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

Literature Review Component

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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 Time
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 to any ad-hoc short-range communication, regardless of the frequency at which it transmits.
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.

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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 everything (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. 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 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 is being heavily investigated) 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 expected safety benefits 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 collision paths with another vehicle or a vulnerable road user. 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 safety and productivity benefits 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) for 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 resembles that 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 (2018) 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 spectrums 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 standard 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 with the base station is not required for this method of communication. The PC5 interface supports V2V, V2I, and

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

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.

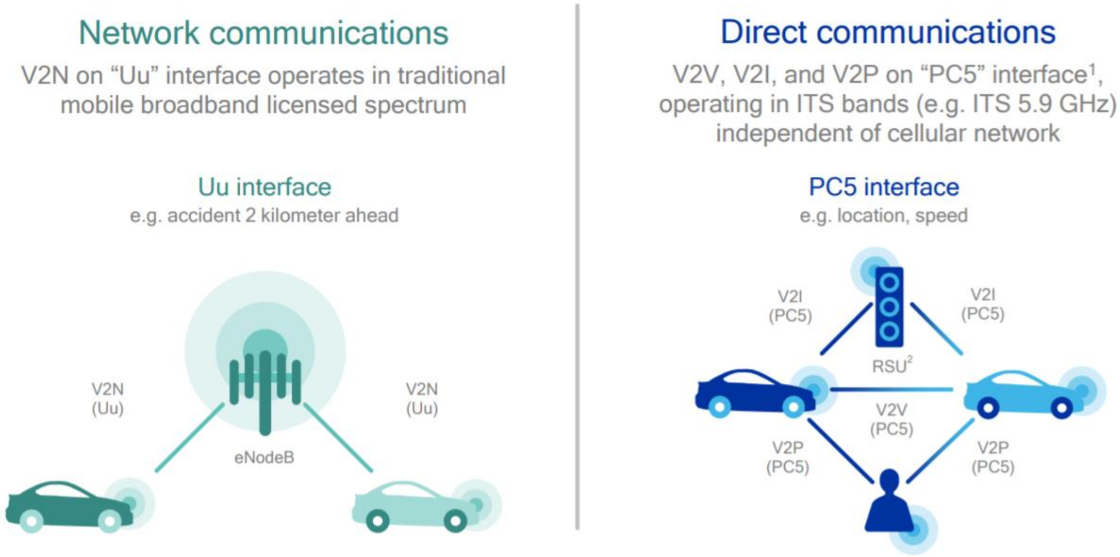

Figure 2.1 C-V2X interfaces for communication (Qualcomm, 2017)

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 opposes 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.)

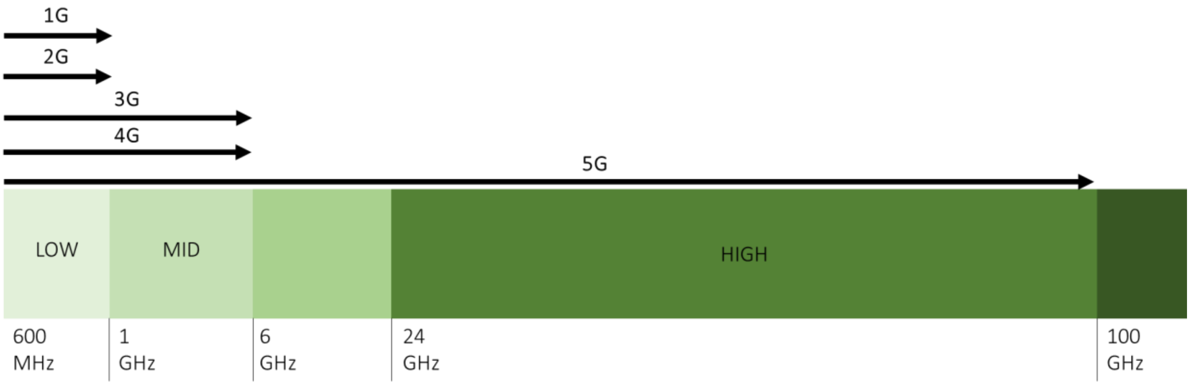

Figure 2.2 Spectrum of operation frequencies for each mobile generation (Thales, n.d.)

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 productivity 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.

