BASIC INFRASTRUCTURE MESSAGE DEVELOPMENT AND STANDARDS SUPPORT FOR CONNECTED VEHICLES APPLICATIONS

C-V2X / DSRC
White Paper

April 24, 2018

Prepared for:

Connected Vehicle Pooled Fund Study

Prepared by:

Southwest Research Institute®
http://swri.org

TABLE OF CONTENTS

Contents

1. INTRODUCTION

This white paper was developed as part of the Connected Vehicle (CV) Pooled Fund Study (PFS) project "Basic Infrastructure Message Development and Standards Support for Connected Vehicles Applications". This whitepaper will provide:

- An overview of Cellular Vehicle-to-Everything (C-V2X) technology (e.g. 5G, 4G LTE Advanced Pro – 3GPP's Release 14)
- An overview of Dedicated Short-Range Communication (DSRC) technology
- A technology comparison to aid in understanding Transportation use cases
- Potential business models

1.1 Project Background

With the clear need for the Basic Infrastructure Message (BIM) to be transmitted via DSRC, it is valuable to understand how this applies in a cellular environment. According to subtask 6.3 of the CV PFS proposal, SwRI has the honor of preparing white papers related to topics that are valuable to the CV PFS group.

> The white papers developed in this task will provide more information and detail that is initially covered and discussed in the regular monthly status meetings. In addition, they will include content such as potential workarounds, best practices, and recommendations on implementing the standards in a way that best aligns with understood operational activities. Other anticipated content includes technical considerations that need to be made regarding implementation and compliance with standards, other opportunities to influence and provide content to the standards organizations, and examples of the current state-of-the-art and state-of-the-practice projects and pilots related to Connected Vehicle deployments.

1.2 Purpose of This Document

This white paper was developed under Task 6 of the project: "Connected Vehicle Standards Support". This paper is intended to provide an overview of Cellular Vehicle-to-Everything (C-V2X) and DSRC Connect Vehicle technologies, capture appropriate transportation uses cases for each technology, and potential business models.

2. CELLULAR V2X (C-V2X) OVERVIEW

The following sections will provide information regarding background on Cellular V2X (C-V2X) technology, including:

- Background
- Technology
- Standards
- Applicable Pilot Projects

As an examination of the technology will be provided in additional detail in the Technology Comparison for Transportation Use Cases section, these sections will be covered at a high level.

2.1 Background

Cellular V2X (C-V2X) technology is designed to allow vehicles to communicate with other entities. This takes many different forms, such as communication between vehicles - referred to as vehicle to vehicle (V2V) communication, vehicle to pedestrian (V2P), vehicle to infrastructure (V2I), and vehicle to network (V2N) communication - resulting in the idea of vehicle to everything (V2X). Among some of the cellular technologies offering to support V2X are: 3G and 4G such as Long-Term Evolution (LTE) and LTE Advanced Pro (LTE-A Pro). Future technology offerings include 5G as a delivery mechanism for this effort, though the timeframe and functionality of 5G are still to be determined.

Cellular technology is one of the most widely successful wireless standards due to the introduction of 3G, also known as third generation, in the early 2000s. Its architecture utilized the radio network controller (RNC) controlled the NodeB, or Wideband Code Division Multiple Access (W-CDMA), 3G base stations[1]. 3G provided a more reliable network for calls than its predecessors and answered consumer's demand for transmitting larger amounts of data, making access to the internet a real option. While 3G was effective at providing more data, its data speeds could still vary and consumed a lot of an end-device's battery.

To provide higher mobile data rates, 2008 saw the release 8 of the Third Generation Partnership Project (3GPP) introducing LTE. LTE's architecture consisted of a series of evolved NodeB (eNB) base stations that have control functionality embedded, removing the need for a RNC, creating a simpler network and quicker response times[2]. LTE has evolved through subsequent 3GPP releases adding features such as LTE

[1] https://5g.co.uk/guides/lte-advanced-pro
[2] https://5g.co.uk/guides/lte-advanced-pro

direct, device-to-device (D2D) communications, Security Assurance Methodology (SECAM) for 3GPP nodes, and LTE broadcast lending itself useful for V2X applications.

A timeline of the main features expected of the latest and upcoming releases is shown in Figure 1.

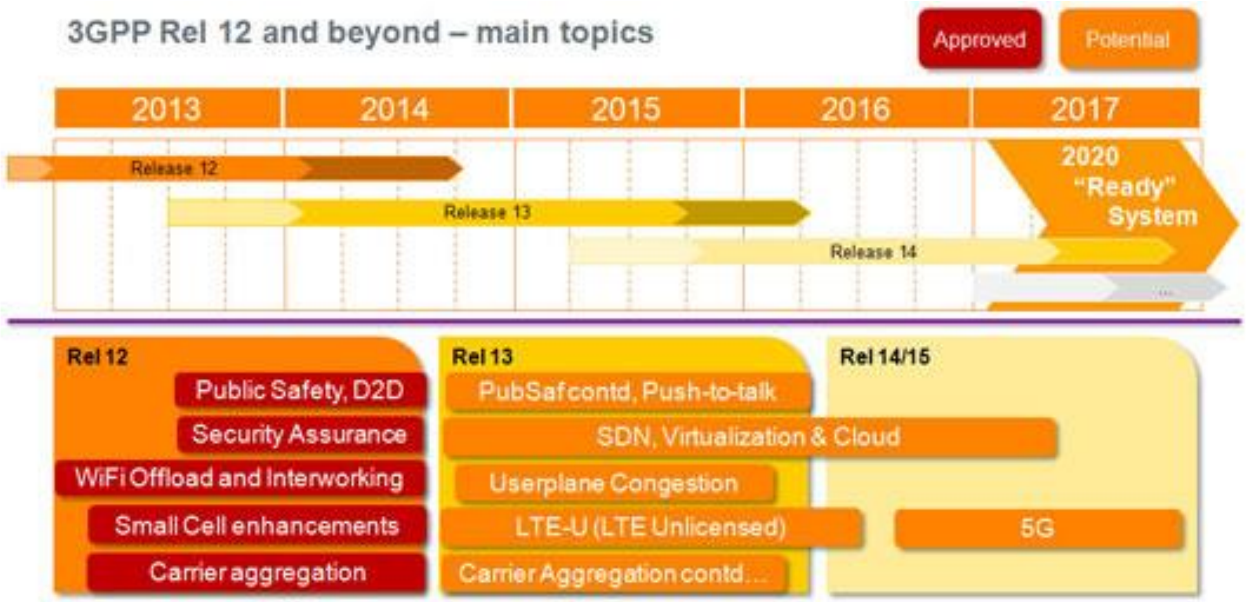

Figure 1. Cellular technology main features and 3GPP timelines[3]

In late 2016, release 13[4], complimenting continuing efforts of release 12[5], introduced LTE-A Pro whose aim was to take the well-developed LTE technology and continue increasing the data speeds and bandwidth. LTE-A Pro also looked at reducing latency and offering power consumption techniques. In preparation for the Internet of Things (IoT) market and 5G technology, LTE-A Pro incorporates numerous enhancements including:

- Machine-type communications (MTC)
- Enhancements for D2D to support public safety (PS) features
- Small cell dual-connectivity and architecture
- Indoor positioning
- Single cell point-to-multipoint
- Work on latency reduction

Release 14[6] is working on the evolution of LTE, was targeted for completion June 2017. Release 14 introduces the following features:

- Multimedia broadcast supplement for public warning systems
- Mission-critical video and mission-critical data services
- LTE support for V2X, providing initial definition of C-V2X
- Latency reduction
- High power LTE for certain bands

[3] http://www.3gpp.org/news-events/3gpp-news/1614-sa_5g
[4] http://www.3gpp.org/release-13
[5] http://www.3gpp.org/specifications/releases/68-release-12
[6] http://www.3gpp.org/release-14

- Channel modelling for LTE in bands above 6 GHz
- Robust call set-up for Voice over LTE (VoLTE) and next generation access technologies

In laying the foundation for 5G, the C-V2X part of 3GPP release 14 leverages existing cellular networks. In one company's representation of a future C-V2X implementation, the technology incorporates direct communications using the PC5 Interface, operating in ITS bands (e.g. ITS 5.9 GHz) independent of cellular network and network communications[7]. The Federal Communications Commission (FCC) is currently investigating sharing of the 5.9 GHz band between proposed Unlicensed National Information Infrastructure (U-NII) devices and Dedicated Short-Range Communications (DSRC) operations in the 5.850-5.925 GHz (U-NII-4) band[8], however this is controversial as the 5.9 GHz band has been reserved for DSRC since 1999.[9] See also section 3.1 below.

Currently, Release 15 (Rel-15) work is anticipated to start in the second half of 2017 and C-V2X will also look at security aspects of LTE support of V2X services while adding further enhancements to LTE D2D. Its completion date is slated for the end of 2018 and commercial release of Rel-15 is expected in 2020[59].

