of data and understanding of connected technology presents the challenge of accurately measuring the impacts of policy implementation, as policies which aim to improve mobility may create unintended safety risks and vice versa. As such, these stakeholders preach caution when tackling the issue of implementation and deployment, insisting that a comprehensive understanding of the wider impacts of policies should be made to avoid trade-offs in outcomes. This idea is not agreed upon by all stakeholders however, with some asserting that mobility is directly influenced by safety, and an improvement to safety should lead to an increase in mobility in tandem.

3 Human-Machine Interaction

3.1 Equipment and Devices for Communication

Communication equipment identified mostly represent in-vehicle messaging systems, which include a Human-Machine Interface (HMI). At the OEM level, the HMI is considered proprietary and represents an important interface with the customer – the driver. Aftermarket devices tend to have less sophisticated interfaces. The predominant communication tool identified was a retrofitted tablet system or analogous HMI with audio and visual functions. The use of visual or audible messaging may depend on the situation and alert level. Other communication methods located away from the main centre of control may include haptic feedback and warning lights. Some stakeholders have also worked on communication solutions for vulnerable road users by developing a smart phone application with alert capabilities.

The design of the HMI has been widely investigated. Stakeholders have suggested that visual communication should be provided in the line-of-sight of the driver to avoid the need to take attention away from the road, but not so direct that it may act as a distraction. Experiments around audible alerts have suggested that some alert methods, such as beeps, are less effective than other methods, such as spoken warnings. As optimal communication method for different hazard scenarios is yet to be created and further research has been recommended.

3.2 Human Factors

A number of key concerns related to human factors have been highlighted by stakeholders. Connected applications are advisory, and the driver must still take appropriate action to avoid a crash or maintain traffic flow. When it comes to safety warnings, it is important that false positives are minimised in order that the system continues to have credibility with the driver. Other concerns are summarised below:

- ***Trust:*** As CAV technologies are relatively new, a lack of trust of the technology may cause drivers to ignore or contradict potentially important warnings. As such, the effectiveness of the technology is hampered not by its own capabilities but by human intervention. The contrary is also true in the sense that overreliance on the technology may also cause drivers to lose concentration, ignore clear hazards or adopt a riskier driving style.
- ***Loss of skill:*** A product of overreliance, loss of driving skill has also been a concern amongst stakeholders. By relying on warnings and automated interventions, drivers may experience a decline in driving skills, which could be potentially dangerous during a technology transition period.

4 Challenges and Opportunities

4.1 Technology Acceptance

Some stakeholders have suggested that the reliability of the external data communicated is a challenge that may translate to users who are more likely to trust information delivered from sensors on a vehicle (e.g. cameras), than data communicated from an external source. With this in consideration, the full benefits of connectivity may not be realised if users are unwilling to use/enable available connectivity technology. The acceptance of V2X technology is noted by stakeholders to be an important factor in deployment. Along with this, there are privacy and cybersecurity concerns which may limit uptake and acceptance, so, even with effective communication methods, uptake and resulting benefits might be lower than predicted.

4.2 Deployment and Penetration

Stakeholders have noted that along with user acceptance, achieving penetration rates that will enable safety and traffic benefits to be fully realised is expected to depend heavily on investment in infrastructure. The costs of implementing roadside units to support connectivity functions is expected to be significant, along with the costs of upgrading existing cellular infrastructure. Several stakeholders have contemplated the "chicken and egg" scenario and are of the view that no one wants to be the first to invest as benefits will not be seen until after the uptake of technology is significant. On the vehicle implementation side, the type of technology integration must be appealing to users so that they will invest their time and money into using the connectivity features. This is a particularly important consideration when attempting to achieve critical mass in uptake. One such example of vehicle connectivity implementation is connectivity that is provided via smartphone applications, where the user can readily access the technology rather than rely on vehicle retrofitting methods.

From the vehicle owner's and driver's perspective, the selection of connected applications is an important consideration. The deployment of applications that avoid crashes is critically important for safety improvement, but crash warnings will be rare events. Drivers need to receive day-to-day value from connected systems, and therefore more informational, less time-critical applications need to be included in a commercial connected vehicle system.

In Victoria, it is noted that the existing fleet has an average age of approximately 10 years, with penetration of connectivity technologies in the market currently limited. Taking into account the fact that fleet age and rate of change are highly variable, as are the number of manufacturers and models of vehicles available to Australian consumers, stakeholders have provided estimates for significant fleet penetration range from a few years, to a few decades for the technology to be commonplace. However, interviewees have noted that benefits to traffic flow and productivity may be seen at penetration rates below 50% which may be achieved in a reduced amount of time.

One stakeholder identified that Australia has one of the lowest fuel quality regulations and as a result, does not receive latest engine technology for the portion of the fleet imported from Europe. Due to the low fuel standards, it is likely that OEM vehicles will not have the latest connectivity technology either. In order to address this issue, changes in fuel requirements and insurance may need to be made to support newer European vehicles.

Other factors which are expected to have a role in determining the deployment and estimated penetration rates include regulation and the type of solution deployed.

4.3 Aftermarket and OEM Technology

There has been some debate surrounding the use of aftermarket solutions versus OEM technology. Some stakeholders note that aftermarket penetration will be difficult to achieve with challenges arising in retrofitting vehicles, including the need for powering the devices and fitting antennas, as well as integrating into the vehicle's data systems. This may not be an economical solution for deployment in large volumes. Some existing devices in the aftermarket sector require an OBD2 port which some manufacturers may no longer provide in the future. This port is the third-party connectivity link which allows the vehicle's safety data (e.g. brake wear and tear) to be diagnosed and communicated. For aftermarket devices used in real-world trials, the installation of antennas requires time whereas OEM equipment is factory fitted into vehicles.

A number of stakeholders believe that aftermarket devices may be a viable option for penetrating the market, particularly given the age of the existing fleet in Victoria. OEM fitment is generally the preferred option. On the other hand, tests have found that there is currently no significant difference between choosing an aftermarket solution or OEM solution. However, looking towards the future with 5G networks, there may well be a difference between aftermarket devices and OEMs in terms of quality, liability, and operability. Specifically, the quality of the aftermarket solution cannot be guaranteed and may present a challenge for the insurance industry. Stakeholders also noted that OEMs have previously experienced the unsuccessful installation of aftermarket solutions in their vehicles.

4.4 Standards, Regulation, and Stakeholders

The interoperability of the technology presents a challenge requiring cooperation between regulators, OEMs, and other relevant stakeholders. Stakeholders note that they are waiting for certainty on regulation, standards, and spectrum allocations from government and regulation bodies. This is particularly important for facilitating the deployment and uptake of technologies.

An opportunity for transport planners and operators identified in interviews is the ability for C-ITS implementation to support the creation of unique policies which may not have been viable for in traditional transport networks. For example, authorities may be able to deliver a prioritised traffic network in response to real-time data, realised with the use of smart intersections and V2I.

5 Conclusion

The stakeholder interviews conducted provided valuable insight into current expert thinking and the future direction for C-ITS technology implementation in Australia and worldwide. It was found that many stakeholders were agnostic towards the uptake and use of DSRC and/or C-V2X and were more interested in the potential for connectivity to provide road safety and traffic efficiency benefits. Several challenges in C-ITS deployment were identified, including user acceptance, and achieving penetration rates that would enable safety and productivity benefits to be realised. Specifically, the availability of infrastructure investment, difficulty in achieving sufficient penetration rates from retrofitting vehicles, and the need for interoperability were of concern. Despite these issues, stakeholders viewed C-ITS technology – deployed in vehicles at both the OEM and aftermarket levels – as an exciting opportunity to improve road safety outcomes.

Connectivity in C-ITS

Road Safety Data Analysis

Putting the Connectivity in C-ITS – Investigating pathways to accelerate the uptake of road safety and efficiency technologies

Victoria Road Safety Data Analysis

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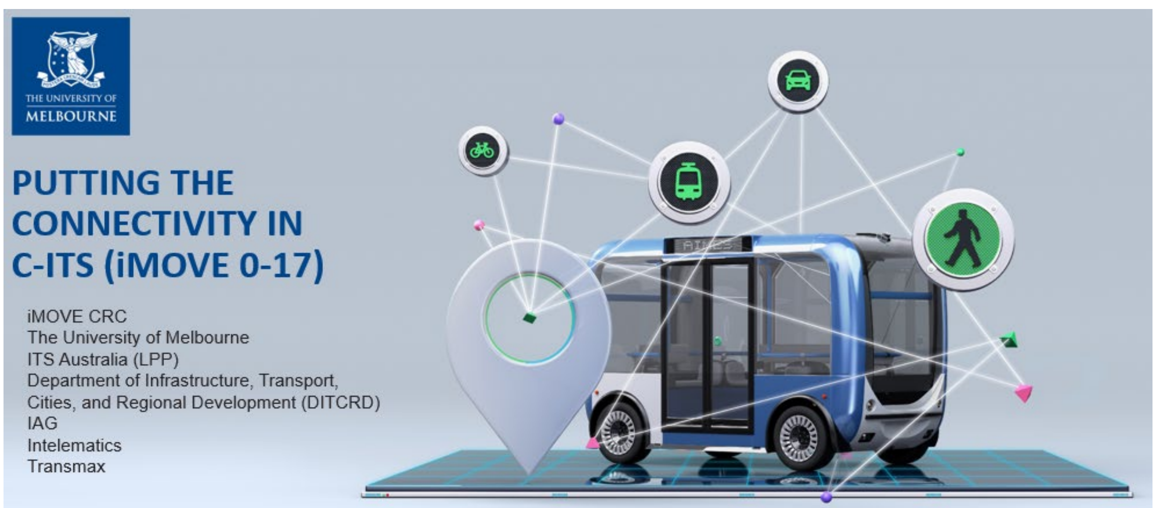

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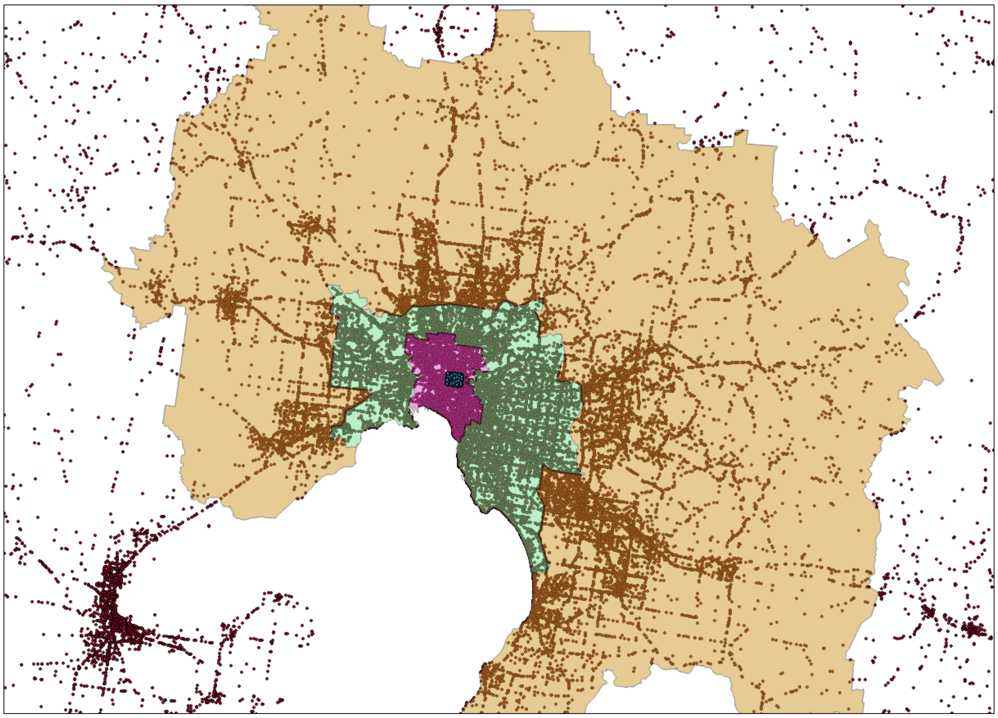
The University of Melbourne

Victorian Road Safety Data Analysis

In order to gain a quantitative understanding of the potential safety benefits of the C-ITS communication technologies in the Australian context, we conducted a comprehensive data analysis with the crash record open database from the Victorian Department of Transport. The crash dataset used in this analysis includes information from all crashes in the state of Victoria, from January 2006 to August 2019, where at least one person was injured. This dataset includes detailed information for every crash event, including crash type and location, crash severity, roadway geometry and type, traffic control devices, lighting and atmospheric conditions, etc., as well as basic information about vehicles and road users involved in the crash event.



