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Technical Review of Safety Use Cases, Benefits and Safety Vulnerabilities Associated with Connected Vehicle Technologies

Prepared for

Motor Vehicle Safety Directorate

Transport Canada

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List of Abbreviations

Abbreviation	Definition
2D	2-Dimensional
3D	3-Dimensional
3GPP	3rd Generation Partnership Project
5G	5th Generation Wireless Telecommunications
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
ADS	Automated Driving System
AEB	Automated/Automatic/Autonomous Emergency Braking
AERIS	Applications for the Environment: Real-Time Information Synthesis
AETC	All-Electronic Toll Collection
AI	Artificial Intelligence
ALPR	Automatic License Plate Recognition
ARIB	Association of Radio Industries and Businesses
BSM	Basic Safety Message
C2C-CC	CAR 2 CAR Communication Consortium
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CAN	Controller Area Network
CAV	Connected Autonomous Vehicle
CCA	Cooperative Collision Avoidance
CCMTA	Canadian Council of Motor Transport Administrators
CCW	Cooperative Collision Warning
CIB	Crash Imminent Braking
CICAS	Cooperative Intersection Collision Avoidance Systems
CN	Core Network

Abbreviation	Definition
CO_2	Carbon Dioxide
CPM	Collective Perception Message
CSM	Cooperative Sensing Message
CV	Connected Vehicle
C-V2X	Cellular Vehicle-to-Everything
CVRIA	Connected Vehicle Reference Implementation Architecture
CVSD	Canadian Vital Statistics - Death Database
D2D	Device-to-Device
DBS	Dynamic Brake Support
DENM	Decentralized Environmental Notification Message
DL	Downlink
DQN	Deep Q-Network
DSRC	Dedicated Short Range Radio Communication
ECU	Electronic Control Units
EEBL	Emergency Electronic Brake Light
eNB	E-UTRAN Node B or Evolved Node B
ETC	Electronic Toll Collection
ETR	Express Toll Route
ETSI	European Telecommunications Standards Institute
EU	European Union
EVP	Emergency Vehicle Preemption
FCC	Federal Communications Commission
FCD	Floating Car Data
FHWA	USDOT Federal Highway Administration
GDM	Global Dynamic Map
GHz	Gigahertz (measure of frequency)
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service

Abbreviation	Definition
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HD	High-Definition
HMI	Human-Machine Interface
HOT	High-Occupancy Toll
HOV	High-Occupancy Vehicle
Hz	Hertz (measure of frequency)
I2I	Infrastructure-to-Infrastructure Communication
I2V	Infrastructure-to-Vehicle Communication
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ISO	International Organization for Standardization
ITM	Information Technology Management
ITS	Intelligent Transportation System
ITS-G5	European standard for ad-hoc short-range communication of vehicles among each other (V2V) and with Road ITS Stations (V2I). Refers to the approved amendment of the IEEE 802.11 (standard IEEE 802.11p).
ITS-G5A	ITS-G5 operating in frequency ranges for safety related applications
ITU-R	International Telecommunication Union Radio Communication Sector
IVI	In-Vehicle Infotainment/Information
kHz	Kilohertz (measure of frequency)
km^2	Square Kilometre (measure of area)
L1	SAE Level 1 Automated Vehicles
L2	SAE Level 2 Automated Vehicles
L3	SAE Level 3 Automated Vehicles
L4	SAE Level 4 Automated Vehicles
L5	SAE Level 5 Automated Vehicles
LA	Los Angeles
LED	Light-Emitting Diode

Abbreviation	Definition
LiDAR	Light Detection and Ranging
LIN	Local Interconnect Network
LOS	Line-of-Sight
LPWAN	Low-Power Wide-Area Network
LTE	Long-Term Evolution
LTE-V2X	LTE-Vehicle-to-Everything
m	Metre (measure of length)
M2M	Machine-to-Machine
MaaS	Mobility as a Service
MAB	dSpace MicroAutoBox
MANET	Mobile Ad-Hoc Networks
MB	Manitoba
Mbps	Megabits per Second (measure of speed)
MCM	Manoeuvre Coordination Message
MHz	Megahertz (measure of frequency)
ms	Millisecond (measure of time)
ms^{-2}	Metre per Second Squared (measure for acceleration)
N-IMC	Non-Signalized Intersection Management Coordinator
NLOS	Non-Line-of-Sight
NR-V2X	Vehicle-to-everything based standard based on 5G New Radio air interface
OBU	On-Board Unit
OEM	Original Equipment Manufacturer
ON	Ontario
OTA	Over-The-Air
PCM	Platooning Control Message
PD	Photodetector
PLR	Packet Loss Ratio
PTC	Positive Train Control

Abbreviation	Definition
QoS	Quality of Service
RAN	Radio Access Network
RDS	Radio Data System
RFID	Radio-Frequency Identification
RSA	Rivest–Shamir–Adleman (encryption)
RSU	Road-Side Unit
RWW	Road Works Warning
SAE	Society of Automotive Engineers
SL	Sidelink
SPaT	Signal Phase and Timing
STD	Standard
SUV	Sport Utility Vehicle
TC	Transport Canada
TCU	Telematics Control Unit
THEA	Tampa Hillsborough Expressway Authority
TMC	Traffic Message Channel
TMI	Traveller Information Message
TO	Traffic Orchestrator
TRL	Technology Readiness Level
TSP	Transit Signal Priority
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
URLLC	Ultra-Reliable Low Latency Communication
US	United States of America
USDOT	United States Department of Transportation
V2B	Vehicle-to-Broadband Communication
V2I	Vehicle-to-Infrastructure Communication

Abbreviation	Definition
V2N	Vehicle-to-Network Communication
V2P	Vehicle-to-Pedestrian Communication
V2V	Vehicle-to-Vehicle Communication
V2X	Vehicle-to-Everything Communication
VANET	Vehicular Ad-Hoc Network
VDOT	Virginia Department of Transportation
VLC	Visible Light Communication
VN	Vehicular Networks
VRU	Vulnerable Road User
VSC-A	Vehicle Safety Communications Applications
VTTI	Virginia Tech Transportation Institute
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WYDOT	Wyoming Department of Transportation

Executive Summary

Connected vehicle (CV) technologies use wireless communication to exchange situational awareness and motion information between vehicles, the infrastructure, the internet, and other road users equipped with connected devices (e.g., pedestrians, cyclists). V2X is an overarching term that refers to various communication modes in a CV network including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N), and vehicle-to-pedestrian (V2P). Wireless access technologies such as IEEE 802.11p based DSRC and LTE & 5G based C-V2X enable extra-vehicular data sharing in a vehicular ad-hoc network (VANET). Sharing of data in VANET networks delivers a number of core functions that potentially result in improved safety and environmental benefits. These core functions include: (a) cooperative sensing and awareness enabled by sharing of vehicle-based sensor data and network provided GNSS (global navigation satellite system) augmentation data for precise localization, (b) cooperative maneuvers enabled by sharing of intent and path information of neighboring vehicles so that their motions can be coordinated to perform complex maneuvers such as lane merging, overtaking, platoon forming, etc., and (c) cooperative traffic management where wireless communication is used to improve safety and system throughput of roadway networks. These core functions can potentially improve safety for all road users.

Correspondingly, CV applications that involve these core functions have been grouped as safety-critical applications in this report. Examples include cooperative collision warning/avoidance, cooperative lane change, blind spot monitoring, intersection management, vulnerable road user (VRU) protection, etc. There is another category of CV applications that are primarily developed for convenience and traffic system efficiency. In this report, these applications are grouped as non-safety applications. Although convenience and traffic system efficiency are the two main goals of these CV applications, improved safety and environmental benefits, such as reduced greenhouse gas (GHG) emissions, can also result from these applications. Examples include traffic congestion warning, cooperative adaptive cruise control, eco-lanes management, electronic toll collection.

A number of pilot projects involving academia, wireless network operators, vehicle manufactures, public bodies, and wireless connectivity software and hardware vendors have been launched in recent years to facilitate collaboration and to implement and physically demonstrate exciting CV technologies. The main focus of these technologies were found to include functionality development and other operational issues such as characterizing the minimum network performance required for effective application deployments. Conventional safety measures such as crash avoidance, potential for injury mitigation, and fatalities per million driven miles were used in some literature to validate safety claims from data obtained from simulation studies and field tests. Because of the inherent challenge of conducting field tests to collect datasets large enough to obtain statistically significant inferences, simulation was observed to be the prevalent safety validation tool in the related literature.

The safety vulnerabilities of CV applications are contributed by two main sources: (a) operational limitations of the network and (b) security of the network. Operational limitations may occur when increased resource demand, limited network range, or signal interference result in reduced network availability, packet loss, increased packet latency etc. to a degree that the underlying CV application cannot perform effectively. Increased resource demand may happen when large number of nodes participate in the network (e.g., a

crowded street with large number vehicular nodes), or when the available network bandwidth cannot support the network traffic. Lack of line of sight (LOS) between two communicating nodes contributes in increased signal interference and possible packet loss. Due to the aforementioned operational limitations, a CV application may no longer operate effectively to deliver improved safety for road users. In addition, if the security of the CV network is compromised because of cyber-attacks, even in the absence of the operational limitations, the application may no longer maintain its safety goal. A cyber-attack may flood the network with extraneous messages to deny access to other nodes, or it may share inaccurate sensing and motion information to disrupt the normal operation of the CV application. Although this is a security issue, given the fact that CV applications are often paired with vehicle automation technologies, a security event can lead to a safety event. For example, an adversarial actor can disrupt the flow of highway traffic by broadcasting a false collision event.

CV technologies can potentially enhance roadway safety. Since CV technologies can provide situational awareness beyond LOS, and can also provide lane-level localization accuracy for vehicles, it can be argued that highly automated vehicles will natively integrate CV features for reliability and redundancy. Development of CV technologies involve a group of heterogeneous stakeholders such as public bodies, automotive OEMs, telecommunications industry. Overcoming logistical challenges to create effective collaboration among them is absolutely necessary for rapid development and well-guided deployment of CV technologies.

1 Introduction

1.1 Background

Connected vehicle (CV) technologies utilize wireless communication to enable the sharing of information between vehicles and connected infrastructure. Research on connected vehicles and connected infrastructure has been conducted over the past several decades, but these technologies, except for a few limited instances, are yet to be widely deployed. Although wireless communication between vehicles featuring a radio-based warning system has been proposed in the literature as early as in 1926 [1], it was only in 2015 when major automaker Toyota announced plans for production vehicles featuring connected features for the Japanese market [2]. However, news reports published later in 2019 indicate that similar plans for the US market did not materialize [3].

It can be argued that the enabling technologies for performant CV applications such as mobile wireless access, embedded computing, network backbone, control/scheduling algorithms have already gained the required maturity. The lack of mass adoption of CV technologies can be attributed to a large set of technological and non-technological challenges. The non-technological challenges include human perception and corresponding behavior, legal issues, the need for collaboration among stakeholders of heterogeneous composition (e.g., government regulators, technology developers, roadway owner and operators, network spectrum owner and operators, connectivity hardware/software vendors and suppliers, certification bodies) and harmonization of guidelines and standards globally and regionally. Technological challenges include the need for development of standards for interoperability between different industries (e.g., automotive, infrastructure, telecommunications) and secure and resilient network technologies capable of delivering the application-specific performance requirements.

Despite these technological, logistical, legal and societal challenges, CV technologies can potentially effect unprecedented transformation in the transportation sector. For example, the U.S. Department of Transportation (USDOT) has estimated that mature systems that enable information sharing between vehicles could minimize around 80% of all vehicle crashes in the United States [4]. In addition to safety benefits, CV technologies will effect mobility benefits (e.g., reduced travel time) and environmental benefits (e.g., reduced emissions). In comparison to vehicle-based driving automation technologies such as advanced driver assistance systems (ADAS) or automated driving systems (ADS) that mainly rely on vehicle-mounted line-of-sight (LOS) sensors to obtain situational awareness, connected vehicle technologies can potentially extend situational awareness beyond what is achievable with LOS sensors (see Figure 1). In addition, CV technologies enable vehicle automation systems to coordinate their motions to cooperatively execute complex maneuvers such as lane merging.

1.2 Communication Modes

Information sharing in a CV application can happen between many different node types. Some of these combinations are identified below to preface the subsequent discussion:

- Vehicle-to-vehicle communication (V2V) takes place between two vehicular nodes.

- Vehicle-to-infrastructure communication (V2I / I2V) refers to the information exchange between road infrastructure and vehicular nodes.
- Vehicle-to-network communication (V2N) includes data exchange between vehicle and the internet such as cloud servers.
- Vehicle-to-pedestrian communication (V2P) occurs between vehicles and connected derives worn/carried by pedestrians.
- Vehicle-to-everything communication (V2X) is an overarching term to include all types of communication that take place in a CV network.

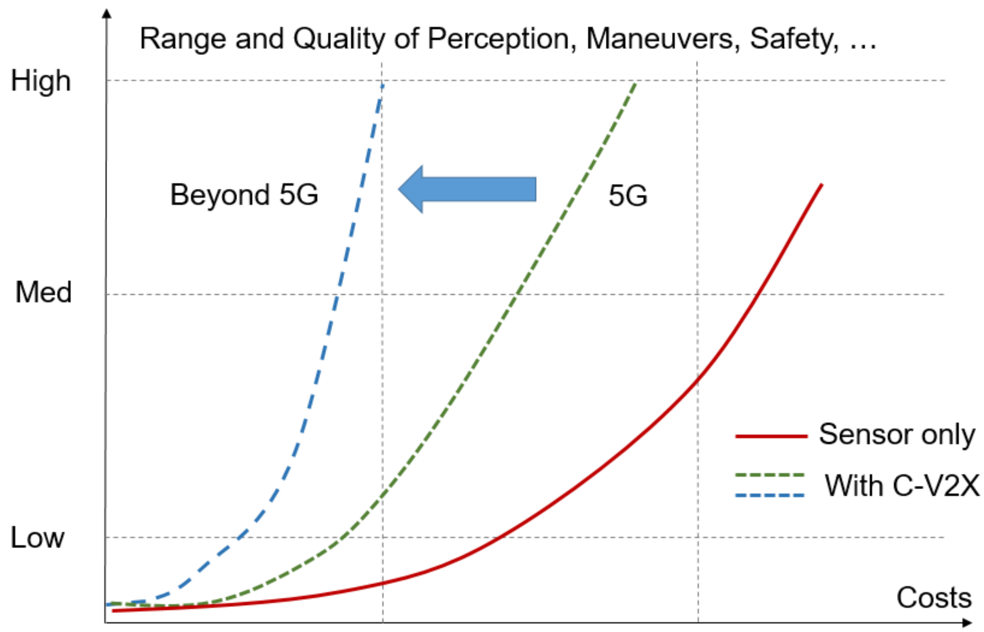

Figure 1: Benefits of C-V2X in implementing driving automation functionalities[1] [5].

1.3 Purpose & Objectives

There are a number of different types of CV technologies under development that can achieve connectivity (e.g., DSRC, C-V2X). This systematic technology review will not seek to determine which CV technology has optimal performance, but rather explore the potential safety benefits and limitations connected vehicle technologies as a whole may present for Canadians, regardless of the technologies used to implement the application. As such, this review will be technology neutral, and will focus on understanding the general safety use cases and benefits as well as the safety challenges associated with CV technologies which may need to be addressed to ensure they can be used safely on Canadian roads. Therefore, the broad objective of this project is to provide Transport Canada (TC) with a systematic technical review of the safety use cases of CV technologies, including research conducted to date on their potential safety benefits and technical limitations that may lead to safety vulnerabilities.

[1] This figure conveys how perception potential (i.e., being able to easily characterize the driving environment from raw & unstructured data) of vehicle-mounted sensors can be improved with the aid of C-V2X technologies. While 5G technologies will significantly improve quality of perception, future technologies (i.e., beyond 5G) are expected to bring about further improvements.

The specific research questions this report is looking to answer are:

- What are the concrete (measureable) safety benefits of CV technologies?
- What use cases are envisioned for CV technologies to specifically enhance safety regardless of communication modes (e.g., V2V, V2I, V2P, and V2X)?
- What research has been conducted to date to demonstrate the potential safety benefits of these use cases?
- What level of deployment needs to be realised before these significant safety benefits can be achieved?
- Are these safety benefits exclusive to CV technologies, or could they be achieved by other technologies/sensors either on the market or in development (e.g. vehicle automation, high definition, real-time mapping etc.)?
- What are the limitations/safety vulnerabilities associated with connected vehicle technologies (e.g. latency, signal loss, crowding and interference, infrastructure requirements and interoperability, weather limitations)?
- Are there limitations/safety vulnerabilities specific to operations in varying Canadian driving conditions (e.g. rural and remote areas, varied geography, winter conditions, etc.)?

Answers to these questions have been summarized from the reviewed literature in Section 5.1.

1.4 Study Methodology & Scope

This technical review was conducted based on expert analysis of the related literature comprised of:

- Reports & guidelines published by regulatory, certification and industrial consortium bodies.
- Technology promotion materials provided by spectrum owner and equipment manufactures.
- Reports of CV pilot projects conducted by roadway operators.
- White papers published by industry stakeholders.
- Peer-reviewed journal & conference paper published by research organizations including universities.

A large body of such literature was reviewed, and concepts, data and information from a subset of them (~200 references) were deemed relevant to this technical review. Operational concepts and instances of implementations were described for a total of 26 use cases. Publications from regulatory bodies list a large number of CV use case ideas. However, only a subset from these ideas were reported in the related literature with instances of implementation in simulation environment and/or pilot testing. Of the 26 reviewed use cases, 17 were categorized as safety-critical applications.

1.5 Limitations

Although every effort was made to include the most current information available from literature found in the public domain, it cannot be guaranteed that all relevant information was reviewed. In order to minimize the likelihood of such unintended omissions, the report went through multiple rounds of internal and external reviews. In addition, content and data from reliable and, whenever possible, peer-reviewed sources were employed in this report. Integrity of the references was considered implied.

1.6 Report Structure

The report is structured in the following way to facilitate a focused discussion: Section 2 provides an overview of connectivity technologies. Safety critical use cases of CV technologies are reviewed in Section 3. A number of non-safety applications are discussed in Section 4. Finally, the findings are summarized in Section 5.

2 Overview of Connectivity Technologies

Perception sensors, actuators, electronic control units (ECU) and embedded software components have provided modern vehicles with unprecedented situational awareness which enables them to initiate corrective and preventative driving actions when unsafe conditions are detected. Examples include pre-tensioning of seat-belts and automated braking for imminent collisions, automated lane centering, adaptive cruise control. Based on the operational scope and the requirements of human supervision, these capabilities are collectively referred to as advanced driver assistance systems (ADAS) and automated driving systems (ADS) in the related literature. The scope of ADAS and ADS features can be further extended if vehicles can exchange information with other entities (e.g., other vehicular traffic, pedestrians, cyclists and infrastructure). The insight and control enabled by extra-vehicular data sharing can potentially improve road safety, help vehicles avoid collisions and minimize their effects, reduce fuel consumption and carbon footprint, and decrease operating costs by implementing distributed sensing, remote computation, and coordinated actuation at larger scales beyond what a single vehicle could achieve [6], [7]. In addition, performance boundaries, especially for safety use cases, of non-connected driving automation systems due to limited range of on-board sensing (e.g., usually not available beyond line of sight) and lack of coordination/knowledge of the motion and intentions of other actors in a roadway scenario can be overcome by leveraging the potential advantages of connected technologies.

A number of foundational technologies have enabled extra-vehicular data sharing and the ability to act on the received information, if necessary. At the vehicle level, these technologies include sensors, actuators, ECUs and intra-vehicle data networks such as CAN-bus (controller area network) and LIN (local interconnect network) that provide the medium for exchanging information *within* the vehicle. While these on-board components are essential building blocks to enable situational awareness and facilitate data-informed actions, foundational technologies that are external to individual vehicles will be the focus of this report. Correspondingly, CV communication networks are discussed next.

2.1 Connected Vehicle Networks

Vehicular communication networks can be regarded as a subset of the traditional concept of machine to machine (M2M) or device to device (D2D) communication networks [8]. A number of terminologies can be found in the literature to refer to CV networks to describe their topologies, operational modes, types of the member nodes and their functions.