Additionally, in early 2017, the International Telecommunications Union (ITU), who is responsible for international standardization of mobile communications technologies, released a draft report containing their current consensus definition of the key minimum technical performance requirements for International Mobile Telecommunications-2020 (IMT-2020) systems. IMT-2020 systems are mobile systems that include new radio interface(s) which support the new capabilities of systems beyond IMT-2000 and IMT-Advanced, which includes 5G.[10] Some of the key performance requirements include:

- 20 Gbps download (with a targeted rate of 100 Mbps for end-users)
- 10 Gbps upload (with a targeted rate of 50 Mbps for end-users)
- Latency of 4 ms for enhanced mobile broadband (eMBB) and 1 ms for ultra-reliable and low-latency communications (URLLC)

Overall, current standardization of LTE-A Pro (Release 14) is still a couple of years out. This means that there will be some additional amount of time before the 5G technology is ready for deployment and commercialization. Qualcomm estimates the commercial launch of 5G in 2020[11].

2.2 Technology

C-V2X technology allows direct and network communication which includes the following modes[12]:

- **Device-to-device** - This is V2V, Vehicle-to-(Roadway) Infrastructure (V2I) and V2P direct communication without necessarily relying on network involvement for scheduling. This mode is analogous to the ad hoc communications paradigm used in 802.11p.
- **Device-to-cell tower** is another V2I communications link which enables network resources and scheduling and utilizes existing operator infrastructure. Device-to-cell tower communications constitute at least part of the V2I proposition and is important to end-to-end solutions.
- **Device-to-network** is the V2N solution using traditional cellular links to enable cloud services to be part and parcel of the end-to-end solution.

[7] https://www.qualcomm.com/invention/technologies/lte/advanced-pro/cellular-v2x/technology
[8] http://transition.fcc.gov/Daily_Releases/Daily_Business/2016/db0601/FCC-16-68A1.pdf
[9] https://www.its.dot.gov/presentations/world_congress2016/Leonard_DSRC_Spectrum2016.pdf
[10] https://www.itu.int/md/R15-SG05-C-0040/en
[11] https://www.qualcomm.com/documents/qualcomm-5g-vision-presentation
[12] http://www.5gaa.org/pdfs/5GAA-whitepaper-23-Nov-2016.pdf

2.3 Standards

The technical specifications related to cellular technologies. C-V2X, are found in the Third Generation Partnership Project (3GPP).

A breakdown of the all releases within 3GPP and which cellular technology is encompassed is shown in Table 1.

Table 1. 3GPP Network Standards Overview[13],

Version[8]	Released	Release Information
Phase 1	1992	GSM Features
Phase 2	1995	GSM Features, EFR Codec,
Release 96	1997 Q1	GSM Features, 14.4 kbit/s User Data Rate,
Release 97	1998 Q1	GSM Features, GPRS
Release 98	1999 Q1	GSM Features, AMR, EDGE, GPRS for PCS1900
Release 99	2000 Q1	Specified the first UMTS 3G networks, incorporating a CDMA air interface.
Release 4	2001 Q2	Added features including an all-IP Core Network. Originally termed "Release 2000."
Release 5	2002 Q1	Introduced IMS and HSDPA
Release 6	2004 Q4	Integrated operation with Wireless LAN networks and adds HSUPA, MBMS, enhancements to IMS such as Push to Talk over Cellular (PoC), Generic Access Network (GAN).
Release 7	2007 Q4	Focuses on decreasing latency, improvements to QoS and real-time applications such as VoIP. This specification also focuses on HSPA+ (High Speed Packet Access Evolution), SIM high-speed protocol and contactless front-end interface (Near Field Communication enabling operators to deliver contactless services like Mobile Payments), EDGE Evolution.
Release 8	2008 Q4	First LTE release. All-IP Network (SAE). New OFDMA, FDE and MIMO based radio interface, not backwards compatible with previous CDMA interfaces. Dual-Cell HSDPA. UMTS HNB.
Release 9	2009 Q4	SAES Enhancements, WiMAX and LTE/UMTS Interoperability. Dual-Cell HSDPA with MIMO, Dual-Cell HSUPA. LTE HeNB.
Release 10	2011 Q1	LTE Advanced (LTE-A) fulfilling IMT Advanced 4G requirements. Backwards compatible with release 8 (LTE). Multi-Cell HSDPA (4 carriers).
Release 11	2012 Q3	Advanced IP Interconnection of Services. Service layer interconnection between national operators/carriers as well as third party application providers.

[13] https://en.wikipedia.org/wiki/3GPP

		Heterogeneous networks (HetNet) improvements, Coordinated Multi-Point operation (CoMP). In-device Co-existence (IDC).
Release 12	2015 Q1	Enhanced Small Cells (higher order modulation, dual connectivity, cell discovery, self-configuration), Carrier Aggregation (2 uplink carriers, 3 downlink carriers, FDD/TDD carrier aggregation), MIMO (3D channel modeling, elevation beamforming, massive MIMO), New and Enhanced Services (cost and range of MTC, D2D communication, eMBMS enhancements).
Release 13	2016 Q1	LTE in unlicensed (LTE-U), LTE-Advanced Pro, LTE enhancements for Machine-Type Communication. Elevation Beamforming / Full-Dimension MIMO, Indoor positioning.
Release 14	June 2017	Energy Efficiency, Location Services (LCS), Mission Critical Data over LTE, Mission Critical Video over LTE, Flexible Mobile Service Steering (FMSS), Multimedia Broadcast Supplement for Public Warning System (MBSP), enhancement for TV service, massive Internet of Things, Cell Broadcast Service (CBS).
Release 15	Planned for Sept 2018	Support for 5G Vehicle-to-x service, IP Multimedia Core Network Subsystem (IMS), Future Railway Mobile Communication System.

2.4 Applicable Pilot Projects and Trial Efforts

While not an exhaustive list, there are several ongoing pilot programs or trial efforts being conducted related to C-V2X, as shown in Table 2.

Table 2. C-V2X Pilot Program and Trial Efforts[14]

Pilot or Trial Name	Location
AURORA CV Testbed	British Columbia, Canada
Royal Automobile Club of Catalonia (RACC) Track	Barcelona, Spain
Connected Vehicle to Everything of Tomorrow (ConVeX)	Germany
Towards 5G	France
Mobilifunk	A9 motorway test bed, Germany
UK Connected Intelligent Transport Environment (UK CITE)	United Kingdom
Deutsche Telekom (DT)	A9 motorway test bed, Germany
Car2X	Germany, China
ICV pilot projects	China
MEC pilot project	Germany
Smart Mobility Consortium	Hong Kong, China

[14] http://www.codecs-project.eu/fileadmin/user_upload/pdfs/Workshop_Hybrid_Communication/2_3_5GAA_Banks.pdf

2.4.1 Canada's AURORA CV Testbed[15]

In British Columbia, the on-road AURORA (AUtomotive test bed for Reconfigurable and Optimized Radio Access) test bed covers up to 10 km along both two- and four-lane roadway within and adjacent to the University of British Columbia (UBC) campus. AURORA incorporates a range of wireless technologies such as LTE and DSRC and permit a variety of radio and network configurations. The test bed aligns with the UBC "campus as a living lab" initiative, enhancing UBC's capacity to partner with industry, government and academic stakeholders to develop, test, demonstrate and commercialize innovations with emphasis on wireless communications for freight security and efficiency.

2.4.2 Royal Automobile Club of Catalonia (RACC) Track[16]

During the Mobile World Congress 2017 (MWC 2017) in Barcelona, Huawei and Vodafone, with the support of Audi, demonstrated for the first time in Europe the use of cellular technology to connect cars to each other, to people, and to roadside infrastructure enhancing safety and delivering a better driving experience. Using a new technology called Cellular V2X (C-V2X) the live demonstration takes place in front of invited guests at the RACC's world famous Circuit de Barcelona-Catalunya race track.

2.4.3 Connected Vehicle to Everything of Tomorrow (ConVeX)

To assist in demonstrating viability of C-V2X, field trials in Germany started in 2017 under the ConVeX consortium. The ConVeX consortium members are comprised of Audi, Ericsson, Qualcomm Technologies, SWARCO Traffic Systems and the University of Kaiserslautern. The field trials hope to demonstrate the benefits of using C-V2X platform as well as demonstrate range, reliability, and latency advantages for real-time V2X communications using 4G/5G LTE-based V2N technology[17].

2.4.4 Towards 5G[18]

The Towards 5G initiative aims to demonstrate how C-V2X technology can support safety and other advanced connected vehicle applications. The initiative members are comprised of Ericsson, Orange, PSA Group, and Qualcomm. The initial phase of Towards 5G developed and tested an experimental network in France to demonstrate C-V2X capabilities in real environment using two uses cases:

1. "See Through" between two connect vehicles on a road
2. "Emergency vehicle approaching" which notified drivers when an emergency vehicle is nearby in real-time.

The next steps of the Towards 5G initiative will focus on:

1. Implementing a dedicated network slice to prioritize intelligent transportation system (ITS) vehicular traffic and show improved isolation while experiencing other mobile broadband traffic in the vehicle
2. Using direct communication features of C-V2X to V2V, V2I and V2P capabilities, while assessing the enhanced performance brought by C-V2X Release 14 with regards to direct communication range, latency and reliability.