Locations of Road Crashes in Victoria

In Section 1 of this report, we present an overview of basic statistics of crash occurrence in the state of Victoria, including statistics on crash severity by different crash types, modes and regions. In Section 2, we summarise a set of dominant C-ITS communication technologies that are widely trialled for crash reduction objectives, both nationally and internationally. We also identify the addressable market for each use case to understand the scale of potential impacts associated with each use case of the technology. In Section 3 we provide insights that are derived from the addressable market and provide a summary of the expected benefits which the use cases considered have in relation to geographics, vehicles involved, and the C-ITS deployment timeline.

Contents

1 Overview of Crashes in Victoria

This section presents overall summary statistics associated with dominant crash types in Victoria and essential information related to crash severity, environment, and vehicular modes involved.

1.1 Crash Type Categories

VicRoads has identified 10 crash type categories that represent the majority of fatal and serious injury crashes. These categories represent a high-level classification but also include detailed level sub-categories based on the standard DCA coding (definition for classifying accident) presented in Appendix A: VicRoads Crash Classifications.

- Pedestrian (DCA 100-109)
- Cross traffic (DCA 110)
- Right turn near (DCA 113)
- Head on - not overtaking (DCA 120)
- Right turn against (121)
- Rear end (DCA 130-132)
- Head on - overtaking (DCA 150-159)
- Off path on straight (DCA 170-179)
- Off path on curve (DCA 180-184)
- Other

Table 1.1 shows the number of fatal crashes (where at least one person died), serious injury crashes (where at least one person sent to hospital, possibly admitted) and other injury crashes, associated with each crash type category. Out of the total 186,546 crashes, 3,528 were fatal, 64,904 lead to serious injuries and another 118,114 crashes lead to other injuries.

Table 1.1 Crash Types by classification and severity of injury (Victoria, 2006-2019)

Crash Type	Fatal	Serious Injury	Other Injury	Total
Cross traffic	161	4,042	8,631	*12,834*
Head on - not overtaking	518	2,980	2,583	*6,081*
Head on - overtaking	101	820	1,115	*2,036*
Off path on curve	532	5,930	6,961	*13,423*
Off path on straight	927	15,357	18,660	*34,944*
Pedestrian	554	7,454	9,821	*17,829*
Rear end	151	7,615	27,107	*34,873*
Right turn against	128	5,609	10,487	*16,224*
Right turn near	105	3,020	5,648	*8,773*
Other	351	12,077	27,101	*39,529*
Total	**3,528**	**64,904**	**118,114**	**186,546**

The crash type "Off path on straight" which is associated with 10 crash definitions (DCA 170-179) is the most numerous fatal crash type in Victoria, followed by crashes with "Pedestrian (DCA 100-109)", "Off path on curve (DCA 180-184)" and "Head on - not overtaking (DCA 120)".

1.2 Geographic Region, Speed Zone, and Lighting Conditions

Figure 1.1 depicts major fatal crash types and their geographical distribution in the state. "Pedestrian" fatal crashes occur most dominantly in the Melbourne metropolitan area, while the other three most common fatal crash types ("Off path on straight", "Off path on curve" and "Head on - not overtaking") are more numerous in rural and remote regions.

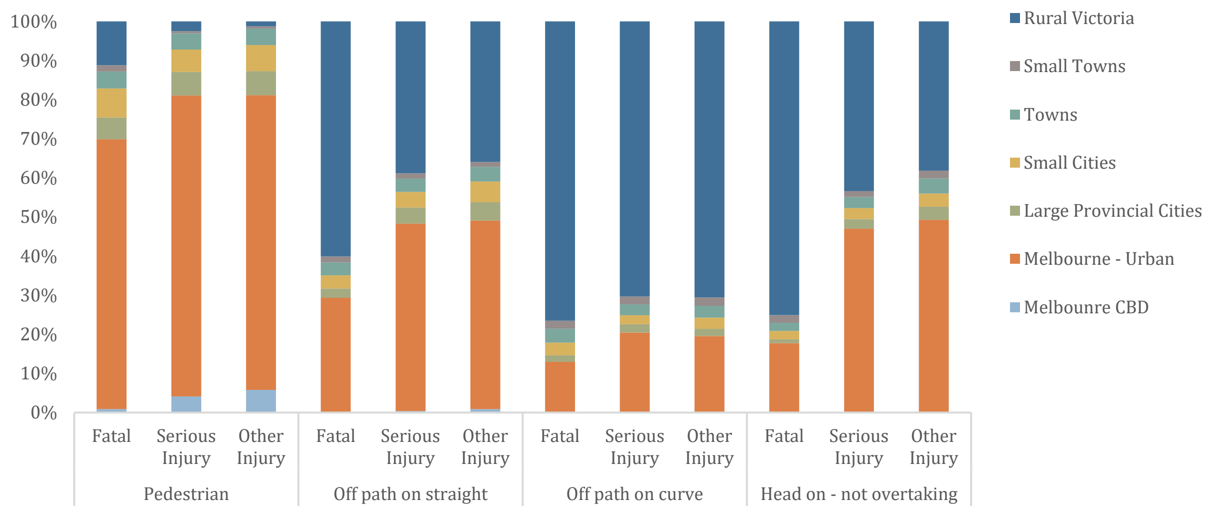


Figure 1.1 Proportion of crashes by severity, geographic region, and classification

"Head on - overtaking (DCA 150-159)" is not as frequent as the other categories, however, these crashes have a higher fatality rate than average (5% vs 2%). These crashes are also more common in rural and remote regions (Figure 1.2) and more frequent in higher speed zones (Figure 1.3).

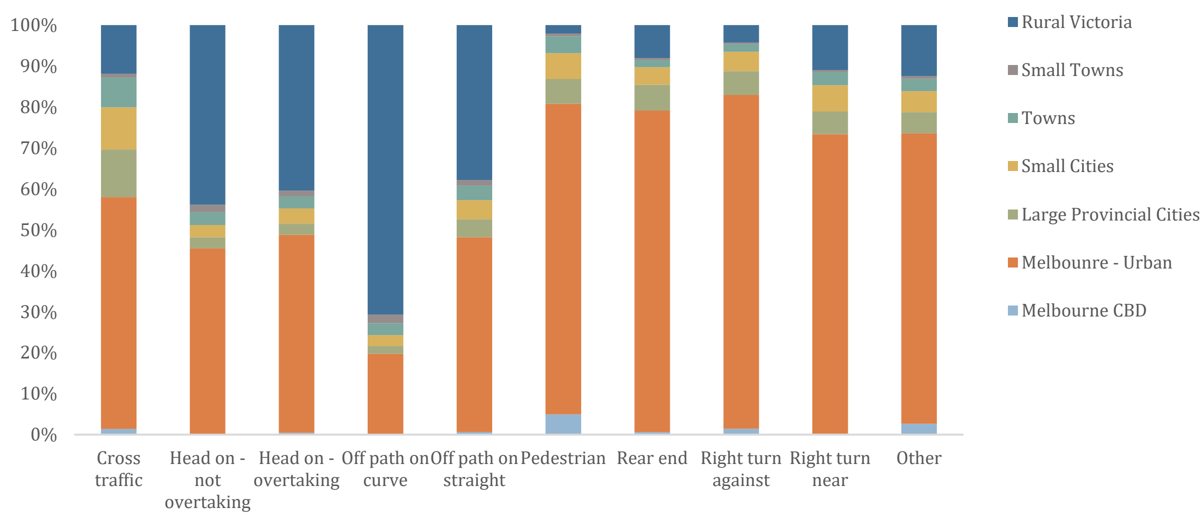


Figure 1.2 Crashes by geographic region and classification

"Rear end (DCA 130-132)", "Cross traffic (DCA 110)", "Right turn near (DCA 113)", "Right turn against (121)" are less severe on average, but very frequent especially in the Melbourne metropolitan area (Figure 1.2). More information regarding crash types, severity, vehicles involved, geographic region and roadway geometry is presented in Appendix B: Victorian Road Safety Data Summary.

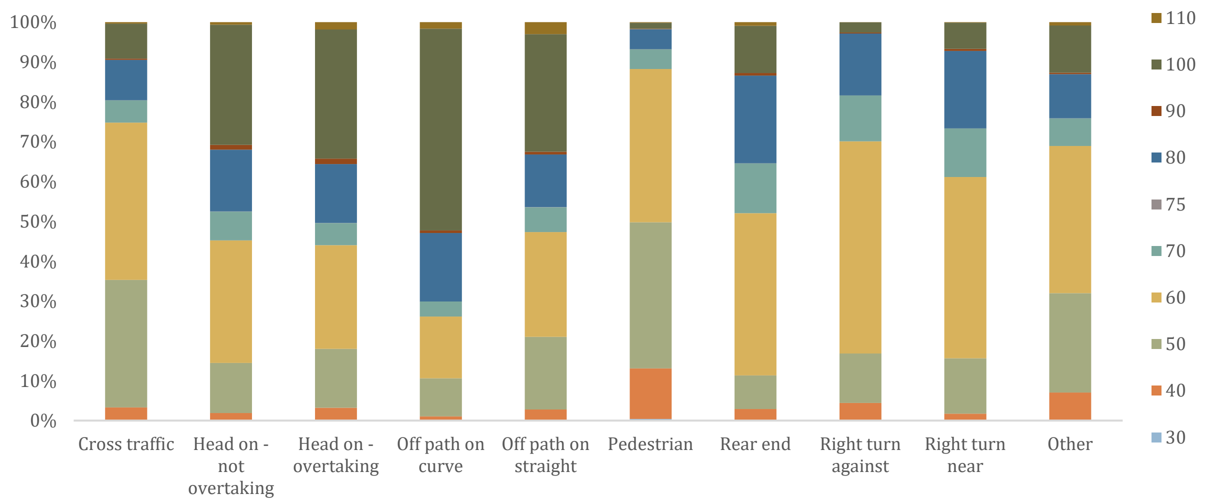


Figure 1.3 Crashes by classification and speed zone

From the perspective of roadway lighting conditions, the majority of Victorian crashes happen during daylight hours (Figure 1.4); however, the three regional fatal crash categories ("Off path on straight", "Off path on curve" and "Head on - not overtaking") occur more than others during hours of darkness and on road segments without proper lighting condition.

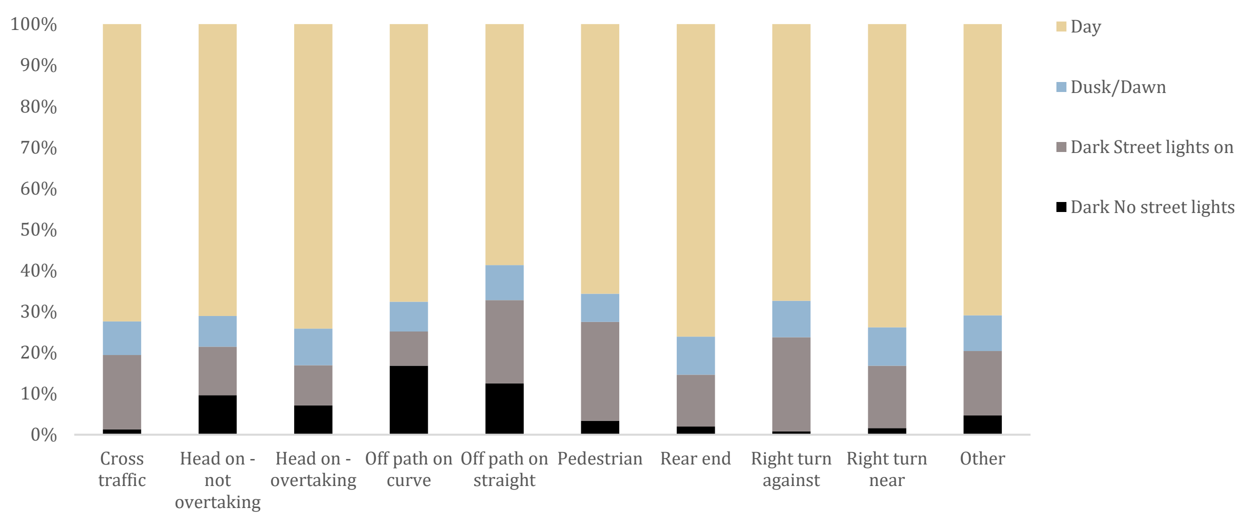


Figure 1.4 Crash type by street lighting condition

1.3 Vehicle Types

On average, 1.8 vehicles are involved per crash in Victoria. This includes vehicles from all possible modes of transport. Table 1.2 summarises all modes into five major vehicle types: car, truck, motorcycle, bike and other. Cars are the most dominant type of vehicles involved in crashes; however, trucks and motorcycles are over-represented in fatal crashes.