Vehicular ad-hoc networks (VANET) is one of the fundamental concepts in CV communication network literature. VANET is a self-organizing CV network composed of mobile (e.g., vehicle) and stationary nodes deployed on the infrastructure, and they are inter-connected via wireless links [9]. It is a subset of the broader concept of mobile ad-hoc networks (MANET) [10]. The nodes in a VANET can be of two types: (a) on-board units (OBU) installed on vehicles to represent vehicular nodes, and (b) road side unit (RSU) to provide the infrastructure the support required for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication [9], [11]. Depending on the network topology and the situation at hand, each node in a VANET network may play the roles of sender, receiver, and router to varying degrees. There might be instances where a node must play all three roles. The OBU of each vehicular node processes the information collected from on-board sensors and ECUs and may exchange this information either directly with another proximate vehicle's OBU (V2V communication) or through an RSU to communicate with another vehicle which may not be close enough for direct communication. In the latter case the RSU acts as a router. The RSU can also be connected to the internet to enable infrastructure-to-infrastructure (I2I) communication [12]. V2I communication has also been termed as vehicle-to-RSU (V2R) in some literature (e.g., [13]).

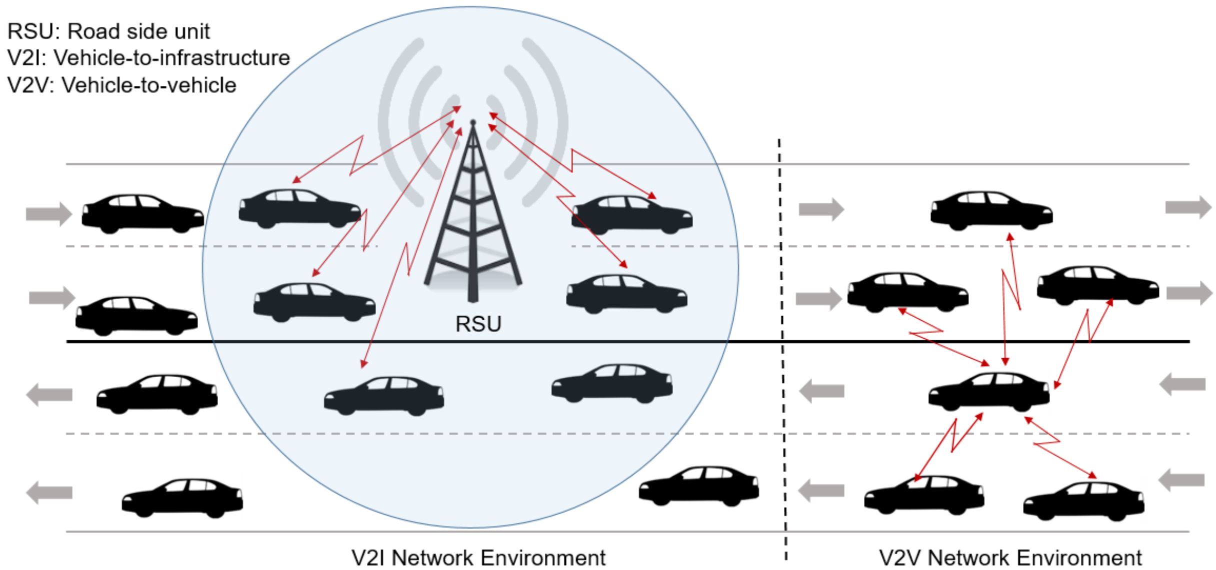

Figure 2: VANET communication scenarios: infrastructure assisted & direct V2V [9].

2.1.1 Network Characteristics

The following characteristics and requirements are cited in literature [14], [15], [16] as prerequisites for a performant VANET network:

- **Dynamic topology:** Depending on the traffic density and proximity, a random collection of vehicles can form a VANET network for V2V and V2I communication. The mobile nodes represented by these vehicles can enter or depart the network at high speeds. Therefore, a VANET network must be robust enough to function despite the dynamically changing topology.
- **Network size:** VANET networks must accommodate scenarios where it must host a large number of nodes (e.g., in a traffic congestion or in densely populated urban areas) represented by high vehicle density on a roadway. Delivering on this requirement becomes more challenging as the dynamics of the underlying network topology increases.
- **Real-time performance:** Safety applications reliant on VANET requires real-time performance for short time horizon scenarios such as avoiding collisions or cooperative collision mitigation maneuvers. The maximum allowable time for the exchange of safety-critical messages must be sufficient for the vehicles to determine, initiate and complete the required safety maneuver.
- **Security & privacy:** Security and privacy can be regarded as two competing requirements of a VANET network. A secure network requires that all nodes have been authenticated to keep malicious actors from disrupting network operations. Since node authentication fundamentally means distinguishing between legitimate vehicles and adversarial actors, newly arriving nodes

must share some form of credentials or security certificates to facilitate authentication, which may not be conducive to privacy. Correspondingly, privacy preserving authentication methods have been a research topic in recent years (e.g., [17], [18], [19]). Security and privacy challenges in a VANET network is further complicated by its highly dynamic nature.

2.1.2 Access Technologies

The nodes in a VANET network may use multiple networking technologies such as wireless access in vehicular environments (WAVE) IEEE[2] P1609, IEEE802.11p, cellular radio networks (GSM, GPRS, UMTS, WiMAX, LTE, 5G), Bluetooth IEEE 802.15.1 and infrared links to facilitate ad-hoc communication [20], [21]. However, communication standards based on IEEE 802.11p and Cellular V2X (C-V2X) are the two most prominently reported in the literature [22], [23].

2.1.2.1 Mesh Networks

Dedicated short range communication (DSRC) and ITS-G5 are two mesh network standards that are based on the IEEE 802.11p technology. In the US, 75 MHz of bandwidth in the 5.9 GHz spectrum was allocated by the Federal Communications Commission (FCC) in 1999 for DSRC-based Intelligent Transportation System (ITS) applications [24]. The European Telecommunications Standards Institute (ETSI) allocated 30 MHz of spectrum in the 5.9 GHz band for ITS applications in 2008 under the ITS-G5 standard [25]. One of the major differences between DSRC and ITS-G5 standards is how the bandwidth is allocated. The DSRC standard does not reserve any part of its bandwidth for time-critical applications, but the ITS-G5 standard is subdivided into two segments: (a) a 30 MHz spectrum for safety-critical applications (ITS-G5A) and (b) a 20 MHz spectrum for other applications [6].

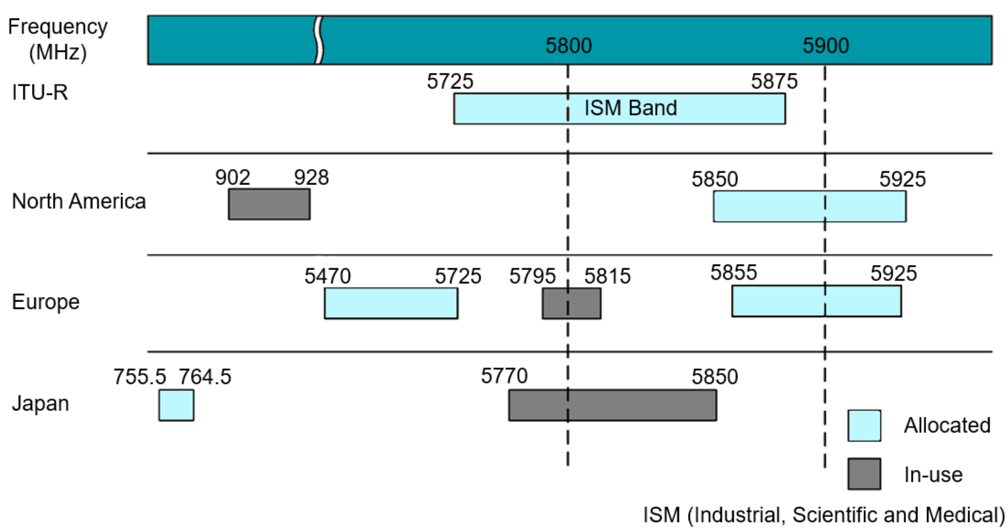

Figure 3: Frequency spectrum allocation for DSRC applications in different jurisdictions [26].

[2] Institute of Electrical and Electronics Engineers (IEEE) is a professional organization that authors/publishes variety of engineering standards related to computer, electrical and electronics engineering. It also facilitates expert knowledge sharing by publishing journals and organizing conferences focusing on engineering topics.

2.1.2.2 Cellular Networks

Citing lack of sufficient adoption, the FCC voted to reallocate the DSRC spectrum for other uses in 2020 [27]. Specifically, the lower 45 MHz bandwidth in the 5.9 GHz spectrum was proposed to be allocated for unlicensed uses such as Wi-Fi and improved automotive safety, and the upper 30 MHz bandwidth of the same spectrum for enhanced automotive safety using Cellular V2X (C-V2X) technology [27]. However, USDOT has opposed this proposition citing maturity of the DSRC technology with decades of development work already invested in DSRC[3].

Depending on the underlying cellular standard, C-V2X technology has also been referred to as the LTE-V2X [23] and 5G-V2X technology [28]. Due to coverage issues especially in non-line of sight (NLOS) environments and in urban canyons, C-V2X is favored over mesh networks [29], [30]. In the same vein, longer range of C-V2X technology under LOS and NLOS scenarios was experimentally demonstrated in a test report generated by the industry consortium 5GAA in 2018 [31]. Other potential advantages include larger coverage area, deterministic security[4], and guarantees on quality of service (QoS) [32], [33]. The characteristics that define QoS are defined in Section 2.2. A simulation study of real-life conditions demonstrated the advantages of C-V2X over DSRC [34]. One of the studied use cases (see Figure 4) conducted by C-V2X supplier Qualcomm argues superior operability of C-V2X in icy and normal road conditions at high speeds for the purposes of reliably stopping a moving vehicle and avoiding collision with a stopped vehicle obstructing its path. Because of the longer range, the vehicle equipped C-V2X equipment could receive the hazard message from the stopped vehicle sooner than the DSRC case. As a result, the C-V2X vehicle was shown to be afforded a larger distance for stopping. It should be noted that superior performance of C-V2X technology cannot be universally claimed in its current state of development. Network topology, network traffic load, environmental features (e.g., roadways free of obstructions vs. urban canyons) are all factors that can influence performance of DSRC or C-V2X communication. As such, considering the current state of both technologies, it might be myopic to claim that one access technology is universally more performant than the other. Given the immensity of the effort required to perform a comprehensive analysis of comparative performance, the related literature only includes test scenarios of a limited scope (e.g., [31], [34]).

[3] USDOT letter to FCC sent on November 6, 2020.

[4] Verifiable security features implemented by design.

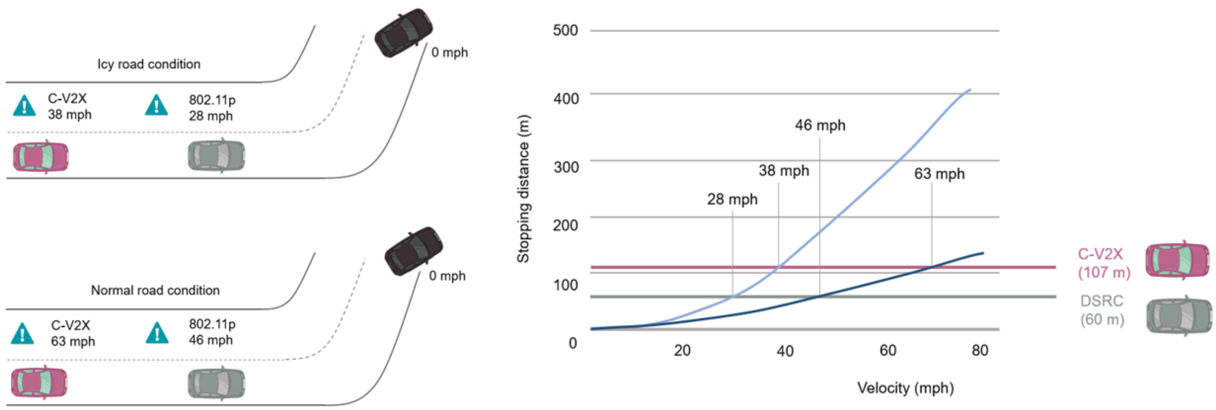

Figure 4: C-V2X vs DSRC collision avoidance example [34]. C-V2X equipped vehicle is afforded longer stopping distance because of the longer communication range.

Besides LTE networks, emerging 5G networks can also be used for C-V2X communication. The terms near radio V2X or NR-V2X have been used to refer to 5G based V2X networks [35]. 5G is expected to deliver on the stringent requirements of time-sensitive and safety-critical V2X applications in terms of ultra-low latency, high reliability, superior coverage etc. [35], [36]. The standardization organization 3GPP (3rd Generation Partnership Project) have covered LTE-V2X in releases 14 and 15, and NR-V2X is covered under releases 16 and 17 [35]. It should be noted that standards published by the 3GPP organization are structured as “Releases.”

C-V2X communication systems can have three operating modes: (a) sidelink (SL)-based, (b) uplink (UL)/downlink (DL)-based, and (c) relay-based (see Figure 6). Vehicles directly exchange information using one-hop transmission in SL-based C-V2X communication. Two transmission hops are made in UL/DL-based communication wherein a vehicle first transmits information to an evolved node B (eNB) or a base station in a UL communication (first hop), and subsequently, the information received at eNB is forwarded to the destination vehicle in a DL communication (second hop). Transmissions that require more than two hops to reach the destination are termed as the relay-based C-V2X mode. Different nodes that participate in this communication chain may include road side units (RSU) and cellular networks. The application layer of C-V2X model can include vehicle-to-vehicle (V2V), vehicle-to-network (V2N), vehicle-to-infrastructure (V2I), vehicle-to-pedestrians (V2P), vehicle-to-broadband (V2B), etc. [6], [32]. The key differences between IEEE 802.11p, LTE-V2X and 5G/NR-V2X technologies have been highlighted in Table 1.

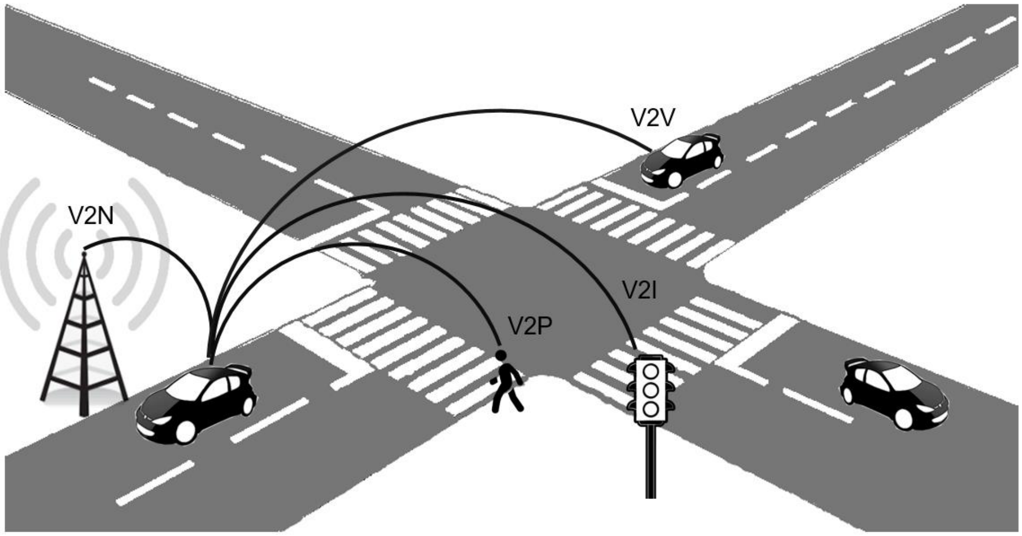

Figure 5: V2X communication modes [37].

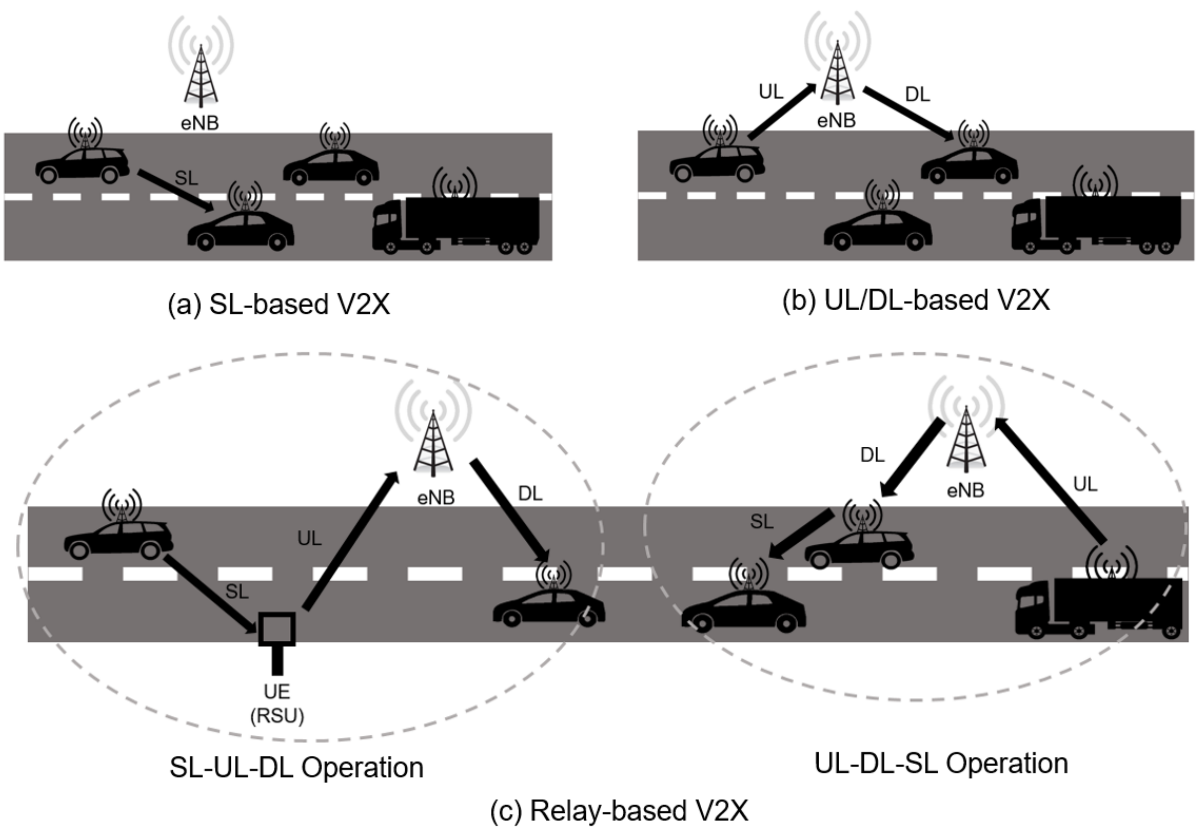

Figure 6: Different modes of C-V2X communication [38].

2.1.2.3 Other Access Technologies

In addition to C-V2X and IEEE 802.11p based access technologies, a number of other wireless technologies have been reported in the literature for extra-vehicular connectivity. Examples include low power wide area network (LPWAN) such as ZigBee [39], Bluetooth [40], and radio frequency identification (RFID) [41]. Although radio waves form the physical link for all connectivity technologies cited thus far, visible light communication (VLC) is a light-based communication technology that has also been used for V2V communication [42]. VLC communication requires LOS path between a light emitting diode (LED) acting as the transmitter and a photo detector (PD) acting as the receiver [43]. VLC offers several advantages over radio based communication including robust and full-duplex high bandwidth communication even in crowded roadway spaces. On the other hand, the main disadvantages include susceptibility to interference from ambient light and weather conditions.

Although the access technologies discussed in this section can be found in the literature, C-V2X and IEEE 802.11p are the two prominent standards with major development efforts undertaken by stakeholders. Comparison of some characteristics of these standards, as reported in related literature, has been provided in Table 1. In addition, characteristics of LPWAN access technologies are summarized in Table 2.

