A Review of Next Generation Communication Technology for Transportation

Final Report

Prepared for:
Transport Canada

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

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Executive Summary

A Review of Next Generation Communication Technology for Transportation

Background:
CV and AV technologies present new possibilities for transportation safety and mobility. CV technology is at a crossroads with relatively mature DSRC devices, but potentially advanced C-V2X devices becoming available. Furthermore, next-generation wireless communication technology such as 5G-NR and IEEE 802.11 NGV technologies are on the horizon. A summary of existing and next-generation CV technology and relevant considerations are provided here.

Relevant Technology Survey Highlights:
This study attempted to aggregate and summarize information about relevant wireless communications technologies for transportation applications. Some highlights of the primary technologies include:

- **DSRC**
  - 802.11p operation in 5.9 GHz band
  - Low latency (< 1 ms)
  - Short-range (> 300 m)
  - In-vehicle (OBU) and roadside (RSU) integration and applications
  - Asynchronous
  - SCMS
  - Potential issues with misbehavior and interoperability

- **C-V2X**
  - 4G LTE operation in 5.9 GHz band
  - PC5 direct communication (in and out of coverage)
  - LTE-Uu interface (in coverage)
  - Synchronous
  - Potential improvements to range, reliability, and congested performance
  - Potential issues with “rogue” base stations, “SIM swapping”, and interference from non-safety data

- **5G NR**
  - Support same PC5 and LTE-Uu interfaces
  - Intended to coexist and be backwards compatible with LTE C-V2X
  - Potential improvements to latency, data rate, reliability and congestion-handling
  - Potentially support HD map transmission and remote driving of automated vehicles

- **NGV**
  - Leverage enhancements to signal processing and wireless technology
  - Intended to coexist and be backwards compatible with DSRC
  - Potential improvements for throughput, reliability/efficiency, range, and congestion-handling
  - Potentially support automated vehicles, unmanned aerial vehicles, and rail operations

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Technology Transition Considerations:
Timelines for the deployment of next-generation communication technologies, such as 5G NR and 802.11 NGV are unclear, but their implications should be considered now as CV deployments become more prevalent. DSRC and C-V2X could be taken advantage of now to begin realizing their benefits, but concerns about making investments now just for the technologies to become obsolete are reasonable. Luckily, backwards compatibility is a goal of both 802.11 NGV and 5G NR with their respective predecessors (DSRC and C-V2X), meaning that 802.11 NGV and DSRC devices should be able to communicate with each other and 5G NR and C-V2X devices should be able to communicate with each other. However, interoperability between DSRC and C-V2X or between 802.11 NGV and 5G NR are unlikely because of inherent differences in the technologies. That being said, formal interoperability testing between the technologies has not been conducted. Furthermore, the likelihood of 802.11-based and cellular-based technologies being able to coexist is largely unknown as concerns about congestion and interference are credible. Again, formal coexistence testing has not been conducted, so no real conclusions can be drawn yet. Coexistence between DSRC and 802.11 NGV and between C-V2X and 5G NR, respectively, seems possible on the other hand, but again, testing is needed to verify.

Sample Research Gaps:
There are likely numerous research gaps when considering the various technologies independently, as well as collectively, in a CV ecosystem. Several sample research gaps include:

- Coexistence Testing and Pilots: There is a need to better understand the performance implications presented by a mixed-technology environment. Near-term coexistence testing could be performed with both DSRC and C-V2X devices.
- CV Misbehavior Detection and Mitigation: There is a need to detect when a CV is broadcasting inaccurate or incorrect information, as well as a need for a system or strategy in place to mitigate these scenarios to avoid false alerts and warnings. Detection could potentially occur using vehicle- or infrastructure-based sensors, and could feed into a voting-based trust system.
- Edge Computing with CV Data: There is likely a benefit to understanding and exploring what can be done “at the edge” with the influx of real-time data that will be made available by CVs.

Recommendations:
With the ongoing evolution of existing CV technologies, and the uncertainty around next-generation technologies, it is understandably difficult to make near-term decisions on deploying CV technologies to realize their benefits. Several recommendations for transportation stakeholders include:

- Monitor ongoing CV pilot deployments to gather lessons learned
- Monitor development and testing of existing and next-generation CV technology to understand capabilities and limitations
- Monitor and engage in relevant standards working groups
- Monitor OEM stances and planning on in-vehicle CV integration
- Avoid basing decisions and development of support systems on a specific technology
Table of Contents

Executive Summary .................................................................................................................. ii
List of Figures ................................................................................................................................... ii
List of Tables .................................................................................................................................... v
Glossary ........................................................................................................................................ vi

1 Introduction ................................................................................................................................. 1

2 Sample Transportation Use Cases for V2X ................................................................................... 2
  2.1 Applications for Smart Transport ............................................................................................... 2
  2.2 Emergency Electronic Brake Lights (EEBL) ............................................................................... 2
  2.3 Queue Warning (Q-WARN) ....................................................................................................... 3
  2.4 Reduced Speed Work Zone Warning (RSWZ) ........................................................................... 4
  2.5 Cooperative Situational Awareness ........................................................................................... 5
  2.6 Integrated Corridor Management Systems ............................................................................... 6
  2.7 Powertrain Optimization .......................................................................................................... 7

3 Survey of Relevant Technologies .................................................................................................. 8
  3.1 DSRC ...................................................................................................................................... 8
    3.1.1 Security ............................................................................................................................ 10
    3.1.2 Risks ............................................................................................................................... 10
  3.2 C-V2X ................................................................................................................................... 11
    3.2.1 PC5 ................................................................................................................................ 11
    3.2.2 LTE-Uu .......................................................................................................................... 13
    3.2.3 Security .......................................................................................................................... 14
    3.2.4 Risks ............................................................................................................................... 15
  3.3 5G New Radio (5G NR) .......................................................................................................... 15
  3.4 IEEE Next Generation V2X (NGV) .......................................................................................... 16
  3.5 Visual Light Communication .................................................................................................... 17
  3.6 Comparison ............................................................................................................................ 18

4 Standards Development Activities .............................................................................................. 19
  4.1 OSI Model .............................................................................................................................. 19
  4.2 SAE ....................................................................................................................................... 20
  4.3 IEEE .................................................................................................................................... 23
  4.4 ISO ....................................................................................................................................... 25
  4.5 3GPP ..................................................................................................................................... 27

5 Technology Transition .................................................................................................................. 28
  5.1 C-V2X to 5G-NR .................................................................................................................... 28
  5.2 DSRC to 802.11 NGV .............................................................................................................. 30
  5.3 Coexistence Between Technologies ........................................................................................... 30

6 Research Gaps ............................................................................................................................... 31
  6.1 Coexistence ............................................................................................................................ 31
  6.2 Edge Computing ....................................................................................................................... 32
  6.3 Misbehavior Detection and Mitigation ...................................................................................... 32
    6.3.1 Vehicle-based Detection .................................................................................................... 32
    6.3.2 Infrastructure-based Detection .......................................................................................... 32
    6.3.3 Trust-based System ............................................................................................................ 32

7 Conclusions and Recommendations ............................................................................................ 33

Appendix A – 3GPP Overview and Standards Setting Process ..................................................... A-1
List of Figures
Figure 1. Example of a Basic Safety Message in a Hard-Braking Event Scenario ............................................. 3
Figure 2. An Example of a Traffic Queue and Q-WARN System ........................................................................ 4
Figure 3. Depiction of a Reduced Speed Zone Warning .................................................................................. 5
Figure 4. Cooperative Vehicle-Infrastructure Situational Awareness .............................................................. 6
Figure 5. Integrated Corridor Management System Showing Traffic Diversions onto Alternate Routes in Response to an Accident on the Freeway ............................................................... 7
Figure 6. Examples of DSRC OBU (left) and RSU (right) .................................................................................. 9
Figure 7: Reference DSRC Architecture ........................................................................................................... 10
Figure 8. C-V2X Communication Over PC5 (top) in coverage (bottom) out of coverage .............................. 12
Figure 9. PC5 Out-of-Coverage Sample Scenario .............................................................................................. 13
Figure 10: C-V2X Communication Over LTE Uu Interface ................................................................................ 14
Figure 11: Multicast vs. Broadcast vs. Unicast ................................................................................................. 14
Figure 12. OSI Model Layers ............................................................................................................................ 20
Figure 13. SAE V2X Communications Steering Committee Overview ........................................................... 21
Figure 14. Proposed 3GPP Release Timeline .................................................................................................... 28
Figure 15. Alternative 3GPP Release Timeline .................................................................................................. 29
Figure 16. Hypothetical Coexistence Between LTE C-V2X and NR-V2X ......................................................... 29

