Spectrum Needs for CDA Use Cases

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FOREWORD

As part of its studies on cooperative driving automation (CDA), the Federal Highway Administration is researching the spectrum required to enable applications and use cases developed at the Saxton Transportation Operations Laboratory. The use cases were developed, tested, and validated using low-latency communications technology operating on the 5.9-GHz safety band (www.transportation.gov/content/safety-band). The researchers considered five scenarios involving one or more use cases in either dense urban or highway environments, thereby placing high demand on the safety band. This report presents the results of the study, which will help shape future decisions and recommendations regarding communication technology use in future CDA use cases and applications.

The project team performed a quantitative analysis for each scenario, considering the sizes of messages, message transmit frequency, and communication range. Since some applications may be able to use higher-latency messaging, the analysis was repeated, with non-safety-critical messages removed from the analysis. The study found that if CDA deployment were scaled up to 100 percent, wireless communication needs would greatly surpass the available spectrum capacity. Based on this limited study, it appears that 30 megahertz of spectrum allocated for vehicle-to-everything communication is insufficient to support the full deployment of CDA technology, and alternative forms of communication should be explored. The findings of this report may be of interest to stakeholders in industry, academia, and government; system developers who create and support CDA algorithms; and analysts, researchers, and CDA application developers.

Carl Andersen
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Research and Development

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16. Abstract

The Federal Highway Administration (FHWA) within the U.S. Department of Transportation has been using its cooperative driving automation (CDA) program to lead research, development, and standardization that demonstrate CDA technologies’ benefits and accelerate industry adoption and deployment. The FHWA and the Intelligent Transportation System Joint Program Office, with support from other modal stakeholders, developed a set of open-source CARMA℠ tools to support research and demonstrate system-level safety and mobility benefits provided by CDA using transportation systems management and operations strategies and vehicle-to-everything connectivity. This document serves to help develop an understanding of spectrum requirements for the deployment of multiple CDA scenarios that would aid in making future decisions and recommendations regarding available communication technologies. The scenarios combine different use cases and applications developed thus far in the CDA Program. For selected combinations of the use cases, the team performed quantitative analyses of the low-latency spectrum needs by using such parameters as message size, transmit frequency, and communication range. The outcome of this analysis indicates the need outpaced the available spectrum in the 5.9-GHz safety band and recommends considering alternative communication paths for non-low-latency messages.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACC	adaptive cruise control
ADS	automated driving system
BSM	basic safety message
CACC	cooperative adaptive cruise control
CAV	connected automated vehicle
CDA	cooperative driving automation
C-V2X	cellular vehicle-to-everything
DSRC	dedicated short-range communications
ERV	emergency response vehicle
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GPS	Global Positioning System
HARQ	hybrid automatic repeat request
HRSO	Office of Safety Operations Research and Development
IEEE	Institute of Electrical and Electronics Engineers
Mbps	megabits per second
MCS	modulation coding scheme
MHz	megahertz
R&D	research and development
RSM	roadside safety message
RSU	roadside unit
SDSM	sensor data-sharing message
SPaT	signal phase and timing
STOL	Saxton Transportation Operations Laboratory
TBD	to be determined
TCM	traffic control message
TCR	traffic control request
TFHRC	Turner-Fairbank Highway Research Center
TSMO	transportation systems management and operations
USDOT	U.S. Department of Transportation
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
WZDC	Work Zone Data Collection
WZDx	Work Zone Data Exchange
XML	Extensible Markup Language

CHAPTER 1. SCOPE AND SUMMARY

IDENTIFICATION

This document serves as the summary report for Task 5: Analysis of Spectrum Needs for Cooperative Driving Automation (CDA) Applications, part of the CDA Design and Architecture project, Task Order 693JJ322F00256N under the Saxton Transportation Operations Lab, IDIQ 693JJ321D000010.

DOCUMENT OVERVIEW

Background

The Office of Safety and Operations Research and Development (HRSO) performs transportation safety and operations research and development (R&D) for the Federal Highway Administration (FHWA). Onsite R&D is conducted at the Saxton Transportation Operations Laboratory (STOL), established at Turner-Fairbank Highway Research Center (TFHRC). HRSO conducts safety and operations R&D based on a national perspective of the transportation needs of the United States.