Table 1.2 No. of vehicles involved by type and severity of injury

Vehicles Types	Fatal	Serious Injury	Other Injury	Total
Car	3,987	84,696	175,147	*263,830*
Truck	710	5,451	9,319	*15,480*
Motorcycle	626	11,734	13,891	*26,251*
Bike	145	5,643	13,865	*19,653*
Other	84	2,235	5,270	*7,589*
Total	**5,552**	**109,759**	**217,492**	**332,803**

About half of fatal car crashes are associated with two dominant crash types of "Off path on straight" and "Head on - not overtaking" (Figure 1.5). The dominant fatal crash types for trucks accidents are "Head on - not overtaking" and "Pedestrians" crashes. For motorcycles, "Off path on straight", "Off path on curve" and "Head on - not overtaking" are the dominant fatal crash types. For pedal cycles, the leading fatal crash type is "Rear end". More information regarding crash types, severity, and vehicles involved is presented in Appendix B: Victorian Road Safety Data Summary.

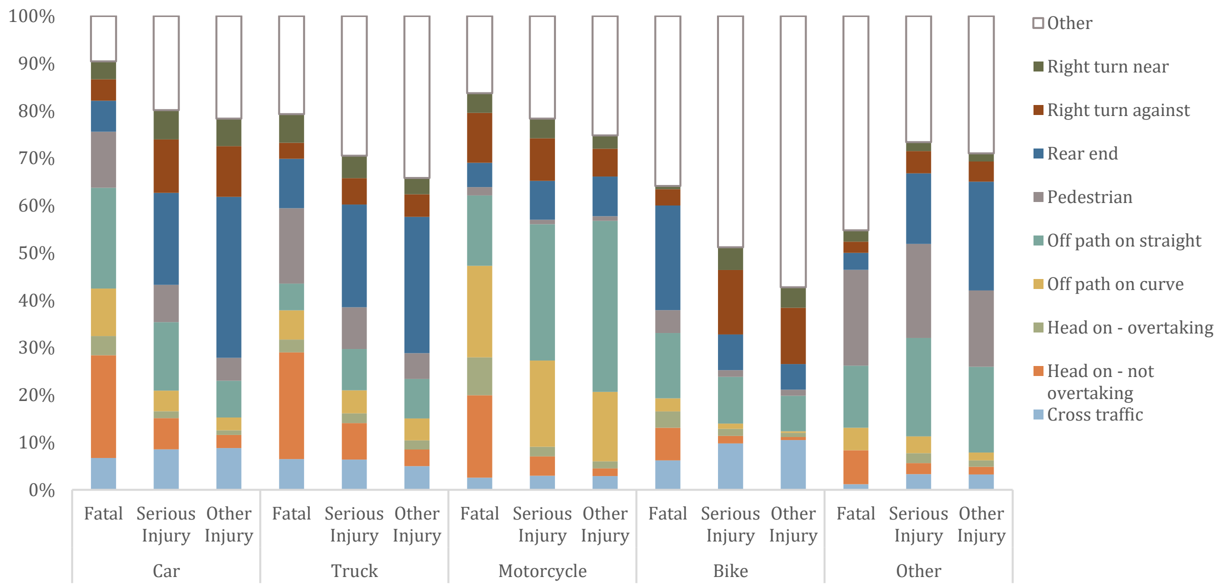


Figure 1.5 Proportion of vehicles involved by type, severity, and classification

The main takeaway here is that each type of road user is prone to a certain set of crash types and this mix varies across modes and different urban environments. As a result, a diverse set of C-ITS communication use cases can potentially lead to the most extensive crash reductions with distributed benefits over all transport modes and both in Melbourne Metropolitan area and rural/remote regions. Section 2 presents a summary list of communication technology use cases that can address a wide range of crash types that are dominant in Victoria.

2 C-ITS Applications

Co-operative intelligent transport systems refer to levels of cooperation between vehicles and their environment; this includes vehicles equipped with Advanced Driver Assistance Systems (ADAS), information exchange with infrastructure, and vehicle-to-other entity communication. C-ITS emerging technologies provide vehicle connectivity and communications with other vehicles (V2V), infrastructure (V2I), and other entities such as motorcycles, pedal cycles, and pedestrians (V2X). These communications will enable connected and automated vehicles (CAVs) to potentially deliver a range of benefits, particularly in road safety and traffic network performance.

There are numerous use cases for connected vehicles which have been trialled and simulated by government endorsed agencies, industry, and in academia. These trials aim to test and demonstrate the safety, environmental, and mobility benefits which connected vehicles (CVs) can provide; road safety applications are the focus of these trials and use cases. We investigate use cases that are expected to provide road safety benefits and identify the proportion of potential crashes that these use cases can address. While the analysis is based on Victorian crashes, the conclusions drawn are relevant to Australia in general.

2.1 European Roadmap to Deployment

Given that Australia is expected to follow the European standards for C-ITS deployment, the European Roadmap to Deployment assists in considering the many stages of deployment despite the differing policy environments. The deployment model is shown in Table 2.1 along with potential safety use cases that are applicable given the level of service and connectivity available. These safety use cases note the difference between awareness and warning messages; specifically, awareness messages are not time-critical and act to provide infrastructure- and location-related safety awareness, while warning messages are time-critical due to the presence of an imminent threat. “Day 1” use cases are expected to be for awareness purposes, while the use cases in “Day 2 and 3+” provide more time-critical and safety-specific warnings.

The model also assumes that the level of automation increases with time. That is, Day 1 C-ITS applications are provided for low levels of automation (and potentially low penetration), but are still effective for increasing awareness of risks and for the dissemination of information to drivers, while, Day 3+ activities assume that there are mid to high levels of technology penetration, as well as high, if not fully automated vehicles available for cooperative use cases. This roadmap is intended to demonstrate a potential model for achieving cooperative automated driving with the objective of crash free road transport and optimal traffic flow.

Table 2.1 European Roadmap to Deployment: Expected Services and Use Cases

Timeframe	Expected Services	Message Types	Potential Use Cases
Day 1 Awareness driving via status data	Cooperative awareness and decentralised notification; and Basic infrastructure support	Cooperative Awareness Message (CAM); Decentralised Environmental Notification (DENM); Basic Safety Message (BSM); Signal Phase and Time (SPaT); Road/lane topology and traffic manoeuvre (MAPEM); In-vehicle-Information Message (IVI); VRU Awareness Message (VAM)	• In-vehicle signage • Hazard Awareness • Intersection Awareness • Curve Speed Warning

Timeframe	Expected Services	Message Types	Potential Use Cases
Day 2 Sensing driving via sensor data	Improved cooperative awareness and decentralised notification; Collective Perception; and Improved Infrastructure Support	Collective Perception Message (CPM)	• Intersection Movement Assist • Red Light Violator Warning • Right Turn Assist
			• Cooperative Forward Collision Warning • Cooperative Blind Spot Warning/Lane Change Warning • Do Not Pass Warning
Day 3+ Cooperative driving via intention and coordination data	Trajectory/manoeuvre sharing; and Coordination/negotiation; and VRU active advertisement	Manoeuvre Coordination Message (MCM); and Platooning Control Message (PCM)	• Vulnerable Road User protection/ Pedestrian Safety Messages

2.2 Use Cases and Implementation Scenarios

A description for each of the use cases investigated in this analysis is presented in Table 2.2 along with any estimated benefits from previous trials and research papers including Austroads' *Safety Benefits of Cooperative ITS and Automated Driving in Australia and New Zealand 2017*, the Safety Pilot Model Deployment, the National Highway Traffic Safety Administration, and Australian-based trials including CAVI, CITI, and AIMES.

We investigate eight use cases, the first being Lane Keep Assist, an advanced driver assistance system (ADAS). This an ADAS-only application – all following use cases are an improvement on ADAS functionalities and are assumed to require communication technologies. That is, use cases such as forward collision warning and intersection movement assist amongst others require some level of ADAS or similar sensing hardware to function effectively.

Table 2.2 C-ITS Road Safety Use Cases

Use Case and Description	Deployment Timeframe
Lane Keep Assist (LKA)	***ADAS-only***
LKA is an advanced driver assistance system (ADAS) which does not require communication between the vehicle and its surrounding environment and instead relies on sensing hardware such as cameras. LKA acts as an automated corrective system which responds to cases of drifting manoeuvres and immediately recorrects a vehicles course to be within lane markings.	
Curve Speed Warning (CSW)	***Day 1***
CSW aims to address *single vehicle crashes* associated with excessive speed in the negotiation of roadway curves. The application compares the car's speed with a safe speed for the curve in question and warns the driver to slow down. Austroads provided an estimated 19-29% effectiveness range for the use of CSW with human intervention which is projected to prevent 75-115 fatal and serious injury (FSI) crashes in Australia.	

Use Case and Description	Deployment Timeframe
Cooperative Forward Collision Warning (CFCW)	***Day 2***
CFCW, also known as stopped or slow vehicle warning, acts to warn drivers of a threat ahead (e.g. stopped, or slowed vehicle), based on information provided by neighbouring vehicles and operates without the need for the ranging sensors used in traditional FCW Advanced Driver Assistance Systems. The lead vehicle is able to convey a message to following vehicles (V2V communication), mitigating or reducing the outcome of rear-end collisions for vehicles travelling in the same lane. Austroads' research report estimated a 20-32% crash avoidance effectiveness when the warning was acted upon by a human driver, and a 44-69% effectiveness when intervention following the warning was automated.	
Right Turn Assist (RTA)	***Day 2***
RTA is another intersection-specific collision avoidance warning which alerts the driver of potential collision with an oncoming vehicle from opposing direction while making a turn at both signalised and unsignalised intersections using V2V communication. This case is discussed specifically due to the safety benefits which are expected, and significant amount of testing and simulation which has been completed. This use case is expected to provide the highest benefit in situations where the driver's line of sight is obscured by other vehicles, road curvature, or road infrastructure. Austroads estimated RTA had an effectiveness range between 27-42% for human intervention cases, increasing to 54-85% when assuming automation was present.	
Do Not Pass Warning (DNPW)	***Day 2***
An Overtake or Do Not Pass Warning (DNPW) operates with V2V communication and alerts the driver that it is unsafe to perform an overtaking manoeuvre as there is an oncoming vehicle. This feature is expected only to operate when the driver has activated their turn signal and therefore does not have the ability to address situations when the driver unintentionally drifts into the oncoming lane. Research funded by the Texas Department of Transportation simulated and trialled DSRC-based V2V warnings for overtaking manoeuvres on two-lane rural highways. This research found that an overtaking warning was successfully sent and received in 77-96% of trials depending on the specific configurations. This use case was also successfully trialled in the SPMD.	
Intersection Movement Assist (IMA)	***Day 2***
IMA is an application designed to address common crash types at intersections. IMA acts to warn the driver that entering an intersection is unsafe due to another vehicle approaching from a lateral direction. This V2V communication exchanges basic safety messages (BSMs) that contain information that can be translated into the distance between two vehicles and the time to collision.	
Cooperative Blind Spot Warning/Lane Change Warning (CBSW/LCW)	***Day 2/3***
Blind Spot Warning (BSW) and Lane Change Warning (LCW) are ADAS functions which warn the driver when a potentially dangerous lane change manoeuvre is detected. With the use of connected vehicle technology, these functions can be enhanced to allow lane change warnings to operate at greater ranges, eliminating a key drawback of lane change warning and allowing for the development of similar applications like Overtake Assistance. Cooperative BSW/LCW can potentially remove the need for sensors within the vehicle to detect the lane change movement, instead, the vehicles performing these manoeuvres may be able to broadcast their movements to surrounding vehicles (V2V communication).	
Pedestrian Safety Messages (PSM)	***Day 3+***
Connectivity has also opened gateways to novel vulnerable road user (VRU) safety applications. VRUs are often considered as non-motorised road users, including pedestrians and pedal cyclists, and may also include motorcyclists and various electrified machines for micromobility. Vehicle to pedestrian collisions usually lead to severe injury or fatality on the pedestrian's part, accentuating the need to protect non-motorised vulnerable road users as a priority. There is a lack of worldwide trials targeting warnings of conflict between a vehicle and vulnerable road users. However, Australian trials including AIMES, CAVI, and the Towards Zero CAV, are investigating these use cases; currently, only qualitative results for expected benefits of connectivity for VRUs have been reported.	