Characteristics	IEEE 802.11p	LTE-V2X (3GPP Rel-14/Rel-15)	5G/NR-V2X (3GPP Rel-16/Rel-17)
Status of standardization	Completed in March 2012	Release 14: Mar 2017 Release 15: Jun 2018	Release 16: Dec 2019 Release 17: Jun 2021
Evolution Path	Forward compatible with IEEE 802.11bd	Forward compatible with NR-V2X	Backward compatible with LTE-V2X
Network coverage	Limited	1.3 to 2.9x of DSRC (LOS, NLOS and interference test cases) [31]	
Latency	Non-deterministic	Release 14: 20ms Release 15: 10ms	3ms or lower [35] <1ms [36]
Reliability	Not guaranteed	Release 14: > 90% Release 15: > 95%	99.999%
Data rate	6 Mbps	30 Mbps	Not determined

Table 1: Key differences among IEEE 802.11p, LTE-V2X and NR-V2X access technologies [31], [33], [35], [36].

Technology	Type	Range	Spectrum	Use-cases
RFID	Simplex	~10m	135kHz, 13.56MHz, 433MHz, 860-960MHz, 2.45GHz, 5.8GHz	Vehicle identification for toll collection/parking
Bluetooth	Simplex	~10m	2.4-2.45GHz	V2I, flow density calculation
ZigBee	Duplex	~20m	2.4GHz	-

Table 2: LPWAN connected vehicle technologies [44].

2.1.3 Message Types

Depending on the use-cases, connected vehicle technologies have varied requirements of latency, data protection, and network range. Correspondingly, the messages that are exchanged in a V2X network are classified according to the corresponding use-cases. SAE standard J2735 [45] specifies a number of messages for the DSRC communication systems. However, because of the proposed FCC reallocation of DSRC bandwidth for other uses, its relevance in future CV development is unclear. The Car 2 Car Communication Consortium (C2C-CC) have described various message types specified by standardization organizations such as SAE and ETSI in [46]. See Table 3 for a compiled list of different messages cited in the literature.

Message Types	Requirements & Examples
CAM – Cooperative awareness messages **DENM – Decentralized environment notification message** **BSM – Basic safety message** **SPaT – Signal phase & time** **MAP – Map message** **IVI – In-vehicle information**	Medium (~10Hz) update rate. Enhance situational awareness: - Intersection collision warning - Emergency vehicle warning - Dangerous situation warning - Traffic jam warning - Pre-/Post crash warning - Enabling I2V communication
CPM – Collective perception message	High (~100Hz) update rate. Perception beyond LOS: - Overtaking warning - Extended intersection collision warning - VRU warning - Cooperative adaptive cruise control - Long-term road works warning - Special vehicle prioritization
MCM – Maneuver coordination message **PCM – Platooning control message**	High (~100Hz) update rate & ultra-low latency. Cooperative driving automation: - Platooning coordination - Cooperative merging - Cooperative lane change - Cooperative overtaking
TMI – Traveller information message	Low (~1Hz) update rate. Awareness of traffic conditions: - Inform about traffic incidents - Pre-planned construction events

Table 3: Various messages in connected vehicle technologies [46] and [47].

2.2 Network Performance Requirements

One category of the broader concept of Internet of Things (IoT) applications is the ultra-reliable low latency communication (URLLC). Examples of URLLC applications include factory automation, smart grid and V2X communication because of the mission-critical nature of these applications. The term QoS or Quality of Service has been cited in the related literature to describe or measure the overall performance of the communication service. Generic QoS parameters include throughput, packet loss ratio, jitter, latency, bit rate and availability [48]. Formal definitions of these parameters can be found in a reference document by the industry organization GSM association in 2018 [49][5]. It should be noted that GSM association is an industry organization that represents the worldwide mobile industry. Although these parameters describe

[5] https://www.gsma.com/newsroom/wp-content/uploads//IR.42-v9.0.pdf

many different and important aspects of communication performance of a network, in the CV literature communication range, availability, reliability in terms of packet loss ratio and latency are often cited as QoS parameters. For example, a study of latency performance of C-V2X applications published in 2017 by a group of university researchers from South Korea employed these aforementioned QoS parameters in [38]. Another bi-national university research effort from Germany and France published in 2018 studied low-latency V2X application requirements employed these QoS parameters for performance benchmarking in [50]. Two other similar academic research efforts [51] (published in 2019) and [52] (published in 2020) also utilized these parameters for performance characterization. The choice of these QoS parameters can be attributed to the limitations of the current state of the art. For the sake of facilitating the discussion in this report, qualitative interpretations of the often cited QoS parameter definitions are provided in the following paragraph.

Packet loss ratio (PLR) measures packet delivery success as the ratio of the number of packets failing to reach their destinations to the total number of packets sent. *Availability* is the percentage of time a system stays fully operational over a period of time. *Latency* refers to the time required for a communication data packet to travel from its source to its destination. Informed mostly by simulation studies, the related literature such as [38], [50], [51] and [52] have identified the required network performance for many V2X applications. The reported requirements are summarized in Table 4.

Application category	**Traffic safety & efficiency**	**Driving automation**	**Infotainment & media services**
Mode	V2V, V2I, V2P	V2V, V2I, V2N	V2N
Max latency (milliseconds - ms)	10 ms for safety 100 ms for efficiency	10 to 100	Not critical
Reliability	~ 99%	99.999%	Not a concern
Data rate[6]	1 Mb/s	10 Mb/s	0.5 Mb/s to 15 Mb/s depending on the media type
Range (m)	2000	Urban – 500 Highway - 2000	Urban – 500, Highway – 2000
Node density (/km^2)	3000	Urban – 3000 Highway – 500	Urban – 3000 Highway – 500
Traffic type	Periodic	Event triggered	Periodic
Examples	Forward collision warning, control loss warning, emergency warning, emergency stop, pre-crash sensing warning	Automated overtake, cooperative collision avoidance, high density platooning, cooperative perception	Video/audio streaming, web browsing, etc.

[6] Estimated for typical scenarios without explicit network congestion consideration. See [51] for further details.

Table 4: Summary of QoS requirements in V2X applications from [38], [50], [51] and [52].

2.3 Key Stakeholders

Successful development and deployment of CV applications involve a diverse set of stakeholders. These stakeholders were categorized with examples in [53] (see Figure 7). Public sector bodies such as USDOT or Transport Canada often facilitate and promote engagements among the stakeholders through conferences and workshops. CV pilot demonstration programs sponsored by public bodies are also allowing stakeholders to work together to collaboratively deliver on the functional requirements of a successful CV application deployment.

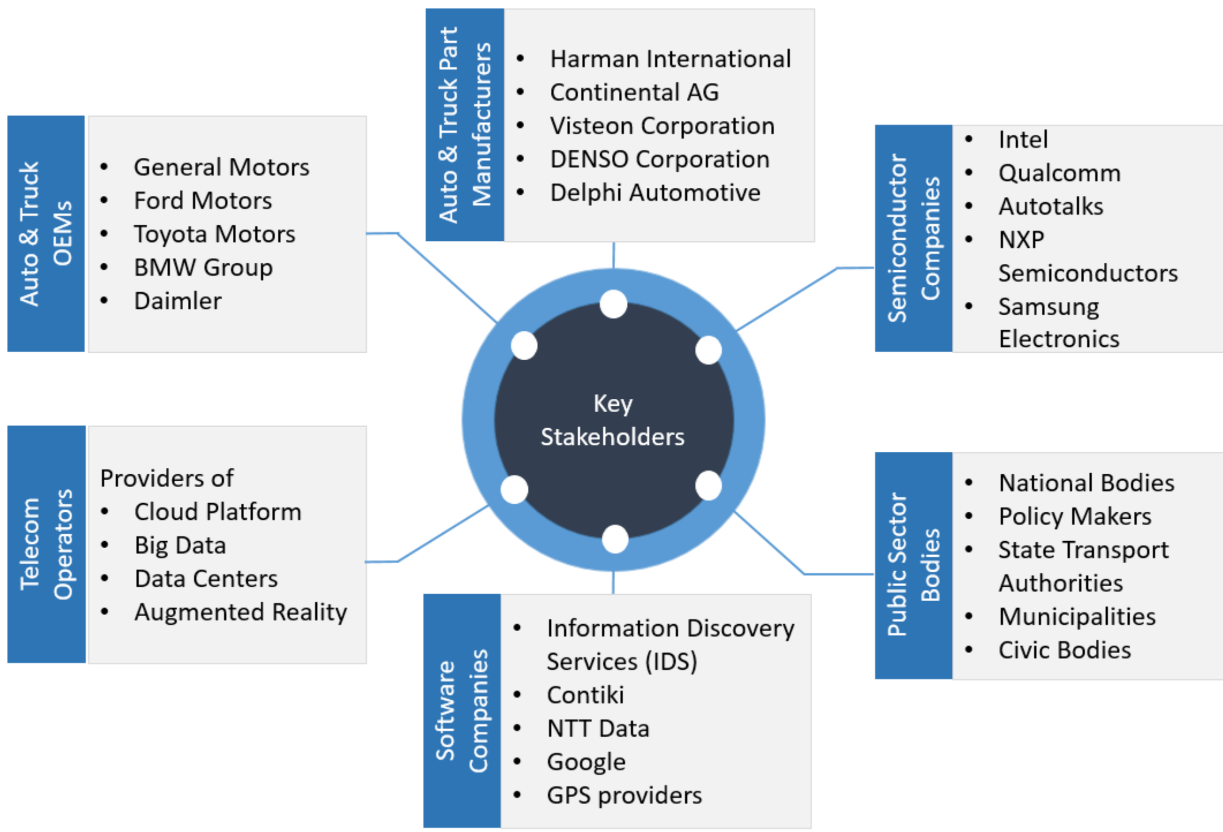

Figure 7: Key stakeholders in V2X applications [53].

3 Safety Critical Use Cases

3.1 Measuring Safety

Use cases of CV technologies may or may not include driving automation features. In the absence of driving automation components, a CV-informed driving advisory can still be beneficial for human drivers. However, since driving automation technologies have a much shorter response time and better interfacing with the vehicle in comparison to manual driving, the full potential of CV safety and environmental benefits may only be fully realized when they are augmented with driving automation systems. On the other hand, competencies such as extending the ability to acquire situational awareness beyond LOS by sharing sensor data, coordinating driving maneuvers with other vehicles by exchanging current and future control actions, collaboratively detecting and responding to unsafe situations are required for performant and reliable vehicle autonomy. Indeed, cellular network-based hyper precision location (HPL) service, which is recently announced by Verizon [54] for US markets, reportedly can provide lane-level positioning accuracy with the aid of GNSS (global navigation satellite system) correction data delivered over the air. This feature can potentially augment and act as a weather-resilient redundancy for sensor-based lane detection, which is required for lateral control of an automated vehicle. It can be argued that as CV and ADS systems gain more maturity, tighter integration of these two technologies will be applied by developers to achieve goals of reliability and performance. In the same vein, this notion of fading distinction between CV and ADS systems in the literature focusing on safety aspects of these technologies can be observed, where safety of CV systems are discussed as a subset of the broad topic of driving automation systems. However, security aspects of CV systems (e.g., node authentication, adversarial attacks) is discussed more prominently than safety aspects in the related academic literature.

Safety, in relation to driving automation technologies, has been defined in a research report [55] published by RAND corporation as the "*elimination, minimization, or management of harm to the public.*" One of the key findings of this report is that "*no standard definition of safety exists in regard to AVs.*" This notion is also reflected in a research paper authored by Philip Koopman of Carnegie Mellon University and Michael Wagner of Edge Case Research LLC, and published by SAE in 2018 [56]. The authors opined that "*there is no generally agreed upon technical strategy for validating the safety of the non-conventional software aspects of these vehicles.*" Although the simulation study results described in a 2014 USDOT report [4] employed concepts from the federal motor vehicle safety standards (FMVSS) such as crash avoidance and injury prevention to quantify safety of two V2V use cases (i.e., intersection management and left turn assist), a later report prepared by Volpe center for NHTSA in 2016 [57] summarized that FMVSS does not explicitly address automated vehicle technology. More recent publications from NHTSA such as [58] (an effort to adopt/translate FMVSS for automated driving systems published in 2019) indicate this gap is being addressed. In the absence of a comprehensive framework for measuring safety in driving automation systems, a benchmark of 1.09 fatalities per 100 million miles was chosen in [59] (a report by research organization RAND corporation published in 2016), which documented a statistical approach to determine the testing requirements for driving automation technologies. Choice of this benchmark was not arbitrary because it reflects the number of fatalities caused by US drivers in 2013. Simply put, the authors in [59] attempted to set the minimum safety performance of AV systems, which qualitatively refers to a performance standard that is at least as safe as human drivers.

Many use cases of CV technologies can be found in the literature, and a number of those have been summarized in the following sections. Given the current level of maturity of the associated technologies, these literature were found to be focusing on the functionalities of the CV applications. The safety argument, if it was entertained, was explored mainly in simulation environment in limited scope.

3.2 **Collision Warning/Avoidance**

3.2.1 Overview

Inability to detect a potential collision event in a timely fashion, combined with a slow response by human drivers, may result in collisions. CV technologies can be leveraged to compensate for such inadequacies of manually operated vehicles. This safety feature can be further expanded in scope for vehicles equipped with braking actuators wherein they can be engaged automatically as soon as unsafe conditions are detected. The research article [60], authored by university researchers from the US and Germany in 2006, employed the term *cooperative collision avoidance (CCA)* to convey the basic premise of this safety application. Another effort undertaken by researchers from University of California, Berkeley and General Motors R&D Center, Michigan in 2005 [61] used the term *cooperative collision warning (CCW)* for the same purpose. Although early implementations/demonstrations limited the operational scope to longitudinal motion of the vehicle (e.g., [60], [61]) only, more recent examples also include lateral motion resulting in more complex scenarios. For example, a proof of concept demonstrated in a simulation environment and reported by researchers from Peking University, China in 2019 [62] discussed CCA as an enabling technology for cooperative lane changing/overtake applications. CCA has also been mentioned in the context of intersection management in [63], which is a V2V implementation published by German researchers in 2017 using the IEEE 802.11p standard to study effects of radio interference from urban environment features such as buildings. A performance benchmarking study reported in 2020 by a team of university and industry researchers from China in [64] employed simulation to evaluate C-V2X technology for the CCA use case. A master thesis from Purdue university published in 2019 [65] proposed CCA to avoid collisions at intersections. CCA has also been discussed as an enabling technology for VRU safety in [66], which is a simulation study published by university researchers from Germany in 2020 that investigated effects of communication delays on CCA involving VRU.

3.2.2 Reported Implementations

While collision avoidance features in ADAS-equipped production vehicles employ vehicle mounted sensors to detect a potential collision, CCA safety applications rely on connectivity for the same purpose. Therefore, it can be argued that the major difference between the two technologies is how situational awareness is achieved (sensor-based vs connectivity-based). Nonetheless, CCA applications can potentially expand the operational scope of sensor-based collision avoidance features beyond line-of-sight (LOS) visibility that currently marketed ADAS features require.

In a typical CCA application, each vehicle must be able to measure its state (e.g., heading, current speed, acceleration/deceleration rates, global position) at a high frequency so that this information can be communicated to proximate vehicles. Data from each vehicular node collectively provides the instantaneous traffic condition of the networked vehicles. Since ADAS systems already possess this capability of measuring vehicle states at a high frequency, the major challenge of CCA implementation involves communication with low latency so that each vehicle is afforded a long enough window of time to process the received information and evaluate the potential for a collision and subsequently, if necessary, to initiate a safety maneuver. Various V2V technologies have been used for this safety use case over the years. For example, IEEE 802.11p based access technologies have been used in [60] and [63], and 5G connectivity in [67] (a CCA field test undertaken in 2017 by researchers from German Aerospace Center and Huawei Technologies, Germany). In addition, a V2N-based application can be found in [68] (a study by Spanish researchers that proposed a V2N-based architecture for CCA in 2019). Regardless of the underlying communication mode, an effective implementation must possess low-latency performance. Correspondingly, literature ranging from early days of the inception of this idea (e.g., [69], [70]) to more recent publications (e.g., [71], [72]) have focused on wireless communication protocols focused on achieving low-latency performance with high network availability.

Although the body of academic literature focusing on CCA is more extensive than other connectivity-based safety applications, instances of commercial deployment were found to be scarce. It was also observed that most of the reviewed literature focused on the time-criticality aspects of the communication layer. The majority of the cited research has been found to employ simulation for functionality testing (e.g., [64], [62], [73]). Limited physical demonstration can be found in the early days of development in [61] and, more recently, in a study by Spanish researchers that proposed a V2N-based architecture for CCA in 2019 [68], and a test-track demonstration performed by automotive engineering company Applus+ IDIADA and published in 2020 [74]. As expected for a developing technology, these simulation studies and physical demonstrations mainly focus on proof of functionality and performance characterization in controlled environments. Discussions on fault-tolerance and fail-safe operation were found to be scarce.

3.3 Blind Spot Monitoring

3.3.1 Overview

The Blind Spot Monitoring systems are used to warn drivers/vehicles about the presence (or potential presence) of another object in their blind spot should a lane changing or turning maneuver be attempted [75]. Vehicle-based blind spot monitoring systems that rely on perception sensors (e.g., cameras, sonar, radar) to monitor blind spots and alert drivers was introduced more than a decade ago. These systems, in their early implementations, did not have extra-vehicular connectivity requirements. Efficacy of vehicle-based blind spot monitoring systems is demonstrated in a report by the Insurance Institute of Highway Safety [76] where a 14% decrease in lane-change crashes, and a 23% decrease in lane-change crashes with injuries, were attributed to the use of blind spot detection systems for crash avoidance.

3.3.2 Reported Implementations

While V2X connectivity has traditionally been seen as a key enabler to communicate awareness of blind spot obstacles [77] (a survey article authored by Chinese and Hong-Kong researchers published in 2020), [78] (a SAE technical paper published in 2020 proposing V2X application optimization through edge computing), the literature on connectivity-based blind spot monitoring is rather scarce. Barmpounakis *et. al.* in [79] presented solutions in 2020 to detect “connected” objects that may be present in blind spots, based on the assumption that these objects are able to connect and communicate their physical states (e.g., global position, heading, current speed) with other vehicles or infrastructure, so that the dynamic traffic condition can be reconstructed from the received messages. Considering the possibility of objects/users that are not equipped with connectivity technologies, some works, such as [80] (a NRC research paper published in

2020), have proposed the use of vision-based vulnerable road user (VRU) detection at road intersections, and the use of V2X connectivity to share awareness of VRU presence to the vehicles at/near intersections. A related use-case is cooperative see-through perception in which V2X communication is utilized by preceding vehicles to share video or object detection data with the following vehicles, effectively helping them to “see through or around” the vehicles ahead [28]. In this regard, the AutoNet2030 project [81] used an occupancy grid that maps the detected objects through an occupancy grid algorithm. It proposed an extension to the CAM message referred to as Cooperative Sensing Message (CSM) to share the occupancy grid data. The NHTSA Vehicle Safety Communications Applications (VSC-A) study [82] reported on developing a blind spot warning and lane change warning safety application using DSRC. In C-V2X, a complimentary transmission mode is defined, operating in ITS bands (e.g., 5.9 GHz), for direct safety communication without dependence on the cellular network. This mode of transmission is claimed to be well-suited for low latency V2V, V2I and V2P communication in [34].

3.4 Cooperative Lane Change

3.4.1 Overview

Lane change maneuvers are more complex than other driving maneuvers because they involve situational awareness of multiple lanes while controlling longitudinal and lateral movements of the vehicle. In human-driven vehicles, a lane change maneuver is usually initiated by engaging the turn signal to communicate intent to neighboring vehicles. A lane change trajectory involving longitudinal and lateral motion of the vehicle is executed in a subsequent step to complete the maneuver. The idea of cooperative lane change pertains to automated vehicles wherein neighboring vehicles coordinate their motions to execute a lane changing maneuver safely. Although this application falls under the broader topic of path planning under dynamically changing constraints, V2V and V2I communications serve as key enablers. An impending lane change/merge intention can be broadcast to the neighboring vehicles employing these communication channels and, subsequently, their motions can be coordinated to execute a safe lane change maneuver. Since automated driving systems have the potential to enhance the control of vehicle motion, cooperative lane changes can be executed within tighter margins to utilize the available roadway more efficiently. The potential advantages of cooperative lane change application have been studied in [83] (a simulation study published in 2020 conducted by a team of university and industry). The authors presented a microscopic simulation-based study to investigate the effectiveness of three CAV applications bundled together (i.e., cooperative adaptive cruise control - CACC, cooperative merge and speed harmonization) in the context of freeway managed lanes under various CAV market penetration rates. The results demonstrated tangible benefits in terms of enhanced system throughput and reduced delay, even at low penetration rates.