In 2014, HRSO designed, built, and installed a cooperative adaptive cruise control (CACC) proof-of-concept prototype system in a fleet of five vehicles. The CACC system was built on the first iteration of CARMA Platform℠—sometimes referred to as CARMA1—which represented an advancement of standard adaptive cruise control (ACC) systems by using vehicle-to-vehicle (V2V) dedicated short-range communications (DSRC) to automatically synchronize the longitudinal movements of multiple vehicles within a string (FHWA 2019). That proof-of-concept system was one of the first in the United States to demonstrate the capabilities of this technology with a five-vehicle CACC string by September 2015.

In 2016, the CARMA Platform effort continued in a new project, titled Development of Connected and Automated Vehicle Capabilities: Integrated Prototype I. The objectives of that project were to develop the second generation of CARMA Platform (i.e., CARMA2) and to advance CACC functionality with a view to develop a proof-of-concept platooning application that both enabled leader–follower behavior and enabled vehicles to begin to seek agreements with one another. The project also developed the Integrated Highway Prototype, which integrated speed harmonization, lane change and merge, and platooning into one trip applying negotiations for the first time. The research focused on the development of an understanding of negotiations among entities and how negotiations could be conducted efficiently to help improve traffic flow based on cooperative tactical maneuvers.

In 2018, a project titled Development of Cooperative Automation Capabilities: Integrated Prototype II worked on the third generation of CARMA. CARMA3 took the platform into the world of automated driving systems (ADS) with SAE International Level 3+ automation. As part of this project—and of other, subsequent projects in the CDA Program (formerly known as the CARMA Program)—TFHRC researchers created the entire CARMA Ecosystem, wherein the focus was not only on CARMA Platform (i.e., the ADS-equipped vehicle piece) but also on infrastructure and the cloud. That approach took advantage of an open-source community and developed tools that equipped engineers and researchers to perform next-generation CDA research.

The CDA Program develops open-source proofs of concept to enhance the tools that support CDA research. The open-source software supports research that advances CDA transportation systems management and operations (TSMO) strategies that will align with the long-term CDA research priorities of the U.S. Department of Transportation (USDOT).

FHWA continues to develop the following five primary open-source software tools and products:

- CARMA Platform℠ adds communication capabilities to automated vehicles, thereby facilitating cooperation with other entities such as vehicles, the cloud, and infrastructure.
- CARMA Messenger℠ adds communication capabilities to nonautomated vehicles, thereby enabling two-way communication between a nonautomated vehicle and other road entities such as vehicles and infrastructure. An example of such communication involves sending emergency responder move-over requests (FHWA 2022).
- CARMA Cloud℠ emulates cloud-based applications to monitor a transportation network and communicates with entities on the road such as vehicles and infrastructure to inform them of current network conditions and, potentially, to enforce new rules such as applying a new speed limit in a particular area because of inclement weather (FHWA 2022).
- CARMA Streets℠ adds communication capabilities to infrastructure—most commonly traffic signals—to enable infrastructure to monitor real-time traffic conditions and coordinate with vehicles and the cloud. When installed on a traffic signal, CARMA Streets can also optimize real-time traffic signal timings (FHWA 2022).
- CARMA Everything-in-the-Loop is continually expanding software that simulates aspects of the transportation system—such as traffic, wireless communications, and vehicles equipped with cooperative automated driving systems—while using any one of the previously noted CARMA products.

The foregoing five software products are meant to be sandboxes wherein engineers and researchers develop their own CDA features. For example, one engineer or researcher might develop a novel speed harmonization algorithm. In that case, the algorithm would be installed on top of CARMA Cloud, CARMA Cloud would apply the algorithm, and it would then send appropriate directions for vehicles (either CARMA Platform, CARMA Messenger, or both) to execute.

Objective

The project has three high-level objectives:

- Develop and/or improve the CARMA Ecosystem's architecture (Task 2) and interfaces (Task 3).
- Develop a CDA domain achievable within the next 5–7 yr (Task 4).
- Develop an understanding of spectrum requirements for deploying the use cases and applications developed thus far in the CDA Program (Task 5).

One of the purposes of the first objective is to improve the architectures of CARMA Ecosystem products such as CARMA Platform so that the architectures are modular, flexible, scalable, and capable of studying many different scenarios. Another purpose is to develop interfaces between the different CARMA Ecosystem products and other potential CDA entities, which would enable the CARMA Ecosystem to facilitate research alongside other intelligent transportation system technologies. The research includes the redesign of CARMA Platform as necessary to make it interface with an independent external ADS. In that case, CARMA Platform would focus on enabling cooperation and not necessarily on the automated dynamic driving task.