2.3 Road Crashes Addressed by Use Cases

Using the DCA codes provided by VicRoads to understand the factors involved in a recorded road crashes, we estimate the percentage of crashes (based on 2006 to 2019 data) which can be addressed by the use cases presented in Table 2.2 above. The full definition for each DCA code is presented in Appendix A: VicRoads Crash Classifications.

Table 2.3 details the specific crash classifications that can be addressed with each use case considered. Both Pedestrian Safety Messages, and Intersection Movement Assist are expected to address the highest number of crash classifications, although this does not necessarily correlate to a higher proportion of crashes addressed overall.

Table 2.3 Types of crashes (DCA codes) that can be addressed by road safety use cases

Deployment and Use Case		Crashes addressed (DCA codes)
ADAS	Lane Keep Assist (LKA)	133, 160, 170, 171, 172, 173
Day 1	Curve Speed Warning (CSW)	180, 181, 182, 183, 184, 189
2	Cooperative Forward Collision Warning (CFCW)	130, 131, 132
2	Do Not Pass Warning (DNPW)	150, 151, 152, 153, 159
2	Intersection Movement Assist (IMA)	110, 111, 112, 113, 114, 115, 116, 117, 118, 119
2	Right Turn Assist (RTA)	121, 123, 124
2/3	Cooperative Blind Spot Warning (CBSW/LCW)	134, 135, 136, 137, 142, 147, 154
3+	Pedestrian Safety Messages (PSM)	100, 101, 102, 103, 104, 105, 106, 107, 108, 109

Assuming the crashes classified above are addressed by the use cases presented, we examine the expected proportion of crashes that could be reduced based on several factors including the severity of injury, geographic region, and type of vehicle involved.

Figure 2.1 shows approximately 80% of all crashes, for all levels of severity can be addressed in aggregate by the eight use cases presented. The deployment of vehicles equipped with ADAS functions along with the connectivity required for Day 1 applications accounts for a little over 40% of all fatal injury crashes. Interestingly, lane keep assist functions have the potential to prevent the highest proportion of fatal crashes.

When C-ITS deployment reaches Day 2, more than 60% of all crashes have the potential to be avoided. The ability for vehicles to provide intersection movement assist and cooperative forward collision warning will help in preventing a significant portion of the serious and other injury crashes on Victorian roads. Meanwhile, the Day 1 use case, curve speed warning, is expected to prevent approximately 10% of fatal crashes.

We note that these percentages are only a proportion of crashes that could potentially be addressed, and the measures provided are only indicative of the scale to which C-ITS applications can improve safety across the network. With this in mind, understanding the potential of Day 3+ applications is of particular interest given the ability for pedestrian safety messages to address crashes involving the most vulnerable road users. Pedestrian safety messages have the potential to address approximately 20% of fatal injuries; this use case has been underexplored in global trials, although some Australian trials have investigated such messages. As previously observed in Section 1.2, fatal pedestrian injuries are most prevalent in higher density metropolitan areas, thus, use cases addressing crashes involving pedestrians are an important avenue of investigation.

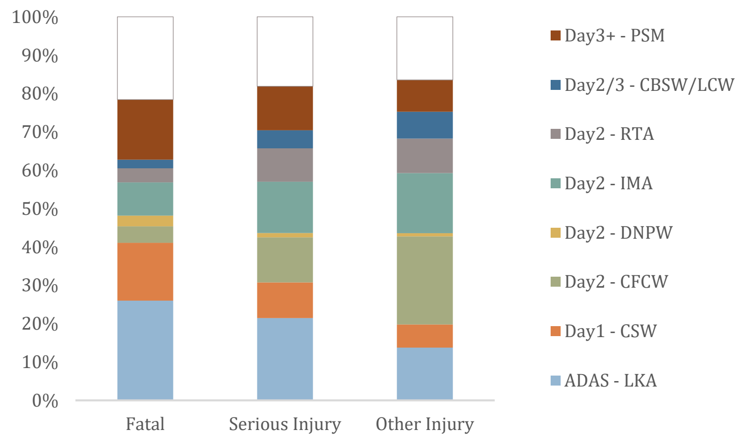


Figure 2.1 Proportion of crashes that specific use cases can address by severity

A more detailed investigation into the types of crashes which C-ITS use cases have the potential to address is presented below; this includes an understanding of the geographic regions affected (Figure 2.2) and the type of vehicles involved (Figure 2.3).

The uptake of ADAS-only technology, specifically lane keep assist functions, has significant potential in addressing road crashes across all areas; this potential increases with decreasing density for all injury types. That is, high density areas like Melbourne CBD are recorded a small proportion of crash-types that could be addressed by LKA, while towns and rural Victoria are likely to see a greater impact. This trend is also observed in curve speed warning applications – locations with decreased urban density have the greatest potential to benefit from this use case.

We observe the reverse trend for the use of intersection movement assist (Day 2) and pedestrian safety messages (Day 3+), with an increasing in capability to address crashes in more urban environments. A significant proportion of fatal and serious injury crashes occur in increasingly dense and urban environments. Notably, pedestrian safety messages have the potential to address more than half of the fatal crashes that occur in Melbourne CBD, and approximately 30% to 40% of other and serious injury crashes in the same area. Additionally, CFCW is expected to have the greatest potential to address serious and other injury crashes in medium to sparse density environments, although have limited potential in addressing fatal crashes.

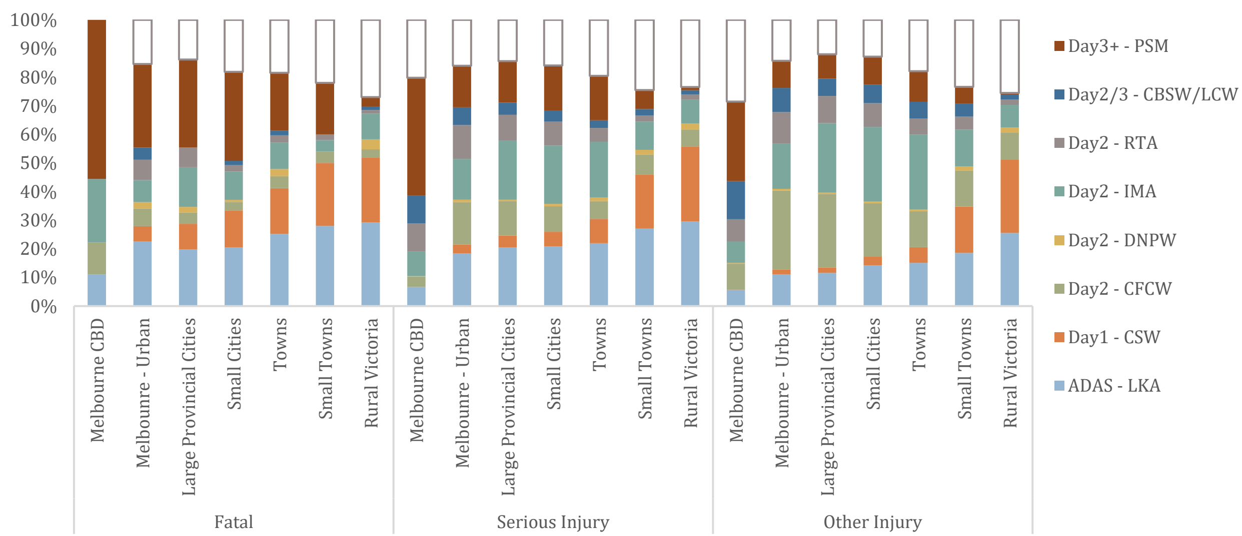


Figure 2.2 Proportion of crashes that specific use cases can address by severity and geographic region

Investigation of the crashes addressed by vehicle type and severity of injury is shown in Figure 2.3. As previously noted, Lane Keep Assist has significant potential to address crashes in all geographic areas, particularly for crashes involving cars. This use case has diminished potential in addressing crashes involving bikes or other vehicles. In fact, all used cases considered have a greater potential in addressing crashes involving cars and trucks than other modes with the exception of pedestrian safety messages. CFCW is still expected to have the greatest potential in addressing serious and other injury crashes; this use case is also considered more likely to reduce crashes that involve cars and trucks. However, approximately 20% of fatal crashes involving bikes could also be addressed by cooperative forward collision warning – this is consistent with the previous finding where the leading deadly crash type for bikes is “Rear end” (Section 1.3).

On Day 1, curve speed warning is most applicable for motorcycle crashes for all severities. As the deployment timeline progresses to Day 2, we observe intersection movement assist to have a similar potential as curve speed warning to reduce crashes across all vehicle types and injury levels. A similar trend is also observed for right turn assist, although for a smaller percentage of crashes. Day 2/3 cooperative blind spot warning and lane change warning is more relevant in addressing crashes involving bikes and trucks. For Day 3+ applications, pedestrian safety messages are observed to have the greatest potential for crashes involving cars, trucks and “other” vehicles.

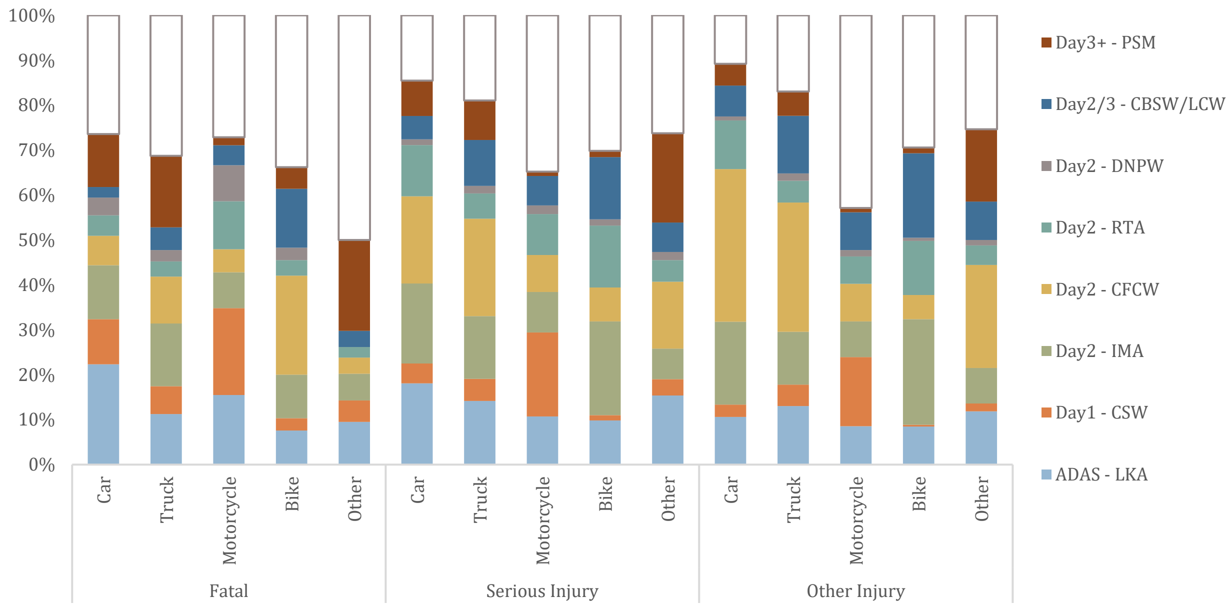


Figure 2.3 Proportion of vehicles involved in crashes that specific use cases can reduce by severity and vehicle type

3 Conclusions and Recommendations

This report presents an analysis of Victorian motor vehicle crashes, covering a fifteen-year period. Eight use cases have been studied: Lane Keep Assist (LKA), Curve Speed Warning (CSW), Cooperative Forward Collision Warning (CFCW), Do Not Pass Warning (DNPW), Intersection Movement Assist (IMA), Right Turn Assist (RTA), Cooperative Blind Spot Warning (CBSW/LCW), and Pedestrian Safety Messages (PSM). These use cases were found to have the capability to address approximately 80% of all crashes on Victorian roads (78% of fatal crashes, 82% of serious injury crashes, and 84% of other injury crashes) and have also been studied in other literature, trials, and simulations.