3.4.2 Reported Implementations

Unlike other CV use cases, the related literature provides quite a few instances of field experiments and simulation studies focusing on the cooperative lane change application. A cooperative lane change field experiment conducted at FHWA in 2020 [84] utilized DSRC-based V2V communications. The proof-of-concept vehicle testing platform was equipped with automated longitudinal speed control and vehicle-based radar systems. BSM message format was used to exchange information. Certain modifications were made to the SAE J2735 standard BSMs to augment lane-changing related data (e.g., radar sensor data, turn signal activation data). Each of the participating vehicles’ Adaptive Cruise Control (ACC) systems were integrated with a proprietary longitudinal controller in order to allow acceleration and braking to be fully automatic. The longitudinal controller was implemented on a specialized real-time computing platform, i.e., a dSPACE MicroAutoBox II (MAB). The MAB was further integrated with a secondary in-vehicle Linux-based computer which is responsible for vehicle data collection, algorithm evaluation and communication with the Human Machine Interface (HMI). The HMI, a tablet computer, was configured to enable vehicle role selection (one of “lead vehicle”, “following vehicle”, or “merging vehicle”) as well as to display the DSRC-based, algorithm-specific messages transmitted or received during the trials. For localization data, PinPoint™ system was utilized to feed the in-vehicle computer with real-time high-accuracy GPS data. The BSMs from other vehicles and RSUs gathered by the DSRC controller was sent to the MAB via the Linux computer along with the radar data. The MAB issued control commands as speed recommendations to be injected into each vehicle’s CAN-bus. The speed recommendations were generated by the Simulink-based control algorithm. RSUs, or other entities at the merge areas, were assumed to be available to serve as local centers in [83]**.** The cooperative merging algorithm in [83] comprised the following four steps: detection, release, speed regulation and gap regulation.

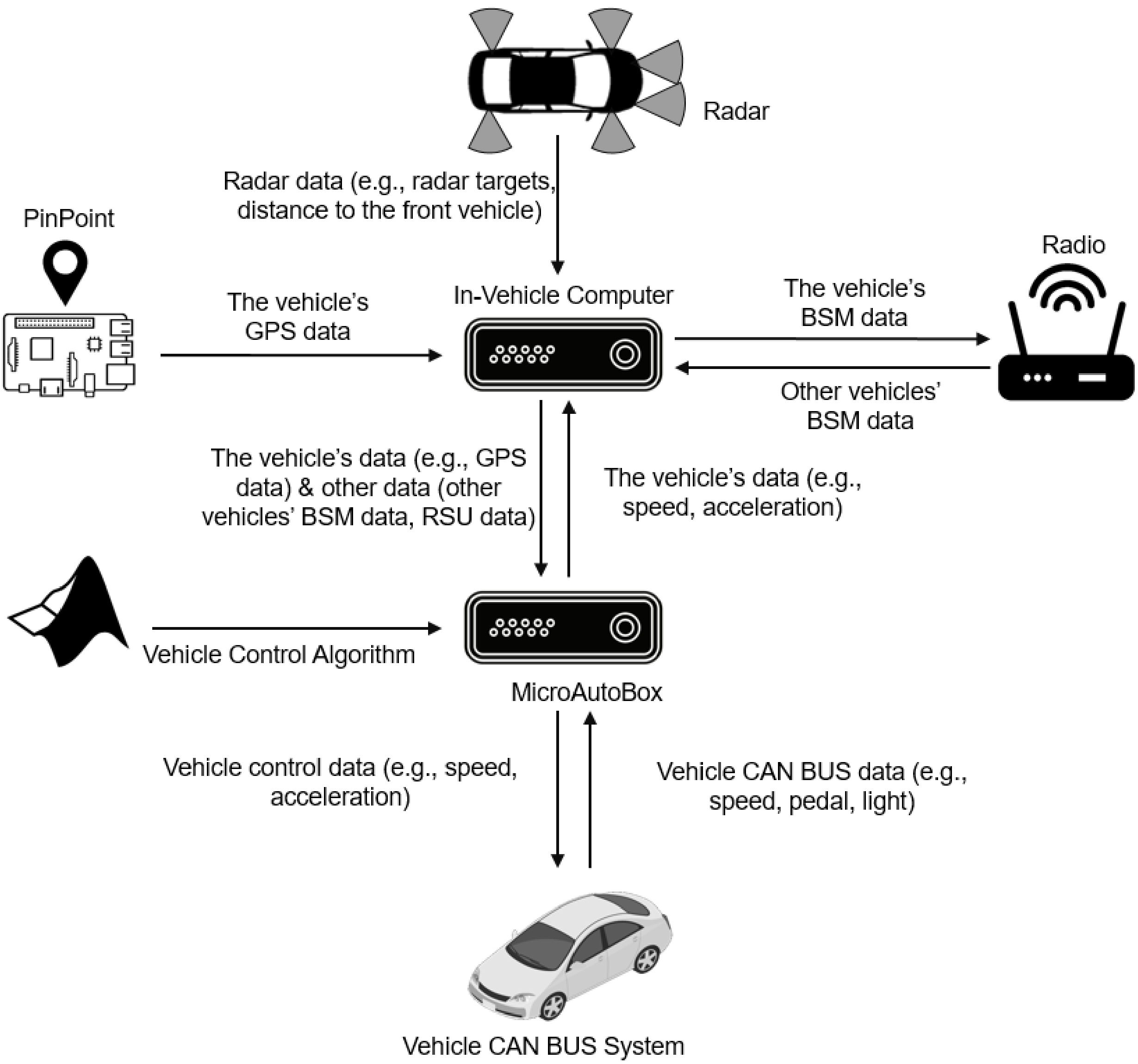

Figure 8: Technology stack and data flow in the testing platform documented in [84].

In the FHWA filed trials [84], three vehicles were considered. Two of these vehicles form an initial CAV platoon where the leading vehicle is manually controlled (maintaining a speed of approximately 40 km/hr), while the following vehicle is a CAV-equipped with automated longitudinal speed control. The third vehicle is a CAV tasked to merge into the platoon from an adjacent lane. Upon receiving a request (broadcasted as a DSRC message triggered by the turn signal) from the third vehicle (i.e., the merging vehicle) to join the platoon, the platoon members form a gap through the longitudinally automated speed control. Once the gap is formed, the third vehicle's speed is automatically adjusted, thus allowing the CAV driver to manually steer into the gap to join the platoon. These experiments in [84] utilized a longitudinal speed controller and the steering maneuver was performed manually. After the merging maneuver was completed, the merged and following vehicles continued to maintain the minimum safe gap as calculated based on their radars. The control algorithm only facilitates the lane changing maneuver by controlling distance (e.g., minimum safe gap) and speed.

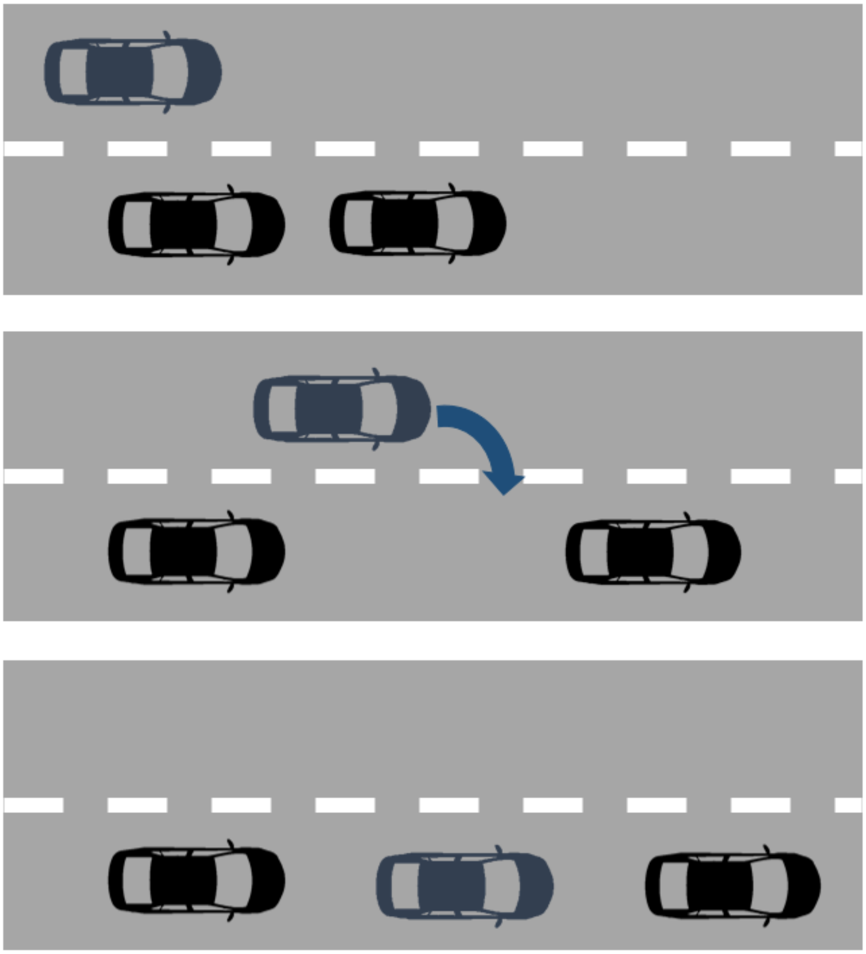

Figure 9: Test scenario in [84] for the cooperative lane changing and merging maneuver to join an automated platoon.

3.4.2.1 Simulation Results

The performance was measured in terms of system throughput and delay in [83] using the VISSIM[7] simulation package. Based on the simulation-based results, it was claimed that even at low CAV penetration rates of 30%, the bundled application yielded reductions in delay and enhancements in system throughput. The study excluded complex scenarios in which vehicles purely driven by humans exist without connectivity technologies. The simulations were focused on a single-lane managed facility on a freeway with exclusively dedicated ramps on the left side of the freeway for CV/CAV operations. The authors argue that the collaborative integration of cooperative merge and speed harmonization could enhance merging area performance. The simulation study in [83] assumes that the managed lane vehicles are equipped with vehicle awareness devices. Moreover, the merging vehicles (on-ramp traffic) are assumed to be CAVs only. The CACC model selected in this study was validated through field tests as reported in [85]. The three scenarios analysed in this work include: CACC operations, CACC platoons and cooperative merging of traffic, and integrating speed harmonization. The simulated road network was comprised of a 3-lane freeway segment, one on-ramp and one off-ramp (see Figure 10), though the study focused on the managed lane (left most lane) and associated on and off-ramps. In [83], "speed harmonization" was defined

[7] https://www.ptvgroup.com/en/solutions/products/ptv-vissim/

as generally involving gradual reduction in "speeds upstream of a heavily congested area in order to reduce the stop-and-go traffic that contributes to frustration and crashes". The cooperative dynamic speed harmonization is envisioned to assist in efficient, safe and smooth freeway merging while keeping the impact on mainline traffic minimal [83].

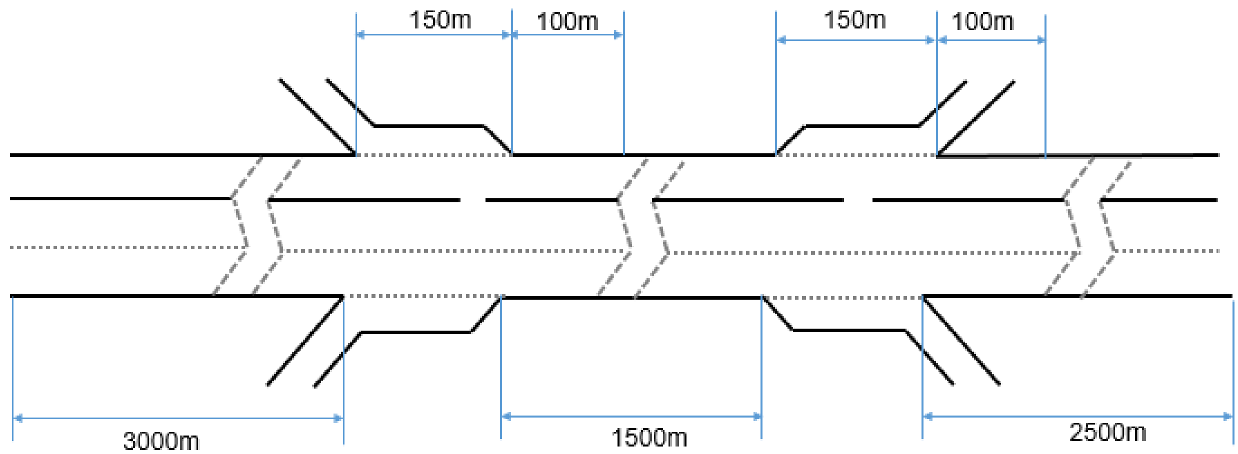

Figure 10: Illustration of the simulated road network employed in [83].

3.4.2.2 Experimental Results

Eight experimental trials were performed in [84] with slightly differing conditions such as turn signal activation time and initial vehicle positions. Results from two experimental runs were presented. In these experiments, the error in gap control maintained by the merging vehicle (after sending a merge request) was within 3 meters. The gap error is measured as the difference between the desired gap and actual gap. The gap control error maintained by the following vehicle after the merge completion was reported to be within 2 and 5 meters in the two experimental runs respectively.

3.5 Cooperative Emergency Braking

3.5.1 Overview

Cooperative emergency braking is closely related to the vehicle-based automated emergency braking (AEB) feature. Conventional AEB systems can be considered as a vehicle-based technology that has inherent limitations owing to the limited detection range of the vehicle's sensors such as cameras, radar, and LiDAR. Furthermore, object detection and segmentation by a today's in-vehicle sensors become extremely difficult under harsh weather conditions and occlusion from roadway elements such as vehicular traffic. Since AEB is a standalone, vehicle-based application without any connected features, emergency braking maneuvers are performed without coordination, and may create hazardous conditions for following vehicles. Since V2X technology can potentially leverage BSM or CAM messages to achieve NLOS situational awareness, cooperative emergency braking can drastically expand the safety benefits of vehicle-based AEB applications. An AEB system contains dynamic brake support (DBS) or crash imminent braking (CIB) that is designed to essentially help drivers avoid rear-end crashes. In a typical cooperative emergency braking scenario, each vehicle in the network (e.g., platoon) is assumed to be equipped with an ADAS system and a V2X communication module. The situational awareness obtained from the vehicle-based ADAS system is broadcast to the network and, from the collective data, a complete picture is produced. The effective range of vehicle-based perception sensors is expanded beyond NLOS ranges including occlusions from objects on the roadway.

3.5.2 Reported Implementations

In the related literature, some efforts have been reported on the coordination of CAVs for cooperative emergency braking systems. Two broad classes of coordination approaches have been studied in the literature:

- V2V-based platooning
    - Examples: a simulation study presented in 2019 [86] by university researchers from Sweden, and a report published in 2018 and a prototype V2V system developed by university and industry researchers for cooperative emergency braking application described in [87].
- V2V-V2P communication
    - Examples: an emergency braking prototype system that was field implemented by a research team from France in 2018 in [88], a simulation study by university researchers from Sweden and published in 2018 [89], a low-level controller prototyping exercise by university researchers from Iran and published in 2019 [90], and a research paper detailing a number of techniques to reduce communication delay in V2V networks authored by US university researchers in 2017 [91].

For example, the authors in [88] propose a low-speed V2X CACC experimental platform with emergency braking that uses V2V and V2P capabilities. The V2V communication scheme is proposed in order to minimize the inter-vehicle distances in the platoon, while the V2P communication is fused with LiDAR data to detect occluded pedestrians and to predict their trajectories and interactions.

Another research work is [91] that considers AEB with V2V and V2P connectivity to potentially reduce both communication and message processing delays. The proposed method in [91] prevents sending messages related to pedestrians who do not pose any collision threat. A V2V-based platooning application is presented in [86], where the aim is to prevent rear-end collisions by proposing an emergency braking strategy. In this application, the leading vehicle communicates its intention prior to braking with CAM and DENM messages. It should be noted that CAM messages include important details of the sender such as global location, speed, and acceleration, while DENM messages are generated by the platoon leader to its following vehicles to perform synchronized emergency braking.

It was also observed in the literature that there are some hardware implementations regarding the cooperative emergency braking. For example, in [87], the authors proposed a low cost hardware emergency braking system. The system was designed to work as a RSU and an OBU. The platform is equipped with two transceivers that operate in the 5.9 GHz band according to the 802.11p and ETSI ITS-G5 specifications and one 760 MHz transceiver that work according to ARIB STD T-109 standard.

3.6 Intersection Management

3.6.1 Overview

Crash statistics from both the European Union (EU) and the US show that more than 20% of traffic fatalities are intersection related [92]. The case of non-signalized intersection management solutions enabled by V2X, data and Artificial Intelligence (AI) technologies is discussed in [93]. As opposed to using traffic lights for scheduling traversals of vehicles at intersections, the concept of non-signalized intersection management seeks to develop customized, fine-grained drive through schemes while considering the goals of throughput enhancement and collision avoidance. According to a report jointly authored by researchers from University of Waterloo (Canada) and Nanjing University (China), and published in 2020 [93], some of the key challenges with regards to V2X-enabled non-signalized intersection management may include: (a) development of efficient methods that ensure effective cooperative system scheduling, (b) accurate and real-time fault detection and control mechanisms that ensure normal operations avoiding system breakdowns, (c) ultra-reliable and ultra-low latency V2X communication, and (iv) fast and low complexity computation for cross scheduling, particularly in cases of traffic congestion. AI-based approaches such as reinforcement learning, artificial neural networks, and multi-agent systems have been explored for intersection management in [93].

3.6.2 Reported Implementations

According to a simulation study authored by university researchers from Spain and published in 2018 [94], in high traffic density conditions (congestions) at intersections, packet reception could become unpredictable which could lead to unreliable information at the application level. To address these issues, several proposals have been made in the literature on the theme of “Adaptive Beaconing”, as discussed in [95] (a survey paper authored by university researchers from multiple countries and published in 2013) and [96] (another survey paper published in 2018 and authored by university researchers from Malaysia, Pakistan and China). The concept of adaptive beaconing deals with the adaptation of cooperative awareness beaconing parameters such as transmission frequency, speed and power with consideration of various factors such as channel load, dynamics of the vehicles, traffic density, application requirements or specific situations [94]. Two broad types of adaptive beaconing protocols are: (a) channel congestion control and (b) situational awareness control [97]. Both protocols are designed to achieve fairness in terms of all nodes in the network being able to utilize the communication channel effectively. The channel congestion control scheme aim to establish fairness in terms of channel load and transmission parameters. However, awareness control schemes aim to achieve fairness at the application level so that all participating applications can operate effectively. An important, yet mostly overlooked metric in analyzing the performance of such protocols is *position error (*i.e., error between a vehicle’s true physical position and its last recorded position) as reported to the RSU [94]. The position error may arise from a vehicle’s positioning/localization inaccuracy as well as from the communication or beaconing protocol latency.

In multi-agent based, non-signalized intersection management systems, vehicles and/or intersections are regarded as intelligent agents that collaborate with each other. Three possible approaches were presented in [93] to implement non-signalized intersection management: (a) centralized isolated intersection, (b) distributed isolated intersection, and (c) multiple non-signalized intersections. The centralized isolated intersection management approach requires a central controller, referred to as a *non-signalized intersection management coordinator (N-IMC)* in [93], to facilitate vehicular communication (i.e. V2X) and computation (i.e. crossing strategy). The distributed isolated intersection management approach on the other hand regards vehicles as intelligent agents in a multi-agent system. Each vehicle interacts with its neighboring vehicles to obtain partial information about the traffic environment and makes independent decisions while considering the traffic environment's feedback. However, a potential drawback of this approach may include communication-related issues such as out-of-range vehicles and higher communication overhead. To mitigate these issues, it was suggested in [93] that the N-IMC could be incorporated to serve as a mediator. The multiple non-signalized intersections management approach differs from isolated non-signalized intersection management approaches by jointly considering multiple intersections rather than focusing on one isolated intersection. Some of the objectives that need to be jointly achieved in non-signalized intersection management include avoiding collisions, reducing waiting times, and shortening queue length [93].