---

[15] http://www.transportation.ualberta.ca/News%20and%20Events/2013/December/TheCSTandtheFirstConnectedVehicleTestBedinCanada.aspx

[16] http://www.huawei.com/en/news/2017/2/Huawei-Vodafone-Future-Connected-Car-experience

[17] https://www.qualcomm.com/news/releases/2017/01/03/consortium-leading-automotive-and-telecom-companies-host-3gpp-release-14

[18] https://www.ericsson.com/en/news/2017/2/towards-5g-initiative-welcomes-qualcomm-shows-fast-results

3. The "Towards 5G" initiative members will help to develop new use cases to assess how C-V2X with 5G NR features will be designed to support advanced applications, including traffic flow optimization, improved safety and automated driving.

2.4.5 Mobilifunk[19]

This trial effort utilizes the wireless communications network along the A9 motorway test route for a Car2Car pilot project between Munich and Nuremberg and was expanded using mobile-edge computing technology from Nokia Networks. The trial was set up to develop, test, and demonstrate a virtually latency-free direct communication link between cars by utilizing mobile communication. The effort records the speed and position of all vehicles within a radius of 320 meters on the test route. The pilot project aims to demonstrate the ability to provide real-time warnings when changing lanes on the motorway. Later, the effort plans to expand to include additional scenarios such as unpredictable braking of vehicles ahead.

2.4.6 UK Connected Intelligent Transport Environment (UK CITE)[20,21]

UK CITE was created for testing connected and autonomous vehicles in which combinations of V2X technologies (LTE, ITS-G5, WIFI, and LTE-V) are tested on over 40 miles of various types of roads. UK CITE is a 30-month project and is jointly led by Visteon Engineering Services Limited and Jaguar and includes Coventry City Council, Coventry University, Highways England company Ltd, HORIBA MIRA, Huawei Technologies (UK) Ltd, Siemens, VodaFone Group Services Ltd, and WMG at University of Warwick. This project will examine how V2X technologies can improve journeys, reduce congestion, and provide entertainment and safety services. Initially testing will be performed on HORIBA MIRA's City circuit followed by public road travels possibly sometime during 2017. Visit the UK CITE website to learn more.

2.4.7 Deutsche Telekom (DT)[22]

Like Mobilifunk, DT infrastructure has been specially equipped with LTE-V hardware to support trial evaluations. This effort is a collaboration between Audi AG, Deutsche Telekom AG, Huawei, Toyota Motor Europe and other car manufacturers. Audi AG, Toyota Motor Europe and other car manufacturers have equipped research cars with the LTE-V hardware developed by Huawei. Technical tests are underway on this connected vehicle technology, which is a potential enabler for road safety and traffic efficiency applications. The partners are conducting these trials on a section of the "digital" A9 motorway test route near Ingolstadt, Germany.

2.4.8 Car2X Communication[23]

Car2X communication is the joint venture traffic management system by Siemens that interconnects vehicles and infrastructure as well as traffic control centers. The Central European "Car2X Corridor" is currently under construction and will connect Rotterdam, Frankfurt, Germany and Vienna, Austria. This project is a collaboration between the Netherlands, Germany and Austria. Through this project, these

[19] http://blog.electronica.de/2017/02/22/lte-v2x-tested-on-german-autobahn/#
[20] https://www.ukcite.co.uk/2016/06/01/uk-cite-consortium-announces-phase-one-uks-first-fully-connected-road-test-environment/
[21] http://connectedautomateddriving.eu/wp-content/uploads/2017/03/4_Day2_BO07_Banks.pdf
[22] https://www.telekom.com/en/media/media-information/archive/connected-cars-meet-next-generation-communications-tech-436104
[23] http://www.mobility.siemens.com/mobility/global/en/urban-mobility/road-solutions/trends-in-urban-traffic-technology/vehicle2x/pages/vehicle2x.aspx

countries are facilitating the deployment of Vehicle-to-X technology in collaboration with industry partners.

Within this system, the control center communicates with vehicles with regards to time critical topics like signal phase and timing (SPAT) via roadside unit (RSU) and with regards to non-time critical topics like IVI via LTE. Goals include improving tail back and accident prevention and reduction of harmful emissions.

Car2X communication trials are also occurring in China utilizing Nokia's Car2X solution based on Multi-access Edge Computing cloudlets[24]. The goals of testing are to achieve real-time communication of V2V and V2I while significantly reducing the latency in the mobile network (i.e. 20ms). By achieving these goals, the hope is that the solution will lay a solid foundation towards the realization of connected car and automated driving.

2.4.9 Intelligent and Connected Vehicle (ICV) Pilot Projects[25,26]

Several ICV pilot efforts have been done in China. One ICV pilot effort was between Shanghai International Automobile City and Tongji University in which the pilot plans to implement a live open-road Smart City testbed featuring both LTE-V and DSRC-based V2X solutions in the National Intelligent CV Pilot in Shanghai's International Auto City. The Smart City will feature more than 10,000 vehicles equipped with Savari's V2X solutions.

A second pilot effort was conducted by General Motors and demonstrated eight safety applications in June 2016 for its latest intelligent and connected vehicle (ICV) technology for the first time at the National Intelligent and Connected Vehicle Pilot Zone in Shanghai, China. As part of the demonstration, six V2V safety applications were highlighted, including:

- Intersection Movement Assist
- Electronic Emergency Brake Light and Control Loss Warning enabled by V2V technology

The demonstration also introduced two newly developed V2I safety applications:

- Red Light Violation Warning
- Reduced Speed Zone Warning

As the ICV applications required a complete set of standards and a security network for interoperability, the collaboration between GM, Tsinghua University and Chang'an Auto led to the development of China's V2X application layer standard with the support of SAE-China and C-ITS.

2.4.10 Mobile Edge Computing (MEC) Pilot Projects[27]

Since 2016, several Mobile Edge Computing (MEC) pilots have been conducted by ZTE Corporation with China Telecom, China Mobile and China Unicom with one effort addressing Internet of Vehicles (IoV) and V2X. In the V2X pilot program, conducted in Ningbo, ZTE completed smart parking and smart park projects based on MEC and narrow band IoT (NB-IoT). Additionally, At MWC Shanghai 2016, ZTE demonstrated a 5G MEC-based virtual reality (VR) service together with China Unicom

[24] https://blog.networks.nokia.com/lte/2016/11/25/x-ray-vision-safer-driving/
[25] http://www.greencarcongress.com/2016/10/20161025-savari.html#more
[26] http://www.greencarcongress.com/2016/11/20161103-gmshanghai.html#more
[27] http://www.zte.com.cn/global/about/press-center/news/2017ma4/0427ma2

2.4.11 Smart Mobility Consortium[28]

The Smart Mobility consortium was formed early in 2017 between the Hong Kong Applied Science and Technology Research Institute (ASTRI), operator Hong Kong Telecom (HKT) and vendors Huawei and Qualcomm to build a smart mobility system for Hong Kong using C-V2X technologies. The goal of this consortium will be to use C-V2X to introduce intelligent transport services, including a warning mechanism for collision and control, assistance for cruise control and parking, and alert systems for speed and lane violations. The program is also expected to generate opportunities for other sectors including shipment, ridesharing, home-delivery, insurance, infotainment and mobile healthcare.

[28] https://www.telecomasia.net/content/hkt-huawei-co-found-c-v2x-consortium

3. DSRC V2X OVERVIEW

The following sections will provide information regarding background on DSRC technology as it is used in V2X communications, including:

- Background
- Technology
- Standards
- Applicable Pilot Projects

As an examination of the technology will be provided in additional detail in the Technology Comparison for Transportation Use Cases section, these sections will be covered at a high level. Additionally, please refer to the Task 3 document for the CV PFS group, which provides further details.

3.1 Background

Dedicated Short Range Communications (DSRC) is a two-way short-to-medium range wireless communication capability that is based on IEEE 802.11p standard for Wireless Access in Vehicular Environment (WAVE) protocol, IEEE 1609.2 Security Services, IEEE 1609.3 Networking Services, and 1609.4 Multi-channel operation. DSRC integrates with SAE J2735 message set dictionaries and utilities SAE J2945 for DSRC performance requirements.

In 1999, the Federal Communications Commission (FCC) first set aside 75Mhz of spectrum in the 5.5Ghz band for DSRC[29] use by Intelligent Transportations Systems (ITS) vehicle safety and mobility applications. Then in 2008, the European Commission (EC) made the decision to set aside 30Mhz in the 5.9GHz band for 'smart' vehicle communications systems[30].

DSRC has since been developed and tested in several pilot programs and numerous state DOT test beds, gaining a lot of V2X support from USDOT due to its low-latency and high-reliability performance 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. Furthermore, DSRC supports the close-range communication requirements to send vehicle Basic Safety Message (BSM) to other vehicles or the infrastructure, and to distribute Traffic Signal Phase and Timing (SPaT) information for intersection-based applications and localized roadway warnings. Automakers are developing safety and mobility applications using DSRC[31].