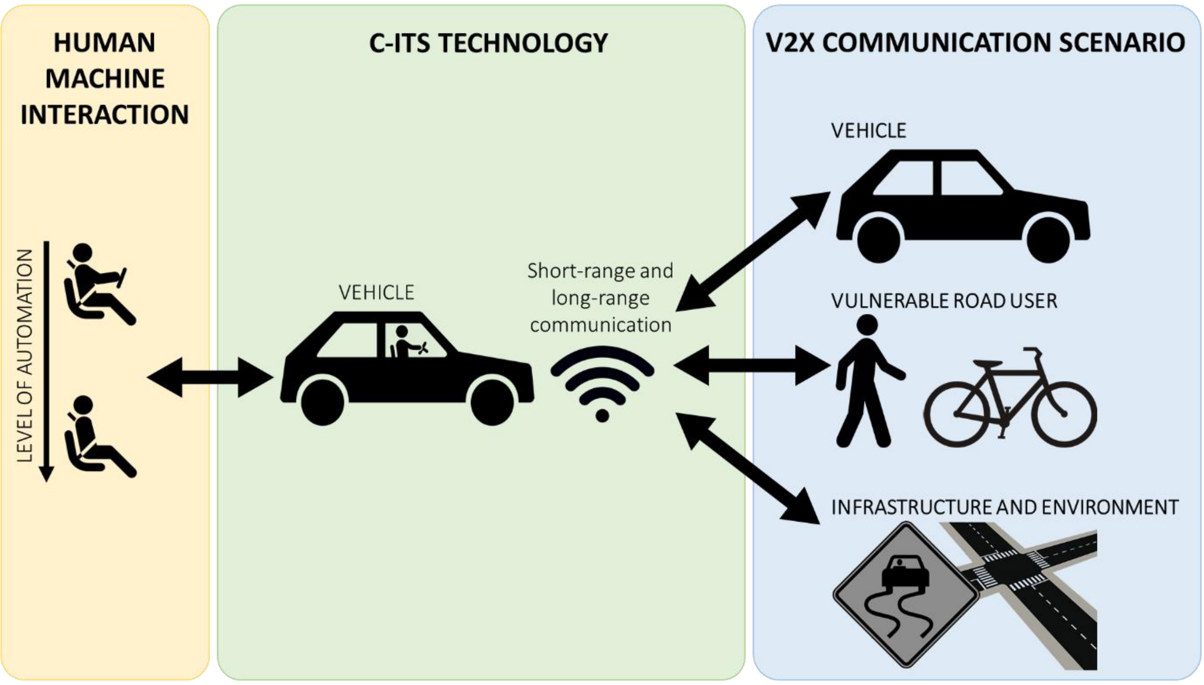

Figure 2.3 Connected and automated vehicle system architecture

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 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 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 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 productivity benefits. However, 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 equipped with a mix of integrated, retrofitted, and aftermarket connected vehicle devices along with 29 connected infrastructure sites. The SPMD costed over $50 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, the USDOT initiated 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.

3.1.2 ITS V2X Spectrum Testing, USDOT, 2020

Following the 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 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. 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.

3.3 AUSTRALIA

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

Austroads' research report 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 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 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 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 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 transport 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 lead by Cisco to determine whether Video Analytics and Artificial Intelligence technology was able to provide insights into road user behaviours and the possibility for predicting these movements in future. 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 identifies a number of following possible use cases for the technology on intersections that will 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 immediate response to road safety incidents identified at intersections.

Cisco (2019b) also trialled the use of insights provided by 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 run 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

As the effectiveness of traditional passive safety systems reach their limits, planners and policy makers are placing a greater emphasis on understanding the potential of connected technology to act as a novel solution to modern safety issues. 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.

Four types of Connected Vehicle Applications: Safety, Environmental, Mobility, and Support are 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) 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 crash volumes primarily by minimising the occurrence of driver errors, a predominant factor in 94% of traffic crashes (Yue, Abdel-Aty, Wu, & Wang, 2018). The 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, the 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. Whilst these findings do not represent actual crash reduction estimations, they act to highlight the pliant nature of CV technologies and its potential to address a broad spectrum of traffic safety issues. Jermakian (2011) investigated the maximum crash mitigation potentials of four existing CV application use cases and determined that certain applications may be more effective at reducing collision and crash related fatality rates than others. As such, an assessment of C-ITS should take a use case-based approach to better compare and identify the efficacy of individual use cases. For this review, use cases in the safety application field are classified by the type of message which is communicated.