Although most of the related literature was found to focus on system architecture, data flow, and algorithms, fail-safe and fail-tolerant operation have been discussed in a few instances. For example, university researchers from TU Dresden, Germany in [98] proposes a fail-safe isolated, non-signalized intersection by adopting priority-based traversal rules that are claimed to be inherently safe. The proposed approach was verified in simulation. However, field verification of fail-tolerant and fail-safe operation of V2X-based intersection management was found to be scarce in the literature.

3.6.2.1 Simulation Results

Simulation experiments used in [93] revealed that under high traffic conditions (i.e., at an "average vehicle inter-arrival time of less than 5 seconds"), both fixed timer-based traffic light and real-time traffic-aware signal controller were reported to yield much lower intersection throughput in comparison to that of a non-signalized intersection management approach. Moreover, it was reported that a cooperative approach, wherein multiple intersections coordinate to determine an optimal scheduling solution, yielded higher intersection throughputs in each intersection on average as compared against the case of each intersection acting independently without interactions with adjacent intersections [93].

Another simulation experiment reported in [94] evaluated the performance of several adaptive beaconing protocols in terms of position accuracy at highly congested intersection scenarios. It was reported that protocols that consider both vehicle dynamics and channel load yielded lower position errors while achieving higher packet delivery rates and lower channel load.

3.7 Cooperative Merging into Highway Traffic

3.7.1 Overview

Cooperative merging maneuvers fundamentally belong to the multi-vehicle motion planning problem [99]. In a typical cooperative highway merging scenario, vehicles on ramps or on local lanes adjacent to the highway attempt to merge into the highway traffic, as depicted in Figure 11. To facilitate a smooth and safe merge, a sufficient gap between two vehicles (a leading and a following vehicle) is necessary. An inter-vehicle gap in a merge scenario can be considered safe if the following vehicle can stop without collision in the event of a sudden braking by the lead vehicle. Therefore, a safe inter-vehicle gap is a function of the braking distance of the following vehicle at the speed of the platoon. A gap can be determined and achieved through a centralized controller (e.g., RSU), or through decentralized cooperation between the vehicles and/or roadside infrastructure. The merge maneuver may also vary based on the type of highway lane merge configuration. For example, in the United States, three types of configurations found are depicted in Figure 12; namely, parallel acceleration lane, tapered acceleration lane, and auxiliary cloverleaf lane [100].

In the related literature, several efforts have been reported on the coordination of CAVs for cooperative highway merging. Two broad categories of coordination approaches that have been studied are centralized and de-centralized merges, according to a survey paper [101] published in 2017. The main difference between centralized and de-centralized merge approaches is the use of a central controller (e.g., an RSU) that takes into account of the instantaneous traffic scenario as reported by the neighboring vehicles to make some globally applicable decisions in terms of prescribing maneuvers that the vehicles will execute to perform merging safely. On the other hand, in the de-centralized approach all the vehicles act as automated agents that cooperate strategically together to orchestrate a safe merging maneuver.

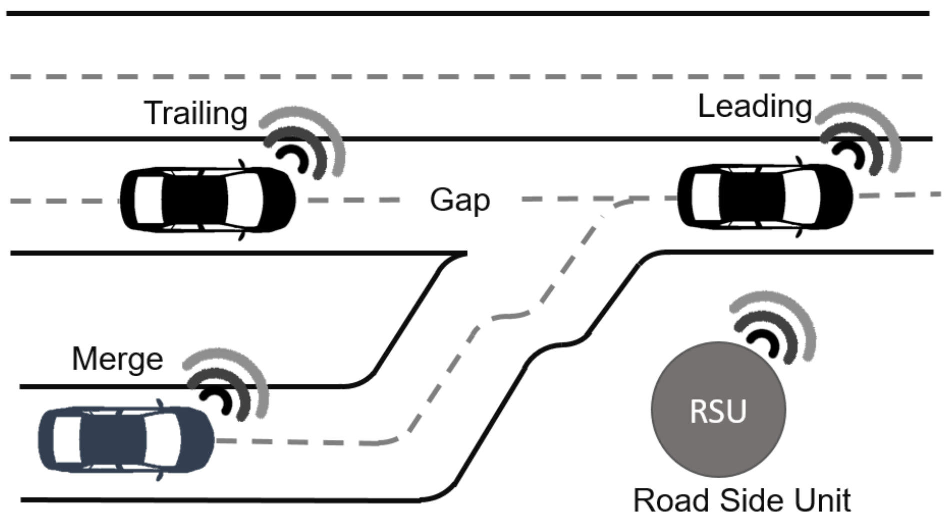

Figure 11: Typical scenario of cooperative merging into highway traffic [100].

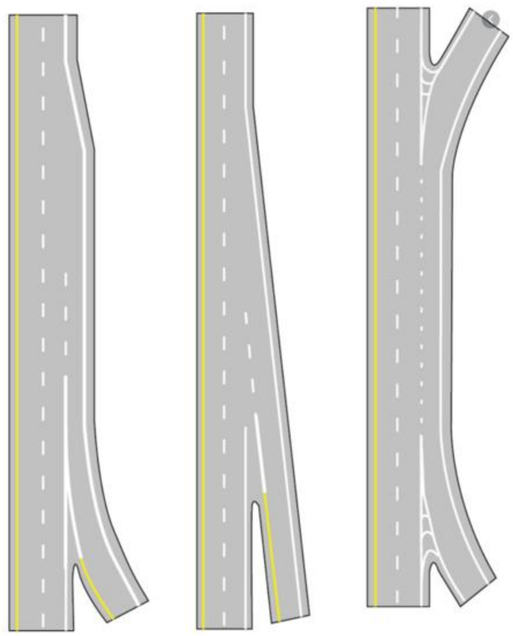

Figure 12: Three types of highway merge lane configurations in the US [100].

3.7.2 Reported Implementations

This use case can be regarded as a special subset of the cooperative lane change maneuver discussed in Section 3.4 without additional safety implications. The requirements of the cooperative lane merging identified in [102], which was published by EU-based industry consortium 5G-CARMEN, have been summarized in Table 5. Examples of centralized approach can be found in [103] and [104] (both research papers from Oak Ridge National Laboratory, TN, USA published in 2015 and 2017, respectively), and the planned path for merging which was solved as an optimization of each vehicle's acceleration profile against competing constraints of fuel economy and collision avoidance. Simulation experiments indicated that up to a 50% reduction in fuel consumption is achievable in merging scenarios. Amongst the decentralized approaches, heuristics-based and optimization-based methods have been proposed. For example, [105] proposed a cooperative merging control algorithm based on slots that vehicles coordinate to occupy. Additionally, a RSU was proposed to act as a proxy between vehicles on the ramp and those on the highway. Based on the results from these simulations, [105] claimed an improvement in throughput and average delay by using the proposed slot-based driving algorithm in comparison to human driving emulation-based merging. VISSIM is the simulation tool employed for this study.

Requirement	Value
Technologies	GNSS, V2V, V2I, V2N
Localization accuracy	4m
Network availability	V2I/V2N - 99% V2V - 99.9%
Network reliability	99.9%

Table 5: Identified requirements for cooperative lane merging use case [102].

It can be argued that emulation of human driving cannot accurately represent actual human driving behavior in merging scenarios. For example, emulation does not consider aggressive merging behavior, nor does it take into account manual cooperation between drivers and the drivers/vehicles who patiently wait for an empty slot to merge onto the highway. Furthermore, [105] assumes a 100% market penetration; i.e., all vehicles in the merging scenario are capable of connectivity based cooperative merging.

An optimization method based on cooperative nonlinear model predictive control was applied by a group of researchers from Caterpillar Inc. and University of Illinois. This study published in 2020 [100] focused on highway lane merge of two CAVs. The simulations-based work focused on developing and evaluating the control algorithm and assumed that V2V and V2I communications were available and used to exchange vehicle states. Several reports also assumed that reliable V2X communications to develop and evaluate the control algorithms for cooperative merging (e.g., [106], [107], [108]). It should be noted that reliable low-latency V2X connectivity is a feature expected to be enabled by 5G networks, and currently it is not widely available.

The presence of vehicles with and without connectivity was considered in [109] (a university-industry partnership project between King's College, London, UK and Orange Labs Services, France in 2020) to generate trajectory recommendations to assist in cooperative lane merging maneuvers. A centralized coordination approach was adopted to realize a data-driven framework that had two main components: *Traffic Orchestrator* and *Data Fusion*. While the former predicts safe trajectories to aid connected vehicles in the lane merging maneuver, the latter uses camera-based vehicle detection to map both unconnected and connected vehicles. To generate trajectory recommendations, deep reinforcement learning algorithms such as Dueling Deep Q-Network (Dueling DQN) and Deep Q-Network (DQN) were employed. Other components of the proposed architecture in [109] included a *V2X Gateway* and a *Global Dynamic Map (GDM).* The V2X Gateway, as the name suggests, served as a gateway between the connected vehicles involved in the merging maneuver and the architecture's interfaces and applications (e.g., Traffic Orchestrator), following a publish-subscribe messaging paradigm. The GDM was used to collect current information (i.e., localization and trajectory) of both connected and unconnected vehicles in the area of interest. Positions and trajectories of the unconnected vehicles are extracted by the image recognition system, and collected by the GDM via the V2X Gateway. The data fusion component was responsible to fuse and synchronize information from the image recognition system and the connected vehicles in order to update the GDM. The architecture based on micro service communication between its components. Figure 13 depicts the considered merging scenario and the proposed architecture's components.

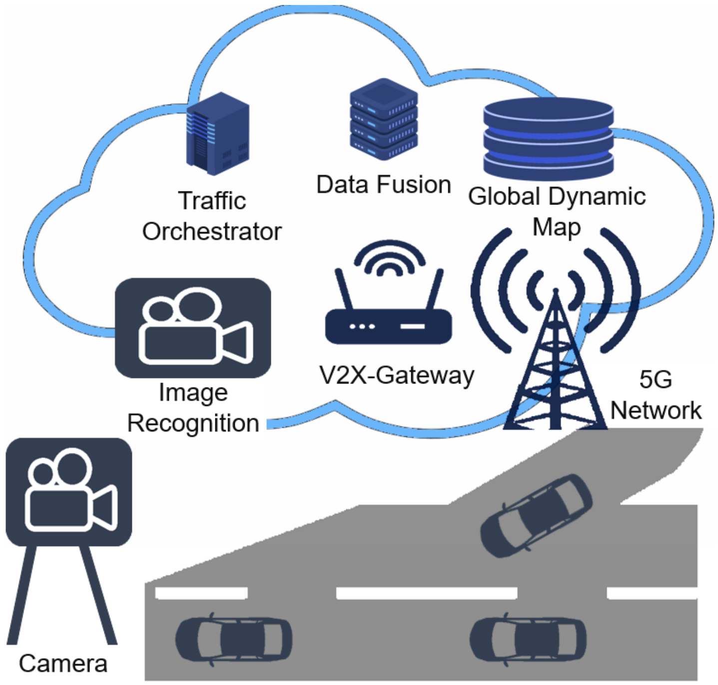

Figure 13: Cooperative merging as proposed in [109].

Figure 14: Field test scenario for cooperative highway merging using connected vehicles [110].

3.7.2.1 Experimental Results

Real world tests were conducted in [109] on a test track (see Figure 14) employing four vehicles. Three of the vehicles were connected and assigned the roles of acting as a preceding, following or merging vehicle. A fourth vehicle represented an unconnected agent in the scenario. The tests first conducted human-driven merges without the proposed TO (traffic orchestrator) to establish human driven trajectories as the baseline. The performance was assessed based on the following performance indices: deviation from the human-driven merge trajectories, inter-vehicle distance during merging, merging acceleration, merge maneuver length, and trajectory delivery time. It was noted that some differences in positioning between human-driven and TO-based merge trajectories were attributed to delays contributed by communication latencies between the different components. Some of the reported performance indices are summarized in Table 6. For cooperative lane merging, the 5GCARMEN project identified "support of high connection density for congested traffic" as a "must have" requirement [111].

Performance Index	Cooperative Merging	Human Driven Merging
Intravehicular distance (~90% cases)	48-60m	5-70m
Merging acceleration	0-2 ms^{-2}	0-2 ms^{-2}
Maneuver completion lengths	~154m	81-91m

Table 6: Performance benchmarking of cooperative merging against human-driven merging [109].

3.8 Emergency Electronic Brake Light

3.8.1 Overview

The CVRIA (connected vehicle reference implementation architecture) initiative by USDOT categorizes the emergency electronic brake light (EEBL) as a V2V safety use case [112]. It enables a connected vehicle to broadcast a self-generated emergency brake event to the neighboring vehicles. Subsequently, the receiving vehicle can evaluate hazard potential in terms of collision likelihood and, if necessary, can engage the braking actuators to initiate a braking event to avoid a crash. Alternatively, if the vehicle is not equipped with such a safety feature, a warning can be provided for the driver to take the appropriate action. A field test focusing on V2X-based safety support services in urban areas has been reported in [113] which details a field test conducted by Korean researchers and published in 2020. EEBL test procedures developed in this project have been adopted by ISO as the EEBL performance standard in [114]. EEBL offers multiple advantages over conventional brake light:

- EEBL can deliver its functionality even when a driver's view is obstructed due to bad weather or occlusion from another vehicle.
- A more robust and reliable redundancy for vehicle-based automated emergency braking feature.
- It is more computationally efficient to maintain situational awareness from wireless broadcasts for forward collision safety, in comparison to sensor-based methods.

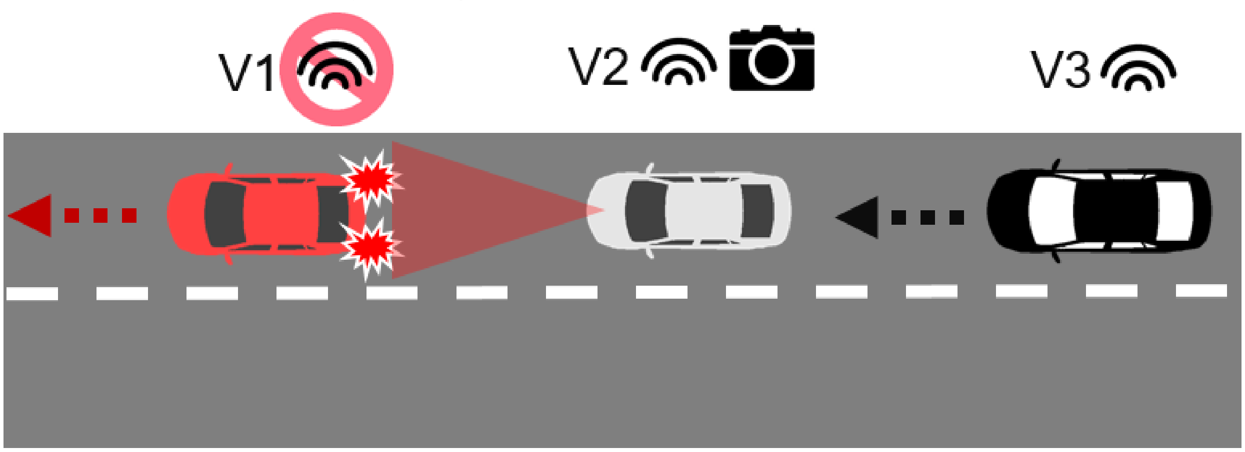

Figure 15: EEBL application enabled by collaborative perception, as described in [115].

3.8.2 Reported Implementations

An EEBL system implemented by DENM messages broadcast over a C-V2X network was simulated in [116] to study the requirements of this use case. DENM message delivery with high reliability and low latency were the two identified requirements. The authors noted that 5G networks will be able to deliver these requirements. A DSRC-based network was considered by a group of industrial researchers from Changan US R&D Center in [115] to conduct field tests on a number of applications including EEBL. This field test employed a camera to detect a stopped vehicle (see Figure 15), and the delay involved in the camera-based deceleration estimation was identified as the contributing factor for the observed average delay of 0.93 seconds in the EEBL tests.

3.9 Vulnerable Road User Protection

3.9.1 Overview

The Vulnerable Road User (VRU) definition provided by Canadian Council of Motor Transport Administrators (CCMTA) includes pedestrians, any device operated by a pedestrian, recreational vehicles when operated on a highway, cyclists, motorcyclists and operators of any other two or three wheeled vehicles [117]. The Intelligent Transportation System (ITS) Directive of European Commission defined non-motorized road users, such as pedestrians, cyclists, motorcyclists and persons with disabilities or reduced mobility and orientation as VRUs [118]. In addition, the VRU definition provided in [119] includes pets and the other groups mentioned in the previous two definitions. VRU safety has been an active topic in motor vehicle safety research because of its strong prevalence in roadway crash statistics. For example, in a report by Statistics Canada, as per the Canadian Vital Statistics - Death Database (CVSD) [120], there were 74 cyclist deaths per year on average between 2006 and 2017. Collisions with a motor vehicle involved 73% of these fatal cycling events [121].

VRUs usually have reduced visibility on roadways, and inattentive drivers can often fail to see or notice them which can result in a failure of drivers to share the road safely. Some ADAS-equipped vehicles on the market employ perception sensors as a safety feature to help detect VRUs. These solutions are vehicle-based, and NLOS cases are not addressed adequately (see Figure 16). Infrastructure-deployed sensors, or connectivity devices that are carried by VRUs can be leveraged to help construct a dynamic map of VRU positions on roadways. Making this map available to vehicles employing V2X technologies enhances VRU visibility. Once VRU locations are known to a vehicle, the vehicle can determine the collision potential and deploy appropriate safety maneuvers, if necessary. While this may mean issuing a warning to the driver for manually driven vehicle, an automated vehicle might perform appropriate safety maneuvers automatically.

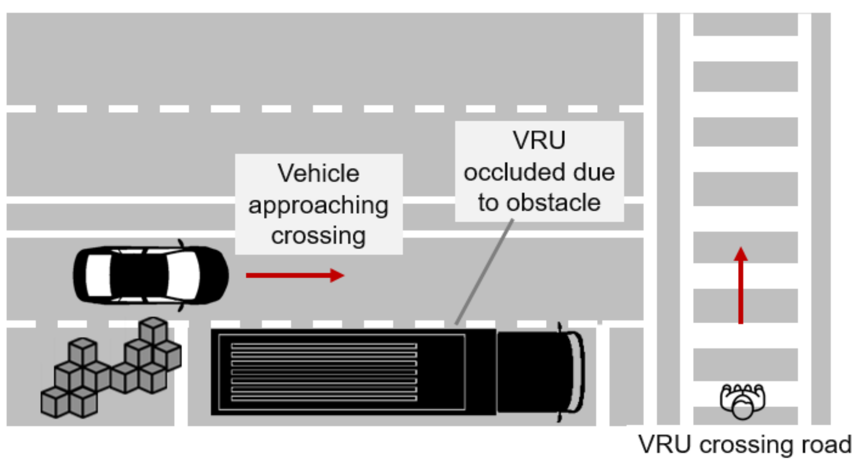

Figure 16: VRU occluded due to a parked vehicle traversing a cross-walk as depicted in [122].

3.9.2 Reported Implementations

In order to implement VRU protection using CV technologies, a number of functionalities must perform together. These functionalities include detection of the VRU, localization of traffic and VRU, movement/path prediction, determining collision potential (centralized or decentralized), communication, and finally, action. In the literature, three broad types of approaches can be found with regards to the detection, localization and movement prediction of vehicles and VRUs: connectivity-based, perception systems-based, and hybrid [123]. The connectivity-based approaches in [124] and [125] require the vehicles and pedestrians to be equipped with tools or devices that are able to communicate with each other or with the infrastructure. In perception systems-based approaches [126], [127] and [128], data (e.g., 2D/3D images) from devices such as cameras, LiDARs or radars may be used to detect and localize the objects of interest. The perception sensors could be deployed on vehicles, infrastructure, pedestrians and/or VRUs. Hybrid approaches combine the advantages of both connectivity and vision-based detection systems. An example is provided in [129] that benchmarked performances of different approaches against a hybrid approach. It was reported that the hybrid approach performed better in terms of lower localization error when compared against a connectivity-based approach. In addition, the hybrid approach demonstrated better ability to detect pedestrians when compared against a perception-based approach, especially in cases when a pedestrian may not be visible to a driver/vehicle [129]. Another implementation of connectivity-based VRU protection is *smart crosswalks* enabled by V2X technologies. Connected vehicles and connected VRUs are alerted and made aware of the presence and traversal paths of each other in a connected and collaborative manner [130], [131]. In terms of communication (i.e., to exchange the information between vehicles, infrastructure and pedestrians), V2V and V2I have been extensively researched. The concept of V2P or I2P has also gained some attention.