Table 3.1 Addressable crashes by severity and use case

Deployment Timeline Severity	ADAS	Day 1	Day 2	Day 2/3	Day 3+	NA	Total
Fatal	917	533	684	79	554	761	3,528
Serious Injury	13,923	6,038	22,686	3,048	7,454	11,755	64,904
Other Injury	16,245	7,140	57,209	8,264	9,821	19,435	118,114
Total	**31,085**	**13,711**	**80,579**	**11,391**	**17,829**	**31,951**	**186,546**

With regards to the types of vehicles involved in crashes, we expect that the arrival and ability to effectively use Day 2 applications will have the most significant impact in addressing crashes for all severities (see Figure 3.1). Notably, Day 2 applications have the greatest potential to address “other injuries” for all vehicle types. This is significant given that "other injuries” account for approximately 60% of all crashes (Table 1.1). Meanwhile, Day 1 applications are expected to have the greatest potential in reducing motorcycle-related crashes. This potential is decreases for other vehicle types, particularly bikes. Day 3+ applications are expected to have the greatest effect in reducing crashes involving “other” vehicles (i.e. pedestrians).

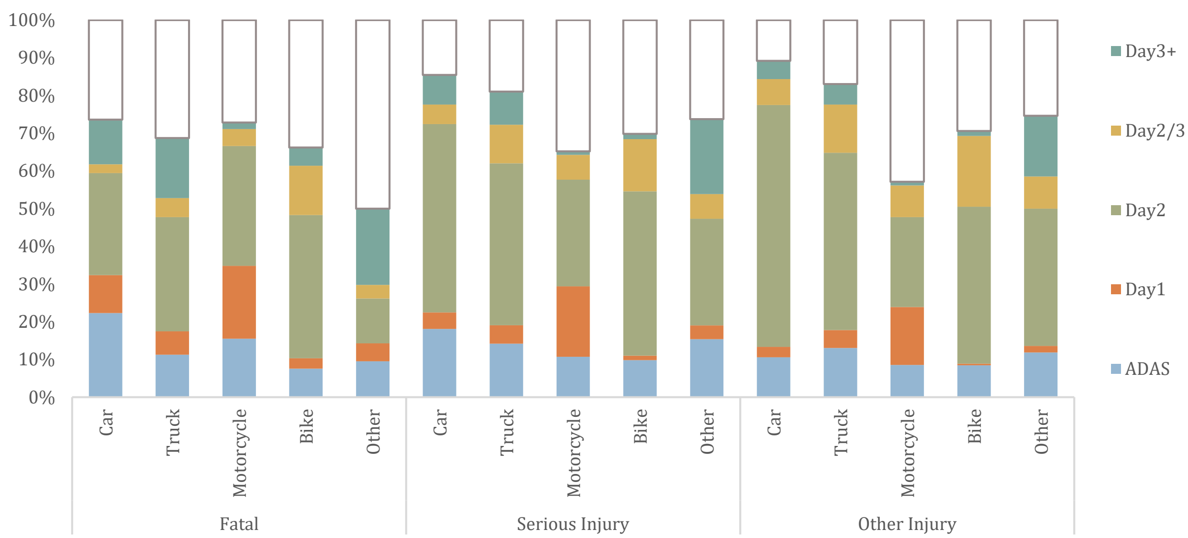


Figure 3.1 Proportion of vehicles involved in crashes by severity and vehicle type that can be addressed by C-ITS deployment timeframe

When expanded to consider the location of fatal and serious injury crashes (Figure 3.2), the potential for each application changes. Lane keep assist, an ADAS-only function, has increasing relevance in sparse environments such as towns and rural Victoria, particularly for crashes involving cars. This trend is more evident in the Day 1 application of curve speed warning for cars, trucks, and more significantly, motorcycles. For the use cases studied, Day 2 will likely have the greatest impact across all geographic locations for crashes involving cars, trucks, motorcycles, and bikes. However, the applications on Day 3+ will have the most significant effect in high density environments like Melbourne CBD and have the potential to address many crashes involving "other" vehicles (i.e. pedestrians).

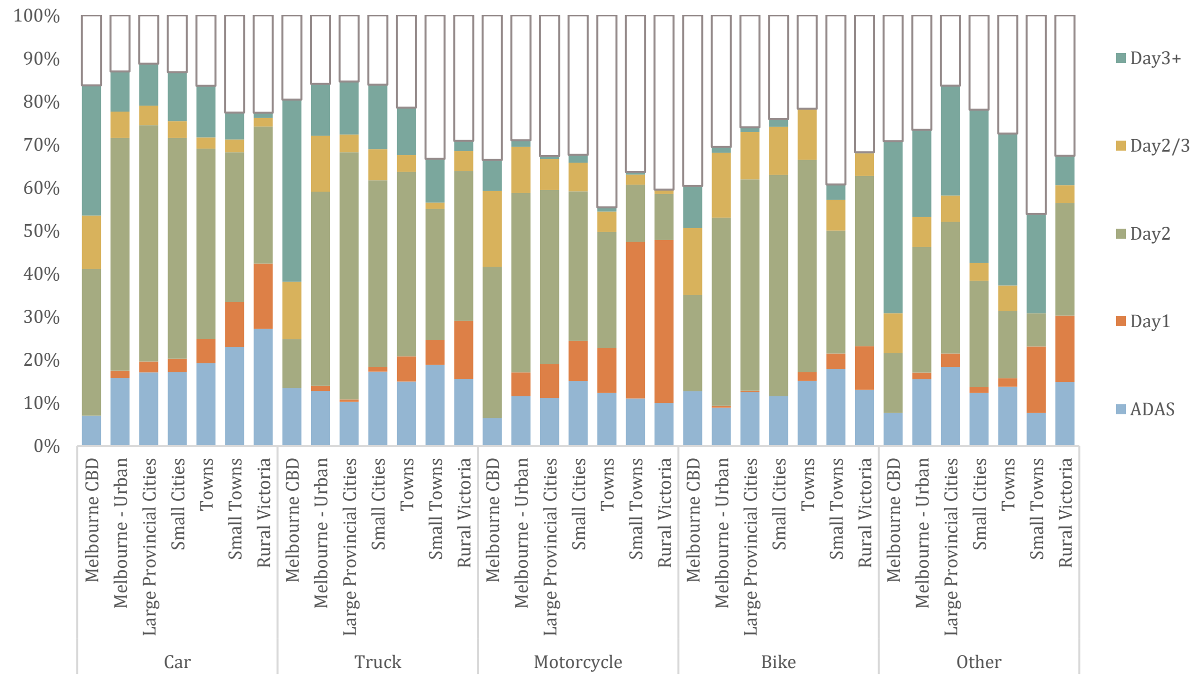


Figure 3.2 Proportion of vehicles involved in crashes by geographic region and vehicle type that can be addressed by C-ITS deployment timeframe (fatal and serious injury crashes only)

We provide a summary of each of the eight use cases investigated below; this considers the number of unique crash classifications addressed, the potential for the use case to reduce injuries by severity and location, and the ease of implementation relative to the required uptake and complexity of communications.

Lane Keep Assist (LKA)

- Six crash classifications can be addressed with this function;
- ADAS-only function that does not require connectivity technology and instead relies on sensing hardware, thus, considered to have the highest ease of implementation;
- Significant percentage of fatal injury crashes could be addressed; and
- Increasing potential for addressing crashes in less-dense regions; and
- Most applicable to crashes involving cars, trucks, and some fatal crashes for motorcyclists.

Curve Speed Warning (CSW)

- Six crash classifications can be addressed with this function;
- Day 1 awareness safety use case with communications that are not time-sensitive;
- Potential to have the greatest impact in small towns and rural locations; and
- Addresses a significant proportion of crashes involving motorcycles.

Cooperative Forward Collision Warning (CFCW)

- Three crash classifications can be addressed with this function;
- Day 2 function requiring improved cooperative awareness;
- Highly relevant to medium-density areas i.e. urban areas and small/large cities; and

- Addresses a significant proportion of “other” injury crashes which are the most common injury type.

Right Turn Assist (RTA)

- Three crash classifications can be addressed with this function;
- Day 2 function requiring improved cooperative awareness; and
- Greatest potential in reducing fatal motorcycle crashes, although broadly applicable to all vehicle types and geographic locations.

Do Not Pass Warning (DNPW)

- Five crash classifications can be addressed with this function;
- Day 2 function requiring improved cooperative awareness;
- Greatest potential in reducing fatal motorcycle crashes, although less so than RTA; and
- Broadly applicable to all vehicle types and geographic locations.

Intersection Movement Assist (IMA)

- Ten crash classifications can be addressed with this function;
- Day 2 function requiring improved cooperative awareness; and
- Greatest relevance to fatal crashes in Melbourne CBD and larger cities in Victoria.

Cooperative Blind Spot Warning/Lane Change Warning (CBSW/LCW)

- Seven crash classifications can be addressed with this function;
- Day 2/3 function requiring improved cooperative awareness and trajectory/manoeuvre sharing;
- Greatest potential in addressing crashes in Melbourne CBD; and
- Applicable to all vehicle types with significant potential regarding crashes involving bicycles and trucks.

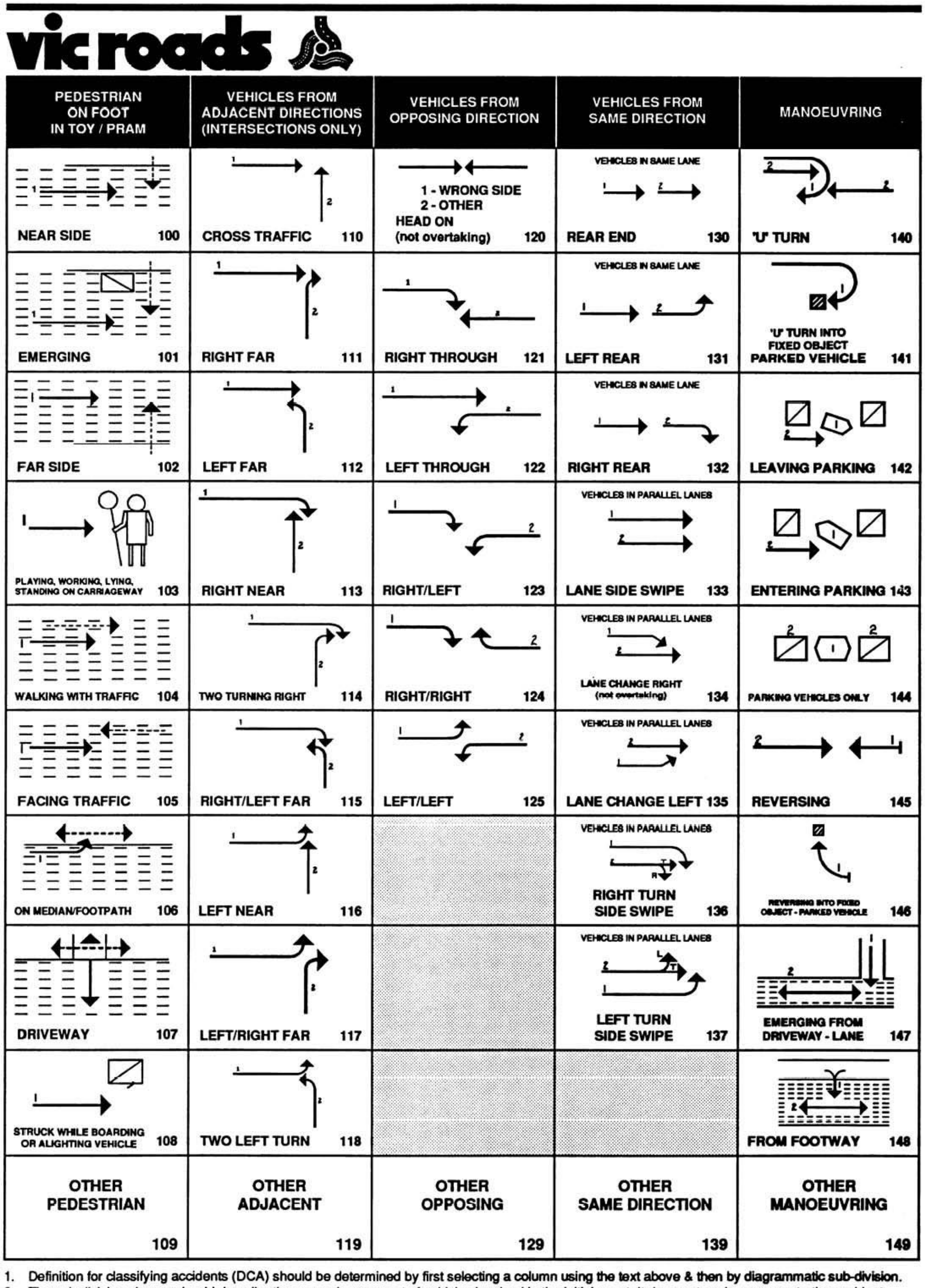
Pedestrian Safety Messages (PSM)