- ***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 literature assessed in this safety application field agrees upon the ability for connectivity to further improve safety outcomes for road users, 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 increase in parallel (Zhang & Cassandras, 2018), the reality of 100% Market Penetration Rate (MPR) may not be realistic in the short term. 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)

Connectivity has the potential to act as an incubator for novel drive assist systems previously considered implausible. A demonstration of this is Intersection Movement Assist (IMA), 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 at an intersection. This V2V communication exchanges of information such as speed and distance between two vehicles approaching an intersection.

The efficacy of IMA has been identified for heavy vehicles in simulations conducted by the NHTSA (2016b). Their 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 predicted that IMA has a 43-56% effectiveness for crash avoidance. It is noted that IMA was tested in the SPMD, and similarly, intersection collision warnings were tested in the CITI project although no quantitative results from either trial are available.

In support of this estimate provided by the NHTSA, Austroads (2017) provided 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 also integrated into the IMA system, overall effectiveness of crash elimination would rise to 56-88%. The estimate provided in this study assumed a 100% penetration rate for vehicles. Wu, Ardiansyah and Ye (2017) also conducted a field experiment test to model the effects of IMA, in which 40 participants were randomly selected to engage in 7 different scenarios at 4 different intersections. Their methodology resulted in 15-26% fewer collisions, indicating a significant benefit to intersection safety, albeit lower than estimates from the NHTSA and Austroads.

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 adjacent 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 from other vehicles, road curvature, or road infrastructure.

The 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. In contrast, 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. This estimate is noted to be lower than that provided by the NHTSA simulation. However, Austroads’ predicts a significantly higher range of 54-85% when assuming automated intervention is present. This use case was tested in the SPMD although no quantitative results from this trial are available.

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 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 in the SPMD although no quantitative results from this trial are available.

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 which a driver has to respond. This use case has been tested by the SPMD, Towards Zero CAV trials, CAVI (called emergency braking warning), and CITI (called harsh breaking vehicles ahead alert). No quantitative results are currently available for any of these specific use cases trialled. Three specific CFCW use cases, emergency break 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.

Expanding on the communication provided by CFCW, CV technology can create the traffic phenomena of platooning, which can have significant positive impacts on safety. Platooning involves the driving of vehicles together in synchronisation, minimising vehicle to vehicle related collisions through communication and harmonization of movement. 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) elaborates 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.

4.1.1.5 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 in the SPMD although no quantitative results are available.

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 market 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 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) furthers 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 trialled in the SPMD although quantitative results detailing benefits of DNPW are unavailable.

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 prepare for an emergency vehicle to overtake or pass, allowing the emergency vehicle to reach its target destination as soon as possible. This warning also acts to reduce the potential for collisions between the drivers and the emergency vehicle. 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 use case may be particularly attractive for user acceptance of technology given its innovative nature when compared to some hazard warnings which are available on smartphone applications.

4.1.2 Warnings for conflicts involving vulnerable road users

Connectivity has also opened up gateways to novel vulnerable road user (VRU) safety applications. 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 an absence of worldwide trials targeted at assessing the safety benefits which can be realised from warnings where there is the potential for 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 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 enable 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 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 insurance for pedestrians who use 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 found that there was a heightened reliance on alerts by users who paid less attention to the roads when crossing, a counterproductive product of such a system. As such, further research into the actual benefits of V2P should be conducted before a conclusion can be made.

4.1.3 Infrastructure and Environment Awareness

4.1.3.1 Road Geometry Awareness

Road geometry awareness messages, commonly known and trialled as Curve Speed Warning (CSW), are another useful drive assist system which aims to address single vehicle crashes associated with a mismanagement of speed at upcoming curves in the roadway. The system works by tracking the cars speed when approaching a curve in the road and warning the driver to slow down if approaching these curves is unsafe. Inputs from vehicles to infrastructure will allow for earlier warnings to vehicles to slow down before a curve, giving more time to drivers and ultimately improving the efficacy of the application.