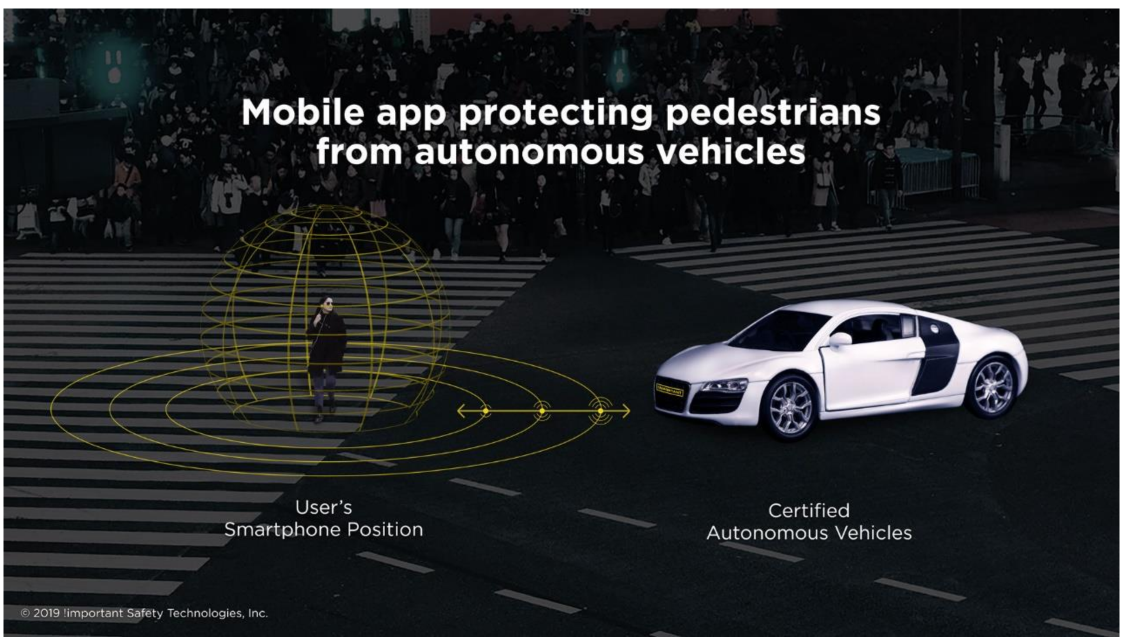

Figure 17: VRU protection enabled by V2P connectivity from Important Safety Technologies (© Important Technologies Inc.).

VRU protection applications enabled by connectivity have been divided into three categories in [122]:

- VRU high risk zones – Examples: pedestrian on crosswalks, pedestrians on crosswalks at intersections, school zone warning.
- VRU communicating directly with vehicles (V2P) – Examples: car doors opening in the path of a cyclist, interactive VRU crossing.
- VRU safety messages and AI – Examples: collision alerts (pedestrian-motorist, cyclist-motorist, cyclist-pedestrian, etc.), high density crosswalks.

Besides the academic research mentioned above, some companies are leveraging cellular networks to provide VRU safety. For example, the companies AVO (https://www.avo-inc.ca/) and Important Safety Technologies (https://www.important.com/) employ location services of mobile devices carried by VRUs for detection and localization. The location data is sent to the network or the vehicle directly to ensure safety of the VRU (see Figure 17).

For connectivity-based approaches, without a 100% market penetration rate, detection and localization of unconnected VRUs is challenging. The limitations of perception technologies (e.g., visibility and weather conditions, occlusions, etc.) may hinder the realization of fully reliable and robust VRU detection/localization. Therefore, hybrid approaches that fuse perception sensors and connectivity-based approaches for detection and localization are regarded as a possible robust solution. However, it must be noted that the requirement for URLLC communication is an imperative for a reliable performant VRU protection application.

3.10 **Work Zone Beaconing and Warning**

3.10.1 Overview

Work zones can be defined as temporarily unusable areas of roadways to accommodate activities such as construction, maintenance and utility work. Depending on the type of work performed, these zones can be short or long term. Normally, the roadway owner and/or operators are required to implement any necessary safety measures (e.g., [132]) to respond to the unique challenges and safety hazards work zones pose. These challenges include lane closures, lane shifts, speed reductions and. Work zones impose increased cognitive load on the driving task for human drivers as well as processing challenges for CAVs. V2X technologies can assist drivers and CAVs to help them traverse through work zones safely. In addition, VRU and roadwork personnel can also receive warnings when a vehicle is approaching the work area. Although work zone warning applications involve certain elements from the merge warning application (see Section 3.11), the work zone scope involves both VRU and maintenance workers rather than just vehicles.

3.10.2 Reported Implementations

Under the Europe-wide cooperative intelligent transport systems (C-ITS) initiative, a field demonstration of roadworks warning (RWW) was performed in 2019 [133]. The system was designed to alert road users approaching short-term roadworks on vehicle display systems with exact position of the roadworks. The connectivity-based warning was complemented by traditional static signage installed on the back of a warning trailer. Furthermore, the traffic control center was also kept informed by broadcasting the work location through V2X connectivity. The data exchange between vehicles and the infrastructure was based on the ITS G5 or (IEEE 802.11p) protocol using the DENM and CAM message formats. The overall architecture is depicted in Figure 18. The trial showed that the wireless communication range achieved was adequate: average – 672m, maximum – 1900m, and median – 641m. In 19% of the total trials the range was observed to be less than 300m due to the fact that work was taking place on a freeway ramp obstructing LOS access to the vehicles. It should be noted that wireless communication is most performant when the receiver and the transmitter have a clear line of sight. Early engagement with stakeholders was identified as the suitable procedure for introducing the new system.

Audi America, Virginia Department of Transportation (VDOT) and Qualcomm are collaborating with wireless communications infrastructure owner-operator American Tower Corporation, C-V2X solution provider Commsignia and research institute Virginia Tech Transportation Institute (VTTI) to demonstrate C-V2X applications on Virginia roadways in 2020 [134]. This demonstration includes OEM supported in-vehicle warning of work zones enabled by C-V2X connectivity (see Figure 19). In addition to vehicles, the demonstration also features C-V2X equipped vests for VRUs and road work personnel for a connected warning solution. Test results of this field demonstration are yet to be published.

Another CV pilot study undertaken by Wyoming Department of Transport (WYDOT) mainly focused on safety of transport trucks in work zones [135] that relied on DSRC technology in the early stages. It is unclear how the pilot is addressing FCC's proposed decision to reassign DSRC spectrum for C-V2X application. However, early simulation studies (e.g., [136]) have shown that improved work zone safety can be achieved by early warnings.

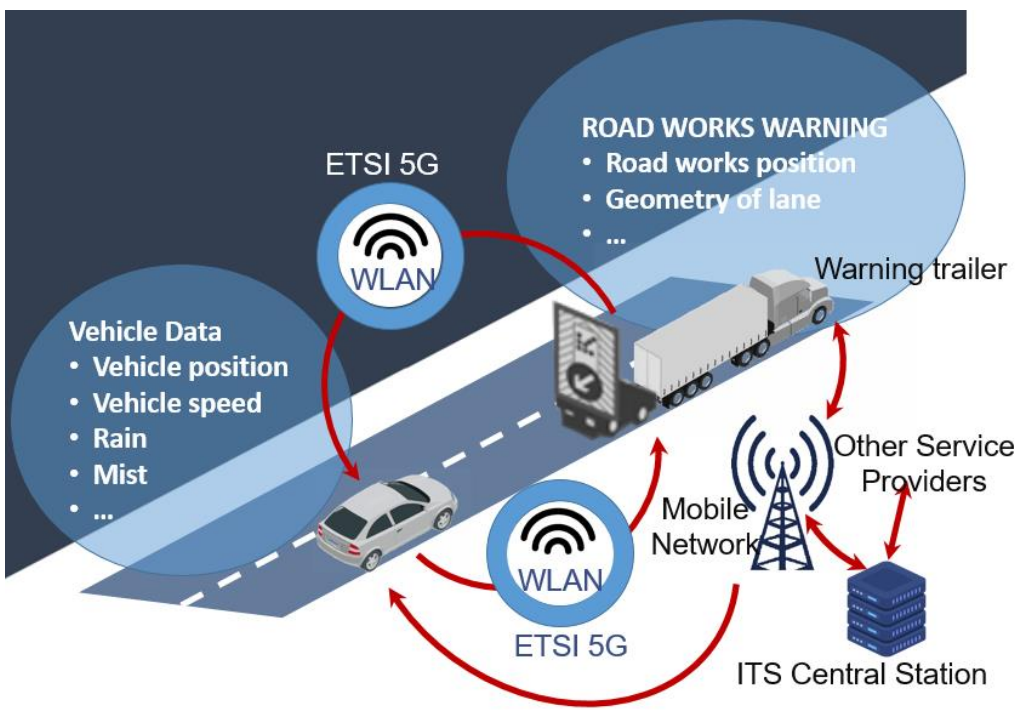

Figure 18: Schematic of the architecture of the RWW system in [133].

Figure 19: Audi Q8 SUV dashboard work zone warning [134].

3.11 Merge Warning

3.11.1 Overview

When two or more highway driving lanes merge into one, indicators such as flaggers, flashers, changeable message signs and speed monitoring displays help alert drivers to slow down and complete a merging maneuver in a safe and timely fashion. Such situations are often found in work zones where lane closures and lane shifts occur to facilitate the ongoing work. However, highway merging due to a reduction in tehn number of lanes is not a unique feature to work zones. Some highways have lane reductions by design, and drivers must perform merge maneuvers to respond to these roadway features. Late and forced merging maneuvers near work zones may create unsafe conditions which may lead to crashes. Although the conventional safety measures used in merge warning situations provide notable safety benefits, CV technologies have the potential to further improve safety by enabling heightened situational awareness about upcoming hazards [136]. In order to provide adequate notice to drivers/vehicles in merge warning situations, safety measures must be deployed several kilometers ahead of the hazard to allow sufficient time for the drivers to process the information and subsequently execute a merging maneuver by harmonizing vehicle speed with nearby traffic. Since vehicle-based hazard detection systems rely on LOS sensors with ranges of at most few hundred meters, the merge warning application can be regarded as a NLOS safety use case, given the requirement of providing/communicating the hazard notice several kilometers ahead. Correspondingly, V2I technologies are better suited to meet these requirements.

3.11.2 Typical Implementations

The literature focusing on V2X-based merge warning systems was found to be scarce. However, the USDOT-sponsored connected vehicle pilot deployment program in Wyoming deployed 75 RSUs along various sections of a highway [135] to demonstrate a number of applications including merge warning in work zones. A driving simulator study undertaken under the umbrella of this pilot program in [136] used a human machine interface (HMI) that utilized V2I communication to alert drivers about upcoming lane closures and merge requirements. This study concluded that early merge warnings enabled by V2I connectivity have the potential to prevent late and force merging behaviours at work zones.

3.12 Stop Sign Violation Warning

3.12.1 Overview

Stop sign violation warning is intended for non-signalized intersections that require vehicles to come to a full stop before proceeding through the intersection [137]. In this regard, the application differs from the traffic signal violation warning use case focused on signalized intersections (see 3.14). When a vehicle approaches a non-signalized intersection equipped with a stop sign, the vehicle's speed can be acquired from BSM/DENM messages broadcast by the vehicle or infrastructure deployed sensors to determine the likelihood of stopping before entering the intersection. After determining that the vehicle is likely to violate the stop sign ahead, a warning message can be issued to make the driver aware of the imminent violation. This is a V2I application because the data exchange occurs between a vehicle and the infrastructure (e.g., RSU).

3.12.2 Reported Implementations

Although this V2I application has been recognized by regulatory and standardization bodies (e.g., [137], [138]), reports of field tests or simulation studies were found to be scarce in the literature.

3.13 Stop Sign Gap Assist

3.13.1 Overview

In a report published in 2015 [139], USDOT has defined stop sign gap assist (SSGA) as a safety application designed to assist drivers to traverse through stop signed controlled intersections on minor roads. Infrastructure- and vehicle-based sensors are employed to obtain the instantaneous traffic state around the intersection in terms of position and speed of all vehicles. Based on the traffic state, the system may provide an application advisory, alert and/or warning messages to the driver through an in-vehicle deployed interface so that the driver has time to perform the appropriate maneuver to traverse safely through the intersection.

3.13.2 Reported Implementations

A simulation study reported in [140] assumed a "downtown" intersection with four way stop signs characterized by slow moving vehicles with high vehicle density. A total of 4 RSU represented the connected infrastructure. This simulated application prescribed deceleration rates to the drivers approaching the intersection through V2I connectivity. The authors claimed that the proposed application improved safety in comparison to emulated human driving behavior without access to V2I guidance.

3.14 Traffic Signal Violation Warning

3.14.1 Overview

In this V2I safety application, position and speed information reported by equipped vehicles and infrastructure-based measurements for non-equipped vehicles in the vicinity of a signalized intersection are utilized to provide advisory and warning messages to drivers before they violate a traffic signal. Although this use case is closely related to intersection management, the two applications differ in scope. While the intersection management application may include clusters of intersections to improve throughput of a large road network, the operational domain of traffic signal violation warning is limited to a single intersection. This safety application has been one of the first conceptualized V2X use cases. Prior to 2010, the US led Cooperative Intersection Collision Avoidance Systems Initiative (CICAS) included a traffic signal violation warning system [141].

3.14.2 Reported Implementations

Since the operational domains of more recent intersection safety related V2X applications are observed to be specific (e.g., stop sign violation, left turn assist, stop sign gap assist), the overarching use case of traffic signal violation warning is being implemented as a collection of use cases in the recent literature. Therefore, although conceptual discussions are available in relatively older literature, the *practical* application of this application is found to be scarce in more recent publications.

3.15 CV Transit Signal Priority

3.15.1 Overview

Transit signal priority (TSP) refers to techniques and strategies that improve the operation of public transportation services at signalized intersections by dynamically manipulating signal durations (e.g., extending green time or reducing red time) to prioritize the pass-through and departure of transit vehicles. A clear distinction was made between traditional and CV-based TSP systems in a study performed by Virginia Tech Transportation Institute (VTTI) and sponsored by USDOT in 2020 [142]. While the traditional systems employed set schedules or infrastructure deployed sensing to detect arrival of a transit vehicle at a signalized intersection, CV-based TSP leverages high-fidelity transit vehicle data through V2I communication to implement a more adaptive system capable of responding to dynamically changing traffic situations in real-time. Thus CV-based TSP applications can potentially overcome the limitations of traditional systems. Potential benefits include faster travel time for transit users, improved safety, and minimized environmental footprint achieved by reduced travel time.

3.15.2 Reported Implementations

One of the earliest field tests of a TSP system with wireless connectivity was conducted in 2011 by the City of Minneapolis. During a two week trial period wireless connectivity was attributed to the observed reduction of travel time by 3-6% [143]. Another field test performed at the Smart Road testbed at the VITTI (Blacksburg, Virginia) showed that the implemented CV-based TSP system achieved 32-75% reduction in delays for transmit buses in all trials [144]. Roadway operator Tampa Hillsborough Expressway Authority (THEA) participated in a CV pilot deployment project in partnership with USDOT where they planned to implement a TSP system in an urban arterial with an objective to prioritize transit buses at signalized intersections and help them maintain a predictable schedule [145]. However, it was reported in [146] that no performance data is available due to failed deployment during the evaluation period.

3.16 Railway Grade Crossing Traversal

3.16.1 Overview

Fatalities and serious injuries due to collisions at highway-rail grade crossing are a major safety concern for railway authorities [147]. Although providing in-vehicle warning when approaching a railway crossing has been proposed as early as in 1975 [148], traditional safety devices such as active signals and passive signs are usually employed to prevent collisions at railway crossings. Connectivity-based railway crossing warning systems have the potential to address NLOS cases to improve safety.

3.16.2 Reported Implementations

A connectivity-based railway crossing safety application was conceptualized in [149] that intended to leverage inter-system communication between VANETs formed by vehicular nodes in the vicinity of the crossing and positive train control (PTC) systems to reduce collision incidents. A DSRC-based implementation was field tested by La Trobe University in Australia [150]. A field test performed by researchers from Shandong University, China and University of Alberta, Canada in 2018 [147] deployed OBUs on the rail vehicle and on the test vehicle. DSRC communication was implemented to exchange information between the OBUs at a rate of 1Hz. Using real-time information collected from the OBUs, the risk of collision was assessed in a decentralized manner by the vehicle deployed OBU. The driver was warned if a high-risk probability was evaluated from the collected information.

Canadian ITS solution provider Trainfo (https://trainfo.ca/) supplies equipment such as sensors, connectivity technology, RSU, and access to cloud servers to instrument railway crossings so that they can be actively monitored to reduce collision risk. Reportedly they have provided a number of briefings to the US Federal Railroad Administration (FRA) as well as collaborated with the cities of London, ON and Winnipeg, MB.

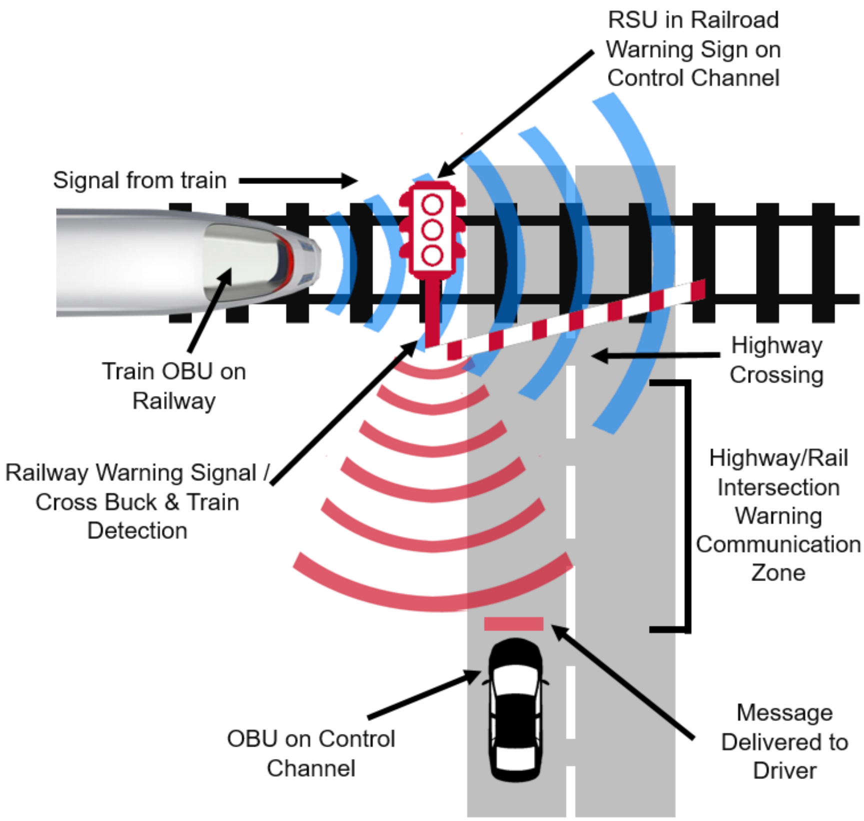

Figure 20; DSRC-based level crossing field trial by La Trobe University [150].

3.17 CV Speed Regulation and Harmonization

3.17.1 Overview

The central premise of CV speed regulation is to employ CV technologies to regulate and prescribe vehicle speeds based on traffic conditions and weather information so that vehicles can operate safely while dynamically addressing events that affect traffic flow. Minimizing safety hazards and inefficiencies due to traffic events (e.g., congestion, bottlenecks, incidents,) and weather events (e.g., fog, rainfall, snowfall) are the two main goals of these CV applications. A closely related use case of CV speed harmonization aims to minimize traffic oscillations in the spatial and the temporal domain. Since traffic oscillations have been associated with increased safety risks and inefficient fuel economy, CV speed harmonization can provide benefits in both areas.

