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

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 the following eight major connected safety use cases 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.

- 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)
- Pedestrian Safety Messages (PSM)

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.

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, 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.

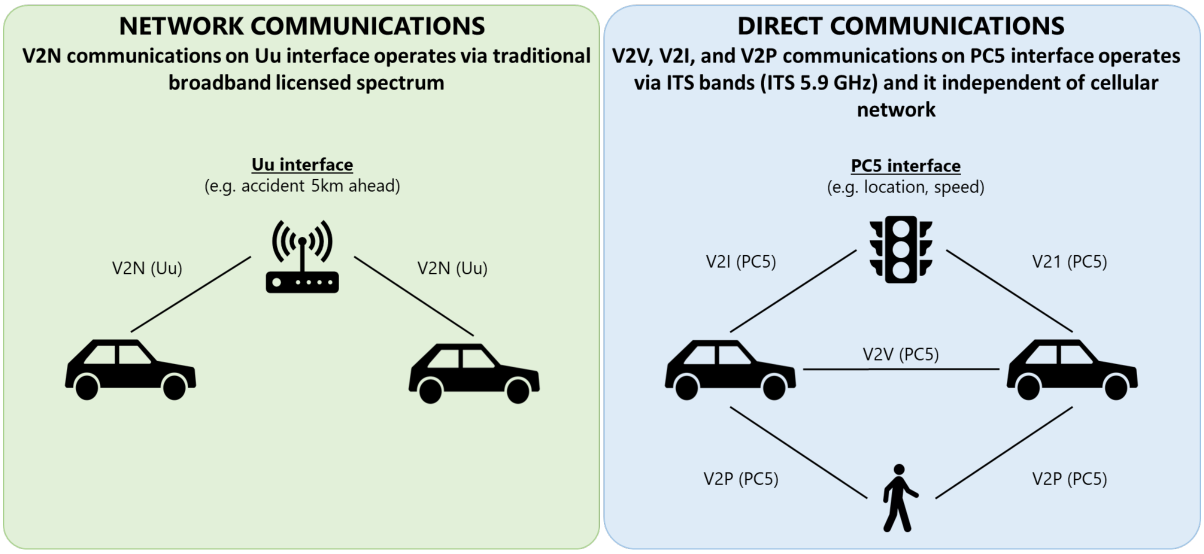

Figure 2.1 C-V2X interfaces for communication

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 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.	***Australia***
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. 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.	***NSW, Australia***
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.	***QLD, Australia***
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: 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.	***VIC, Australia***

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, a comprehensive data analysis was conducted 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. Basic statistics were analysed 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, and estimating 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.

The investigation targeted the eight use cases noted in the European Roadmap to Deployment (Section 2.4 Table 1.3) with the first use cases assessed 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.

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.

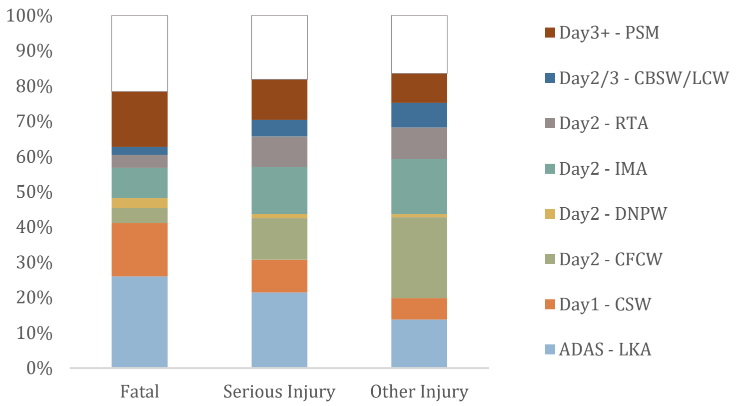

Figure 3.1 Proportion of crashes that specific use cases can address by severity

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.