Austroads (2017) 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. 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. CSW was also trialled in the SPMD although no quantitative results are available to compare with the estimations provided by Austroads.

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 which may be approaching the curve at too great a speed using a variable message sign. They found that such a system yielded positive results, with a clear reduction in speed for most vehicles entering the curve 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 quicker 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 that there is the potential for a vulnerable road user to be at an upcoming intersection/crosswalk. This increased awareness has the potential to reduce the number of road safety incidents involving vulnerable road users at crossing and has been tested by the SPMD as well as CAVI, although no quantitative results are available to demonstrate the expected benefits. Similarly, the Towards Zero CAV trials conducted by Telstra successfully demonstrated the ability for road infrastructure to communicate to vehicles the presence of crossing pedestrians or bicycles at an upcoming intersection.

A similar awareness communication to the signalised crosswalk is the red light awareness message where drivers are alerted when lights at the upcoming intersection are red or amber. This specific use case has been tested by both CAVI and CITI. 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. 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 and 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 when there are upcoming hazards (see Hazard Awareness above) or when the driver is over the speed limit. With CVs, 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 its capacity to foster safety on roadways, connected vehicles also 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 vehicular transport dependency has created inextricable challenges for planners, with resultant congestion costs rising not only from direct productivity loss, but also indirect emission and pollutant driven environmental damage. 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 disruptive solution.

4.2.1 Traffic Network and Signalling

4.2.1.1 Cooperative Adaptive Cruise Control (CACC)

Vehicle platooning is a method of driving multiple vehicles together in order to reduce the occupied space-time (headway) between vehicles and increase roadway capacity. V2V communication can be utilised for creating vehicle platoons. Advancing traditional Adaptive Cruise Control (ACC) technology, Cooperative Adaptive Cruise Control (CACC) employs V2V communication to effectively achieve platooning effects throughout vehicles with such a function. 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.

As with any other connected technology, the benefits of CACC 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 a promising use case for CACC, 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 CACC 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 Variable Speed Limit (VSL)

Another example of connectivity's ability to transform mobility on roads is through V2I Variable Speed Limit (VSL) controls. VSL is a connective 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 productivity and fuel consumption reduction at different connectivity penetration rates. Their predictive model allowed for the optimisation of the VSL system to maximise benefits in either minimising total travel time or fuel consumption and compared that to a control scenario. 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.

4.2.1.3 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 our economy and 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 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 optimization.

In addition, a connected V2I system can also allow traffic signal times to optimise 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 indicate that a V2I centralised traffic control system can reduce total travel times between 17% to 48% (depending on the level of congestion) as compared to individually optimized traffic signals (Al Islam & Hajbabaie, 2017).

With V2I connectivity, other traffic management possibilities also emerge for more efficient utilisation of existing roadway capacities. For example, a connected central navigation system can help avoid the onset and propagation of traffic congestion in the network by communicating, monitoring, incentivizing, and enforcing advanced traffic routing directions to drivers. System optimal traffic assignment models have been extensively studied for optimizing traffic routing advisory information and other applications in traffic management (Tajtehranifard et al., 2018; Nassir et al., 2014). 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 et al 2005; Tajtehranifard et al., 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 can be viewed as a potential deployment model. This framework is summarised in Table 5.1 with a description of the timeframe of possible applications and reference to potential use cases in Section 4 which provide the expected service.

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 an increased knowledge to the driver of the surrounding infrastructure, 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 warnings.

The model also 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) • Personal Safety Message (PSM)	• In-vehicle signage • Hazard Awareness • Intersection Awareness

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 • 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 • Cooperative Adaptive Cruise Control • Connected Signal Optimisation and Traffic Routing

Source: Car 2 Car Communication Consortium (2019)

This roadmap demonstrates 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). To achieve this target, several factors must be considered, including:

- ***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. In particular, safety applications where warnings are time critical and require high accuracy and quality messages to be transmitted to allow drivers/vehicles to react appropriately should be considered. 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 on 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 to 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 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 must 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:*** Autonomous vehicles 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 lead 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 led 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 used to inform final technology deployment decision.

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 with 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 productivity 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 the 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 is analysed for DSRC and C-V2X Mode 3 and Mode 4 and measures 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.

5.2.3.3 Mobility Applications: Traffic Management

A traffic management technique using DSRC beacons to provide variable speed advisory is 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 for 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 when compared to the existing approach.