3.17.2 Reported Implementations

The related literature provides a few reports on concepts, simulation studies, and field demonstrations of these applications. Since these are relatively new CV applications, the related literature varies widely in terms of application objectives, implementation methodology, and targeted outcomes. Simulation studies reported in [151] implemented vehicle speed advisory systems which recommended optimal speeds to drivers through connected OBUs in response to diminished visibility caused by foggy conditions. Another driving simulator study reported in [152] showed that professional truck drivers are less likely to crash when they receive speed advisories through vehicle mounted OBU under adverse weather conditions. Simulation studies and field experiments implementing CV speed harmonization application in [153] showed V2I connectivity can be utilized to minimize spatial and temporal traffic oscillations on a highway.

3.18 CV Emergency Vehicle Preemption

3.18.1 Overview

Emergency vehicle preemption (EVP) systems aim to provide right of way to emergency vehicles such as fire trucks, ambulances and police vehicles heading towards the incident location through a network of signalized intersections to minimize the travel time[8]. Intended route, position, speed, and heading of the emergency vehicle can be disseminated through V2V and V2I communication to evacuate the entire route or the approaching lane [154]. EVP systems augmented with CV technologies to receive real-time traffic information can potentially reduce the elevated safety risk associated with emergency vehicles while reducing travel time.

3.18.2 Reported Implementations

The related literature on CV based EVP systems is relatively richer than other use cases. However, most academic research focuses on simulation studies of delay analysis, traffic safety, emergency vehicle behavior, etc. [155], [156].

A few ITS solution providers supply deployment ready CV based EVP systems. The EVP system developed by EMTRAC (https://www.emtracsystems.com/) is deployed in three cities (Sunnyvale & Novato, California, and Coquitlam, British Columbia) and can be integrated with legacy systems. This system features an OBU that transmits a priority request to intersections equipped with a priority detector module installed in the traffic signal controller cabinet through a 900MHz radio communication. It is claimed that reductions of response times between 20-45% have been achieved by this system. Another commercial EVP system by Orange Traffic (https://www.orangetraffic.com/) leverages GPS positioning and cellular connectivity to deliver as high as 20% reduction in response time while improving safety of the emergency vehicles.

[8] Preemption differs from TSP which only request priority while pre-emption interrupts the regular cycles of the signalized intersection to grant emergency vehicles the highest priority.

4 Non-Safety Applications

4.1 Traffic Congestion Warning

4.1.1 Overview

Knowledge of traffic congestion or traffic density can be used in applications such as rerouting, first-aid response and city planning. Rerouting of vehicles to lesser congested areas can help reduce travel time, resulting in a reduction in environmental impacts, such as carbon emissions and noise pollution, as well as improve the mental health of both drivers and passengers. As high traffic congestion is often an indirect consequence of irregular or unplanned events, such as traffic accidents, this information can help improve first aid response. Identifying areas of frequent high traffic congestion can help city planners improve overall traffic flow by identifying roads that need repair, creating alternative routes or implementing new road rules.

CV technologies can be used to accurately identify traffic congestion at a local level in real-time with a fine granularity such as specific intersection or road lane traffic activity. One possible implementation to estimate traffic congestion is through microphones installed by roadside to measure acoustic noise signals, such as honks, engine noises and tire noises [157]. Another implementation evaluates texture and edge image features captured through roadside video cameras [158]. A final example implementation is through algorithms that group clusters in VANET frameworks [159].

4.1.2 Reported Implementations

The major implementation challenge is the rate of adoption of CV technology, either for infrastructure or in vehicles. For V2I-based solutions that rely on sensors such as cameras or microphones, one can only estimate the traffic congestion on intersections or areas where these sensors are deployed. These methods would be expensive to use to study traffic congestion occurrences over a large area like a city, and would require a substantial investment in infrastructure. Likewise, for V2V-based solutions, including those of VANET frameworks, traffic congestion estimates would require a substantial number of vehicles to be equipped with CV technology capable of sharing their information.

Another challenge is the computational load, which may often be in excess to what a RSU or vehicle can handle. This is particularly apparent with traffic congestion estimates over large areas, or the application of this information towards queries such as rerouting or path optimization. A possible solution to this challenge presented in the literature is FCD (Floating Car Data) that seeks to offload all the information from vehicles and RSU via a protocol such as cellular networks to command centers that are responsible for performing the required computations and then relaying back the results (e.g. [160], [161], [162]).

4.2 Cooperative Adaptive Cruise Control

4.2.1 Overview

By incorporating V2V communication to adaptive cruise control (ACC) systems, the cooperative adaptive cruise control (CACC) application coordinates the speeds and the positions of multiple neighboring vehicles to form a platoon. The leading vehicle in the platoon sets the desired speed adaptively as required by the traffic situation ahead, and the follower vehicles adjust their speeds to maintain a fixed inter-vehicle gap.

Since CACC utilizes longitudinal speed control automation, the limitations of human driving do not necessarily affect CACC performance. Furthermore, as V2V communication enables the immediate broadcasting of acceleration/deceleration events as they are initiated by any vehicle in the platoon, the system can perform safely even within relatively short inter-vehicle gaps. Correspondingly, a tighter platoon formation can be achieved to improve roadway utilization and overall roadway throughput. In addition, CACC systems reduce spatial and temporal traffic oscillations, which improves safety and reduces fuel consumption. Therefore, CACC systems can potentially improve road network performance, especially for high vehicle density highways typically observed in large urban environments [163].

4.2.2 Reported Implementations

A simulation study performed by a team from Nokia Networks, Poland & USA, Poznan University of Technology, Poland, Vodafone Group R&D, UK benchmarked the V2V communication performance of IEEE 802.11p (DSRC) and 3GPP C-V2X in a CACC application for trucks in [164]. Even for high density platoons and the corresponding crowding in the wireless spectrum due to the large number of nodes, C-V2X technology provided reliable and robust performance resulting in tighter platoon formations. A collaborative project between the University of California, Berkley and automaker Nissan field tested a prototype CACC system based on DSRC communication in [165]. The system was sufficiently adaptive to accommodate unequipped vehicles disrupting the platoon formation. Furthermore, the CACC system showed reduced traffic oscillations in terms of inter-vehicle gap variability in comparison to the OEM-installed ACC system on the test vehicles. A CACC control algorithm under constraints of passenger comfort (i.e., smooth acceleration and deceleration profiles), safety and prescribed speed limit was developed in [166], which describes a control law prototyping exercise for CACC speed regulation and was published in 2020. The prototyped controller, by regulating vehicle speeds in both dimensions (i.e., lateral and longitudinal), demonstrated reliable CACC performance in simulation studies.

4.3 Eco-Lanes Management

4.3.1 Overview

Eco-lanes are dedicated lanes akin to managed lanes including high-occupancy vehicle (HOV) or high-occupancy toll (HOT) lanes that are optimized for eco-friendly vehicle operation [167]. The USDOT-led initiative AERIS[9] employed model-based study of this application, and reported up to 22% fuel savings on a real-world highway corridor [168]. The concept has been elaborated in the USDOT National ITS Reference Architecture in [169], which envisioned eco-lanes as dynamically defined managed lanes to effect environmental benefits. Furthermore, they can be created or decommissioned along a roadway based on the real-time traffic and environmental data collected from multiple sources including vehicles, infrastructure and other systems employing CV technologies. The relevant data may include the types of vehicle allowed to drive on eco-lanes, specification of geo-fences defining the eco-lane boundaries, emission parameters for entering eco-lanes.

Eco-lane management is closely related to other CV applications such as speed harmonization and dynamic eco-routing that also yield environmental benefits. Although high-level descriptions of this

[9] https://www.its.dot.gov/research_archives/aeris/index.htm

application can be found in several documents published by regulatory bodies or research organizations (e.g., [167], [168], [169]), the related literature reporting on implementation was found to be scarce.

4.4 Dynamic Eco-Routing

4.4.1 Overview

Similar to traditional navigation systems that propose routes based on shortest distance or time, eco-routing proposes routes based on minimum emissions or fuel consumption. For dynamic eco-routing, changes are made in the proposed eco-route, typically in real-time, due to new information such as road closures and traffic information. One implementation of this application involved developing an eco-routing strategy that made use of fuel consumption of drivers in a similar vehicle class as well as individual drivers [170]. Another implementation made use of historical and real-time traffic information, emission factors for a variety of vehicle types under various road and traffic conditions, along with shortest distance optimal route calculation to determine the most eco-friendly route in terms of fuel consumption [171]. A third implementation used prediction of traffic variables such as average vehicle speed, density flow, travel time, emission reduction and fuel economy to design an optimal eco-routing strategy [172].

4.4.2 Reported Implementations

Like other connectivity use cases, the majority of the work done on this topic has only been tested in a simulation setting. There are also similar requirements and challenges, ranging from the infrastructure needed to compute and propagate information between vehicles, to the rate of adoption which would limit how much information is available to update the dynamic eco-routing policies.

Specific to eco-routing is the challenge of complexity. Route fuel cost is dependent on many factors compared to the shortest route problem. These include route characteristics, vehicle characteristics and driving behavior. Average fuel consumption tends to be higher in high traffic areas, as higher congestion leads to more stops, increased travel time and frequent braking and acceleration. Another factor is the design of the communication system, which has been shown to have a significant impact on network-wide fuel consumption [173]. Higher traffic areas imposes a higher network load from a large number of vehicular nodes, which results in deterioration of network performance (e.g., dropped packets, increased communication delays).

4.5 Smart Parking Management

4.5.1 Overview

Smart parking management involves real-time monitoring of the vacancy spaces in parking lots and relaying this information to waiting V2X technologies. This allows parking users, operators and owners to obtain real-time information about parking occupancy and availability. Benefits of smart parking management include reduction in emissions and traffic load due to reduction in idling and circling time, reduction in cost due to the use of automatic vehicle identification and online payment, and improvement in parking enforcement. An extension to smart parking management could include automated valet parking. Another extension is automated park assist to enter and exit a nearby parking space.

4.5.2 Reported Implementations

One implementation of smart parking is for community-based parking such as the solution proposed by Bosch Mobility Solutions[10], where available parking spaces are determined through ultrasonic sensors equipped on passing vehicles. This data is anonymized, sent to the cloud and compiled so that a parking spot vacancy map is generated and shared to the community in real-time. Challenges include having sufficient adoption to compile information and keep the parking space network map up-to-date, as well as the necessary infrastructure and applications to handle and analyze this data.

Another implementation of smart parking management is to have demand-responsive parking pricing. Examples of this implementation include the SFpark[11] pilot project in San Francisco and LA Express Park[12] in Los Angeles. Using sensors to determine occupancy and smart parking meters, the cities were able to charge the lowest price possible without creating a parking shortage using a transparent and data driven pricing policy. Over the course of the SFpark pilot of 2 years [174], the average hourly rate at on-street meters was lowered by 4% and at garages by 12%, while the overall revenue, due in part to an increase in operational time, increased by USD$1.9 million per year. In addition, the reported time to find a parking spot decreased by 43%. Furthermore, due to a more connected, streamlined experience to pay for parking, there were 23% fewer parking meter-related citations per meter. Other benefits included a reduction in vehicle cruising, vehicle congestion, traffic accidents related to distracted driving, greenhouse gas emissions, and air pollution.

Implementation requirements for demand-responsive parking pricing include parking garage equipment, sensors to keep track of the number of vehicles entering and exiting the garage, parking sensors to detect whether or not a vehicle is parked in a spot, smart networked parking meters, roadway sensors, real-time data and mobile applications, and data management and reporting tools. Challenges include battery life for the smart meters and sensors, placement of the sensors and determining the factors that have an impact on parking availability to better optimize pricing.

4.6 In-Vehicle Infotainment

4.6.1 Overview

In-vehicle infotainment (IVI) is a combination of vehicle systems that deliver information and entertainment to the driver, passengers and surroundings through hardware and software. Since car radios and cassette/CD players to navigation and on-demand entertainment, IVI continues to evolve to improve the vehicle experience. In regards to connectivity, 3G, 4G-LTE and 5G provide car manufacturers, electronics suppliers and software developers more possibilities to create an immersive, safe and connected experience.

[10] https://www.bosch-mobility-solutions.com/en/products-and-services/mobility-services/connected-parking/community-based-parking/

[11] https://www.sfmta.com/projects/sfpark-pilot-program

[12] https://www.laexpresspark.org/

With 3G, IVIs, such as General Motors OnStar[13], provided services that included automatic crash notification, emergency rescue, and on-demand diagnostics. 3G also allowed vehicles to access the internet and with the interconnection of cellphones and vehicles, and applications such as hands-free calling.

4G and LTE improved on these services and allowed for more applications to improve the overall user experience. One key addition is online audio services such as SiriusXM Internet Radio and Spotify that offers personalized playlists, stations and news. A second addition is AI-powered in-vehicle voice assistants from automakers like the BMW Intelligent Personal Assistant and the Hey Mercedes voice assistant from Mercedes-Benz to technology companies like Google's Android Auto and Apple's CarPlay. This includes Mobility as a Service (MaaS) applications such as e-commerce order services and appointment bookings. A third addition is the integration with smart-home appliances like Google Nest and Apple's HomeKit. This home-vehicle ecosystem allows an individual to control vehicle-related functions from their home and vice versa. From the home, one could pre-heat the vehicle or check if the vehicle doors are locked. Likewise, from the vehicle, one could check and change the state of home amenities including lights, temperature or the state of garage door. A fourth and final addition is the transformation of the cabin as a mobile home office. From interaction between multiple screens, heads-up display on windshields and surround view, the requirements for connectivity and corresponding infrastructure becomes more significant.

IVI applications make use of 5G which is still in the early phases of development. One proposition is to extend IVI to the exterior of the vehicle. One such 5G-enable method would be the use of dynamic large displays on the surface of the vehicle [175]. Applications for this include marketing that could display dynamic, personalized advertisements and an environmentally -friendly digital alternative to changing the cosmetic appearance of the vehicle. Another proposition is to share the computational load for common, resource expensive tasks using a network of vehicles or surrounding infrastructure such as VANETs [176]. These tasks could include video streaming, image processing, augmented reality and 3D visualizations.

4.6.2 Reported Implementations

One of the challenges with IVI is the problem of interoperability. Every OEM has their own propriety ecosystem. This adds to the complexity when developing IVI applications and solutions that operate between different makes of vehicle or the infrastructure. Another challenge is the limitation of space and computation for hardware inside the vehicle for IVI. This may be alleviated through solutions mentioned above such as shared computing or cache-aided content sharing in a network of vehicles and with the infrastructure. However, these solutions require an infrastructure such as 5G that allows for high data and time-synchronous data streams [177]. A third challenge is the lack of IVI on the exterior of the vehicle, to communicate information to the surroundings.

4.7 Electronic Toll Collection

4.7.1 Overview

Electronic toll collection (ETC) is a system to collect tolls charged to vehicles for traversing infrastructure such as toll roads, highways, tunnels or bridges through electronic means. ETC is meant to supplement or replace traditional tollbooths, providing both economic and environmental benefits. Among the economic

[13] https://www.onstar.com/us/en/home/

benefits, ETC allows for improved traffic flow by reducing transaction and waiting times and thus congestion. As a result, the overall system throughput is increased. Table 7 outlines the volume of vehicle flow for different toll collection technologies and accuracy. Manual toll collection can process 250 – 350 vehicles per hour, and automated toll collection can process from 450 – 500 vehicles per hour. Having dedicated ETC lanes with a barrier can process 900 – 1100 vehicles per hour and, if these barriers are removed, upwards to 1800 – 2400 vehicles per hour can be processed. Along with the increased number of vehicles that can be processed, there is a possible reduction in the cost of operation resulting from the increased accuracy and enforcement, along with the reduction or removal of manual toll collectors. Furthermore, for open road all-electronic toll collection (AETC) solutions such as Highway 407 ETR in Ontario, there are added safety benefits as vehicles travel at normal highway speeds, without the distraction of queuing at tollbooths and preparing methods of payment. In terms of environmental benefits, the reduction in waiting times and congestion results in a reduction in fuel consumption and air pollution.

Toll Collection Technology	Toll Volume (Vehicles Per Hour)	Accuracy
Manual Collection	250 – 350	98.00%
Automatic Coin Machine with Barrier	450 – 550	98.50%
Automatic Coin Machine without Barrier	500 – 700	95.00%
Magnetic Stripe Tickets	500 – 900	98.50%
Automatic License Plate Recognition (ALPR)	600 – 1000	85.00%
Smart Card with Barrier	700 – 900	99.50%
Electronic Toll Collection – Dedicated Lane with Barrier	900 – 1100	99.96%
All Electronic Toll Collection – Open Road Tolling	1800 – 2400	99.25%

Table 7: Performance and accuracy of different toll collection technologies [178], [179].

4.7.2 Reported Implementations

Vehicle identification and recognition are two of the main challenges in ETC applications. Figure 21 highlights the typical infrastructure needed to implement AETC. Vehicle identification is performed either through an OBU, typically a transponder, or through a series of cameras taking photos of the vehicle license plate. Vehicle recognition is then performed by matching the information provided through the OBU or a database of license plates. For tolling of vehicles without an OBU, some technologies that are used for the classification of the vehicle include inductive loop sensors and overhead cameras. Recent studies have also shown the possibility of replacing transponders with cell phones or integrated vehicle solutions, such as ITM[14] (Integrated Toll Module) devices found on selected Audi models.

[14] https://www.itmsignup.com/audi

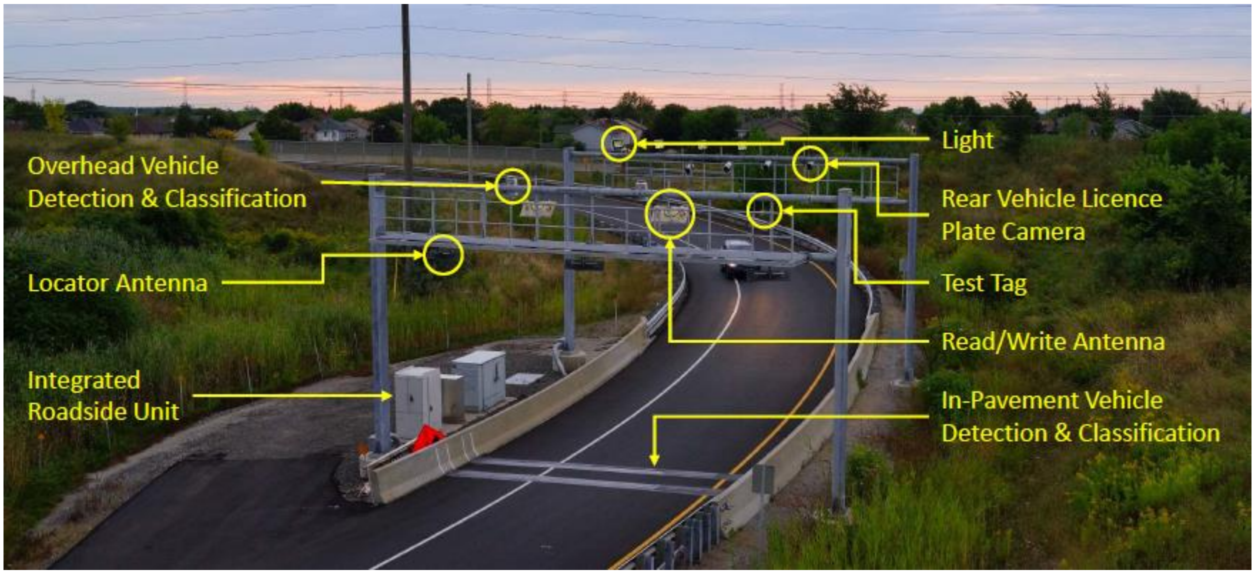

Figure 21: Typical infrastructure for AETC open road tolling (407 Express Toll Route in Canada [180]).

Similar to other connectivity use-cases, the challenges for ETC implementation include cost, privacy and security. The costs include those relating to infrastructure such as the installation and maintenance of the sensors, to operation such as the fee per transaction and the people required to operate the ETC, and to implementation such as the user cost to purchase or rent the OBU. Table 8 and Table 9 outline the privacy concerns of open road tolling compared to traditional tolling methods. In order to address some of these privacy concerns that pose a security risk, multiple solutions in the field of cybersecurity are adapted for this use-case. An example is using an IOTA framework for payments and Hyperledger Indy architecture for secure transmission and validation of information through 5G C-V2X for an open road tolling system [181].