The purpose of the second objective is to develop an understanding of what a realistic CDA-enabled arterial and/or freeway looks like 5–7 yr into the future. In this project, such a realistic CDA-enabled arterial and/or freeway is referred to as a "CDA domain." Defining a CDA domain will help inform future projects.

The purpose of the third objective is to understand the spectrum requirements of the use cases and applications developed in the CDA Program. Understanding those requirements will help research teams make future decisions and recommendations regarding available communication technologies and feasible use cases.

This document focuses on the third objective and analyzes spectrum needs, with suggestions for future work.

Audience

The intended audience for this document consists of the following stakeholders:

- USDOT and CDA Program participants.
- System developers who will create and support CDA algorithms based on the system concepts described in this document.
- Analysts, researchers, and CDA application developers.

Document Structure

The following summarizes the document's content:

- Chapter 1 introduces the project and describes its background and overall goals.
- Chapter 2 describes CDA applications and the messages on which the applications rely.
- Chapter 3 describes scenarios built from one or more CDA applications that will form the basis of the analysis.
- Chapter 4 analyzes spectrum needs along with assumptions made.
- Chapter 5 is a conclusion and suggests areas for future work.

CHAPTER 2. CDA USE CASES

This chapter describes the CDA use cases the project team considered in this study, along with the messages on which the use case applications rely. For this study, the team considered only proof-of-concept applications developed for STOL's use cases in the CDA Program (Ghiasi et al. 2022; Soleimaniamiri 2021).

APPLICATIONS

This section describes the goal of the applications, the intended use case, and the vehicle-to-everything (V2X) messages that the applications rely on. Because this study focuses on using the 5.9-GHz band, it assumes that messages will consume that band. However, applications may be tolerant of higher-latency messaging, so the team included a secondary analysis that assumes that higher-latency messages (for mobility) get moved away from the 5.9-GHz band and that only low-latency (safety) messages remain in the 5.9-GHz band. Messages are defined primarily by SAE International standard J2735, but others were developed internally by researchers at STOL (SAE International 2020a).

Eco-approach and Departure

Road infrastructure at signalized intersections can communicate with CDA-equipped vehicles about upcoming traffic signal timing such that the vehicles can optimize their trajectories when traveling through the intersection (SAE International 2020b). The result of eco-approach and departure is that both average delay and fuel consumption in all cooperation class vehicles are reduced, which in turn reduce average stopping time and eliminate stop-and-go traffic patterns and backward shock wave propagations.

The following messages are involved:

- MAP message.
- Signal phase and timing (SPaT) message.

CACC

The CACC application implements a communication layer on top of an ACC implementation. Via CACC, the vehicles share their ACC speed set points and coordinate on upcoming speed adjustments such as braking. That sharing facilitates increased string stability between vehicles engaged in CACC compared with ACC. CACC was implemented as part of the first rounds of CDA prototyping at STOL. Future versions of STOL's CDA research have evolved into a broader-featured platooning implementation.

The following messages are involved:

- Basic safety message (BSM) with CACC-specific extension fields.

Platooning

“Platooning” refers to a hierarchical control framework in which a group of vehicles communicate and drive together. As a result of the communication, the intervehicle gap is smaller than regular car following, and the platoon leader is responsible for coordinating platoon members’ maneuvers. Potential advantages of platooning include reduced fuel consumption, reduced congestion, and increased safety.

The following messages are involved:

- Mobility request message.
- Mobility response message.
- Mobility operation message.

Speed Harmonization

Speed harmonization is a concept wherein a traffic management center directs the speed of traffic—based on changing traffic conditions—in order to maximize throughput and minimize travel time. Speed harmonization is used primarily to slow vehicles as they approach a traffic jam on a freeway. The algorithm is segment based. An optimal speed gets calculated based on inputs from various roadway sensors, and speed commands are applied uniformly to all vehicles within each predefined segment of the roadway. As vehicles move from segment to segment, the directed speed may change.

The following messages are involved:

- Traffic control request (TCR) message.
- Traffic control message (TCM).

Road Weather Management

Road operators use TCMs to publish travel-affecting weather impacts to CDA-equipped vehicles that use TCR messages to request local route information. The TCMs can help mitigate the effects of, say, flooding conditions by both providing early alerts and alternative travel paths and better equipping agencies’ response and recovery efforts. The information may be passed by means of short-range communications (e.g., DSRC or cellular vehicle-to-everything [C-V2X]) or cellular networks.

The following messages are involved:

- TCR message.
- TCM.