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.

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 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 accepted 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 which allows C-ITS communications to occur must be made available within user vehicles. This can be achieved through retrofitting the existing fleet with technology capable of providing the required communications, or provided by original equipment manufacturers (OEMs). 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 improve safety outcomes for users (Austroads, 2017).

When considering the equipment that can be deployed for C-ITS communications, the functions which this equipment must perform need to be considered. 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 the 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 BSM which alerts surrounding or nearby vehicles of their presence; no safety applications or use cases can be performed with this device. This device still requires a certified installer for the placement of antennas and security certification.

Kawser et al. (2019) noted the following hardware equipment 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 productivity benefits discussed in Section 4.

In addition to these sensing hardware, to communicate with other road users and infrastructure, vehicles must be equipped or retrofitted with an antenna for direct communications. 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 automotive aftermarket has been a long standing and lucrative market, with the sale of vehicle parts representing 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 expediate deployment of devices and tools necessary for vehicle communication to older fleets. The NHTSA (2016c) agreed with this idea and determined 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.

The 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. The 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, the 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/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 alongside 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 centre), 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. 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 of safety message communications. 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 CAV's in Victoria through the provision of cellular towers for network (4G and planned 5G) coverage would be in the order of magnitude between 1.1 and 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 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 sentiment is supported 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 used assumed three broad cost categories for infrastructure deployment:

- Vehicle ITS system: C-ITS communication technology fitted by the vehicle manufacturer.

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[2] 2018 dollars

- Roadside ITS system: C-ITS stations fitted to signs, signal gantries, poles, and cabinets.
- 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.

5.5 PENETRATION AND BENEFITS

The penetration rates required for safety and productivity benefits to be realised is heavily dependent on the type of message being communicated. When considering Day 1 applications, awareness messages do not require significant penetration for benefits to be realised. 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 is 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%) when providing estimates. 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 rapid 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, 40% in 2030, and 0% in 2040
- Moderate: 35% 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 penetrations rate, 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

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[3] 2015 dollars

[4] 2015 dollars

[5] 2015 dollars, 7% discount rate

when waiting to deploy C-ITS crash reduction measures (do nothing scenario) (Sayer, Flannagan, & Leslie, 2018). Debate surrounding the *type* of communication technology (i.e. DSRC or C-V2X) to deploy results in negative consequences as the ability to prevent two-vehicle crashes, injuries, and fatalities is not realised. 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 fatal equivalents 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

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 in developing 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 interferences 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 roof 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/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 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 MNOs 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, 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

Human and machine interactions (HMI) are an important factor when considering and evaluating the overall effectiveness of C-ITS communication technologies in increasing road safety and productivity. This is particularly true under three conditions:

1. The connectivity is provided through a retrofitting an aftermarket device to the vehicles. Here it is not possible or practical to re-certify the control system as “fit for purpose”.
2. The level of automation is between 0 to 3, where a human driver is at the receiving end of the communication and ultimately determines the appropriate response.
3. The vehicle is of level 4 automation, but operating out-of-scope/bounds and requires the human driver to intervene if a communication is received.

In order for the benefits of C-ITS to be realised messages from the vehicle to the driver must be conveyed carefully and conveniently, a simple concept which is difficult to examine and measure. This section aims to identify key equipment used for communication, factors to be considered for effective messaging and the potential dangers of human machine interaction.

5.8.1 Equipment for Interactions

The mode of message conveyance to humans 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 connectivity technology should not be linked to the arrival of fully autonomous driving vehicles (5GCAR, 2019), and human drivers are still expected to have a level of control in vehicles. OEMs will likely provide the equipment needed to facilitate the communication between humans 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 provides an option for increase the penetration of technology, discussed further in 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 smartphones. 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:* stated to function with both DSRC and C-V2X, and provides driver alerts in real time via a built-in speaker and mic. 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*: stated to collect real-time information via either DSRC or C-V2X radios and 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:* stated to communicate via DSRC and interacts with vehicle drivers via integration with smartphones and via an application and has the ability to provide visual on-screen warnings.