List of Tables
Table 1: 5G Targeted Performance Values ........................................................................................................... 16
Table 2. 802.11 NGV Physical Layer Compatibility Suggestion ........................................................................... 17
Table 3. Comparison of Primary V2X Technologies ...................................................................................... 18
Table 4: SAE V2X Standards and Recommended Practices .............................................................................. 22
Table 5. Sample DSRC Minimum Performance Requirements from SAE J2945/1 for DSRC OBUs ............ 23
Table 6. DSRC Spectrum ..................................................................................................................................... 24
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
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<tr>
<td>4G LTE</td>
<td>4th Generation Long-term Evolution</td>
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<td>5G</td>
<td>5th Generation Wireless</td>
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<td>5G Automotive Association</td>
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<td>5G- NR</td>
<td>5th Generation New Radio</td>
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<td>AERIS</td>
<td>Application for the Environment: Real-time Information System</td>
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<td>Advanced Traffic Management System</td>
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<td>Basic Safety Message</td>
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<td>Channel Busy Percentage</td>
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<td>Dedicated Short Range Communications</td>
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<td>DSS</td>
<td>Decision Support System</td>
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<td>EC</td>
<td>European Commission</td>
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<td>EEBL</td>
<td>Emergency Electronic Brake Lights</td>
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<td>eNB</td>
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<td>E-UTRAN</td>
<td>Evolved Universal Terrestrial Radio Access Network</td>
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<td>EVA</td>
<td>Emergency Vehicle Alert</td>
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<td>FCC</td>
<td>Federal Communications Commission</td>
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<td>Forward Collision Warning</td>
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<td>FTP</td>
<td>File Transfer Protocol</td>
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<td>Greenhouse Gas</td>
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<td>HTTP</td>
<td>HyperText Transfer Protocol</td>
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<td>Host Vehicle</td>
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<td>Integrated Corridor Management System</td>
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<td>ICT</td>
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<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<td>IOO</td>
<td>Infrastructure Owner and Operator</td>
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<td>IP</td>
<td>Internet Protocol</td>
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<td>IPv6</td>
<td>IP version six</td>
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<tr>
<td>ISED</td>
<td>Innovation, Science and Economic Development</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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<td>ITS</td>
<td>Intelligent Transportation System</td>
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<td>ITSS</td>
<td>Intelligent Transportation Systems Society</td>
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<td>LED</td>
<td>Light Emitting Diode</td>
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<td>Abbreviation</td>
<td>Description</td>
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<td>LiFi</td>
<td>Light Fidelity</td>
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<td>LLC</td>
<td>Logic Link Control</td>
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<td>LTE</td>
<td>Long Term Evolution</td>
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<td>MAC</td>
<td>Medium Access Control</td>
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<td>MAP</td>
<td>Map Data Message</td>
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<td>MBMS</td>
<td>Multimedia Broadcast / Multicast Service</td>
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<td>NYCDOT</td>
<td>New York City Department of Transportation</td>
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<tr>
<td>OBU</td>
<td>On-board Unit</td>
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<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>OFDM</td>
<td>Orthogonal Frequency-division Multiplexing</td>
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<tr>
<td>O&amp;M</td>
<td>Operations and Maintenance</td>
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<tr>
<td>OSI</td>
<td>Open Systems Interconnection</td>
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<tr>
<td>PER</td>
<td>Packet Error Rate</td>
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<tr>
<td>PRESTO</td>
<td>Preemption and Prioritization Signal Systems for Emergency and Public Transport Vehicles</td>
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<td>ProSe</td>
<td>Proximity-based Services</td>
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<tr>
<td>RAN</td>
<td>Radio Access Network</td>
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<td>RFIC</td>
<td>Radio Frequency Integrated Circuit</td>
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<tr>
<td>RP</td>
<td>Radiated Power</td>
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<tr>
<td>RSU</td>
<td>Road-Side Unit</td>
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<tr>
<td>RV</td>
<td>Remote Vehicle</td>
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<td>SAE</td>
<td>Society of Automotive Engineers</td>
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<tr>
<td>SC-FDMA</td>
<td>Single Carrier Frequency-Division Multiple Access</td>
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<tr>
<td>SCH</td>
<td>Service Channel</td>
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<tr>
<td>SDO</td>
<td>Standards Development Organization</td>
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<tr>
<td>SIM</td>
<td>Subscriber identity Module</td>
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<tr>
<td>SPaT</td>
<td>Signal Phase and Timing</td>
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<td>SRM</td>
<td>Signal Response Message</td>
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<td>SSM</td>
<td>Signal Status Message</td>
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<tr>
<td>TC</td>
<td>Technical Committee</td>
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<tr>
<td>THEA</td>
<td>Tampa Hillsborough Expressway Authority</td>
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<tr>
<td>TIM</td>
<td>Traveler Information Message</td>
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<tr>
<td>TMC</td>
<td>Transportation Management Center</td>
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<tr>
<td>UICC</td>
<td>Universal Integrated Circuit Card</td>
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<tr>
<td>UE</td>
<td>User Equipment</td>
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<tr>
<td>USDOT</td>
<td>United States Department of Transportation</td>
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<tr>
<td>Uu</td>
<td>UTRAN to User Equipment Interface</td>
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<tr>
<td>V2I</td>
<td>Vehicle-to-Infrastructure</td>
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<tr>
<td>V2N</td>
<td>Vehicle-to-Network</td>
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<td>V2P</td>
<td>Vehicle-to-Pedestrian</td>
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<td>V2X</td>
<td>Vehicle-to-Everything</td>
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<td>V2V</td>
<td>Vehicle-to-Vehicle</td>
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<td>VLC</td>
<td>Visual Light Communication</td>
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<td>VRU</td>
<td>Vulnerable Road User</td>
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<td>VTS</td>
<td>Vehicular Technology Society</td>
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<td>WAVE</td>
<td>Wireless Access in Vehicular Environments</td>
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<td>WIP</td>
<td>Work in Progress</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>WSM</td>
<td>WAVE Short Message</td>
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<tr>
<td>WSMP</td>
<td>WAVE Short Message Protocol</td>
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<tr>
<td>WYDOT</td>
<td>Wyoming Department of Transportation</td>
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1 Introduction

The transportation sector is undergoing a period of transformative change as a result of increased connectivity and automation. On-road Connected Vehicle (CV) and Automated Vehicle (AV) systems are creating new possibilities within the road transportation sector. They have the potential to reduce greenhouse gas (GHG) emissions and fuel consumption; improve safety and security; enhance efficiency, mobility, and accessibility; and foster economic opportunities for advanced clean technology jobs and investments in Canada.

Canada’s road transportation system will be increasingly reliant on Information and Communications Technologies (ICT), to provide safety and mobility benefits to road users. The integration of these vehicular communication technologies into the on-road transportation domain is creating new demands on regulators at all levels of government to find practical and efficient spectrum management and policy models that ensure the consistent and reliable uptake and deployment of these new and emerging technologies.

Substantial research and development have been undertaken to develop Dedicated Short-Range Communication (DSRC) for CVs. The high frequency broadcast protocol was originally envisioned to facilitate safety applications such as red-light violation warning, forward-collision warning, pedestrian in the crosswalk warning and others. Data was transmitted as quickly as possible to reduce unnecessary latency.

Over the last few years, the ICT sector has been developing an alternative solution called cellular vehicle-to-everything (C-V2X). “As part of the 3rd Generation Partnership Project (3GPP) Release 14, C-V2X defines two transmission modes that, together, enable a broad range of use cases. Direct C-V2X, which includes vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P), provides enhanced communication range and reliability in dedicated intelligent transportation system (ITS) 5.9 GHz spectrum that’s independent of a cellular network, as well as network communications (V2N) in traditional mobile broadband licensed spectrum.”[1] In the proposed work, C-V2X refers to 3GPP Release 14.

Finally, 5G or fifth generation wireless technology standards are currently being developed, with equipment expected to be deployed by 2020. “5G brings three new aspects to the table: greater speed (to move more data), lower latency (to be more responsive), and the ability to connect a lot more devices at once (for sensors and smart devices).”[1] The ICT sector sees great potential for 5G technology to be used for vehicle connectivity. In the proposed work, 5G refers to 3GPP Release 16.

This report provides a review of the recent technical literature and summarizes the state of the art in DSRC, C-V2X and other relevant, anticipated transportation communications technologies. It also provides an overview of relevant standards development and potential research gaps and

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1 https://www.abijita.com/5g-everything-need-know-5g/
opportunities. While the intended audience is infrastructure owners and operators (IOOs), the report includes discussion of vehicular equipment as well as roadside equipment.

2 Sample Transportation Use Cases for V2X

Wireless communication technology can play an important role in improving safety and mobility for the broad transportation network, spanning V2V, V2I, and V2P applications, as well as advanced applications that may supplement or go beyond safety and mobility applications. This section provides concise descriptions of a few sample use cases.

2.1 Applications for Smart Transport

There are a wide variety of applications that a Smart City can utilize to enable Smart Transport. These range from safety applications that allow vehicles to communicate with other vehicles and infrastructure to environmental and mobility applications such as transit signal priority. These applications also range in complexity and maturity. Some applications have only been identified and defined. Others have been deployed, tested, and refined. The following sections provide an overview of some example Smart Transport applications that a Smart City can leverage.