Traffic Incident Management

Road operators use TCMs to publish travel-affecting traffic incident information to CDA-equipped vehicles that use TCR messages to request local route information. The TCMs can help vehicles avoid an incident by using alternative travel paths. TCMs can also assist vehicles in safe passage through the incident, thereby decreasing the likelihood of injury to people involved in the incident and first responders at the scene.

This use case implementation focuses on facilitating lane closures adjacent to emergency response vehicles (ERVs) to ensure vehicles comply with traffic laws regarding pulled-over ERVs. The ERV (CARMA Messenger) would broadcast a mobility request message containing the Global Positioning System (GPS) point, desired speed reduction, and desired safety margins of the ERV. The vehicle would interpret the information to avoid the lane adjacent to the ERV and perform a slowdown maneuver when passing the incident. The information may be passed by means of short-range communications (e.g., DSRC or C-V2X) or cellular networks.

The following messages are involved:

- Mobility request message (custom—but used to inform the Work Zone Data Exchange [WZDx] standard) (FHWA 2022).

Work Zone Navigation (Signals)

Road operators can use TCMs from CARMA Cloud to publish work zone information about signalized intersections to CDA-equipped vehicles (CARMA Platform) that use TCR messages to request local route information. Infrastructure at the work zone (V2X Hub^{SM}) will publish SPaT messages indicating timing of the signals controlling the available lanes (FHWA 2021). The vehicle uses this information to follow a safe and efficient trajectory through an intersection where work is occurring, thereby also increasing the worker safety in the vicinity.

The following messages are involved:

- TCR message.
- TCM.
- SPaT message (linked to TCM via field in TCM removing need for map message).

Work Zone Navigation (WZDC)

The WZDC tool is designed for the WZDx use case. The goal is to enable a construction manager in the field and a transportation system manager in the infrastructure owner–operator back office to map work zones and distribute generated map messages to third parties. The system managers can quickly and accurately accomplish the mapping in a few steps by using Web-based and onsite tools. First, the event is initialized on the WZDC website by the system engineer in the office with such information as event name, date, times of day, number of lanes, lanes affected, responsible party, and contact information. The work zone is then mapped out by the field operator in lane-level detail by driving the work site with a lightweight tool and a GPS receiver. The process creates a breadcrumb trail of GPS points and marks the exact locations of workers and lane closures. The data are uploaded to the WZDC website, where the system engineer in the office makes final adjustments and configurations, and the work zone is published. Once published, the WZDC website serves as a work zone publisher using a representational state transfer application programming interface in the form of a roadside safety message (RSM) in Extensible Markup Language (XML). CARMA Cloud then subscribes to the RSM XMLs and converts them into a CARMA Cloud traffic control to be used in the standard CARMA TCR message and TCM exchange.

The following messages are involved:

- RSM (in XML format).
- TCR message.
- TCM.

All-Way Stop

CARMA Streets optimizes the departure sequence of connected automated vehicles (CAVs) and estimates each vehicle's stopping time at, entering time to, and departure time from the intersection box. In this use case, vehicles cannot enter the intersection box unless they receive access from CARMA Streets. Vehicles receive updates from CARMA Streets that include scheduling information until the vehicles depart the intersection box. The benefit of this application is smoother, faster, and more efficient travel as well as increased traffic safety.

The following messages are involved:

- BSM.
- Mobility path message.
- Mobility operation message.

Freight Port Drayage

A CDA-equipped freight truck arrives at a port entrance and broadcasts to port infrastructure a mobility operation message that consists of a vehicle identifier, an identifier related to the cargo, and an event flag signifying the truck's arrival. After that initial message, port infrastructure responds with a mobility operation message containing the coordinates of the next port location that the truck must navigate to, along with the event that will take place at that location. After arriving at that next location, the truck broadcasts another mobility operation message to signify it has arrived. The process repeats as the truck navigates to locations throughout the port to pick up cargo, drop off cargo, and undergo inspection by port authority personnel. To support this message exchange, port infrastructure is connected to a database that is preloaded with actions for each truck the port expects to arrive at the port.

The following messages are involved:

- Mobility operation message (FHWA 2022).

Adaptive Signal Timing

Road infrastructure in intersections not only broadcasts current and upcoming signal timings to CDA-equipped vehicles but also optimizes each vehicle's entering time for passing through the intersection. CDA-equipped vehicles smooth and optimize their own trajectories individually based on their given entering times. Infrastructure optimizes again based on the status and intent information broadcast by the vehicles. That simultaneous and continuous optimization of signal timing and vehicle trajectories can achieve higher throughput because of increased entering speeds, lower travel delay due to optimized signal timing, and lower fuel consumption due to smoother trajectories facilitated by the following messages:

- MAP message.
- SPaT message.
- BSM.
- Mobility operation message.
- Mobility path message.