- Ten crash classifications can be addressed with this function;
- Critical use case given the vulnerability of pedestrians compared to other road users (e.g. cars);
- Highest degree of difficulty in implementation requiring a high level of coordination; and
- Potential to addressing a significant percentage of crashes in high density areas, specifically Melbourne CBD (more than 50% of fatal crashes);

While there is capability for ADAS-only lane keep assist and Day 1 curve speed warning to address a large proportion of crashes in Victoria, our analysis shows that these use cases are more applicable to medium to sparse environments such as small towns and rural regions. Given most of the population lives in denser and more urban regions, there is a need to consider pathways towards to implementing Day 2 to 3+ use cases as they are more likely to provide benefits across all geographic regions and vehicle types. Perhaps most importantly, these cases will address road safety cases involving the most vulnerable road users.

In this report we have provided a summary of trends for Victorian crashes over the last fifteen years. By considering some of the major C-ITS safety use cases that have been investigated globally and nationally, we present an estimate for the proportion of crashes that can be addressed considering the severity, location, and types of vehicles involved in each crash; approximately 80% of all crashes can be addressed by the eight use cases investigated. We note that the analysis provided only indicates a proportion of crashes that could potentially be addressed, and the measures provided are only indicative of the scale to which C-ITS applications can improve safety across the network. Further investigation into the effectiveness of the applications in addressing the specific crash types would be required to estimate the proportion of crashes that could be effectively addressed with the use cases presented.

Appendix A: VicRoads Crash Classifications



1. Definition for classifying accidents (DCA) should be determined by first selecting a column using the text above & then by diagrammatic sub-division.
2. The sub-division chosen should describe the general movement of vehicles involved in the initial event. It does not assign a cause to the accident.
3. Supplementary codes have been defined for most sub-divisions. These codes give further detail of the initial event.

DEFINITIONS FOR CLASSIFYING ACCIDENTS

OVERTAKING	ON PATH	OFF PATH ON STRAIGHT	OFF PATH ON CURVE	PASSENGER AND MISCELLANEOUS
HEAD ON (not sideswipe) 150	PARKED 160	OFF CARRIAGEWAY TO LEFT 170	OFF CARRIAGEWAY RIGHT BEND 180	FELL IN/FROM VEHICLE 190
OUT OF CONTROL 151	DOUBLE PARKED 161	LEFT OFF CARRIAGEWAY INTO OBJECT - PARKED VEHICLE 171	OFF RIGHT BEND INTO OBJECT/PARKED VEHICLE 181	LOAD OR MISSLE STRUCK VEHICLE 191
PULLING OUT 152	ACCIDENT OR BROKEN DOWN 162	OFF CARRIAGEWAY TO RIGHT 172	OFF CARRIAGEWAY LEFT BEND 182	STRUCK TRAIN 192
CUTTING IN 153	VEHICLE DOOR 163	RIGHT OFF CARRIAGEWAY INTO OBJECT - PARKED VEHICLE 173	OFF LEFT BEND INTO OBJECT/PARKED VEHICLE 183	STUCK RAILWAY CROSSING FURNITURE 193
PULLING OUT - REAR END 154	PERMANENT OBSTRUCTION ON CARRIAGEWAY 164	OUT OF CONTROL ON CARRIAGEWAY 174	OUT OF CONTROL ON CARRIAGEWAY 184	PARKED CAR RUN AWAY 194
	TEMPORARY ROADWORKS 165	OFF END OF ROAD 'T' INTERSECTION 175		
	STRUCK OBJECT ON CARRIAGEWAY 166			
	ANIMAL (not ridden) 167			
				OTHER 198
OTHER OVERTAKING 159	OTHER ON PATH 169	OTHER STRAIGHT 179	OTHER CURVE 189	? UNKNOWN 199

4. The number 1,2 identify individual vehicles involved when the DCA is linked with other vehicle/driver information.
5. These codes were used for 1987 accidents and replace the Road User Movement (RUM) code.

Appendix B: Victorian Road Safety Data Summary

Crashes 2006-2019		GEOGRAPHIC REGION							
	Crash Type	**Melbourne CBD**	**Melbourne - Urban**	**Large Provincial Cities**	**Small Cities**	**Towns**	**Small Towns**	**Rural Victoria**	**Total**
FATAL INJURY CRASHES	Cross traffic	2	35	7	8	8	2	99	*161*
	Head on - not overtaking	0	92	5	11	11	10	389	*518*
	Head on - overtaking	0	29	2	2	3	0	65	*101*
	Off path on curve	0	69	9	17	19	11	407	*532*
	Off path on straight	0	272	22	31	31	14	557	*927*
	Pedestrian	5	382	31	41	24	9	62	*554*
	Rear end	1	81	4	4	5	2	54	*151*
	Right turn against	0	93	7	2	3	1	22	*128*
	Right turn near	0	51	2	3	2	0	47	*105*
	Other	1	204	12	13	13	1	107	*351*
	Total	*9*	*1,308*	*101*	*132*	*119*	*50*	*1,809*	*3,528*
SERIOUS INJURY CRASHES	Cross traffic	55	2,315	367	312	244	39	706	*4,038*
	Head on - not overtaking	2	1,393	74	82	84	45	1,288	*2,968*
	Head on - overtaking	1	366	19	25	27	11	369	*818*
	Off path on curve	0	1,204	123	135	164	118	4,136	*5,880*
	Off path on straight	62	7,301	634	605	514	211	5,920	*15,247*
	Pedestrian	308	5,722	446	428	307	42	185	*7,438*
	Rear end	27	5,842	370	240	123	44	957	*7,603*
	Right turn against	74	4,621	274	223	94	14	304	*5,604*
	Right turn near	5	2,158	159	137	97	14	444	*3,014*
	Other	213	8,470	601	505	320	94	1,836	*12,039*
	Total	*747*	*39,392*	*3,067*	*2,692*	*1,974*	*632*	*16,145*	*64,649*
OTHER INJURY CRASHES	Cross traffic	120	4,909	1,114	1,005	679	72	723	*8,622*
	Head on - not overtaking	0	1,266	87	86	99	52	980	*2,570*
	Head on - overtaking	8	586	35	48	30	17	387	*1,111*
	Off path on curve	1	1,339	126	197	205	147	4,833	*6,848*
	Off path on straight	165	8,904	866	982	691	231	6,639	*18,478*
	Pedestrian	570	7,386	601	655	413	55	124	*9,804*
	Rear end	185	21,397	1,814	1,251	483	116	1,786	*27,032*
	Right turn against	158	8,496	658	543	210	42	368	*10,475*
	Right turn near	13	4,197	328	423	185	27	470	*5,643*
	Other	827	19,231	1,426	1,490	859	168	2,955	*26,956*
	Total	*2,047*	*77,711*	*7,055*	*6,680*	*3,854*	*927*	*19,265*	*117,539*

Crashes 2006-2019		VEHICLES INVOVLED														
	Crash Type	Bike	Bike-Car	Bike-Car-Motorcycle	Bike-Car-Truck	Bike-Motorcycle	Bike-Truck	Car	Car-Motorcycle	Car-Motorcycle-Truck	Car-Truck	Motorcycle	Motorcycle-Truck	Truck	Other	Total
FATAL INJURY CRASHES	Cross traffic	0	7	0	0	0	2	94	15	0	40	0	1	1	1	*161*
	Head on - not overtaking	0	4	1	0	0	4	276	76	0	131	6	9	5	6	*518*
	Head on - overtaking	1	1	0	0	0	2	43	33	1	14	5	1	0	0	*101*
	Off path on curve	3	1	0	0	0	0	366	10	1	1	104	0	42	4	*532*
	Off path on straight	18	0	0	0	0	0	770	11	0	5	80	1	31	11	*927*
	Pedestrian	5	1	0	0	0	0	411	1	0	18	10	0	92	16	*554*
	Rear end	0	24	0	0	0	5	44	21	2	45	2	3	2	3	*151*
	Right turn against	0	4	0	1	0	0	48	50	1	12	0	10	0	2	*128*
	Right turn near	0	1	0	0	0	0	41	22	0	34	0	3	2	2	*105*
	Other	4	14	0	2	1	23	109	55	1	51	13	24	16	38	*351*
	Total	*31*	*57*	*1*	*3*	*1*	*36*	*2,202*	*294*	*6*	*351*	*220*	*52*	*191*	*83*	*3,528*
SERIOUS INJURY CRASHES	Cross traffic	0	524	0	0	1	13	2,783	329	0	290	2	12	14	74	*4,042*
	Head on - not overtaking	2	58	0	2	2	12	2,096	322	0	352	52	20	10	52	*2,980*
	Head on - overtaking	4	43	0	1	0	5	419	171	3	70	41	12	5	46	*820*
	Off path on curve	46	10	0	0	2	0	3,461	59	2	13	2,014	6	240	77	*5,930*
	Off path on straight	299	161	0	0	1	9	10,709	248	1	80	3,034	11	354	450	*15,357*
	Pedestrian	70	8	0	0	0	1	6,353	7	0	45	103	0	426	441	*7,454*
	Rear end	14	305	0	2	5	11	5,172	724	12	895	69	35	61	310	*7,615*
	Right turn against	0	710	3	1	2	18	3,513	987	1	224	0	39	6	105	*5,609*
	Right turn near	0	246	0	0	2	11	2,024	456	3	215	1	14	6	42	*3,020*
	Other	73	2,202	1	16	19	164	5,420	1,509	16	1,012	783	97	181	584	*12,077*
	Total	*508*	*4,267*	*4*	*22*	*34*	*244*	*41,950*	*4,812*	*38*	*3,196*	*6,099*	*246*	*1,303*	*2,181*	*64,904*
OTHER INJURY CRASHES	Cross traffic	1	1,369	0	0	4	27	6,260	383	0	394	0	7	16	170	*8,631*
	Head on - not overtaking	5	64	0	0	7	3	1,965	139	0	261	32	2	22	83	*2,583*
	Head on - overtaking	5	86	0	0	0	6	615	144	1	132	38	8	10	70	*1,115*
	Off path on curve	28	10	0	0	0	2	4,423	51	0	30	1,942	6	383	86	*6,961*
	Off path on straight	472	359	0	0	2	29	11,321	573	1	106	4,258	38	569	932	*18,660*
	Pedestrian	166	12	0	0	0	0	8,170	12	0	46	119	2	451	843	*9,821*
	Rear end	22	534	0	4	5	16	22,072	935	13	2,157	53	28	131	1,137	*27,107*
	Right turn against	1	1,561	1	1	5	20	7,498	777	1	374	0	20	9	219	*10,487*
	Right turn near	1	557	0	0	1	12	4,324	371	2	271	1	7	11	90	*5,648*
	Other	108	6,803	4	19	35	270	12,531	2,140	11	2,105	1,054	109	409	1,503	*27,101*
	Total	*809*	*11,355*	*5*	*24*	*59*	*385*	*79,179*	*5,525*	*29*	*5,876*	*7,497*	*227*	*2,011*	*5,133*	*118,114*