2.2 Emergency Electronic Brake Lights (EEBL)

The EEBL application is a prime example of why Vehicle-to-Everything (V2X) communication is critical to realizing safety benefits. When a vehicle experiences a hard-braking event (> 0.4G deceleration), it will transmit a Basic Safety Message (BSM) to nearby vehicles and infrastructure with an event flag set that indicates the presence of the hard-braking event. This allows surrounding vehicles to detect a hard-braking scenario from a vehicle that cannot be “seen” directly using onboard sensors. An EEBL scenario is depicted in Figure 1, where the blue car ahead of the bus is quickly decelerating and transmitting a BSM with a hard-braking event flag set to all vehicles. The white car cannot directly “see” the blue car’s context or braking event due to occlusion by the intervening bus.

While this may seem purely like a V2V communication scenario on the surface, it is quite important to a Smart City. With properly placed infrastructure to communicate with these Connected Vehicles, cities will be able to also receive the BSMs and monitor the data for detecting and responding to incidents as well as determining areas in which hard-braking events are common and performing root cause analysis to possibly improve both the digital and physical infrastructure assets.
2.3 Queue Warning (Q-WARN)

Once a Smart City has deployed Roadside Units (RSUs) in strategic locations, it can then use its communication backbone to notify upstream traffic of downstream hazards, or traffic queues. An example of a traffic queue is shown in Figure 2 where slow or stopped vehicles (label 1) have queued up ahead due to some external problem. In the figure, RSUs aggregate slowed vehicle positions and provide context information to approaching vehicles (label 2).

This queue can be detected via several mechanisms including the BSMs that are transmitted from the vehicles and infrastructure-based sensing such as radar or cameras. A combination of these mechanisms provides a more robust queue detection mechanism which can reduce false positives. The warning of the upcoming queue can also be accomplished using a variety of communication mechanisms such as DSRC, C-V2X, and/or 4th generation wireless telephony (4G LTE).
2.4 Reduced Speed Work Zone Warning (RSWZ)

Construction is a reality for even the smartest of Smart Cities. Cities are constantly trying to maintain and repair their roadways while simultaneously trying to keep traffic moving. Work zones are difficult for AVs to navigate as the vehicles often depend on high definition maps to localize and navigate, and these maps are not updated at a frequency that would accurately reflect the work zone which can change frequently.

This is a great example of how a Smart City can help to enable AVs that are not able to sufficiently deal with work zones. As part of a city’s digital infrastructure, up-to-date maps can be transmitted to vehicles approaching a work zone to let it know about speed limit changes, lanes that are closed and the appropriate route to take to navigate the work zone. An example of a construction zone with RSWZ is shown in Figure 3. In the figure, the RSU broadcasts reduced speed warning signals to approaching cars.

Maintaining up-to-date maps of work zones is not an easy task. This is also an opportunity for communications infrastructure to play an important role in monitoring traffic flow and communicating this information to upstream vehicles. This can help with work zones that are changing frequently or are very short lived, but it can also help with situations such as temporary obstacles in the roadway that vehicles are slowing down and going around to avoid.
2.5 Cooperative Situational Awareness

Breakthroughs over the last decade in the areas of deep learning and increased computational capabilities have led to a transition of intelligence in ITS to the edge. The deployment of intelligent situational awareness hubs at key intersections allows vehicles to see pedestrians that are not detectable with sensors and to see around corners. This also allows complex computation to take place immediately where the data is received at the roadside and then information extracted from that data is exchanged with a traffic management center (TMC). This is in stark contrast to the
traditional means of bringing all data back to the TMC and then dealing with it there. This capability can enable cooperative situational awareness for all users at the edge whether it is pedestrians, bicyclists, or vehicles. Figure 4 provides a descriptive perspective of cooperative situational awareness in a metropolitan area. In the figure, a situational awareness system located in/near a busy intersection aggregates information from cars, pedestrians, buses, and other transportation systems and communicates useful situational context to user systems.

![Cooperative Vehicle-Infrastructure Situational Awareness](image)

*Figure 4. Cooperative Vehicle-Infrastructure Situational Awareness.*

### 2.6 Integrated Corridor Management Systems

As ITS deployments become more mature and widespread, there is a growing need to augment these systems with Decision Support Systems that regions can use to optimize the transportation network across modes. This capability is called Integrated Corridor Management Systems (ICMS) and is the wave of the future for Smart Transportation.

An ICMS collects data from a variety of public and private sector sources along a corridor, uses advanced modeling to predict the future state of the corridor if various actions are taken, and then takes the best course of action to optimize the flow of travelers along that corridor. Figure 5 provides an example of an ICMS in action. In the figure, accident detection and lane closures are used to redirect incoming traffic to alternate routes via connected-vehicle broadcast messages.

For example, consider the case shown in the following image in which a major accident has occurred on the freeway and traffic begins to back up significantly along the corridor. In an ICMS, the decision support system (DSS) will monitor the flow of traffic along the freeway and arterials,
predict the future state of various potential scenarios (including rerouting traffic along arterials), then implement the best course of action. In this case the DSS routes traffic along the arterials while interfacing with the arterial signal systems to optimize the signal timing to allow the most traffic to flow along those arterials.

![Integrated Corridor Management System](image)

**Figure 5. Integrated Corridor Management System Showing Traffic Diversions onto Alternate Routes in Response to an Accident on the Freeway.**

Following the event, the DSS can compare the impacts of the implemented response plan with the predicted impact. Machine Learning techniques along with traffic engineering expertise can be utilized to tweak the capabilities of the system such that there is continual improvement in the ICMS in response to future events. This capability can be extended across many other modes including rail and buses.

### 2.7 Powertrain Optimization

The applications discussed so far illustrate the ability of Smart Transport technology to improve safety and mobility of travelers throughout the transportation network, but what about environmental impacts and fuel efficiency? There is a growing amount of research into this very question and it leverages the early work of the Applications for the Environment: Real-Time Information Synthesis (AERIS) program along with other US Department of Transportation (USDOT) initiatives. The Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-e) has initiated a $30M program investigating various techniques that would combine to enable connected-automated vehicles (CAVs) to achieve at least a 20% fuel efficiency gain by optimizing the powertrain based on Connected Vehicle data. Imagine if your vehicle could get a preview of the traffic flow ahead and then optimize its powertrain accordingly. For example, the vehicle could more intelligently traverse a corridor based on the signal timing and other surrounding vehicles.
Another example is the ability to optimize the power split in hybrid engines to utilize more battery and less fuel.

This capability is generating a lot of excitement not only in the passenger vehicle market but also heavy-duty vehicles. Large trucks and busses consume a significant amount of fuel and even a small savings can reduce their CO2 emissions while simultaneously saving them significant amounts of money. Fuel is often the largest operations and maintenance (O&M) cost for a fleet operator.

3 Survey of Relevant Technologies

3.1 DSRC

DSRC is a two-way short-to-medium range wireless communication capability that is based on IEEE 802.11p wireless technology. It permits very high data transmission (up to 27 Mbps)\(^2\) at low latencies (less than 1 ms)\(^3\) critical in communications-based active safety applications. DSRC technology is deployed on vehicles as on-board units (OBUs) and as part of the roadway infrastructure as roadside units (RSUs), examples of which are shown in Figure 6. RSUs can use existing roadway infrastructure, including traffic lights, traffic signal controllers (which create SPaT data) and traffic signs, and be collocated with these devices. Many CV deployments utilizing this configuration are underway or getting underway, and while more testing and data analysis may be required no significant interference or other ill effects have been observed from this integration and collocation.

In 1999, the Federal Communications Commission (FCC) first set aside 75Mhz of spectrum in the 5.9 GHz band for DSRC use by ITS vehicle safety and mobility applications. The Innovation, Science and Economic Development (ISED) Canada followed suit in 2004 with a moratorium on non-DSRC systems operating in the same band in 2006. Then in 2008, the European Commission (EC) made the decision to set aside 30 MHz in the 5.9GHz band for ‘smart’ vehicle communications systems.

DSRC has since been developed and tested in several pilot programs and numerous state department of transportation (DOT) test beds, gaining a lot of V2X support from USDOT due to its low-latency and high-reliability performance (low packet error rate [PER]) that can be used to reduce fatalities through active safety applications, including collision avoidance, incident reporting and management, emergency response, and pedestrian safety. Low latency, on the order of a few milliseconds, is essential for safety-critical applications. DSRC technology is the only low-latency method available today (enabled by a smaller transmission time slot than other technologies). Furthermore, DSRC supports the close-range communication requirements to send vehicle BSMs to other vehicles or the infrastructure, and to distribute Traffic Signal Phase and Timing (SPaT)

\(^2\) https://www.sciencedirect.com/science/article/pii/S1877042813023628
\(^3\) https://ecfsapi.fcc.gov/file/7020920832.pdf
 Automakers are developing safety and mobility applications using DSRC.

Each DSRC device manufacturer normally creates their own custom units with varying components, but the system architecture and components for each OBU/RSU is essentially the same (see the major components of a DSRC device in Figure 7) with some variance on the standard interfaces (e.g., Ethernet, USB, Wi-Fi, CAN). OBU and RSU performance at face value is very comparable; however, antenna configuration may affect performance, and installation location (elevated antenna mounting) may increase range and coverage for RSUs (depending on line-of-sight). Some OBUs and RSUs come with dual 802.11p modems allowing for communications to operate across more channels. This requires larger units with additional antennas to be used. While nothing is standardized, there is motivation to use one antenna (or two antennas on dual-modem units) for safety data and the other antenna(s) for control and other channel data. DSRC only uses an orthogonal frequency-division multiplexing (OFDM) modulation scheme across a 10 MHz channel for communication. More discussion on OFDM can be found later in the report.
A number of states in the US have active DSRC deployments or are in the process of deploying DSRC equipment, including Michigan, Utah, Arizona, Georgia, Texas, and Florida, among many others. Several automotive original equipment manufacturers (OEMs) have already integrated DSRC (General Motors) or plan on integrating DSRC into future model light-duty vehicles (Toyota).