3.2 Technology[32]

DSRC is a two-way short-to-medium-range wireless communications capability that permits very high data transmission at low latencies critical in communications-based active safety applications. DSRC is deployed using on-board units (OBUs) and road-side units (RSUs). 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.

V2V and V2I applications utilizing DSRC are looking to reduce types of crashes through real time advisories such as:

---

[29] https://transition.fcc.gov/Bureaus/Engineering_Technology/News_Releases/1999/nret9006.html
[30] http://www.etsi.org/index.php/news-events/news/226-press-release-30th-september-2008
[31] https://ntl.bts.gov/lib/56000/56800/56823/V2I_1st_Annual_Report__508_compliant_12_14_15.pdf
[32] https://www.its.dot.gov/factsheets/dsrc_factsheet.htm

- Alerting drivers to imminent hazards–such as veering close to the edge of the road
- Vehicles suddenly stopped ahead
- Intersection movements, such as red-light running and turning movements
- Collision paths during merging
- Presence of nearby communications devices and vehicles
- Sharp curves or slippery patches of roadway ahead

Additionally, convenience V2I services like e-parking and toll payment can communicate using DSRC. Anonymous information from electronic sensors in vehicles and devices can also be transmitted over DSRC to provide traffic and travel condition information to travelers and transportation managers.

Crash prevention and mobility applications utilize DSRC technology in the following ways:

- Connected Vehicle ITS applications provide connectivity
    - Among vehicles to help prevent crashes
    - Between vehicles and infrastructure to enable safety, mobility and environmental sustainability
    - Among vehicles, infrastructure, and passengers' wireless devices to provide continuous real-time connectivity to all system users
- DSRC Technology Behind Crash Prevention and Mobility Supports
    - Active safety transportation applications
    - Reliable, secure communications
    - Fast communication speed low latency
    - Invulnerability to extreme weather
    - Tolerance of multi-path transmissions
    - Technology based on standards to enable interoperability

Now, DSRC is the only technology that provides the low latency needed for crash-avoidance technologies and has been tested extensively to demonstrate its performance in field conditions.

3.3 Standards

DSRC is based on IEEE 802.11p standard at the physical layer for the Wireless Access in Vehicular Environment (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 2 demonstrates how the DSRC related standards come together within the Open Systems Interconnection (OSI) communications stack.

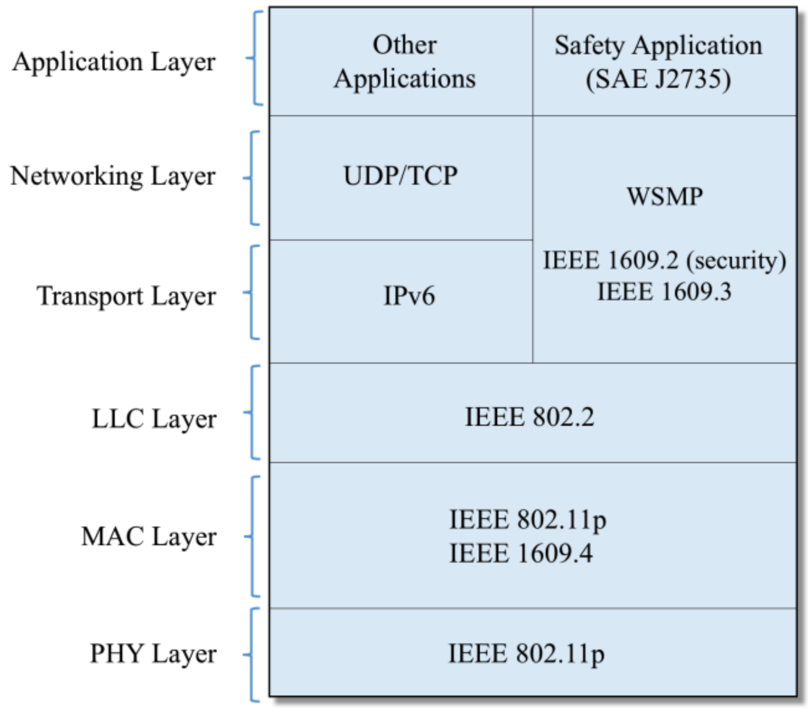

Figure 2. OSI Communications Stack and DSRC Standards[33]

The IEEE 802.11p standard establish the rules for accessing and sharing the physical (PHY) layer and medium-access control (MAC) layer of wireless mediums to support Intelligent Transportation Systems (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.

Table 3. DSRC Spectrum[33]

Channel Number	172	174	176	178	180	182	184
Bandwidth	5.855 -5.865 GHz	5.865 -5.875 GHz	5.875 -5.885 GHz	5.885 -5.895 GHz	5.895 -5.905 GHz	5.905 -5.915 GHz	5.915 -5.925 GHz
Class	SCH	SCH	SCH	CCH	SCH	SCH	SCH
Application	Primary Safety	Extended Safety		Control			Secondary Safety

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, including data encryption, which uses a combination of symmetric and asymmetric cryptography so that it's possible for a message to be both

[33] http://library.ctr.utexas.edu/ctr-publications/0-6845-1.pdf

signed and encrypted. The secured envelope or message then becomes the payload of a 1609.3 WAVE Short message (WSM). [34]

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. These WSMs rarely exceed 20 bytes.[34]

IEEE 1609.4 provides specifications standards regarding the medium access control (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 require for WAVE devices to operate over multiple wireless channels, which is applicable when DSRC is operating in the U.S. 5.9 GHz band.

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 (see section 3.4.5)
- Tampa-Hillsborough Expressway Authority (THEA) Pilot (see section 3.4.7)
- Wyoming DOT (WYDOT) Pilot (see section 3.4.8)

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)

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 to identify 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.

[34] http://ieeexplore.ieee.org/document/5888501/

3.4 Applicable Pilot Projects and Trial Efforts

There are several pilot programs or trial efforts that have been and are currently being conducted related to DSRC which are listed in Table 4.

Table 4. DSRC Pilot Program and Trial efforts

Pilot Program / Trial Name	Location
Vehicle Infrastructure Integration Proof of Concept	Michigan, USA
Anthem Test Bed	Arizona, USA
Safety Pilot Model Deployment	Michigan, USA
Southeast Michigan CV Testbed	Michigan, USA
New York City DOT (NYCDOT) CV Pilot	New York, USA
NY Commercial Vehicle Infrastructure Integration (CVII)	New York, USA
Tampa-Hillsborough Expressway Authority (THEA) Pilot	Florida, USA
Wyoming DOT (WYDOT) Pilot Deployment	Wyoming, USA
CAMP - Cooperative Adaptive Cruise Control (CACC) Project	Michigan, USA
CAMP - Advanced Messaging Concept Development (AMCD) Project	Michigan, USA
Palo Alto Test Bed	California
Contra Costa Transportation Authority (CCTA) – GoMentum Station	California
Canada's AURORA CV testbed	British Columbia, Canada
Colorado DOT (CDOT) Pilot	Colorado
Colorado Smart Truck Parking (Pre-Pass, Cellular and DSRC)	Colorado
Florida 2011 World Congress Deployment	Florida
Idaho	Idaho
Pennsylvania DOT's (PennDOT's) Ross Township	Pennsylvania
PennDOT / CMU Cranberry Township and Pittsburgh Test Bed	Pennsylvania
Maryland DOT (MDOT)	Maryland
Nevada	Nevada
Texas I-35 Connected Work Zone (CWZ)	Texas
Texas CV Research	Texas
Utah DOT (UDOT) CV Deployment	Utah
Virginia Connected Corridors	Virginia
Washington, D.C.	Washington, D.C.

3.4.1 Vehicle Infrastructure Integration Proof of Concept[35]

The USDOT and the Vehicle Infrastructure Integration Consortium (VIIIC) was a joint effort with the USDOT to develop and test a Proof of Concept (POC) Vehicle Infrastructure Integration (VII) system, based on DSRC to demonstrate applications for improvement in safety and mobility and was completed in 2009.

3.4.2 Anthem Test Bed[36]

MCDOT constructed a test bed in Anthem, Arizona to test the MCDOT SMARTDrive℠ Program's vehicle prioritization technology in 2011. It was one of the first seven test beds in the country. Currently in phase two of the pilot, the Anthem Test Bed leverages V2X sensors based on DSRC technology, using RSUs fixed to light poles in conjunction with aftermarket OBUs mounted in buses and emergency vehicles.[37] The Arizona CV program has now expanded its testing to include new applications such as a pedestrian traffic signal crosswalk application, transit priority application and a trucking priority application. In the future, the AZ CV Consortium hopes to expand its program even further by testing these applications in "real world" scenarios where residents and businesses in Maricopa County can participate.

3.4.3 Safety Pilot Model Deployment (SPMD)[38]

CV Safety Pilot is a research program that demonstrates the readiness of DSRC-based CV safety applications for nationwide deployment. The vision of the CV Safety Pilot program is to test connected vehicle safety applications in real-world driving scenarios to determine their effectiveness at reducing crashes and to ensure that the devices are safe and do not unnecessarily distract motorists or cause unintended consequences.