	Crashes 2006-2019	ROAD GEOMETRY								
	Crash Type	**Cross intersection**	**Dead end**	**Multiple intersection**	**Not at intersection**	**Private property**	**Road closure**	**T intersection**	**Y intersection**	**Total**
FATAL INJURY CRASHES	Cross traffic	159	0	2	0	0	0	0	0	*161*
	Head on - not overtaking	8	0	0	469	0	0	41	0	*518*
	Head on - overtaking	2	0	0	82	0	0	16	0	*100*
	Off path on curve	2	0	4	486	0	0	37	2	*531*
	Off path on straight	43	2	7	777	0	0	98	0	*927*
	Pedestrian	108	0	9	330	0	0	107	0	*554*
	Rear end	15	0	3	112	0	0	21	0	*151*
	Right turn against	36	0	10	14	0	0	68	0	*128*
	Right turn near	27	0	2	0	0	0	76	0	*105*
	Other	28	0	10	232	0	0	80	0	*350*
	Total	*428*	*2*	*47*	*2,502*	*0*	*0*	*544*	*2*	*3,525*
SERIOUS INJURY CRASHES	Cross traffic	3,931	0	95	4	0	0	2	2	*4,034*
	Head on - not overtaking	122	1	11	2,468	0	0	363	7	*2,972*
	Head on - overtaking	57	0	4	590	0	0	168	1	*820*
	Off path on curve	48	2	43	5,306	0	0	505	17	*5,921*
	Off path on straight	1,379	30	191	10,985	0	1	2,688	38	*15,312*
	Pedestrian	1,864	8	83	3,833	1	0	1,643	9	*7,441*
	Rear end	1,270	0	148	4,373	0	0	1,803	16	*7,610*
	Right turn against	2,370	0	298	562	0	0	2,358	17	*5,605*
	Right turn near	570	0	141	2	0	0	2,293	14	*3,020*
	Other	1,458	15	224	7,562	2	1	2,752	39	*12,053*
	Total	*13,069*	*56*	*1,238*	*35,685*	*3*	*2*	*14,575*	*160*	*64,788*
OTHER INJURY CRASHES	Cross traffic	8,377	0	206	25	0	0	8	1	*8,617*
	Head on - not overtaking	113	0	14	2,104	0	0	344	4	*2,579*
	Head on - overtaking	110	0	8	704	0	0	291	1	*1,114*
	Off path on curve	73	0	65	6,202	1	0	573	25	*6,939*
	Off path on straight	2,209	33	282	12,503	0	1	3,510	58	*18,596*
	Pedestrian	2,705	15	127	4,670	2	1	2,270	15	*9,805*
	Rear end	6,372	6	722	13,278	0	0	6,629	66	*27,073*
	Right turn against	4,659	0	476	1,024	0	0	4,305	20	*10,484*
	Right turn near	992	0	225	2	0	0	4,386	34	*5,639*
	Other	4,013	28	472	15,646	3	0	6,806	72	*27,040*
	Total	*29,623*	*82*	*2,597*	*56,158*	*6*	*2*	*29,122*	*296*	*117,886*

Connectivity in C-ITS

Traffic simulation report

Putting the Connectivity in C-ITS – Investigating pathways to accelerate the uptake of road safety and efficiency technologies

Traffic Simulation Report

University of Melbourne

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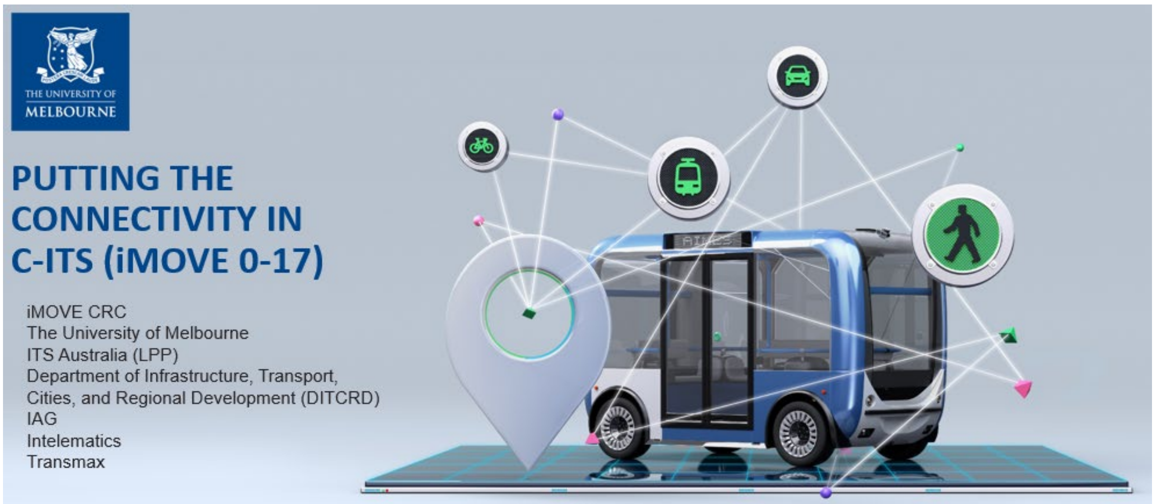
Majid Sarvi, Peter Sweatman

ITS Australia

Stacey Ryan, Susan Harris



October 2020

The University of Melbourne

Connected Vehicle Data in Traffic Control

The emergence of connected vehicle (CV) technology is promising for traffic control and can provide benefits for traffic circulation. CVs are a rich data source that can be collected and used for smart, pre-emptive, and proactive traffic control schemes. We integrated the CV data into traffic signal control to investigate the improvements and benefits that can be observed in traffic circulation over variety of different metrics. Traffic signals (installed at intersections) are critical points in any traffic control system. We tested the integration of CV data with the traffic signal control scheme (TSCS) over varying levels of available CV data (known as CV penetration rate, PR), called TSCS+CV in this paper. The outcome of this investigation is to identify the minimum penetration rate of CV technology at which the benefit of the CV data can be observed.

1 Methodology

A traffic control schemes (TSCS) generally consists of two components: i) an optimisation framework to minimise vehicles' delay behind the signals or to increase the throughput (number of vehicles that signals can process), and ii) loop detector models to estimate or measure number of vehicles entering the signals and those stuck behind the queue as input to the optimisation framework. The total number of CVs compared to the total number of vehicles in a network/fleet (i.e. CVs and ordinary vehicles combined) is called the "penetration rate" (PR). We tested the addition of CV data into a traffic signal control scheme (TSCS) over varying levels of penetration, called TSCS+CV, to evaluate the minimum level of penetration at which benefit of the CV data could be observed. CV data (such as speed and position) was added to the inputs to increase TSCS awareness of traffic conditions; we expect that the additional information to such systems achieves a reduced delay at intersections and allows for a higher number of vehicles to pass through the signals. We compared the performance of the TSCS+CV with actuated technology (a TSCS without CV) and an advanced academic method (Balance[1]) over several PRs.

This traffic simulation has two parts: 1) corridor management comparison of TSCS+CV against the Balance method, and 2) network management comparison of TSCS+CV against the Actuated system.

The performance of the TSCS+CV method is compared with both the Balance signal control strategy and Actuated system in Vissim; Balance is one of the best available methods in literature. We demonstrate the potential strength of three levels of penetration, integrating CV data with TSCS against the two other methods. The layout of the network is first is exported from the Visum simulator with real demand data for peak hours. The adjustment of the Balance signal controller is then conducted in Visum, with the required files then exported to Vissim. Meanwhile, the Actuated system is planned in VisVap. The three algorithms are compared in terms of the total intersection throughput within the given time interval; this is the objective function in traffic optimisation.

[1] Based on a traffic simulation model (more precisely a dynamic traffic assignment) to find the traffic state (i.e. traffic volume, speed, etc.) for a prolonged period in the future. Data is then fused with an optimisation algorithm (the Genetic Algorithm) to set traffic signals (i.e., phase structure, green/red time, etc.).

1.1 Corridor Management

Existing signal control strategies are known to be effective when dealing with a series of intersections along a specific corridor. This test was carried out with data from three intersections from the AIMES testbed in Victoria, along the intersection of Queensberry Street with Lygon Street, Drummond Street, and Rathdowne Street (shown in Figure 1.1). Comparison of results was made to the Balance method to show the effectiveness of incorporating CV data into traffic control schemes.

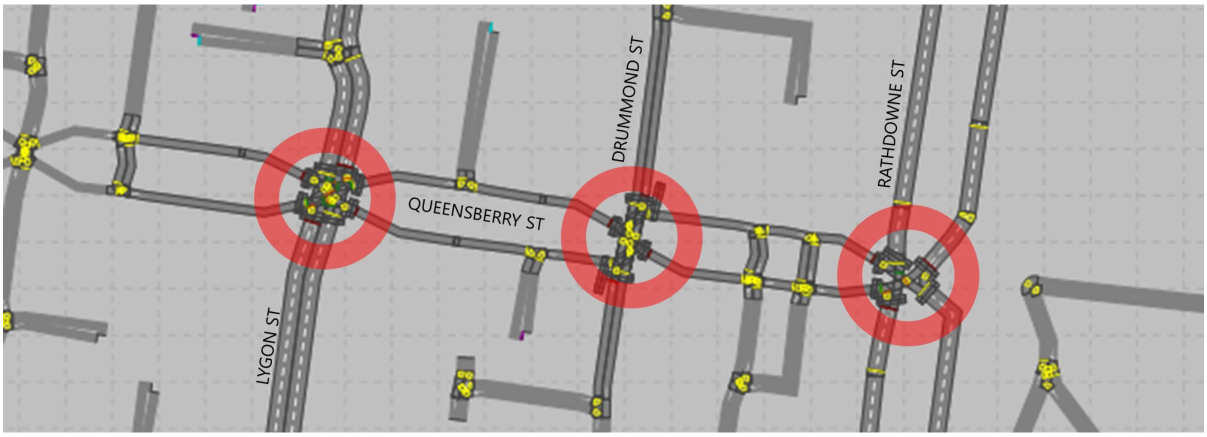


Figure 1.1 Test corridor network layout in Vissim

1.2 Network Management

Unlike corridor management, traffic signal coordination for a network of intersections can be challenging. We tested the TSCS+CV over a network of 17 intersections near Melbourne City (shown in Figure 1.2) and compared this with the best of the available technology in place, an actuated system[2] based on inductive loop detector sensors.

Figure 1.2 Testbed network layout

[2] An actuated traffic signal is one which has a type of computer, called a "signal controller", that determines the timing and even the sequence of traffic movement for each phase and cycle, based on whether vehicles or pedestrians are detected at the intersection. Actuated signal timing is completely influenced by traffic volumes and is detected through sensors at all or some of the approaches called loop detectors; these are magnetic tubes installed on the pavement right at the stop line to sense the presence of vehicles.

2 Results and Discussion

Following the methodology presented in Section 1, the results from the corridor and network traffic simulations are presented below.

2.1 Corridor Management

The comparison between TSCS+CV and the Balance method is made for several metrics: signal throughputs, vehicle speeds, CO emissions, NOx emission, Volatile Organic Compounds (VOC) emission, and fuel consumption. Results are presented in Figure 2.1 to Figure 2.6

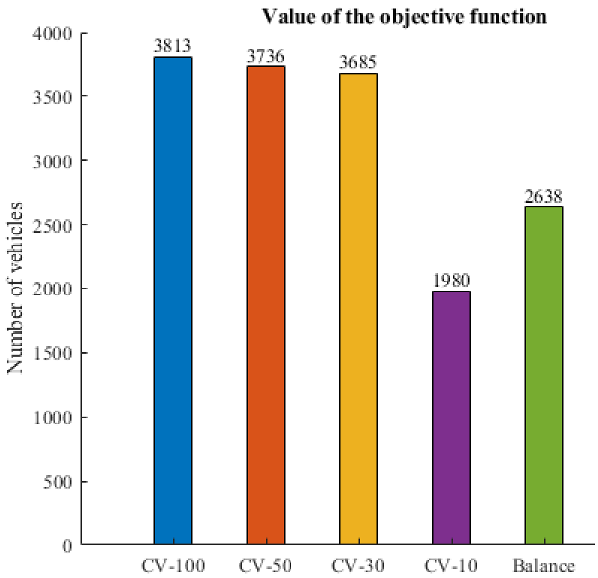


Figure 2.1 Vehicle throughput (Objective function) comparison of TSCS+CV to Balance method

Figure 2.1 demonstrates that event at a 30% penetration rate, the total number of vehicles processed through the intersections (the throughput or objective function) is higher than that of the Balance method. This is true for PRs of 30% or higher.