### 3.1.1 Security

The Security Credential Management System (SCMS) is a proof-of-concept security solution for V2V and V2I messaging. A Public Key Infrastructure (PKI) approach is used that includes encryption and certificate management to attempt to ensure trust. Digital certificates are loaded on DSRC devices and changed periodically (e.g., based on distance driven [2 km] or timeout [5 min] for OBUs). The intended benefits of the SCMS include:

- Integrity – maintain trust between transmission and reception
- Authenticity – trust that source is trustworthy
- Privacy – trust that message protects identify
- Aid with Interoperability – differing vehicles can exchange trusted information without pre-agreement

Several projects are underway to deploy and study the efficacy of the SCMS.

### 3.1.2 Risks

Several risks associated with DSRC deployments include:
• Interoperability – Standards are still evolving and deployments using devices that conform to the latest versions will likely not interoperate with devices that do not. Implementation differences are also proving to cause difficulties for interoperability. These evolving standards mainly apply to the internal radio architecture and performance, and therefore would not likely affect external connections or interfaces (e.g., power, ethernet, USB, CAN, etc.)

• Bad actors / Misbehavior – Inaccurate data contained in CV messages could lead to false-positives or false-negatives in safety or mobility applications. These inaccuracies could be intentional or unintentional, but the results may be the same.

Protection of ITS spectrum – The 5.9 GHz band was set aside for safety-critical transportation applications over 20 years ago. The uncertainty and risk associated with unlicensed devices potentially gaining access to this band could present significant challenges to realizing the full benefits of DSRC.

3.2 C-V2X

Cellular vehicle-to-everything (C-V2X) follows the 3GPP set of standards which governs the two interfaces for V2X communication. In the telecommunication communities they refer to OBUs, RSUs and hand-held devices as user equipment (UE). Radio access networks (RAN) that support 4G-LTE communications are called evolved universal RAN (E-UTRAN). E-UTRAN contain hardware called evolved node B (eNB) that is used to connect the UE to rest of the cell network. In normal LTE communications, the eNB uses OFDMA in the downlink (network infrastructure to device) while single-carrier frequency-division multiple access (SC-FDMA) is used in the uplink (device to network infrastructure). C-V2X will use SC-FDMA, which offers similar capacity with better power efficiency\(^4\), in both directions. It is likely that most RSUs that support C-V2X will be independently owned and operated, but E-UTRAN will remain in the hands of the mobile service providers. Questions then arise as to who will install and maintain cell-based RSUs, and how will they be integrated into the network. With DSRC deployments, IOOs are procuring, installing, and maintaining the RSUs and integrating them into their own network backhauls. If this same model is used with C-V2X devices, the IOOs will then need to work and collaborate with the mobile service providers to integrate the devices into the appropriate networks. Alternatively, the mobile service providers may offer to install and maintain RSUs if given access to IOO-managed easements and right-of-way. This has further implications in terms of IOOs being beholden to when and where the providers choose to deploy the equipment as well as potential financial implications for IOOs getting relevant transportation data onto (e.g., traveler information messages [TIMs]) or off of (e.g., BSMs) the devices and network.

3.2.1 PC5

The PC5 interface (also known as sidelink) supported by C-V2X works when both UE are within communication range of each other by providing direct communication independent of a cellular network. This interface is useful for transmitting and receiving relevant, localized safety and

\(^4\) [https://pdfs.semanticscholar.org/8a4b/dca78313580049a3adae6ecedacf4c9c55aa.pdf](https://pdfs.semanticscholar.org/8a4b/dca78313580049a3adae6ecedacf4c9c55aa.pdf)
mobility information. Communication occurs directly between equipped vehicles, roadside infrastructure, and potentially vulnerable road users such as pedestrians. There are two methods of scheduling that is uses depending if both the UE are being served by the same evolved E-UTRAN. During PC5 communication, one of the UE acts as the eNB. Communication over PC5 works if the UE are both in or out of range of E-UTRAN, as shown in Figure 8. If one or both are not within range of an E-UTRAN (out of coverage), as shown in the bottom of Figure 8 as well as in Figure 9, then the UE can only use its autonomous resources selection mode (asynchronous scheduling/distributed scheduling). Figure 9 further shows how communications range between OBUs can be extended by an RSU, similarly to a DSRC network. The scenario shown in Figure 9 has the data routed through a backhaul to a server and then back out to roadside equipment; however, the routing through the backhaul network is not absolutely necessary as the data could simply be routed through the RSU to other OBUs within range. The autonomous resource selection mode is a piece of firmware on the radio MAC and PHY layer that senses what portion of a channel is being used or planned on being used and reserves what is needed and available. If they’re both in coverage of an E-UTRAN then the UE has the option of using its network scheduled operation mode (synchronous scheduling/centralized scheduling) over the autonomous resource selection mode. The PC5 interface supports unicast messages of both internet protocol (IP) and non-IP based packets. IP-based packets are tied to a source and destination address(es), while non-IP-based packets do not have specific destinations, but rather are meant for broadcast.

Figure 8. C-V2X Communication Over PC5 (top) in coverage (bottom) out of coverage.
PC5 communications are subject to regional regulatory requirements and the user agreement for the V2X application. The information contained in the data sent over the PC5 interface should not contain any information that can be used to identity or track the OBU beyond the required amount of time by the application. Pseudonymity should be used to conceal the true identities from potential eavesdroppers and attackers. The source IP address and Layer2-ID should change whenever the vehicle identity in the application layer changes to protect the user’s identity. Receivers of message sent over the PC5 interface are not always known in advance of the transmitting vehicle due to the lack of network assistance and are therefore not supported current LTE or Proximity-based service (ProSe) security, which is described in Section 3.2.3. Instead, application-layer security covered by other standards organizations will be implemented (e.g., IEEE1609.2, ETSI TS 102 940). It also only operates on the 5.9 GHz ITS band.

### 3.2.2 LTE-Uu

When a vehicle is inside network coverage it can also send its messages over the LTE-Uu interface to a server that can be used to deliver the messages to the target devices via unicast or multimedia broadcast/multicast service (MBMS) during the downlink, as seen in Figure 1110. This allows OBUs to communicate with each other even when they are not in direct communication range. LTE-Uu only supports IP based messages but can operate in several different bands (e.g., @900 MHz, @1.8GHz, @1.9GHz, @2.5GHz or @2.6GHz). Non-IP based messages (i.e., SAE J2735) will have to be encapsulated in an IP header to communicate over the LTE-Uu interface. LTE-Uu will require a mobile provider subscription to connect to the E-UTRAN.
3.2.3 Security

Communication over the LTE-Uu interface use a security mechanism, referred to as ProSe, for confidentiality outlined in 3GPP TS 23.303, 33.303, 33.401 and 33.402. A UE being serviced by an E-UTRAN sends a discovery request message to the ProSe function of the public land model network (PLMN). The PLMN then returns a discovery key to the UE if the application code in the discovery request message passed authentication. The UE stores the discovery key along with the application code and a current time parameter provided by the ProSe function. The UE then starts announcing messages with a message integrity check (MIC) which is calculated using the discovery key and the current time. These messages are then cast over the PLMN or PC5 if monitoring UE is being serviced.
by the same E-UTRAN. Once the monitoring UE receives the messages from either the PC5 or LTE-Uu interface it checks the MIC by sending a match report message containing the MIC to the ProSe function in the PLMN if it has not already done so previously. The PLMN then verifies the MIC in the transmitted messages and sends back an acknowledgment report to the monitoring UE if the MIC passed the integrity check. The SCMS could theoretically be used for PCS and LTE-Uu wireless communication security; however, it is unlikely that the SCMS would be used for the 4G LTE core network backhaul.

3.2.4 Risks

One of the biggest known risks involved with LTE-Uu security is the possibility of fake E-UTRAN (i.e., a “rogue base station”) forcing UE to connect to them instead of the official E-UTRAN which can prevent UE from communicating to each other because of the lack of security verification, track the UE and intercept the communications. There are even companies that designed and sell hardware that act as rogue eNB for law enforcement to use in their investigations.

SIM swappers use social engineering to convince telecommunications customer service representatives to switch out people’s SIM information to gain control of that person phone number. Once they have use of the victim’s phone number they can then request that their victims’ email be reset using the authentication code provided to their phone if the email is link to the phone number. From there the SIM swapper can then request that the victims other online accounts tied to that email also be reset giving them full control of that person’s online persona. If someone swaps out their own SIM information connected their vehicle with their someone else’s and then use the vehicle in a crime, could they potentially frame their victim for a crime?