Freight Work Zone

Road operators use TCMs to publish travel-affecting lane closure and lane restriction information to CDA-equipped vehicles that use TCR messages to request local route information. The TCMs can help vehicles safely navigate active work zones by using alternative travel paths, and they can lower speeds for passing through the work zone environment, thereby decreasing the likelihood of injury to work zone personnel at the scene. In this specific application, infrastructure installed near a work zone broadcasts TCMs to approaching vehicles to communicate that the road segment in the work zone has a reduced speed limit and that the lane immediately adjacent to the work zone is closed to heavy vehicles. CDA-equipped vehicles respond to each TCM with a TCM acknowledgment in the form of a mobility operation message so that infrastructure can alert work zone personnel if an approaching vehicle has not properly acknowledged a specific TCM.

The following messages are involved:

- TCR message.
- TCM.
- Mobility operation message.

Freight Emergency Response

A manually driven, connected ERV is actively being driven to an emergency. The ERV repeatedly broadcasts BSMs identifying itself as an active ERV and includes its future route destination points. Through either direct V2V communication or message-forwarding via vehicle-to-infrastructure, downstream CAVs receive the BSMs; adjust their trajectories, if necessary, to lane change out of the path of the approaching ERV; and reduce their speed when being actively passed by the ERV. If a CAV determines it is unable to change lanes to a desirable lane before the ERV gets close, the CAV broadcasts an emergency vehicle response message to warn the ERV that the CAV might be obstructing the ERV's path. The CAV will repeatedly broadcast the emergency vehicle response message until an emergency vehicle acknowledgment message is received.

The following messages are involved:

- BSM, with part II content and regional extensions.
- Emergency vehicle response message.
- Emergency vehicle acknowledgment message.

Yield and Situational Awareness: Cooperative Lane Change

CDA-equipped vehicles achieve cooperative driving by supporting proximity to one another. In this use case, vehicles cannot enter the merge lane unless they receive a positive response from the vehicle already in the lane. Vehicle A trying to merge into a lane with an existing vehicle B sends a request to merge into the lane. In the case of a positive response, vehicle A starts a lane merge into the adjacent lane, and vehicle B allows the incoming vehicle to join the lane by slowing down and maintaining a minimum gap. Cooperation among multiple participants in traffic can improve safety, mobility, situational awareness, and operations.

A mobility request message is sent with BSM information from the vehicle, the vehicle’s planned trajectory, and its maneuver plan. The mobility response message contains information about whether the lane merge was accepted. The mobility path message is used to plan around the position of obstacles the vehicle is trying to avoid.

The following messages are involved:

- BSM.
- Mobility request message.
- Mobility response message.
- Mobility path message.

Traffic Controls, or Geofence, Updates

Road operators use traffic control updates when using the road infrastructure to communicate changes to the local road. For example, changes can be emergency road closures, lane changes, speed changes, and enabling of selected road participants. CDA-equipped vehicles continuously send TCR messages—based on their travel route to the infrastructure—in order to receive TCMs that indicate any changes affecting their travel, as seen in other applications like the aforementioned freight work zone.

The following messages are involved:

- TCR message.
- TCM.

Cooperative Perception Vulnerable Road User

CDA-equipped infrastructure and vehicles use sensor data-sharing messages (SDSMs) and BSMs to share information about surroundings and about objects around the vehicle or infrastructure. That shared information can be received by another vehicle and combined with that vehicle's own sensor data to better understand the whole situation both vehicles are in. The second vehicle becomes aware of objects beyond its own perception range to help it safely travel through areas where unexpected conditions exist. CDA-equipped vehicles may also receive BSMs and pedestrian safety messages directly from connected vehicles and vulnerable road users that serve to prevent injuries caused by mixed use of road space. The use of BSMs expands upon previous cooperative perception work that has been done.

The following messages are involved:

- SDSM.
- BSM.
- Personal safety message.

MESSAGES

This section lists the messages that enable the applications the project team considered in this study and describes the purposes of the messages. For more information on which message is used by each application, see figure 1.