In 2012 University of Michigan Transportation Research Institute (UMTRI) and the USDOT established a test environment (SPMD) located in the northeast quadrant of the city of Ann Arbor and equipped it with the latest connected vehicle and connected infrastructure technology including: 73 lane miles, 25 roadside equipment and roughly 2,800 vehicles (including cars, trucks, etc.) Results from this deployment were significant. They demonstrated the viability of DSRC communication in a live-traffic environment and indicated that 81 percent of unimpaired vehicle crashes could be mitigated with these technologies[39][40]. This information provided the basis for NHTSA to move forward with rulemaking to require DSRC equipment in light vehicles.

3.4.4 Southeast Michigan CV Testbed[41]

A roughly 125-mile sensor installation near I-96 near General Motors Co.'s Milford Proving Grounds, I-94 from Ann Arbor to metro Detroit, U.S. 23 from Ann Arbor to Brighton, and elsewhere. The sensors connect vehicles to infrastructure, such as traffic lights, to help alleviate traffic congestion.

In that area are many sensors and other wireless equipment on roadsides to broadcast signals to and from CVs equipment with receivers. About 115 of these sensors exist in the test area, including:

---

[35] https://ntl.bts.gov/lib/31000/31000/31079/14443.pdf
[36] http://www.aztech.org/projects/connected-vehicles-research.htm
[37] http://iotdesign.embedded-computing.com/articles/v2x-test-beds-for-faster-cleaner-safer-transportation/
[38] https://www.its.dot.gov/research_archives/safety/aacvte.htm
[39] https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/readiness-of-v2v-technology-for-application-812014.pdf
[40] https://ntl.bts.gov/lib/60000/60200/60240/FHWA-JPO-16-4201.pdf
[41] http://www.gomobilemichigan.org/planetm/southeast-michigan-connected-vehicle-test-bed.html

- 17 within the Detroit city limits
- 25 within the Ann Arbor city limits
- 17 along I-96 from Milford Road to M-5, and at M-5 and 12 Mile Road
- the rest along I-696 between I-275 and Telegraph Road, and along Telegraph Road in Oakland County

3.4.5 New York City DOT (NYCDOT) CV Pilot[42]

The NYDOT CV Pilot Deployment project is one of three USDOT-funded Pilot Deployments initiated in 2016. The deployment area encompasses three distinct areas in the boroughs of Manhattan and Brooklyn. Approximately 5,800 cabs, 1,250 MTA buses, 400 commercial fleet delivery trucks, and 500 City vehicles that frequent these areas will be fitted with CV technology. Using DSRC, the deployment will include approximately 310 signalized intersections for V2I technology. The pilot will also focus on reducing vehicle-pedestrian conflicts through in-vehicle pedestrian warnings and an additional V2I/I2V project component that will equip approximately 100 pedestrians with personal devices that assist them in safely crossing the street. To learn more about the NYCDOT Pilot, please visit the NYCDOT Pilot website.

3.4.6 NY Commercial Vehicle Infrastructure Integration (CVII)[43]

Commercial Vehicle Infrastructure Integration (CVII) is a term coined by New York State DOT to refer to the development, adaptation and application of IntelliDrive^{SM} technology (the term previously used for "connected vehicles") using 5.9 GHz dedicated short range communications (DSRC) with a focus on commercial vehicles.

The CVII Program develops and tests the exchange of real time information between IntelliDrive^{SM} compliant roadside infrastructure and vehicles to improve safety, security, mobility, and transportation system asset management. This project has the potential to improve future safety through crash avoidance technology. The technology used in this project will focus on commercial vehicles, but is applicable to any IntelliDrive^{SM} compliant vehicle.

3.4.7 Tampa-Hillsborough Expressway Authority (THEA) Pilot[44]

The THEA CV pilot is one of three USDOT-funded Pilot Deployments initiated in 2016. The pilot will employ DSRC to enable transmissions among approximately 1,600 cars, 10 buses, 10 trolleys, 500 pedestrians with smartphone applications, and approximately 40 roadside units along city streets. To support this initiative, THEA will be working with their primary partners, The City of Tampa (COT), Florida Department of Transportation (FDOT) and Hillsborough Area Regional Transit (HART) to create a region-wide Connected Vehicle Task Force. The primary mission of this Task Force is to support the deployment of Connected Vehicle infrastructure in the region in a uniform manner to ensure interoperability and interagency coordination as these deployments transition from concept to planning to operations. For more information, please visit the THEA Pilot website.

3.4.8 Wyoming DOT (WYDOT) Pilot

WYDOT connected vehicle pilot is one of three USDOT-funded Pilot Deployments initiated in 2016. The pilot will develop systems that support the use of CV Technology along the 402 miles of I-80 in Wyoming. This pilot will deploy approximately 75 roadside units (RSUs) that can receive and broadcast message using Dedicated Short-Range Communication (DSRC) along various sections of I-80. WYDOT will equip around

[42] https://www.its.dot.gov/pilots/pilots_nycdot.htm
[43] http://i95coalition.org/projects/commercial-vehicle-infrastructure-integration-project-library/
[44] https://www.its.dot.gov/pilots/pdf/03_CVPilots_Tampa.pdf

400 vehicles, a combination of fleet vehicles and commercial trucks with on-board units (OBUs). Of the 400 vehicles, at least 150 would be heavy trucks that are expected to be regular users of I-80. In addition, of the 400 equipped-vehicles, 100 WYDOT fleet vehicles, snowplows and highway patrol vehicles, will be equipped with OBUs and mobile weather sensors. For additional information, please visit the WYDOT Pilot website.

3.4.9 CAMP - Cooperative Adaptive Cruise Control (CACC) Project[45]

The overall objective of the CACC Project, conducted by Crash Avoidance Metrics Partners (CAMP) LLC, a consortium of automakers, was to assess the feasibility of prototyping a CACC system by assessing technical and safety issues, gaps and challenges. The CACC Project considered the feasibility of implementing this concept utilizing Dedicated Short-Range Communication (DSRC) and framed the future research work needed to move the concept toward potential implementation.

3.4.10 CAMP - Advanced Messaging Concept Development (AMCD) Project

The overall objective of the AMCD project was to evaluate the ability of connected vehicles to generate and infrastructure to collect Basic Safety Message (BSM), Probe Data Message (PDM), and Basic Mobility Message (BMM) alternatives using cellular and DSRC communications under simulated data message control schemes, including emulating elements of Dynamic Interrogative Data Collection (DIDC) control where applicable, in real world driving conditions for non-safety critical applications.

Research Topics:

- Characterize Dual Mode Communication
  - DSRC
  - Cellular
- Evaluate message control schemes
  - DIDC
  - PMM
- Message Type Characterization
  - BSM
  - PDM
  - BMM

3.4.11 CCTA – GoMentum Station[46]

GoMentum Station in Concord, California is where Contra Costa Transportation Authority (CCTA) leads and facilitates a collaborative partnership amongst multiple Automobile Manufacturers; OEMs and Tier-1 suppliers; communications companies; technology companies; researchers and academia; public agencies and other partners that converge in research, development, testing, validation and commercialization of CV applications and AV technologies to define the next generation of transportation network infrastructure. This 5000 –acre former Navy Weapons Station is one of the largest CV/AV test facilities in the world.

Designated in January 2017 as one of ten USDOT Automated Vehicle Proving Grounds, several automobile manufacturers will test and validate their CV/AV technologies at the GoMentum Station Testbed to advance their research and accelerate commercialization.

---

[45] https://ntl.bts.gov/lib/56000/56800/56823/V2I_1st_Annual_Report___508_compliant_12_14_15.pdf
[46] www.ccta.net/about/download/Website_one_pager.pdf

3.4.12 Palo Alto Test Bed[47]

PATH and Caltrans are upgrading their Palo Alto test bed and are supported by the U.S. Department of Transportation (USDOT). USDOT is encouraging the development of DSRC by supporting up-to-date test beds on public roadways, which are essential to further testing and developing the technology. This upgrade will assist the test bed in becoming a key element in the national network of DSRC test beds. This location is especially crucial as several major international vehicle manufacturers have built research facilities in the area.

3.4.13 Canada's AURORA CV Testbed[48]

In British Columbia, the on-road AURORA (AUtomotive test bed for Reconfigurable and Optimized Radio Access) test bed covers up to 10 km along both two and four-lane roadway within and adjacent to the UBC campus. AURORA incorporates a range of wireless technologies such as LTE and DSRC and permit a variety of radio and network configurations. The test bed aligns with the UBC "campus as a living lab" initiative, enhancing UBC's capacity to partner with industry, government and academic stakeholders to develop, test, demonstrate and commercialize innovations with emphasis on wireless communications for freight security and efficiency.

3.4.14 Colorado DOT (CDOT) Pilot[49]

Interstate 70 intends to be the testing ground for the CDOT's CV Pilot Program. This program is a collaborative effort with Panasonic and is part of an initiative to use new technology to improve safety and traffic. This program aims to leverage DSRC to facilitate communication between cars and traffic lights or other smart objects on the road. It is anticipated that the protocol will manage data in real-time and may also be used to send timely information to moving vehicles. This type of communications and reporting could provide early warning notifications related to icy roads, obstructions and car accidents.