Telecommunications companies plan on using C-V2X technologies for other things besides safety applications. They would like it to be used to provide entertainment for the driver and passengers in the vehicle. This will cause the C-V2X radio to have less resources available to handle the safety critical messages coming from the PC5 and LTE-Uu interfaces. Making it decide which ones have priority.

3.3 5G New Radio (5G NR)

First introduced in 3GPP Release 15, 5G promises to support most of the services currently being used by the previous generation while also improving the latency and throughput of current services. Table 1 list some targeted performances for UE inside of vehicles but they’re currently aren’t requirements for 5G V2X communication. There will be two different architectures that 5G supports. The first is a stand-alone where the NR is connected to the 5G core network allowing all the services it offers. The second architecture is the non-stand-alone version which is when the NR is connected to a 4G core network instead of a 5G core network. This allows the 4G network to

5 3GPP TS 22.261: “Service Requirements for the 5G System”
offer its services using the LTE-Uu interface at 5G over-the-air speeds. 5G will also support OFDM in the uplink meaning that there is a possibility that 5G will be interoperable with DSRC. 5G will have the same security and privacy requirements of 4G.

**Table 1: 5G Targeted Performance Values.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>120</td>
<td>20</td>
<td>50</td>
<td>25</td>
<td>100</td>
<td>50</td>
<td>10,000</td>
</tr>
<tr>
<td>Rural</td>
<td>120</td>
<td>20</td>
<td>50</td>
<td>25</td>
<td>1</td>
<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>Highway</td>
<td>250</td>
<td>50</td>
<td>50</td>
<td>25</td>
<td>100</td>
<td>50</td>
<td>4,000</td>
</tr>
</tbody>
</table>

### 3.4 IEEE Next Generation V2X (NGV)

IEEE 802.11p has been shown to be fairly mature and reliable for DSRC-based CV environments, although more work and testing are to be done. Even considering this maturity, technical advances for some of the underlying layers (i.e., evolution of PHY and MAC layers from technologies such as low-density parity-check [LDPC] code allowing transmission of messages over a noisy transmission channel and space-time block codes [STBC] to avoid interference) have led to a call to adopt these advances for 802.11-based V2X equipment and applications. The adoption of these new technologies targets new V2X applications that require higher throughput, better reliability and efficiency, and extended range. The study group also collected input to identify several use cases for the new radio technology:

- **BSM – NGV** could increase range (target of 25% increase over 802.11p for urban intersections)
- **Sensor Sharing – NGV** could carry higher number (target greater than 50% increase) of transmitted packets
- **Multi-channel Operation – NGV** would set up one safety channel and a second non-safety channel (non-safety channel may impact driving decisions [e.g., platooning] and/or may only receive V2I data)
- **Infrastructure Applications – NGV** could support high amount of data (e.g., for high-definition maps for AVs)
- **Vehicular Positioning and Location – NGV** could support positioning of a vehicle with respect to other road users and/or support positioning of a vehicle in locations with limited or absent GPS coverage.

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6 [https://mentor.ieee.org/802.11/dcn/18/11-18-1323-02-0ngv-ngv-5g-use-cases.pptx](https://mentor.ieee.org/802.11/dcn/18/11-18-1323-02-0ngv-ngv-5g-use-cases.pptx)
• Automated Driving Assistance – NGV could support coordinated maneuvers between AVs
• Aerial Vehicle ITS Applications – NGV could provide line of sight communications to allow aerial vehicle to provide roadway safety monitoring
• Train-to-Train – NGV could provide data connectivity for collision avoidance, remote control, and viral coupling (platooning), among other applications
• Vehicle-to-Train – NGV could provide real-time data between trains and vehicles in shared space (light rail adjacent/collocated to public roads)

Another major discussion topic within the study group has been backwards compatibility with 802.11p. This would be incredibly important for 802.11-based CV early adopters to avoid their CV systems becoming obsolete and to ensure that all their road users enjoy the safety and mobility benefits. The study group has suggested modifications to the channel configuration in the current 5.9 GHz band to attempt to maintain compatibility. Table 2 shows this suggested reconfiguration.

### Table 2. 802.11 NGV Physical Layer Compatibility Suggestion.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Use-case</th>
<th>Candidate channels</th>
<th>Method of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legacy</td>
<td>Channel is used; Existing broadcast services</td>
<td>172, 178</td>
<td>802.11p only</td>
</tr>
<tr>
<td>Greenfield</td>
<td>Channel is currently unused; Expecting new broadcast and unicast services</td>
<td>174, 180, 182</td>
<td>802.11ngv</td>
</tr>
<tr>
<td>Mixed</td>
<td>Channel is partially used; Existing broadcast services continue to use 802.11p; Unicast and new services will use 802.11ngv (with fallback option to 802.11p)</td>
<td>176</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: These are merely suggestions at this point and may change as new DSRC services may be introduced before NGV specifications are complete.

### 3.5 Visual Light Communication

Light fidelity (Li-Fi) is a nascent technology that connects devices by using light. Common light emitting diodes (LEDs) are used to transmit data at very high speeds (>200 Gbps claimed) to a photovoltaic collector. In general, Li-Fi requires line-of-sight and therefore cannot penetrate walls or other opaque barriers; however, tests have shown that beam reflection could still provide 70

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Mbps throughput. Companies such as Oledcomm\(^9\), WiSeKey\(^{10}\), and Philips\(^{11}\), among others, are now developing Li-Fi based technologies. Li-Fi is modeled off of IEEE 802.11 protocols, with IEEE task force 802.15.7 working on a draft standard.

In the automotive space, Li-Fi has been discussed for communication between vehicles via LED headlights and taillights\(^{12}\). In practice, this may make Li-Fi V2V feasible for communication with a vehicle immediately in front and a vehicle immediately behind\(^{13}\), whereas other technologies can typically broadcast data further upstream or downstream. Li-Fi also has the likely drawback of being impacted by environmental and weather conditions (e.g., rain, snow, fog, smoke, etc.).

### 3.6 Comparison

Table 3 shows a comparison of some of the features and key performance indicators for the primary V2X technologies discussed in this section. Note these comparisons are being made for operation (or theoretical operation) within the 5.9 GHz band (next generation technologies may operate outside of this band as well [e.g., 5G NR may also operate in the 50-60 GHz band]).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>DSRC</th>
<th>C-V2X</th>
<th>802.11 NR</th>
<th>5G-NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiplexing</td>
<td>TDM</td>
<td>TDM/FDM</td>
<td>?</td>
<td>TDM/FDM(^{14})</td>
</tr>
<tr>
<td>Latency [ms]</td>
<td>1 – 20 (max)</td>
<td>20 – 100 (max)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Modulation</td>
<td>OFDMA</td>
<td>SC-FDMA</td>
<td>OFDMA</td>
<td>OFDMA/SC-FDMA</td>
</tr>
<tr>
<td>Security</td>
<td>Public Key Cryptography and Infrastructure</td>
<td>?(^{15})</td>
<td>?(^{15})</td>
<td></td>
</tr>
</tbody>
</table>
## 4 Standards Development Activities

This section describes works conducted by several standards development organizations (SDOs) that are relevant to CV communications.

### 4.1 OSI Model

The Open Systems Interconnection (OSI) model\(^\text{23}\) seeks to standardize the communications-related functions of a telecommunication or computing system without considering the underlying technology. The model, shown in Figure 1211, does this by abstracting the communication system into seven layers:

- **Layer 1 – Physical Layer** – Manages transmission and reception of unstructured raw data between a device and a transmission medium (e.g., coaxial cable, ethernet cable, etc.). Converts digital bits into electrical, radio, or optical signals (or vice-versa).
- **Layer 2 – Data Link Layer** – Manages node-to-node transfer in a network. Divided into two sublayers:
  - Medium access control (MAC) layer – Manages how a device on a network gains access to the transmission medium and gains permission to transmit data.
  - Logical link control (LLC) layer – Manages identifying and wrapping network layer protocols.

\(^{16}\) This is requirement per standard, in practice range has been observed over 1000 m in line-of-sight field tests over flat terrain

\(^{17}\) Based on line-of-sight results from preliminary field tests.

\(^{18}\) Vehicle-to-tower (base station)

\(^{19}\) Application-dependent

\(^{20}\) Probably comparable to DSRC and C-V2X


\(^{22}\) NOTE: These are based on sample quotes for a single base radio and associated antennas (no integration or installation costs included) and should be considered notional examples.

• Layer 3 – Network Layer – Manages transfer of variable length data sequences (also known as data packets) from one node to another on different networks.

• Layer 4 – Transport Layer – Manages transferring data packets from a source to a destination host.

• Layer 5 – Session Layer – Manages connections between computing systems.

• Layer 6 – Presentation Layer – Manages mapping between application-layer entities.

• Layer 7 – Application Layer – Provides interface(s) to end-user (e.g., File Transfer Protocol [FTP], HyperText Transfer Protocol [HTTP], etc.)

The OSI model is referenced in several other areas of this report to describe connected vehicle technologies and standards.