Experiments conducted by Lerner et al. (2014) make use of visual displays with OEM display screens, portable displays, response touchpads, LED lights, as well as audio communication (e.g. through headphones or in-vehicle voice navigation) and tactile stimuli (C2 tactor and a RadioShack amplifier attached to the drivers 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. To determine the ideal equipment for deployment alongside C-ITS technology, further study into the ideal mode of communication with humans as well as a cost benefit analysis need to be conducted.

5.8.2 Message Conveyance and Effectiveness

The effectiveness of communication between machines and humans depends heavily on the mode of message conveyance. The NHTSA (2014) conducted 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***
   This experiment consisted of several sub-experiments which 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 of the experiment. Half these 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.

The 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.

5.8.3 Human Factor Issues

One of the main drivers for C-ITS and ADAS deployment is the improvements to safety outcomes for road users. Whilst the concept and theory behind the technology is sound, some researchers are concerned over some of the human factor issues which may threaten the intent of CVs. This is because 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:

1. ***Driver Overreliance***
   Driver-Overreliance is a likely output of CV and ADAS applications. Overreliance can be defined as drivers delegate too much responsibility to or incorrectly assume the functions of an application. This could be a case of forgetting to apply the brakes at curves when using CSW or failing to head check when changing lanes when LCW is in effect. The resultant consequences to users who overly rely on a specific function could range from a near miss to fatality, an outcome which may have been avoided without the technology.
2. ***Adoption of Risky Driving Behaviour***
   A generally understood phenomenon is the tendency for humans to increase their tolerance for risk in tandem with improvements to safety. This tendency is one of the main arguments against the theorised effectiveness of CV and DA. Drivers may adopt riskier driving styles/speeds in order to improve mobility or convenience with disregard for other commuters and a misconception or negligence of the functions' limitations.
3. ***Driver Distraction***
   While several CV and DA technologies are designed with the intention of allowing drivers to pay less attention to the roads without suffering consequences, they may instead act to unintentionally amplify the required attentiveness and workload of drivers and acting as a potential hinderance rather than assistance. This may be due to an excessive number of confusing, ambiguous or false alerts, which may distract drivers and shift their attention away from the roads. As such, the way messages are designed to inform drivers should be well designed and regulated by authorities.
4. ***Loss of Skill***
   A continuation on the issue of overreliance, a long-term issue of dedicated CV and ADAS use is the loss of driver skills important to safe driving. In the rare but possible case of system failure requiring the regaining of manual control, drivers who have relied on the system to address driving errors may be unable to react accordingly due to this loss of skill overtime. Other issues may stem from reduced situational awareness or loss of concentration on the roads. Drivers who switch from one vehicle with certain CV and ADAS systems to another without the same functions may also become a hazard on the road.

5.9 SECURITY, PRIVACY, AND USER ACCEPTANCE

A major challenge with V2X technology is the threat of network performance problems and multiple types 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 data when compared to the traditional network. 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 events traceability
- Real-time constraints e.g. Timing attack

The 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. The FCC notice of proposed rulemaking (Dec, 2019) notes that the technology may not function adequately if the certificates are out of date. As noted by Competitive Enterprise Institute (2020), this sentiment fails to address situations where users have not updated the technology, which 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 assumes that both DSRC and C-V2X technologies are both equally ready for deployment and neither presents any significant issues that would delay implementation. 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. Thus, it is noted that some performance evaluation 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 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, infrastructure deployment cost estimates are 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. There is currently limited deployment in the market, with few original equipment manufacturers committing to implementing one or the other technology (DSRC or C-V2X) in new vehicles. This review finds that there is divide between stakeholders of C-ITS communication technologies in regard to the type of technology which should be implemented; these stakeholders include Original Equipment Manufacturers and Mobile Network Operators.

Performance comparisons show both C-ITS technology has the potential to provide significant positive outcomes in roadway crash reduction and in alleviating traffic congestion in freeways and at urban intersections. 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 testing involving C-V2X technology is limited. A review of the expected road safety and productivity 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 relatively unknown or debateable and only qualitative 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 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. Infrastructure Victoria and WSP (2018) estimated that the required investment into network infrastructure for the state-wide deployment of CAV's in Victoria would be in the order of magnitude of 1.1 and 1.7 billion dollars. 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. Similar studies in USA indicated 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, challenges are expected to be faced arising from interference and congestion issues, human machine interaction factors, security, privacy, and user acceptance.

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