The program will equip more than 700 CDOT first responder, ski shuttle and commercial vehicles on I-70 with DSRC devices that use radio waves to transmit information on road conditions, traffic and closures. The devices will also be installed on roadside infrastructure to collect data on vehicle speeds and incidents. Vehicles installed with DSRC will function as "data collectors" for the pilot program, automatically sending information to CDOT that can be sent out to drivers along the corridor in a timely fashion. The project will stretch between C-470 in Denver and Edwards.

Additionally, CDOT vehicles, such as snowplows, installed with friction sensors could send information on icy or snow packed road conditions to this database. Sensors installed on highway infrastructure tracking traffic volume, travel speeds and accidents could also feed this data into the system for real-time traffic updates.

3.4.15 Colorado Smart Truck Parking (Pre-Pass, Cellular and DSRC)[50]

Using detection and cloud-based software that understands and can report available parking spots to truckers will improve:

---

[47] http://www.path.berkeley.edu/research/modal-applications/palo-alto-test-bed

[48] http://www.transportation.ualberta.ca/News%20and%20Events/2013/December/TheCSTandtheFirstConnectedVehicleTestBedinCanada.aspx

[49] http://www.futurecar.com/article-606-1.html

[50] https://www.codot.gov/programs/roadx/projects-in-motion

- Truckers' time and fuel consumption.
- Excess wear and tear on Colorado's roadways.
- Excess pollution.

The first phase of this project will integrate six existing parking facilities into the Smart Truck Parking System.

3.4.16 Florida 2011 World Congress Deployment[51]

Roadside infrastructure was deployed for the demonstrations that took place at the ITS World Congress in the fall. Five units were installed along John Young Parkway, 11 units were installed along I-4, and 11 units were installed along International Drive/Universal Boulevard.

3.4.17 Idaho[52]

In collaboration with the Idaho Transportation Department (ITD), the Idaho National Laboratory (INL) is implementing CV research in two phases:

- Phase 1 2015-2016
    - Mobile road weather data collection
        - First installation: INL scout vehicle, May 2015
        - Three additional units installed 2016
        - One unit pending repair return
    - Snow plow controller data uploads to Vaisala Navigator website
    - Scout vehicle V2V safety (DSRC)
        - Forward collision warning
        - Electronic brake light warnings
        - Intersection moment assist
        - Blind spot and lane change warning
- Phase 2 2016-2017 (pending funding)
    - Signal phase and timing broadcasts along US 20, 14 intersections
    - Bus and snow plow V2I
    - Dashboard camera images
    - 511 Connected Vehicle modules
    - Two animal detection zones

3.4.18 Pennsylvania DOT's (PennDOT's) Ross Township[53]

In 2014, PennDOT was awarded a FHWA Accelerated Innovations Deployment (AID) grant. PennDOT plans to use the grant to deploy innovative technologies, including adaptive traffic control signals and DSRC, along McKnight Road (SR 4003) from I-279 to Perrymont Rd/Babcock Blvd. in Ross and McCandless Townships. This corridor consists of 11 traffic signals, is roughly 4.8 miles and serves 30,000 ADT. McKnight Road is one of the most heavily traveled arterials in PennDOT District 11-0. It consists of three through

[51] https://www.michigan.gov/documents/mdot/09-12-2013_International_Survey_of_Best_Practices_in_ITS_434162_7.pdf

[52] http://www.westernstatesforum.org/Documents/2016/presentations/Idaho_KoeberleinPray_FINAL_CV_CRADA.pdf

[53] http://www.itspennsylvania.com/wp-content/uploads/2015/05/ITSA-App-Connected-Automated-Section.pdf

lanes in each direction divided by a concrete median with one or more turning lanes at the signalized intersections.

While installing adaptive system equipment, crews will install (DSRC) technology into the traffic signal controllers. The DSRC equipped signals will be used to assist Carnegie Mellon University's research on vehicle-to-infrastructure (V2I) and autonomous vehicle technology. PennDOT will also be working with CMU.

3.4.19 PennDOT / CMU Cranberry Township and Pittsburgh Test Bed[54]

Through a collaboration between Carnegie Mellon University (CMU), Cranberry Township, the City of Pittsburgh, PennDOT, and the Southwestern Pennsylvania Commission (SPC), 11 traffic signals in Cranberry Township and 24 traffic signals in Pittsburgh were equipped with DSRC radios. In January 2015, CMU entered into a Memorandum of Agreement with the US Department of Transportation (DOT) Intelligent Transportation Systems Joint Program Office as a member of the Affiliated Test Bed Program.

Cranberry Township, which is a suburb located in Butler County, 20 miles North of Downtown Pittsburgh. With a population of 30,000 it is the fastest growing area of the Pittsburgh Metro and hosts almost 24,000 commuters daily, who are employed at companies such as Westinghouse International Nuclear Engineering and Mine Safety Appliances, MSA. As a major employment hub and its proximity to the Turnpike and I-79 the area experiences significant commuter and freight congestion.

The connected vehicle environment is located at the intersection of Routes 19 and 228 which is a rapidly growing retail and commercial district. PennDOT reports that over 100,000 vehicles routinely pass through the Intersection of Routes 19 228. This is just 1 of 48 signalized intersections maintained by township staff. The traffic light infrastructure has been updated and 11 of the intersections have been equipped with DSRC radios. In addition, there is backhaul support at each of the intersections connecting to a state of the art municipal traffic management center.

3.4.20 Maryland DOT (MDOT)

Current MDOT plans are centered on responding to the National SPaT Challenge[55], to achieve deployment of DSRC infrastructure with SPaT broadcasts in at least one corridor or network by January 2020. MDOT is implementing DSRC at many signalized intersections in pursuit of broadcasting SPaT and MAP data. The current focus on V2I applications such as TSP, Eco-Approach, Red Light Warning, Curve-Speed Warning, and Work Zone Warning are of interest as well in this deployment and potentially others.

3.4.21 Nevada

Various companies showcased DSRC and LTE technologies at the CES 2017 in Las Vegas, Nevada. However, no permanent infrastructure has been deployed in the state.

3.4.22 Texas I-35 Connected Work Zone (CWZ)

The CWZ activity expanded existing I-35 traveler information during construction, including:

- In-vehicle messaging for commercial vehicles
- Communications
    - 1st Phase: Cellular
    - 2nd Phase: DSRC

[54] http://www.itspennsylvania.com/wp-content/uploads/2015/05/ITSA-App-Connected-Automated-Section.pdf
[55] https://transportationops.org/spatchallenge

- Enhancement to the Texas component of the U.S. DOT's Freight Advanced Traveler Information System (FRATIS) project
  - Corridor optimization for freight
- Texas CV Research programs[56]
  - TxDOT 0-6836: Commercial Truck Platooning
  - TxDOT 0-6837: Assessment of Innovative and Automated Freight Systems and Development of Evaluation Tools
  - TxDOT 0-6838: Bringing Smart Transport to Texans: Ensuring the Benefits of a Connected and Autonomous Transport System in Texas
  - TxDOT 0-6845: Connected Vehicle Problems, Challenges and Major Technologies
  - TxDOT 0-6847: An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs
  - TxDOT 0-6848: Transportation Planning Implications of Automated/Connected Vehicles on Texas Highways
  - TxDOT 0-6849: Implications of Automated Vehicles on Safety, Design and Operation of the Texas Highway System
  - TxDOT 0-6851: Strategies for Managing Freight Traffic Through Urban Areas
  - TxDOT 0-6867: Wrong-Way Driving Connected Vehicle Demonstration
  - TxDOT 0-6875: Autonomous and Connected Vehicle Test Bed to Improve Transit, Bicycle, and Pedestrian Safety
  - TxDOT 0-6877: Communications and Radar-Supported Transportation Operations and Planning (CAR-STOP)

3.4.23 Utah DOT (UDOT) Connected Vehicle Deployment

The Utah Connected Vehicle deployment is using DSRC to provide smart transit signal priority to Utah Transit Authority (UTA) buses along Redwood Road, a significant arterial in Salt Lake County. The instrumented corridor is 11 miles long and crosses through 35 signalized intersections. Thirty of those intersections have DSRC equipment, with three different DSRC vendors included. Two brands of signal controller are also involved in the project. DSRC units on the UTA buses allow the bus to request signal priority when the bus is behind schedule and meets an occupancy threshold. UDOT modified the Multi-Modal Intelligent Transit Signal Software (MMITSS) developed at the University of Arizona for the CV Pooled Fund Study for this project. This DSRC-based transit signal priority system will be operational on daily bus service beginning in October 2017 and plans are underway for this system to be used on a new Bus Rapid Transit line in Utah County in 2018.

The Redwood Road DSRC corridor will also be used to test and deploy other connected vehicle applications. Having three brands of DSRC installed will facilitate testing of hardware and software interoperability.