4.2 SAE

SAE International is an international standard developing organization focusing on the transportation industry. Its membership is based on individuals instead of companies. Members normally fall under three different categories (Producer, User, General Interest). Each technical committee (TC) headed by a chair and vice-chair works on keeping a fair balance of voting members in their committee. Prior to 2019, there were two separate TC focusing on DSRC and C-V2X communication standards independently of each other, but they’ve since merged under one steering committee (See Figure 1312). Most of the old task forces that were under each of the old TC have become their own TC under the new steering committee. Task forces with overlapping focuses from the old TC have also merged to form their own TCs.
Under the new organizational structure there are nine TC which will focus on the following V2X aspects:

- **DSRC**: DSRC Radio access-specific items
- **C-V2X**: C-V2X Radio access-specific items
- **Advanced Applications**: Lower layer applications that may require new communication technologies
- **Security**: Over the air security
- **Cross-cutting**: Common to multiple applications or communication technologies
- **Infrastructure Applications**: Infrastructure application that do not require traffic signal data
- **Traffic Signal Applications**: Infrastructure applications that require traffic signal data or interface
- **Vehicular Applications**: Vehicle communication needs
- **Tolling Applications**: Applications for tolling and financial transactions

Each TC have released a standard, recommended industry practice or are currently developing such documentation. Table 4 lists all the current SAE Standards/Recommend Industry practices that each TC have approved or are still developing.
Table 4: SAE V2X Standards and Recommended Practices.

<table>
<thead>
<tr>
<th>TC</th>
<th>Document</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSRC</td>
<td>J2945/0: Dedicated Short-Range Communications (DSRC) Systems Engineering Process Guidance for SAE J2945/X Documents and Common Design Concepts</td>
</tr>
<tr>
<td>DSRC</td>
<td>J2945/1: On-Board System Requirements for V2V Safety Communications</td>
</tr>
<tr>
<td>C-V2X</td>
<td>J3161: On-Board System Requirements for LTE V2X V2V Safety Communications (WIP)</td>
</tr>
<tr>
<td>Advanced Applications</td>
<td>J3186: Maneuver Sharing and Coordinating Service (WIP)</td>
</tr>
<tr>
<td>Security</td>
<td>J2945/5: Service Specific Permissions and Security Guidelines for Connected Vehicle Applications (WIP)</td>
</tr>
<tr>
<td>Cross-Cutting</td>
<td>J2735: Dedicated Short-Range Communications (DSRC) Message Set Dictionary</td>
</tr>
<tr>
<td>Cross-Cutting</td>
<td>J2945/7: Positioning Enhancements for V2X Systems (WIP)</td>
</tr>
<tr>
<td>Infrastructure Applications</td>
<td>J2945/3: Requirements for V2I Weather Applications (WIP)</td>
</tr>
<tr>
<td>Infrastructure Applications</td>
<td>J2945/4: DSRC Messages for Traveler Information and Basic Information Delivery (WIP)</td>
</tr>
<tr>
<td>Infrastructure Applications</td>
<td>J2945/12: Traffic Probe Use and Operation (WIP)</td>
</tr>
<tr>
<td>Traffic Signal</td>
<td>J2945/10: Recommended Practices for MAP/Spat Message Development (WIP)</td>
</tr>
<tr>
<td>Vehicular Applications</td>
<td>J2945/2: Dedicated Short-Range Communication (DSRC) Performance Requirements for V2V Safety Awareness</td>
</tr>
<tr>
<td>Vehicular Applications</td>
<td>J2945/6: Performance Requirements for Cooperative Adaptive Cruise Control and Platooning (WIP)</td>
</tr>
<tr>
<td>Vehicular Applications:</td>
<td>J2945/8: Cooperative Perception System (WIP)</td>
</tr>
<tr>
<td>Vehicular Applications:</td>
<td>J2945/9: Vulnerable Road User Safety Message Minimum Performance Requirements</td>
</tr>
</tbody>
</table>

The SAE J2735 standard specifies a message set, and its corresponding data frames and data elements, specifically for use by applications intended to utilize the 5.9 GHz DSRC/WAVE communication systems. The usage of the messages and performance requirements are then specified in SAE J2945 standards. Some of the message sets which are critical to V2V and V2I applications include the BSM, SPaT, and the intersection geometry definition (MAP). The initial SAE J2735 standard was released in 2009 with the intent of supporting prototype deployments for testing and debugging, whereas the latest 2016 release is meant to be deployment ready and incorporates lessons learned from previous pilots and testbeds and international harmonization efforts, including standardization of both MAP and SPaT messages with European and Japanese pilots. The J2735 2016 standard is currently being implemented by the following USDOT-funded Pilot Deployments:
- New York City DOT (NYCDOT) CV Pilot
- Tampa-Hillsborough Expressway Authority (THEA) Pilot
- Wyoming DOT (WYDOT) Pilot

SAE J2945 DSRC performance requirements standards specify the use cases and DSRC requirements for the following applications:

- On-board V2V safety communications system for light vehicles
- V2V safety awareness
- Cooperative Adaptive Cruise Control (CACC) and Platooning
- Vulnerable Road User (VRU)

Some of the minimum performance requirements for DSRC OBUs from J2945/1 are listed below in Table 5 for safety-critical V2V applications. J3161 for C-V2X is under-development but is largely transposing the requirements for DSRC from J2945/1. There is not a formal standard that calls out performance requirements for DSRC RSUs; however, a high-level RSU specification has been developed that is leveraged by some deployments\(^{24}\).

Table 5. Sample DSRC Minimum Performance Requirements from SAE J2945/1\(^{25}\) for DSRC OBUs.

<table>
<thead>
<tr>
<th>Range [m]</th>
<th>Latency [ms]</th>
<th>Transmission Rate [Hz]</th>
<th>Packet Error Rate(^{26}) [%]</th>
<th>Data Rate [Mbps]</th>
<th>Horizontal Positional Accuracy(^{27}) [m]</th>
<th>Vertical Positional Accuracy(^{27}) [m]</th>
<th>Time Accuracy [ms]</th>
<th>Speed Accuracy(^{27}) [kph]</th>
<th>Heading Accuracy(^{27}) [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>100</td>
<td>10</td>
<td>&lt;10</td>
<td>6</td>
<td>1.5</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

4.3 IEEE

The Institute of Electrical and Electronics Engineers (IEEE) is an industry professional society that also maintains an active portfolio of over 1,200 published standards and works under development covering a broad range of topics. The primary relevant sponsoring committees within IEEE are the Intelligent Transportation Systems Society (ITSS\(^{28}\)) and Vehicular Technology Society (VTS\(^{29}\)). Some of the relevant working groups include:

- WG802.11 – Wireless LAN Working Group

\(^{24}\) [https://trid.trb.org/view/1477562](https://trid.trb.org/view/1477562)

\(^{25}\) J2945/1 targets OBU performance for V2V

\(^{26}\) With 400 octet PSDU length and receiver sensitivity input level is -92 dBm at 6 Mbps

\(^{27}\) Over 1-sigma of test measurements

\(^{28}\) [https://www.ieee-itss.org/](https://www.ieee-itss.org/)

Some of the relevant standards that have been published and are considered mature include:

- IEEE 802.11 – Medium Access Control and Physical Layers for Wireless Local Area Networks

DSRC is based on IEEE 802.11p standard at the physical layer for the WAVE protocol. DSRC is also based on IEEE 1609.2 Security Services, IEEE 1609.3 Networking Services, and 1609.4 Multi-channel operation standards, and integrates with SAE J2735 message set dictionaries, and SAE J2945 DSRC performance requirements. Figure 1211 shows how some of the DSRC related standards come together within the OSI communications stack.

The IEEE 802.11p standard establishes the rules for accessing and sharing the physical (PHY) layer and medium-access control (MAC) layer of wireless mediums to support ITS communication, including V2V and V2I, collectively termed V2X. 802.11p operates the 5.9 GHz frequency range using 75 MHz bandwidth (i.e., 5.850-5.925 GHz) which is half the bandwidth of 802.11a. DSRC bandwidth further subdivides the 75 MHz into seven 10 MHz bandwidth channels and one 5 MHz guard band. The seven channels comprise six service channels (SCHs) and one control channel (CCH). Two channels, 172 and 184, are reserved for safety applications and channel 178 is designed for control signaling. The remaining channels, 174, 176, 180, and 182, are reserved for non-safety applications. Some of the relevant information about the band is provided in Table 6.

IEEE launched a Next Generation V2X (NGV) study group in the spring of 2018 to work toward a new standard on 802.11 NGV, while attempting to maintain backward compatibility with 802.11p. The study group published Project Authorization Request (PAR) and Criteria for Standards Development (CSD) in late 2018. The PAR indicated a target date of submission of a draft of the proposed standard for initial sponsor ballot in September of 2020 and a projected completion date for submittal to standards review committee in September of 2021.

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>172</th>
<th>174</th>
<th>176</th>
<th>178</th>
<th>180</th>
<th>182</th>
<th>184</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>SCH</td>
<td>SCH</td>
<td>SCH</td>
<td>CCH</td>
<td>SCH</td>
<td>SCH</td>
<td>SCH</td>
</tr>
</tbody>
</table>

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30 https://mentor.ieee.org/802.11/dcn/18/11-18-0861-09-0ngv-ieee-802-11-ngv-sg-proposed-par.docx
31 https://mentor.ieee.org/802.11/dcn/18/11-18-0862-03-0ngv-ieee-802-11-ngv-sg-proposed-csd.docx
IEEE 1609.2 Security Services standard is utilized by DSRC for authentication of vehicle safety messages. The standard defines the process for creating a security envelope, which is additional data added by the security services when transforming it into a secured protocol data unit. This envelope includes data encryption, which uses a combination of symmetric and asymmetric cryptography so that it’s possible for a message to be both signed and encrypted. The secured envelope or message then becomes the payload of a 1609.3 WAVE Short message (WSM).