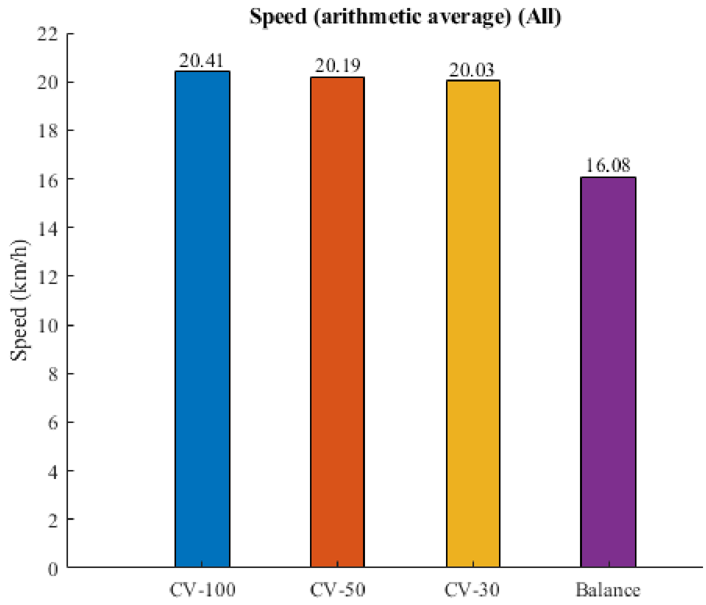


Figure 2.2 Speed comparison of TSCS+CV to Balance method

A similar result is observed when comparing the average vehicle speed through the intersections. At a PR of 30% or greater, CV data can improve the overall mobility of the network based on a comparison to the Balance method.

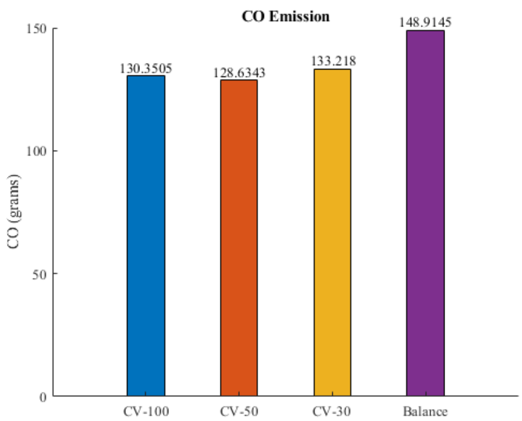


Figure 2.3 CO emission comparison of TSCS+CV to Balance method

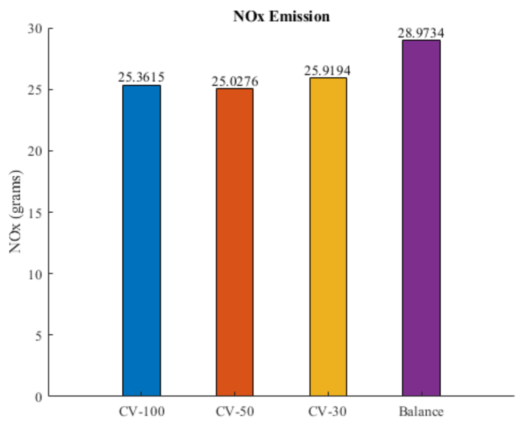


Figure 2.4 NOx emission comparison of TSCS+CV to Balance method

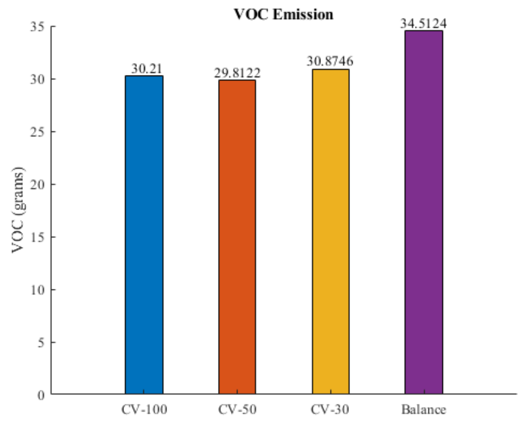


Figure 2.5 VOC emission comparison of TSCS+CV to Balance method

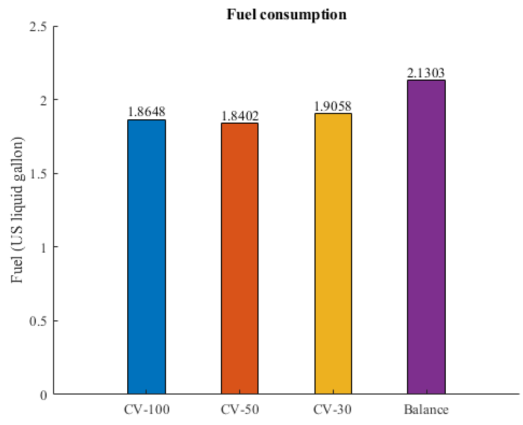


Figure 2.6 Fuel consumption comparison of TSCS+CV to Balance method

Figure 2.3 to Figure 2.6 show the impact of CV data when used in traffic control on the environment. That is, the change in levels of emissions and fuel consumption. In all accounts a PR of 30% can reduce negative environmental consequences by almost 11% compared to the Balance method.

2.2 Network Management

In a similar manner to the corridor management simulation, we compared TSCS+CV again the Actuated system across a number of metrics with results shown in Figure 2.7 to Figure 2.9.

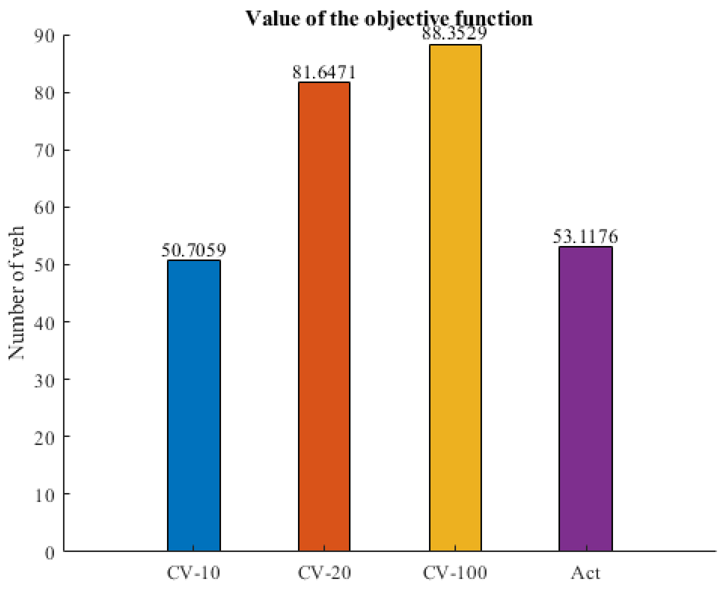


Figure 2.7 Vehicle throughput (Objective function) comparison of TSCS+CV adaptive to actuated signal control strategies

Figure 2.7 demonstrates that at a PR of 20%, the addition of CV data to TSCS can improve the throughput at an intersection by approximately 50% when compared to a traffic signal control without CV data (actuated signal).

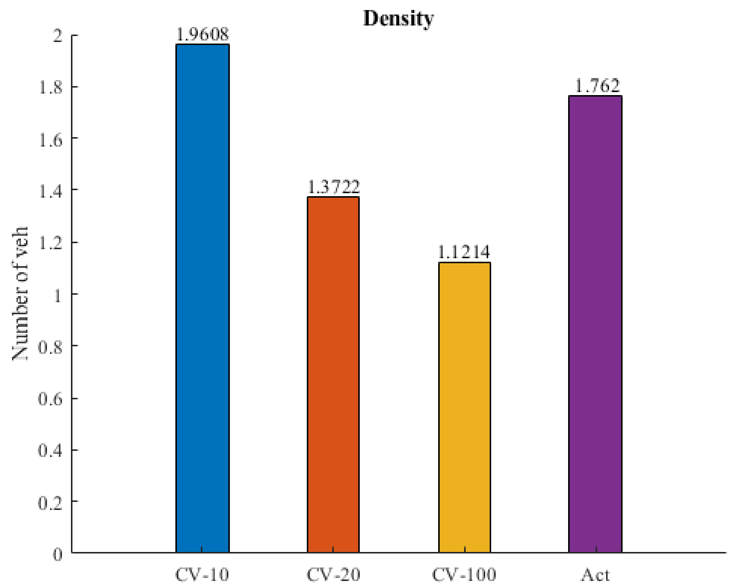


Figure 2.8 Density comparison of TSCS+CV adaptive to actuated signal control strategies

A similar result is observed when comparing the density of vehicles within a network.

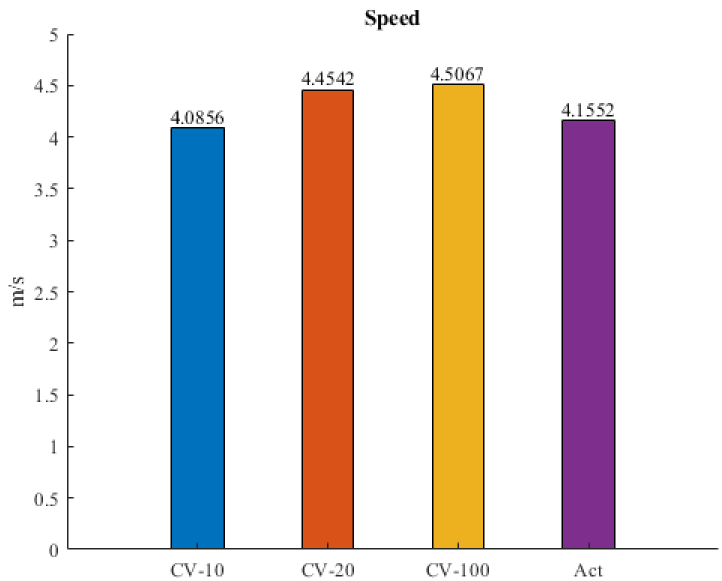


Figure 2.9 Speed comparison of TSCS+CV adaptive to actuated signal control strategies

Perhaps the most important metric is the average speed of vehicles. Figure 2.9 shows the variation of the speed over different CV PRs. At the threshold of 20%, vehicle speeds have increased approximately 10% compared to the actuated method – a significant improvement.

As can be inferred, the TSCS+CV can result in a network that outperforms the traffic signal control provided by the actuated method with a connected vehicle PR of 20% or greater.

3 Conclusion

The numerical analysis shows that even with a relatively low number of CV's (say PR of 20%), TSCS+CV can significantly improve the efficiency of traffic circulation when compared with the existing actuated systems. With a 30% PR of CVs, the TSCS+CV can also outperform the Balance control model.

Why CV data can help us achieve this? The reason is twofold: i) When using CV data, one can arguably obtain a full understanding of the traffic state, particularly as speed and queue lengths can be detected. In comparison, the current practice using the actuated system only has available data for the traffic throughput at the stop line of the intersection rather than the length of the queue or actual vehicle speeds. Moreover, by tracing the trajectory of CVs, one can connect isolated intersections in such a way that they can communicate with one another; this is an important factor in improving the operations of the traffic signals.

Across the corridor and network simulations, CV data was found to increase efficiency in traffic control, minimise delays at traffic signals, increase average vehicle speeds, and reduce pollution when used in a robust framework. The TSCS+CV is a suitable alternative to the best of available technology and the state of the art of methods proposed in academic literature. With a relatively low PR of 30%, a significant improvement in traffic efficiency (up to 10%) can be achieved.

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ABOUT THIS REPORT

ITS Australia and research partner The University of Melbourne developed this project through iMOVE to better understand how connectivity and intelligent transport systems can improve safety and productivity outcomes for our communities and networks. We would like to thank our project partners and participants, The Department of Infrastructure Regional Development Transport and Communications, IAG, Intelematics, and Transmax.

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