3.4.24 Virginia Connected Corridors[57]

The Virginia Connected Corridors (VCC) is an initiative developed by Virginia Tech Transportation Institute (VTTI) in partnership with the Virginia Department of Transportation (VDOT) that includes the installation of DSRC devices. The VCC encompasses both the Virginia Smart Road and the Northern Virginia Connected-vehicle Test Bed, which is located along one of the most congested corridors in the United States. The VCC is facilitating the real-world development and deployment of CV technology using more

[56] https://static.tti.tamu.edu/conferences/tsc16/presentations/traffic-ops-1/ma.pdf
[57] http://www.vtti.vt.edu/facilities/vcc.html

than 50 roadside equipment units. VTTI, VDOT, and researchers from across Virginia are already implementing connected applications using the VCC, including traveler information, enhanced transit operations, lane closure alerts, and work zone and incident management.

Additionally, the VCC Cloud Computing Environment incorporates a cellular communication interface that enables bi-directional communication to vehicles over a cellular connection. A mobile application that runs on Android smart phones supports receiving TIM and custom messages for CV functionality including work zones, weather advisories, traffic incidents, Dynamic Message Sign (DMS) information and issues that are reported by drivers. Through the use of a back-end TIM Server, drivers that are using the mobile application receive alerts according to their geo-location, potentially enabling state-wide CV functionality for these informational applications.

3.4.25 Washington DC

Seven DSRC RSUs were deployed along 7th Street and Independence Ave for testing during the Washington DC Auto Show. They are mostly for sending Traveler Information Messages but are envisioned to support SPaT also. There are tentative plans to deploy 20 units on New York Ave and Pennsylvania Avenue in the future. [58]

[58] https://ddot.dc.gov/sites/default/files/dc/sites/ddot/page_content/attachments/District%20of%20Columbia%20Smart%20City%20Application%20Part%201.pdf

4. TECHNOLOGY COMPARISON FOR TRANSPORTATION USE CASES

When implementing technological solutions for transportation use cases, the technologies under consideration must meet or exceed the salient requirements for each particular use case. It is not surprising that C-V2X specifications generated in 2017 compare favorably with DSRC V2X IEEE802.11P standards that were developed in 2010. Thus, on paper, C-V2X should meet the same use cases whose requirements are met by DSRC IEEE802.11P with the assumption that production C-V2X device performance in the field will meet this specification as written. However, the only mechanism for verifying performance characteristics is robust testing to verify consistent performance in a variety of conditions over time. This is especially important for safety applications in which human lives are at risk. And it is this aspect in which DSRC holds a distinct advantage over C-V2X, as DSRC has been tested and vetted in the context of V2V and V2I, starting with the Vehicle Infrastructure Proof of Concept testing completed in 2009 (see 3.4 above). Compare this with C-V2X, which has had various trials in Europe and Asia starting in 2016 (see 2.4 above), with additional C-V2X Technology Field Trials scheduled for 2017. Qualcomm predicts a commercial launch of 5G in 2020[59].

This is not to say that C-V2X may not prove to be suitable for safety applications in the future, but we suggest the use of DSRC V2X for performance critical use cases such as safety applications until such time as C-V2X performance has been verified via complete test coverage comparable to what has been done for DSRC V2X. Furthermore, C-V2X may provide capabilities that can augment and/or complement DSRC V2X performance in non-performance-critical use cases, and we recommend its inclusion when appropriate. We present comparisons of the performance characteristics of both C-V2X and DSRC V2X in Table 5 below. Note that values are obtained from published sources and not the results of internal testing; as such they are only meant to convey a general sense of how C-V2X may compare with DSRC V2X and in what areas C-V2X may provide additional functionality.

[59] https://www.qualcomm.com/documents/qualcomm-5g-vision-presentation

Table 5. C-V2X DSRC-V2X Performance Characteristics

Characteristic	C-V2X specified performance	DSRC V2X	Comments
Latency	4ms 5G eMBB/1ms 5G URLLC	2ms	C-V2X 5G expected 2020[59]
Frequency	Cellular, shared 5.9 GHz	75 MHz at 5.9 GHz	See section 2.1
Bandwidth	LTE 50.4 Mbps[60] 20 Gbps/100 Mbps Download[61] 10 Gbps/50 Mbps Upload[61]	6 - 27 Mbps[62]	
Range	> 2 km via LTE networks[63]	> 2km depending on line of sight[64]	DSRC range is typically 800m with LOS, documented ranges vary, you will see ranges as low as 100m quoted

Some safety and non-safety related connected vehicle applications applicable to these technologies include[65]:

- Safety applications: exchanging information that warns drivers of imminent or potential threats and requires low latency
  - Red light violation warning that are broadcasted to nearby vehicles
  - Blind spot and lane change warnings that are broadcasted to nearby vehicles
  - Emergency brake warning that is broadcasted to nearby vehicles
  - Do-not-pass warnings to inform the passing driver of an undetected danger such that they should not attempt to pass a car
  - Cooperative forward collision warning that informs a moving vehicle of another vehicle approaching from behind
- Mobility Applications: when traffic information is exchanged between neighboring vehicles and infrastructure
  - Variable speed limit (VSL) system to provide speed guidance to drivers based on traffic conditions
  - Enhanced route guidance and navigation using RSUs to inform drivers of congested areas
  - Green light optimal speed advisories to inform drivers about traffic signals and surrounding traffic flow
- Infotainment applications: providing passengers with information about nearby attractions, possibly providing internet connectivity

---

60 http://www.3glteinfo.com/lte-data-rate-throughput/
61 https://www.itu.int/md/R15-SG05-C-0040/en
62 https://arxiv.org/ftp/arxiv/papers/1304/1304.3357.pdf
63 http://www.5gamericas.org/files/2914/7769/1296/5GA_V2X_Report_FINAL_for_upload.pdf
64 https://www.auto-talks.com/wp-content/uploads/2017/09/Whitepaper_LTE-V2V_USletter__05.pdf
65 http://library.ctr.utexas.edu/ctr-publications/0-6845-1.pdf (page 17-19)

  - Point-of-interest notifications allowing nearby business, tourist attractions, and other points of interest, to advertise to nearby vehicles using RSUs to broadcast and OBUs to capture the information
  - Affordable in-vehicle internet access allowing connected vehicles to provide passengers with internet access and turning vehicles into Wi-Fi hot spots

Additional CV applications can be found at https://www.its.dot.gov/pilots/cv_pilot_apps.htm.

4.1 C-V2X Potential Use Cases

C-V2X technology lends itself well to non-safety related use cases and some potential safety use cases. In particular, C-V2X may leverage potential benefits such as greater bandwidth, range, and a mature LTE network in the following use cases:

- Recommended speeds to reduce congestion:
  - Speed Harmonization - Determines speed recommendations based on traffic conditions and weather information. Developing roadway or congestion conditions could be detected that might necessitate speed adjustments for upstream traffic and broadcasts such recommendations to vehicles long before they reach the affected area. Note that for close proximately applications, such as platooning, DSRC may be a better choice due to low latency requirements.
- Enhanced situational awareness through soft safety alerts and graduated warning systems:
  - Queue Warning - Intended to engage well in advance of any potential crash situation, providing messages and information to the driver in order to minimize the likelihood of needing to take action to avoid or mitigate a future crash. The infrastructure will broadcast queue warnings to vehicles in order to minimize or prevent rear-end or other secondary collisions.
  - Vulnerable Road User Discovery – Providing the ability to identify potential safety conditions due to the presence of vulnerable road users such as pedestrians or cyclist.
  - Real Time Situational Awareness – Providing the mechanisms for vehicles to receive real time information about city/roadway projects, lane closures, traffic, and other conditions that may necessitate adjustments to driving patterns.
  - Real-Time High Definition Maps - Provides situational awareness for Autonomous vehicles at critical road segments in cases of changing road conditions (e.g. new traffic cone detected by another vehicle some time ago).
- Information sharing:
  - High Definition Sensor Sharing - Providing the mechanism for vehicles to share high definition sensor data (Lidar, cameras, etc.) to enable better driving coordination for platooning and intersection management.
  - See-Through - Providing ability for vehicles such as trucks, minivans, cars in platoons to share camera images of road conditions ahead of them to vehicles behind them.
  - Remote Vehicle Health Monitoring - Providing the mechanisms to diagnose vehicle issues remotely. As driving becomes more autonomous this becomes the key mechanism for remote supervision of vehicle functions and its health.
- Updates over the air:
  - Software Packages - Providing the mechanisms for vehicles to receive the latest software updates, with secure communication to an agent authorized to provide the update.
  - Security Credentials - Security credentials would be used to identify misbehaving agents, and would be managed through a Security Credential Management System. The SCMS list could be communicated over C-V2X.