IEEE 1609.3 defines the services, operating at the layer 3 (networking) and layer 4 (transport) of the OSI communications stack, in support of wireless connectivity among vehicle-based devices, and between fixed roadside devices and vehicle-based devices using the 5.9 GHz WAVE Short Message Protocol (WSMP). Packets, sent using WSMP, are referred to as WSMs and contain the host vehicle’s location, speed, and vehicle type.

IEEE 1609.4 provides specifications standards regarding the MAC sublayer functions and services that support multi-channel wireless connectivity between WAVE devices without requiring knowledge of physical parameters. This standard describes the channel coordination required for WAVE devices to operate over multiple wireless channels, which is applicable when DSRC is operating in the U.S. 5.9 GHz band.

It is also useful to note that IEEE 1609.12 Identifier Allocations standard was released in late 2016 describing WAVE identifier allocations for the following:

- Provider service identifiers like Intelligent Transportation Systems Application Identifiers to identify services,
- Object identifiers for ASN.1 objects,
- EtherTypes for networking protocols,
- Organization identifiers to identify the organization responsible for the definition of the content of “vendor-specific” information,
- Management identifiers to distinguish among different WAVE management functions (i.e. WME, expansion code) that may send or receive management information.

### 4.4 ISO

The International Organization of Standardization (ISO) is an independent organization comprised of representatives from 163 national standards bodies that develops and publishes technical standards that cross geographical boundaries. The primary technical committee within ISO that
addresses needs related to transportation communication is Technical Committee 204 (TC 204\textsuperscript{32,33}) for ITS. TC 204 is comprised of 12 working groups focusing on various topics:

- WG 1 – Architecture
- WG 3 – ITS database technology
- WG 5 – Fee and toll collection
- WG 7 – General fleet management and commercial/freight
- WG 8 – Public transport/emergency
- WG 9 – Integrated transport information, management and control
- WG 10 – Traveler information systems
- WG 14 – Vehicle/roadway warning and control systems
- WG 16 – Communications
- WG 17 – Nomadic devices in ITS systems
- WG 18 – Cooperative systems
- WG 19 – Mobility integration

Some of the standards published by TC 204 that are relevant to infrastructure owners and operators include:

  - This standard defines the messages, data structures, and data elements to support periodic CV information exchanges. The information requirements are primarily focused on SPaT messages, MAP, signal status messages (SSMs), and signal response messages (SRMs).

  - This standard describes communications message sets and a data dictionary related to priority signal control information used by emergency vehicles.

- ITE/AASHTO TMDD Standard v3.03 – Center-to-Center (C2C) Communications
  - This standard provides a center-to-center concept of operations and requirements for an Advanced Traffic Management System (ATMS), as well as a design for an ATMS based on the requirements.

Some of the ISO standards that are related to CV leverage works from other SDOs (e.g., ISO/TS 19091 references messages from SAE J2735); however, there are no explicit changes made to

\textsuperscript{32} https://www.iso.org/committee/54706.html
message data structures or performance requirements that may contradict or overrule other standards.

Other potentially relevant standards that are in progress include:

- ISO/AWI TS 22726 – Dynamic data and map database specification for connected and automated driving system applications
- ISO/AWI TR 23254 – ITS – Architecture – Use cases and high-level reference architecture for connected, automated vehicles
- ISO/DIS 19082 – ITS – Definition of data elements and data frames between roadside modules and signal controllers for cooperative signal control

### 4.5 3GPP

The 3GPP is a collaborative group composed of seven partner organizations from Asia, Europe and North America that work on creating general standards (referred to as releases) for the telecommunication industry. Each of their releases references hundreds of technical specifications, requirements and reports detailing the various methods of cellular communication. C-V2X was first introduced in 3GPP Release 14\(^{34}\) in 2017. It outlined how both the PC5 and LTE-Uu operate along with some basic performance requirements for V2X communication.

Release-15\(^ {35}\) introduced some improvements to C-V2X along with support for the 5G-NR. Specifically, it introduced the first phase of the 5G NR, including 5G core network support (i.e., what will 5G core network do and what are its service requirements). While 5G-NR will hypothetically support all the same V2X safety applications that DSRC or C-V2X support or will support, Release-15 also detailed some performance requirements to support the following V2X use cases depending on the vehicle’s degree of automation\(^ {36}\):

1. **Vehicle Platooning:** Vehicles moving dynamically together in a group.
2. **Advanced Driving:** Semi-Automated or fully automated vehicles sharing states and intentions to coordinate their movements.
3. **Extended Sensors:** RSUs or OBUs sharing raw or analyzed data from sensors mounted along the road or vehicle respectively, providing users with more information about their surroundings.
4. **Remote Driving:** Having a remote driver or application operate a vehicle when the passenger or automated system is unable to do so.

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\(^ {34}\) 3GPP TR 21.914: “Summary of Rel-14 Work Items”

\(^ {35}\) 3GPP TR 21.915: “Summary of Rel-15 Work Items”

\(^ {36}\) 3GPP TS 22.186: “Enhancement of 3GPP Support for V2X Scenarios”
5 Technology Transition

5.1 C-V2X to 5G-NR

3GPP and other C-V2X/5G stakeholders have proposed several timelines for Release 15 and Release 16, examples of which are shown in Figure 14 and Figure 15. These timelines allude to 5G NR devices being commercially available in roughly the 2019 or 2020 timeframe. In the meantime, it appears development of LTE C-V2X will continue and devices will become more readily available.

5GAA makes claims about the ease of coexistence between LTE C-V2X and 5G-NR devices, as shown in Figure 15. The proposed 5G core network technology is planning on supporting all the 3GPP services up to Release 15, with the exception of some voice service continuity prior to 3G technology and video service from 4G technology. All C-V2X equipment that are compliant with 3GPP Release 14 and Release 15 should be compatible with 5G NR technology and later releases when 5G starts to support V2X services. Currently, there are no plans for 5G networks to develop their own V2X services outside of the ones currently offered by the 4G core network. Any 5G NR OBUs and RSUs should presumably be backwards compatible with C-V2X OBUs and RSUs. 5G NR is intended to operate within the 5 GHz band, as well as outside of the band (e.g., in the 50-60 GHz band). While promising, this remains hypothetical to a large degree until devices are available for testing.

![Figure 14. Proposed 3GPP Release Timeline](http://www.3gpp.org/specifications/releases)
Figure 15. Alternative 3GPP Release Timeline.  

Figure 16. Hypothetical Coexistence Between LTE C-V2X and NR-V2X. 

38 https://www.qualcomm.com/media/documents/files/5g-nr-based-c-v2x-presentation.pdf
mit_07_5GAA_FLAMENT.pdf
5.2 DSRC to 802.11 NGV

With the proposed standard and specific requirements for 802.11 NGV not expected to be finalized and submitted for ballot until late 2021, it is reasonable to expect that DSRC will be the prevailing 802.11-based technology for quite some time (and considerably longer if the standard development process and balloting takes longer than currently anticipated, which is not uncommon). The IEEE study groups referenced in Section 4.3 have been developing high-level requirements for NGV, which include:

- Interoperability – 802.11p devices should be able to decode NGV transmissions and vice-versa
- Coexistence – 802.11p devices should be able to detect NGV and vice-versa
- Backward Compatibility – NGV devices should be able to operate in a mode in which they can interoperate with 802.11p devices

If these requirements are met, coexistence of 802.11p and NGV devices in a hybrid environment seems achievable, but that remains to be seen at this point.

5.3 Coexistence Between Technologies

The 75 MHz band around 5.9 GHz is a valuable one. Proponents of opening up the band argue that it has not been utilized enough in the 20+ years since it became protected and should be available for unlicensed use. Opponents argue that progress is being made and that the potential safety benefits for the transportation space should continue to supersede other uses.

Proponents of C-V2X and DSRC alike tend to fit within this latter group, but rather have differing opinions about the right technology to deploy. The concept of channel partitioning or spectrum sharing has been proposed as a workable solution to allow both technologies to coexist while attempting to avoid interference. In this scenario, “preferred channels” are specified for respective technologies, which are tuned to operate within those channels and thereby avoid co-channel interference. The concept further proposes that these preferred channels are offset by an “open channel” that either technology could operate within but would require a “detect-and-vacate” behavior where if a technology wanted to transmit in the open channel it would need to monitor activity and proceed only if no transmissions from the other technology are detected.