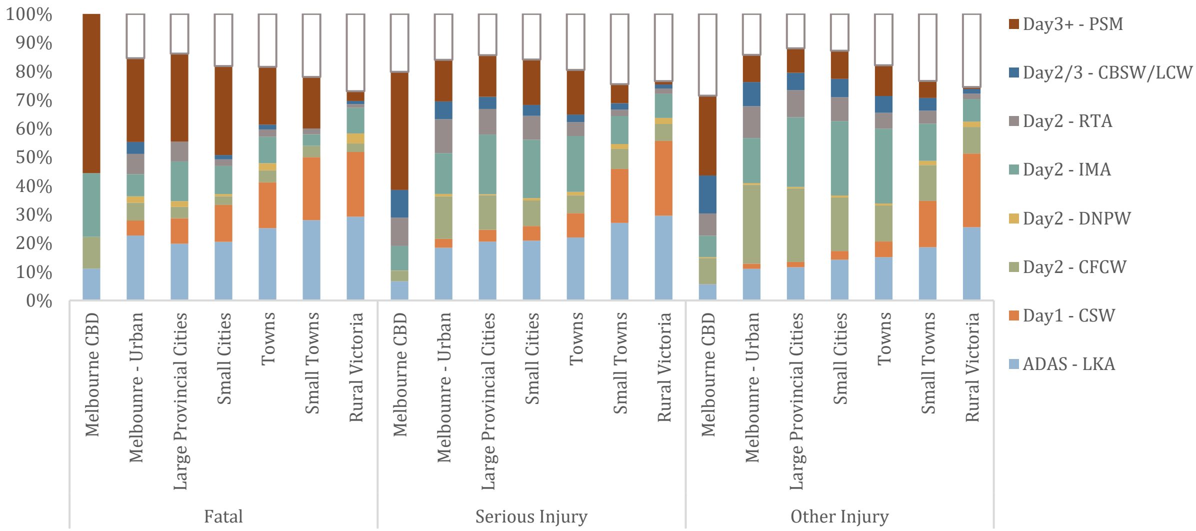

Figure 3.2 Proportion of crashes that specific use cases can address by severity and geographic region

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.

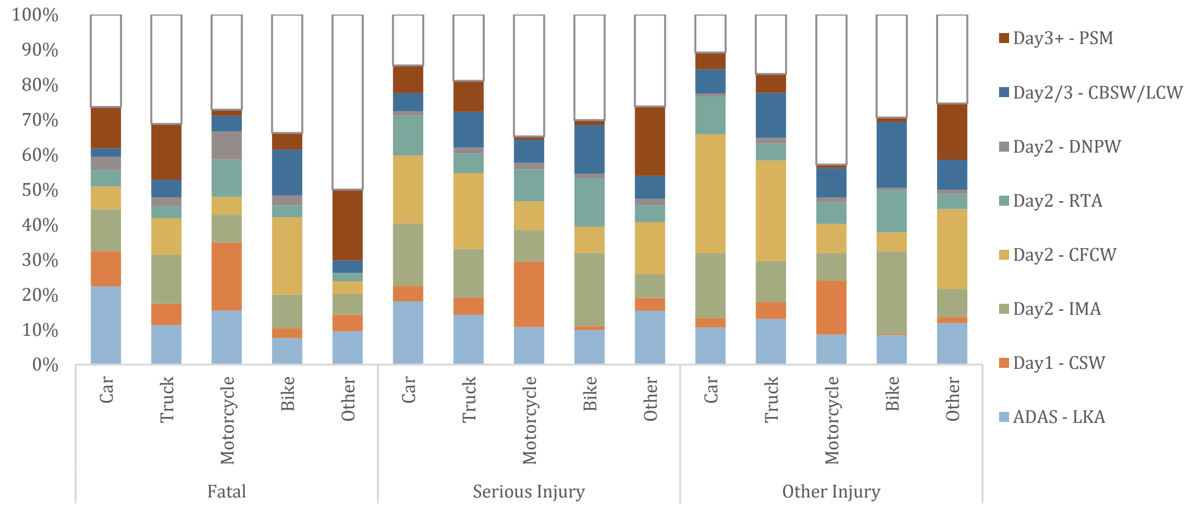

Figure 3.3 Proportion of vehicles involved in crashes that specific use cases can reduce by severity and vehicle type

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.

Importantly for small towns and rural regions there is capability for ADAS-only lane keep assist and Day 1 curve speed warning to address a large proportion of crashes in Victoria, as our analysis shows that these use cases are more applicable to less dense, sparser environments . For benefits in denser and more urban regions, there is a need to consider pathways towards to implementing Day 2 to 3+ use cases being 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). The study 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; anticipate 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. The study also 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. The simulations 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. These 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

[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.).

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.

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 can be a divide between stakeholders of C-ITS communication technologies with regard to their apparent technology preferences (DSRC or C-V2X); including Original Equipment Manufacturers and Mobile Network Operators.

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 and importantly these use cases are more applicable to medium to sparse environments such as small towns and rural regions. For denser urban environments 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) and they are also likely to provide benefits across all geographic regions and vehicle types.

Perhaps most importantly, these day 2 to 3 cases will address road safety cases involving the most vulnerable road users such as pedestrians, cyclists, and motorcyclists. 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, with some jurisdictions requiring 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 and Australia 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.

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