Additionally, C-V2X can assist with providing infrastructure related information from applications such as these:

- Static Signage
  - Digital representations of physical signs and placards is provided by infrastructure to be displayed or otherwise conveyed to the driver. Sign authority provides static sign content and location, as well as applicable region information.
- Dynamic Traveler Information
  - Information to be displayed dynamically to drivers in a region are transmitted digitally through BIMs. CVs can then display this information to drivers. Sign authority provides static sign content and location, as well as applicable region information.
- Map Information
  - Information pertaining to the localization and navigation of an area, including any adjustments to the typical driving pattern. This includes highways, intersections, lane adjustments, road closures, and route changes.
- Public Safety Announcements
  - Congestion (expected/unexpected)
  - Amber/Silver/Blue alerts
- Situational Awareness
  - Contextual information about the environment and any situational-specific details that would be relevant to safe vehicle operation in an area.
- Limited Access
  - Restrictions for vehicles operating in specific roadway areas. Receive limited access information from traffic authority or other external source. Traffic authority provides content and timeframe, as well as applicable region information.
- Data collection requests
  - Vehicles have data that can be useful when aggregated, such as traffic conditions and environmental responses (wind-shield wipers, traction control activation, temperature, etc.). This data can be aggregated and anonymized to provide contextual information to a traffic authority.
- Incidents
  - Provide information about incidents to nearby vehicles. Roadway authority provides incident content and timeframe, as well as applicable region information.
- Vehicle Enforcement (primarily commercial, but can be passenger)
  - Enforcement of laws or restrictions on specific vehicles in a roadway area including roadside screening.
- Driver Safety/Assistance/Support
  - Vehicles that must stop along a roadway can rapidly and accurately provide information regarding a loss of safety or capability to an authorized authority
- Emergency Vehicle Operations
  - Information about emergency response vehicles that are operating on a roadway are provided to vehicles
- Intersection
  - Potential vehicle interaction between vehicles and between infrastructure and vehicle at cross-roads and intersections including indications of dilemma zones are communicated to vehicles through a BIM

Additional details about the above use-cases can be found in accompanying reference material such as the corresponding paper for Task 2 under the CV PFS.

4.2 DSRC Use Cases

As DSRC was designed with the vehicle environment in mind, the technology is designed to handle both non-safety and safety related use cases. The unique benefit of DSRC is its capability for low-latency communications for crash avoidance.

Many of the use cases discussed in sections 4.1 are also applicable over DSRC, the following are safety critical use-cases that require low-latency communication that DSRC has been proven to provide and are available today[66]:

- V2I Safety [67,68,69]:
  - Red Light Violation Warning– Using signal phase and timing and vehicle positions, infrastructure warns nearby vehicles about impending red-light violations that may result in a collision.
  - Curve Speed Warning – As connected vehicles approach a curve, infrastructure can provide alerts when the CV is traveling at a speed too high to safely navigate the curve.
  - Stop Sign Gap Assist – Using BSMs, infrastructure equipment can warn drivers about potential collisions at intersections with stop signs.
  - Spot Weather Impact Warning – Drivers of connected vehicles can be alerted about weather in the immediate area that may affect driving conditions. The information is provided by traffic management or weather authorities.
  - Reduced Speed/Work Zone Warning – Drivers of connected vehicles are warned about the existence of work zones and reduced speed zones.
  - Pedestrian in Signalized Crosswalk Warning (Transit) – Infrastructure equipment sends out a warning when vulnerable road users are in the crosswalk of a signalized intersection.
- V2V Safety
  - Emergency Electronic Brake Lights (EEBL) – Vehicles send information about hard braking events through DSRC. Drivers on the road are alerted about the situation in order to take appropriate and immediate action.
  - Forward Collision Warning (FCW) – Alerts are provided to drivers who are in imminent threat of impacting a vehicle in front of the driver. Through this alert, drivers can avoid or mitigate the severity of crashes into the rear end of other vehicles.
  - Intersection Movement Assist (IMA) – Vehicles are warned of impending dangerous conditions prior to entering an intersection. Each vehicle that is involved needs to be a Connected Vehicle in order to provide or receive the information in this application.
  - Left Turn Assist (LTA) - Alerts are given to the driver if they are performing an unprotected left turn across traffic and would otherwise encounter another CV (approaching the intersection from the opposing direction or turning right onto the intended street).
  - Blind Spot/Lane Change Warning (BSW/LCW) - Alerts are displayed to the driver that indicate the presence of another CV traveling the same direction in an adjacent lane (Blind

[66] https://www.its.dot.gov/pilots/cv_pilot_apps.htm
[67] http://ntl.bts.gov/lib/48000/48500/48523/272C82A5.pdf
[68] http://ntl.bts.gov/lib/48000/48500/48527/ED89E720.pdf
[69] http://ntl.bts.gov/lib/54000/54000/54069/14-117.pdf

Spot Warning), or alerts given to drivers when another adjacent vehicle changes lanes (Lane Change Warning) to help the driver avoid crashes associated with potentially unsafe lane changes.

- Do Not Pass Warning (DNPW) - Alerts are provided to drivers to help avoid a head-on crash in the case of performing a passing maneuver of a vehicle traveling in the same direction.
- Vehicle Turning Right in Front of Bus Warning (Transit) – Alerts a transit bus operator of vehicles attempting to go around the bus to make a right turn in front of the bus.

5. POTENTIAL BUSINESS MODELS

Business models are proposed below, the information presented here represents a research-based best-guess of the business models. These were developed independently by the writers, though the business case models are high-level and do not include extensive details.

5.1 Potential Business Models Utilizing DSRC Technologies:

- Infrastructure operators (DOTs, Tollway Authorities) deploy DSRC infrastructure
  - Ownership, operation, and maintenance will be the responsibility of the operators, like other ITS equipment
  - Setup:
    - Requires the purchase, installation, and integration of the radio equipment with associated software applications
    - Vehicles that already adhere to the standard would provide standardized BSMs for use by the infrastructure operators
    - Standards around the information provided to vehicles from infrastructure devices would be established, vehicles utilizing the compatible standards would use this information
      - Vehicle operators could optionally pay the infrastructure operator for usage of the information from infrastructure, such as a monthly subscription to the non-safety critical data, or a one-time use fee per application
  - Business model options for the in-vehicle portion
    - OEMs provide J2945 Standard compliant hardware and integrated Human Machine Interfaces (HMI) (for example through infotainment centers, haptic feedback, seatbelt tensioners)
    - OEMs provide J2945 Standard compliant hardware, and optional interfaces (such as Bluetooth) for external HMIs (such as apps running on cellphones)
    - Vehicle operators bring their own J2945 Standard compliant hardware devices and HMIs, OEMs provide integration point with the vehicle (standards still to be determined)
- Infrastructure operators use DSRC as a service
  - Operators pay a provider to deploy, operate, and maintain the infrastructure
  - Setup
    - Provider based
    - Integration with information to/from the vehicles would follow the same business model as the above model

5.2 Potential Business Models Utilizing C-V2X (LTE and 5G) Technologies:

- Infrastructure operators establish relationships with 5G network operators to use their network to disseminate info
  - May offer exchange for use of right of way to deploy cell network if they can disseminate info over the medium
  - Could also negotiate collecting revenue from the cell operator for use of their right-of-way
  - Setup
    - Requires a cellular capable device with a sim card and a cellular service plan

- Third parties (like signal controller vendors, or application providers like Waze) establish relationships with 5G network operators
    - Information is disseminated through the third parties
        - Interoperability is enforced through standards bodies
        - Service charge options
            - All information is free to the vehicle operators (possibly in exchange for some non-monetary cost such as advertising space, agreeing to terms such as data gathering or tracking)
            - Information is free to the vehicle operators for safety-critical applications (also potentially offset by costs paid by others for data or ads)
            - Monthly subscription fees are paid by the vehicle operator for non-safety-critical services
            - As needed fees are paid by the vehicle operator for non-safety-critical services
            - One-time fees are paid by the vehicle operator for non-safety-critical services
            - Ad revenue pays for non-safety-critical services
            - Vehicle operators purchase in-vehicle devices based on the information that they would like to receive from the infrastructure, equipment costs are defrayed by the cell service providers in exchange for monthly service fees. Infrastructure operators roll out new features to entice future hardware/software purchases and more utilization of the infrastructure network

It should be noted that both DSRC and C-V2X technologies will need a back-end service to handle the messages and sensor information being transmitted.

6. CONCLUSION

Today, DSRC has an advantage of being stable and well-established, having been developed and tested in V2X applications for more than a decade. DSRC already meets V2X requirements regarding latency (~5ms[70]), accuracy, and reliability for active safety with several states actively deploying DSRC devices to begin instantiating what may end up being their V2X infrastructure. DSRC deployments are increasing through trial efforts and pilot programs. Additionally, NHTSA currently has a proposal to mandate DSRC communications in vehicles, which may spur significant growth in DSRC deployment density if and when the mandate is implemented.

In the next few years, the potential speed advantages proposed by C-V2X, offering data rates at 20 Gbps download / 10 Gbps upload speeds with 1 ms latency, may prove crucial to gathering data at the speed necessary to prevent crashes. Cellular communication has been in use for years and it's uses continue to expand which is evident by the recent C-V2X extension in 3GPP standards releases.

While there are a lot of documents that may support going with one technology or the other, it seems planning to utilize both, DSRC for safety-critical applications and C-V2X for mobility and infotainment applications, would be an optimal route for providing safer roads today and allowing for growth over time.

[70] http://www.sciencedirect.com/science/article/pii/S235286481630075X