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40 https://www.rand.org/pubs/research_reports/RR2720.html
6 Research Gaps

6.1 Coexistence

Demonstrating interoperability between DSRC devices has proven challenging due to implementation differences and differing interpretations of the related industry standards. Due to the difference among layers that make up the DSRC and C-V2X radios, the two V2X systems are unable to communicate with one another. While it is technically feasible to make a radio that is interoperable with both DSRC and C-V2X it would require new technology to be created that supports both protocols since they currently do not support interoperability. For example, DSRC uses only OFDM access scheme in the physical layer providing a “half-clocked” operation (using 10 MHz channels) while C-V2X plans on using 20 MHz channels with SC-FDMA but does plan on supporting 5 MHz and 10 MHz channels as well.

It is possible that both DSRC and C-V2X could coexist on the same channel, but it is likely that they would hinder each other’s performance due to the possibility of their resource elements overlapping (same subchannel frequency over a given time). Both are expecting different size resource elements (subchannel selection, time slots) in order to put together the analog encode message. They also encode the message in different ways - DSRC uses convolution coding while PC5 uses turbo coding. The radio frequency integrated circuit (RFIC) is normally configured to handle one or the other. Once the message is decoded and converted to a digital message, it is up to each respective interface to handle transport of the rest of the message. The interface will not understand the rest of the message if it does not have the headers required for each layer.

USDOT issued a request for comments on a variety of issues related to V2X⁴³, including coexistence between a variety of communications technologies. The responses to this request are still being aggregated and analyzed, but early summaries indicate responses were mixed. While it has not been thoroughly tested yet, industry professionals do believe that if both technologies operated in the same channel that they would greatly hinder the performance of each other. There has been request made to the FCC in the United States from 5GAA to share the ITS band with C-V2X⁴⁴. They’ve requested that channels 182 and 184 be used exclusively for C-V2X deployments which will likely not cause any interference to the safety critical applications DSRC runs in channel 172. This will allow C-V2X to operate in the US but does not solve the problem on interoperability between the two technologies. There has been some consideration on creating OBUs and RSUs that have both a DSRC and C-V2X radio housed in them to handle both forms of communication, but this will likely increase the cost of the hardware.

It is unknown at this point if or how the next-generation technologies (5G NR and 802.11 NGV) could coexist.

6.2 Edge Computing

While CV-equipped vehicles on the road will realize real-time benefits of V2V and to a similar extent V2I applications, the data coming from these vehicles (BSM and otherwise) present many interesting opportunities for additional benefits. Researchers and deployers are beginning to investigate and develop data management and processing strategies and pipelines. These data will likely be run through a backhaul to a centralized data store and then made available to a variety of stakeholders and consumers through various interfaces. However, the advent of edge computing could offer opportunities for infrastructure-based resources to process CV data “at the edge” to deliver other real-time benefits to CVs as they navigate through urban corridors. Examples of applications could include intersection navigation assistance for AVs, comprehensive intersection situational awareness and sharing, decongestion inputs into traffic signal controllers, etc.

6.3 Misbehavior Detection and Mitigation

A robust and reliable CV ecosystem can likely offer significant benefits to the broader transportation system. The developed industry standards give great attention to detail when developing minimum performance requirements and performance targets; however, varying implementations may present challenges or contribute to some of these benefits not being fully-realized. Another factor that could similarly present challenges is CV misbehavior, for example a vehicle broadcasting inaccurate data. If a CV’s positioning system is offset by some amount or if its actual speed is misrepresented, this could lead to false triggers of certain safety or mobility applications (e.g., false forward collision warnings or red-light violation warnings, etc.). As such, methods and techniques for identifying misbehaving CVs need to be addressed. The end-result could be revoking a CV device’s security certificates for some period of time (ideally until the device stops misbehaving).

6.3.1 Vehicle-based Detection

Some efforts are beginning to leverage other sensor-equipped vehicles to detect misbehaving CV’s. If the misbehaving vehicle is broadcasting its position, but numerous other vehicles are detecting it with their onboard RADAR, LIDAR, or cameras and determining that there is a discrepancy, that could trigger the alert of a misbehaving CV.

6.3.2 Infrastructure-based Detection

In addition to other vehicles detecting a misbehaving CV, sensor-based infrastructure could similarly be used for detection. As CV RSUs are deployed along roadways to collect and parse BSM data from CVs, this information could be compared to roadside sensor data detecting and localizing vehicles in real-time to similarly determine discrepancies between a CV’s stated position and its position as determined by those sensors.

6.3.3 Trust-based System

If misbehaving CVs are detectable, a system may be necessary to determine what the appropriate course of action is to mitigate the misbehavior. One potential approach could be to develop a trust-based system to poll adjacent vehicles or infrastructure to “vote” on whether a particular CV is
trustworthy. If not, the system could revoke credentials from the misbehaving CV. A misbehaving vehicle whose credentials have been revoked could still receive critical information being broadcast by other CVs to still activate its own safety warnings; however, the messages it broadcasts could be ignored by other receiving CVs who recognize its credentials are not valid.

7 Conclusions and Recommendations

CV technology takes several forms and those forms are evolving. While it is yet-to-be-determined which form is ideal or best meets the needs of the transportation system or is the most cost-effective, several things are arguably certain:

- CV technology has the potential to improve many aspects of the transportation network (safety, mobility, reliability, environmental effects)
- CV technology is available today, and more is coming

Two questions posed, understandably so, by many road operators and maintainers are “What is the right technology in which to invest our limited funds” and “When is the right time to make that investment?” Unfortunately, there is not enough data and information available at the moment to directly answer the first question, at least to the liking of many, but if the focus remains on improving safety and mobility for road users there is likely no right or wrong answer. DSRC technology is available today and, while there are still questions to be answered and developments and improvements are still being made, has shown that it can provide the desired results. C-V2X technology is advancing rapidly, and while there is fewer objective data available, there is little reason to suspect that it will not similarly deliver the desired safety and mobility improvements. 5G NR and 802.11 NGV propose advancements to what DSRC and C-V2X are already delivering.

The answer to the second question is still somewhat unclear from a cost-benefit perspective, but the simple answer could be to deploy sooner rather than later, to learn about the technologies and the challenges and complexities associated with their installation, operation, and maintenance. One variable that road operators and maintainers have little to no control over is the technologies that will be deployed in OEM vehicles and what the timelines for those deployments are. We are seeing some OEMs taking stances on technologies and proposing deployment timelines, but only some, and there is nothing to say that they will not change their minds along the way.

It is recommended that all interested parties:

- Monitor ongoing CV pilot deployments to gather and take advantage of lessons-learned,
- Monitor the development and testing of existing and next-generation CV technology to understand their performance, as well as limitations,
- Monitor OEM stances and planning related to CV technology integration
- Monitor or engage in relevant SDO working groups to contribute I00 perspectives (e.g., Infrastructure Applications TC, Traffic Signal Applications TC, DSRC TC, C-V2X TC, Security TC, etc. within SAE V2X Steering Committee)
- Establish or expand V2X “sandboxes” to evaluate and integrate CV technologies as part of pilot studies or deployments
- Consider abstracting CV hardware considerations out of any software systems that may integrate with CV ecosystem (e.g., ATMS) so that these systems can support any of the potential technologies discussed in this report
Appendix A – 3GPP Overview and Standards Setting Process

The 3rd Generation Partnership Project (3GPP\footnote{http://www.3gpp.org/}) is an international industry group initiated to develop technologies for the next generation of cellular networks. This began with 3rd generation (3G) at the time 3GPP was formed in 1998 and continued with 4th Generation Long-term Evolution (4G LTE) and currently 5th Generation (5G).

3GPP develops technical specifications, which are subtly different than formal industry standards. 3GPP specifications are distributed between 16 working groups (WGs) that operate with 3 governing Technical Specifications Groups (TSGs):

- **Radio Access Network (RAN) TSG** – defines functions, requirements, and interfaces of new radio network technologies
- **Service/Systems Aspects (SA) TSG** – defines overall architecture and service capabilities of systems based on 3GPP specifications
- **Core Network and Terminals (CT) TSG** – specifies terminal interfaces and capabilities, and core network of 3GPP systems

New features outlined in the technical specifications are published in major “releases”. Release 14\footnote{http://www.3gpp.org/release-14} provides specifications for Cellular Vehicle-to-Everything (C-V2X) technology. Release 15\footnote{http://www.3gpp.org/release-15} is well underway and will provide initial specifications for 5G, and Release 16\footnote{http://www.3gpp.org/release-16} will provide specifications for an initial full 3GPP 5G system.

3GPP works with seven regional standards setting organizations (SSOs) that form the 3GPP partnership to transpose the technical specifications into standards works and make them available to the wireless industry at large. The SSOs in turn provide feedback on general policy and strategy to 3GPP for future development. The seven regional SSO partners are:

- The Association of Radio Industries Businesses (ARIB), Japan
- The Alliance for Telecommunications Industry Solutions (ATIS), USA
- China Communications Standards Association (CCSA)
- Telecommunication Technology Committee (TTC), Korea
- Telecommunication Engineering Centre (ETSI), Europe
- Telecommunications Technology Development Institute (TSDSI), India
- TTA (Korea)

\footnote{http://www.3gpp.org/}
• The European Telecommunications Standards Institute (ETSI)
• Telecommunications Standards Development Society, India (TSDSI)
• Telecommunications Technology Association (TTA), Korea
• Telecommunication Technology Committee (TTC), Japan