Level of Privacy	Brief Description	Comment
A	No ability to detect or track vehicles or individuals	No detection
B	Low ability to detect or track vehicles or individuals	Manual data extraction from selective single-location, single-source records (e.g. recorded video)
C	Medium ability to detect or track vehicles or individuals	Automatic data extraction (e.g. ALPR) from single-location, single-source records
D	High ability to detect or track vehicles or individuals	Automatic data extraction from multiple-location, single-source records
E	Very high ability to detect or track vehicles or individuals	Automatic data extraction from multiple-location, multiple-source records (e.g. video and toll transponder)
F	Full ability to detect or track vehicles and individuals inside and outside of the vehicle	Automatic data extraction from continuous multiple-source records (e.g. GPS, cellular transmitter, live HD video and ALPR)

Table 8: Rating scale to assess privacy impacts [178].

Toll Collection System	Toll Collection Technology	Payment Systems	Convenience to Users	Operational Cost	Level of Privacy		
					Anonymity/ Pseudonymity	Unlinkability	Undetectability/ Unobservability
Traditional Toll Road	None / Video Enforcement	Cash, Token	Low	High	B	B	B
	Smart Card Reader / Video Enforcement	Smart Card	Medium	Medium	C	C	C
Open Road Tolling	E-Cash Technology	E-Cash	High	Low	A	A	A
	Unregistered Transponder / ALPR Enforcement	Cash	High	Low	B	E	D
	Registered Transponder / ALPR Enforcement	Credit Card	High	Low	D	E	D
	ALPR	Mail-In	Medium – High	Medium	D	E	D
Vehicle-Miles Traveled Fee on Selected Highways	In-vehicle GPS / GSM	Various	High	Medium	D	E	E

Table 9: Levels privacy provided to road user by various payment systems [178].

4.8 **OTA updates**

4.8.1 Overview

Similar to how a vehicle needs regular mechanical and electrical maintenance, there is a need to maintain and update the software on-board the vehicle. Whereas one would traditionally bring a vehicle to a dealer or mechanic for maintenance or repair, over-the-air (OTA) updates allow for software and firmware updates to be performed remotely over a wireless connection. Figure 22 and Figure 23 depict the procedures for local and remote software updates.

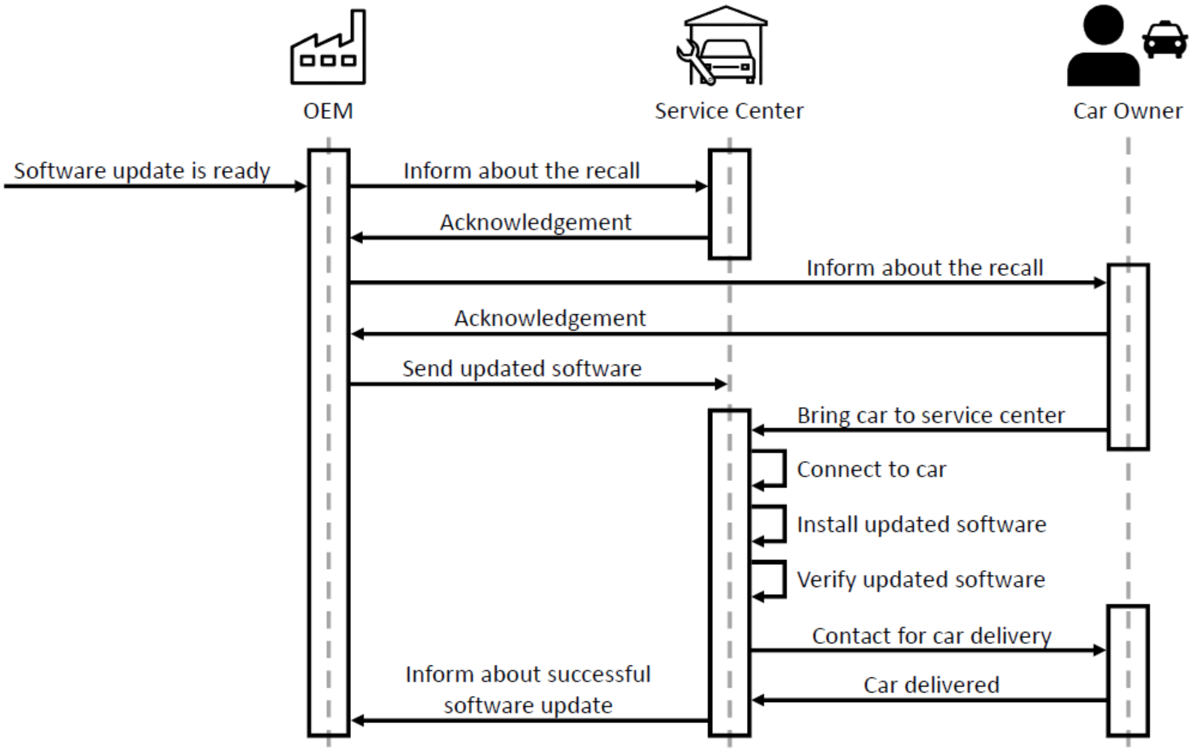

Figure 22: Local software update procedure [182].

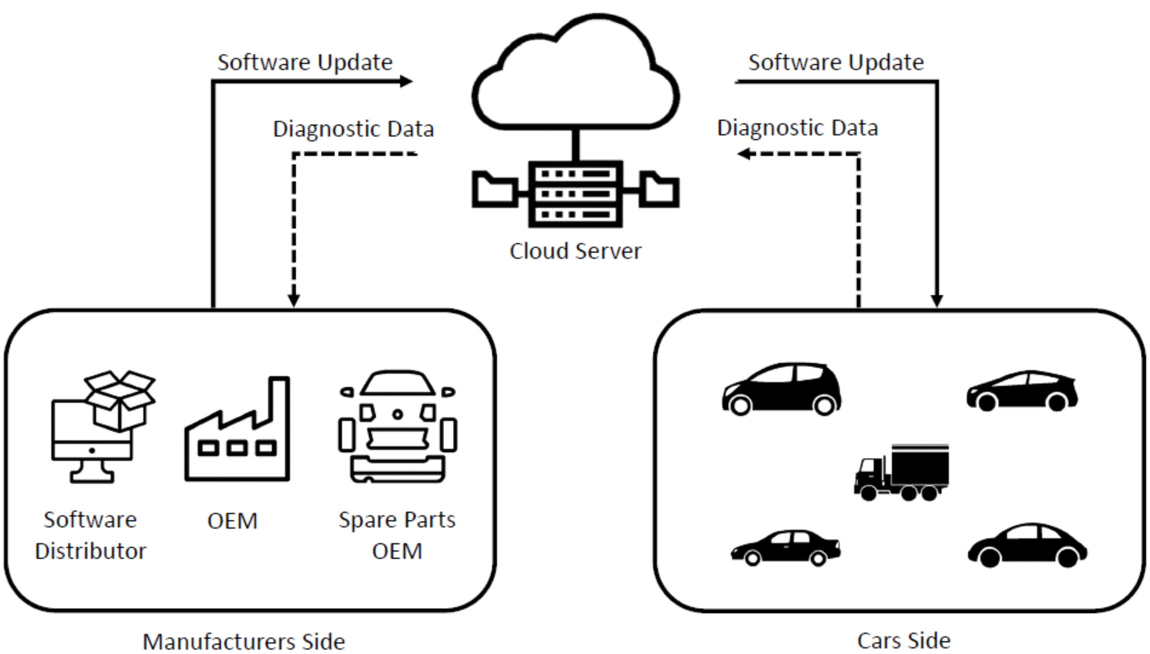

Figure 23: Remote software update procedure [182].

OTA updates provide several advantages over traditional methods via a cable connection. One such advantage is lower recall costs, providing savings for the consumer, the dealership and the OEM as the updates can be executed remotely. Another advantage is the reduction in depreciation due to the implementation of new features and upkeep of existing features. These could include updates to the infotainment system or the map used for navigation applications. Perhaps most importantly, OTA updates allow for greater vehicle safety and security. These could range from updates to safety-critical systems such as the ECU to dealing with cyber threats.

4.8.2 Reported Implementations

The requirements to allow a vehicle to perform OTA updates are a telematics control unit (TCU) and a wireless connection, whether that be through Wi-Fi or a cellular network. There must also be an onboard fallback in case there are issues with the performed update. Updates are performed at scheduled intervals or patches for critical updates. Drivers could be notified of an update through multiple means depending on the nature and size of the update. This includes automatic updates, notifications displayed through the in-vehicle infotainment system, e-mails or public messaging. Service centers or dealerships would need to continue to provide assistance for critical repair or troubleshooting issues related to OTA updates.

In terms of challenges, there is the issue of cybersecurity as connected services such as OTA open the possibility to cyber-attacks. These attacks can be on mobile applications or to the Controller Area Network, the network that controls all the in-vehicle components, such as steering and brakes. A security framework identifying these risks and points of attack was studied in [183]. Early studies have also been performed to detect the presence of these attacks through machine learning approaches [184], [185], [186]. There is also the challenge to ensure the update is safe, secure and reliable for all variants of the vehicle. In this regard, many state-of-the-art security mechanisms primarily used in OTA for mobile devices have been extended to vehicles, including symmetric key encryption based techniques [187], [188], hash function based techniques [189], block chain based techniques [190], RSA and steganography based techniques [191] and hardware security module based methods [192], [193]. Another challenge is the priority and selection of what to include in each OTA update, as there is a wide variance in the type of environment, driver behavior and driver values. Other challenges include the dependency of a stable wireless connection, how the updates should be priced, and user privacy.

The above-mentioned challenges address questions of integrity of the OTA update and its delivery process. If an OTA update involves the autonomy software stack or ECU firmware related to driving automation, they can have deep impact on the autonomous performance. In the software industry, updates go through established testing procedures to ensure that the update will improve system functionality, not disrupt it. In this regard, the OEMs can adopt the best practices from the software development community, especially those involved in safety-critical software development.

4.9 Road Weather Advisory

4.9.1 Overview

Adverse weather conditions, which include rain, snow, strong winds, and visibility limitations, can affect driver behavior, vehicle performance and road surface conditions. During the period of 1999 to 2017, 30% of vehicle collisions in Canada were attributed to such conditions, representing 33,716 collisions in 2017 [194]. Vehicle connectivity can potentially reduce the number of collisions and accidents by providing relevant weather information in real-time that contains the nature, the location and appropriate driver response to the weather hazard. Advisory to the driver may include warnings, prohibitions or reductions in speed. In situations with low visibility or low traction such as fog, rain or snow, cooperative adaptive cruise control through connected vehicle technologies, as described in section 4.2, can be implemented for improved safety. Another example would be broadcasting of real-time road conditions such as road closures or dangerous road sections with snow banks or black ice, preventative measures such as whether the road has been salted, or if snow is covering road signs or lane markings. The communication of this information can aid the connected vehicle operate more safely [195].

4.9.2 Reported Implementations

Aside from the shared common implementation requirements and challenges of other CV use-cases, the use-case of road weather presents an additional challenge. This challenge is the transition from autonomous driving to manual driving. The impact of adverse weather on autonomous driving is often accounted for in a way that is “hidden”. If this compensation for the adverse weather is not communicated to the driver, there is a risk of the driver not adequately compensating when they retake control of the vehicle [196], [197]. Local weather changes incorporated to an adaptive cruise control system was shown to reduce CO2 emissions and was tested using a prototype vehicle [195].

5 Summary of Findings & Conclusion

5.1 Research Questions & Answers

This technology review set out to answer a number of research questions. After reviewing the related literature, the following answers are proposed:

- **What are the concrete (measureable) safety benefits of CV technologies?**
  Human drivers play the role of decision maker in conventional vehicles. In case of CAVs, as the level of automation increases, software plays an increasingly active role in all decision making including those involving safety-critical functions. Therefore, it is expected that a conventional safety framework for motor vehicles cannot be directly translated to the CAV case. Despite this gap, conventional safety metrics such as crash avoidance, minimizing likelihood of bodily injury (reducing the severity of crashes) and fatalities per million driven miles have been employed to measure safety benefits of CV technologies. Depending on the nature of the application, CV applications can improve safety of low frequency (e.g., train and automotive collision at railway crossing) to high frequency events (e.g., motor vehicle collision at intersections). Related literature predominantly evaluated the safety of CV applications in simulation environment.

- **What use cases are envisioned for CV technologies to specifically enhance safety regardless of communication modes (e.g., V2V, V2I, V2P, V2X)?**
  Use cases with pilot projects such as VRU protection, intersection management, railway crossing traversal and work zone beaconing have strong safety potential. If adopted, even with the current limited access technologies (LTE and DSRC), they can enhance safety.

- **What research has been conducted to date to demonstrate the potential safety benefits of these use cases?**
  The related research mostly focused on functionality aspects of CV applications. Field operational testing with any statistical significance will require outfitting a large number of vehicles with CV features since they are not yet available in production vehicles. However, USDOT is running several pilot projects in New York, Florida, and Wisconsin representing urban, urban-suburban, and rural roadway environments. The data from these pilot projects demonstrate strong safety potential of the CV applications studied. It was observed that research from academia principally focused on functionality and performance of the CV application. Potential safety benefits were argued either qualitatively or validated in simulation environments.

- **What level of deployment needs to be realised before these significant safety benefits can be achieved?**
  The body of literature that studied safety benefits of CV applications as a function of technology penetration rate is rather scarce. However, the few that were found to study this aspect of CV applications demonstrated in simulation that even at low penetration rate (characterized as 30%) safety benefits can be attractive.

- **Are these safety benefits exclusive to CV technologies, or could they be achieved by other technologies/sensors either on the market or in development (e.g. vehicle automation, high definition, real-time mapping etc.)?**
  Vehicle-based driving automation systems are entirely dependent on their sensors for environmental perception and for localization. These two basic competencies of automation are highly weather-dependent. On the other hand, CV technologies can provide situational awareness

beyond LOS by sharing sensor data and precise localization by leveraging network provided GNSS correction data in a HPL scheme. Therefore, it can be argued that full vehicle automation without connectivity might be too challenging to implement. On the other hand, the safety potential of CV applications is maximized when they are interfaced with driving automation systems. For example, in a connectivity-only implementation of VRU protection use case, the OBU in a vehicle's cabin and the mobile device carried by the VRU can provide warnings if they are in a collision path. In this case, the safety responsibility is on the human driver and, to a lesser degree, on the VRU to take evasive actions. If the human driver is distracted or too slow to respond, a collision may be unavoidable. However, if the CV application is interfaced with the automated braking system of the vehicle, collision avoidance can be made much more reliable, which will enhance VRU safety. Therefore, it can be said that safety benefits are enabled by CV technologies and are further enhanced by vehicle automation technologies.

- **What are the limitations/safety vulnerabilities associated with connected vehicle technologies (e.g. latency, signal loss, crowding and interference, infrastructure requirements and interoperability, weather limitations)?**
  Performance benchmarking tests on access technologies such as IEEE 802.11p based DSRC or LTE cellular show that loss of line of sight, limited range, crowding and interference can degrade network performance to a degree that safety-critical messages cannot be delivered with the required latency and frequency. These operational vulnerabilities can lead to unsafe conditions, when the CV application can no longer perform reliably because of degradation of network's quality of service. Another limitation is cybersecurity of the network. If the security of the network is breached, even in the absence of the aforementioned operational limitations, a network can be rendered ineffective by staging attacks such as denial of service and spoofing,. Therefore, issues of cybersecurity and the safety of CV applications are equally important. Harmonization of CV standards regionally and globally is necessary so that technology developers can utilize their resources to develop a globally deployable feature, without requirements of region-specific customizations. Unlike some vehicle-based perception system technologies such as LiDAR and camera, whose sensing modalities are greatly affected by weather, CV applications are not typically influenced by weather events.

- **Are there limitations/safety vulnerabilities specific to operations in varying Canadian driving conditions (e.g. rural and remote areas, varied geography, winter conditions, etc.)?**
  As long as the necessary CV infrastructure is available, population density or remoteness of a location will not introduce limitations to CV applications. However, compared to urban areas, infrastructure needs might be lower for remote and rural areas because network crowding is not likely to occur. Geographical features such as hills and mountains may hinder LOS access to the wireless network, and may result in network interruptions. Since radio waves is the connection modality for CV applications, connectivity is not affected by winter conditions. However, CV equipment (electronics, infrastructure deployed sensors, power sources) might be susceptible to winter related complications.

5.2 Findings

5.2.1 Technological Aspects

- Access technologies such as IEEE 802.11p based DSRC and C-V2X enable data exchange between different nodes in a VANET. For example, in a CACC application, the platooned vehicles receive position and velocity information from neighboring vehicles through DSRC or C-V2X. OBU software utilizes the received data to obtain situational awareness, and to evaluate the required actuation tasks. As defined by the application-specific requirements, the wireless network must accommodate data exchange at a sufficiently high enough rate so that fine-grained control of the vehicle velocity can be performed to maintain the intended inter-vehicle gap.

- Access technologies for CV applications is a highly evolving field. Recent proposed radio spectrum reallocation by FCC may lead to increased popularity for C-V2X. Current limitations of LTE networks are expected to be addressed by 5G connectivity, but the related technology development work is still in an early phase.
- Focus of current CV research were found to include development of new architectures and concepts (e.g., centralized vs de-centralized coordination), coordinated path planning, and software techniques to mitigate connectivity disruptions, formulation of new algorithms for cooperative path planning and coordinated dynamic vehicle control.
- Current research direction for the development of the access technology includes privacy preserving authentication protocols, management of highly dynamic network topologies, network security, deterministic network performance, and resilience against cyber threats.
- Performant and robust L4 and L5 driving automation system will immensely rely on CV technologies for redundancy, weather resilient situational awareness, motion coordination to perform complex driving maneuvers (e.g., lane change, overtake), and obtaining perception coverage beyond LOS. Although the current efforts in automated driving systems development are largely vehicle-based (i.e., little reliance on V2X functions), as CV technologies mature it is expect that they will find increasing prevalence in automated driving systems as a key enabling technology.
- Safety potential of CV applications were found to be a largely qualitative proposition. The related development work was observed to be more focused on functionality and resilient operation, rather than validating the safety benefits with convincing statistical rigor. However, some research work quantified the safety benefits in simulation environments. This is not surprising because of the inherent difficulties with field trials that may involve outfitting a fleet of vehicles with CV equipment.

5.2.2 Deployment & Regulatory Aspects

- Publicly funded pilot projects focusing on field testing and demonstration of CV applications will foster collaboration among the key stakeholders comprised of public sector bodies, network equipment manufacturers, automotive OEM, auto parts manufactures, roadway owner/operators, freight companies, commercial motor carriers and telecommunication operators.
- Although the safety potential of CV applications can be fully realized when they are paired with vehicle automation, popularity of mobile phone based automotive apps (e.g., Apple CarPlay, Android Auto) can be leveraged to implement CV applications in limited scope in conventional vehicles to enhance road safety. In such a limited scope implementation, mobile phone will serve as an OBU that provides advisory to the human driver.
- Since municipalities typically own both urban road networks and transit vehicle fleets, may be easier for municipalities to deploy CV applications for the transit vehicle and emergency vehicle use cases. These use cases are expected to experience early public deployment.
- As the population density in urban areas is expected to grow continually in Canada, some of the transportation challenges can be addressed by leveraging connected vehicle technologies. Eco-driving, dynamic route optimization, and connected intersection management are some key applications.

- New business models enabled by CV technologies will need to be introduced. Products such as mobility as a service, dynamic ridesharing, and usage based driver insurance are already being offered for public consumption.
- National bodies can benefit from a harmonized regulatory requirements, CV standards, transport protocols at global and regional scales so that technology developers and service providers are incentivized to develop globally deployable CV applications.
- Partnerships, collaborations, and consortiums comprised of key stakeholders are a necessary ingredient to help promote rapid development of CV applications.

5.3 Concluding Remarks

At present, CV technologies can potentially render transportation safer for all road users more readily than driving automation technologies due to the technological maturity of the CV building blocks. Even when the actual dynamic driving task is being performed manually with advisories provided by V2X networks, safety benefits of these applications are evident in the simulation and field test studies. Despite this optimistic outlook, logistical challenges associated with creating effective collaboration among heterogeneous stakeholders (public bodies and regulators, automotive OEMs, telecommunications industry) for successful deployments remain present. Harmonization of standards of connectivity, equipment, and interfaces at the regional and the global scales are a necessary ingredient to help promote a well guided foundation development and deployment process.

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