- **BSM** (SAE J2735™ standard) provides the status of a vehicle.
- **SPaT message** (SAE J2735™ standard) provides the status of the traffic signals at an intersection.
- **MAP message** (SAE J2735™ standard) provides the detailed lane-level geometry of a section of road—especially of intersections.
- **TCR message** (custom) requests periodic updates about the driving environment along a vehicle's current path of travel; the updates are sent from the vehicle to the infrastructure (CARMA Cloud).
- **TCM** (custom) responds to a TCR message describing traffic controls for vehicles to follow, such as a lane closure due to roadwork, advisory speeds, or platoon headway; the TCM is sent from infrastructure to vehicles in response to TCR messages.
- **Mobility operation message** (custom) provides the status of a vehicle and direction from CARMA Streets.
- **Mobility request message** (custom) starts negotiations for a cooperative maneuver between CAVs.
- **Mobility path message** (custom) provides the status and intent of a vehicle.

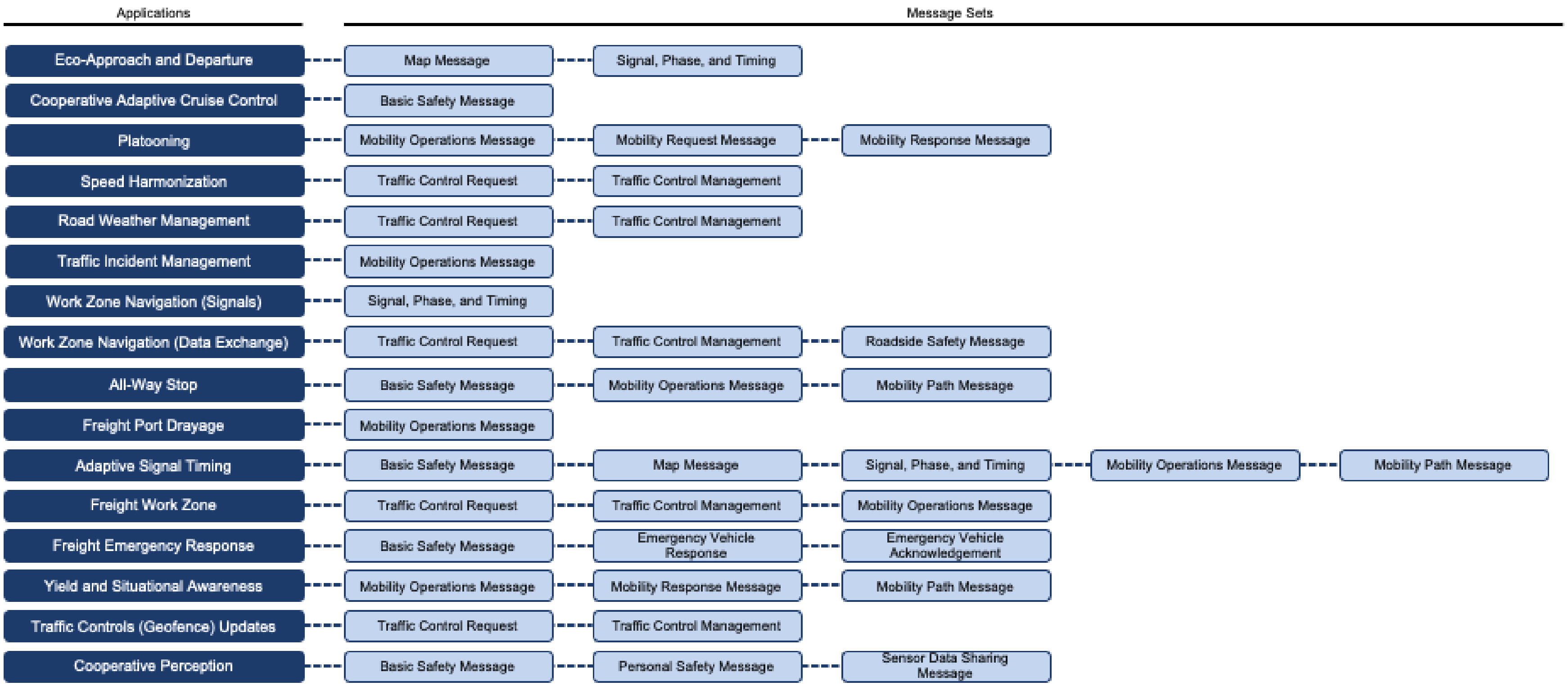
- **Mobility response message** (custom) responds to an incoming request in order to accept or deny a join or depart request.

- **Personal safety message** (SAE J2735™ standard) provides the status and intent of a vulnerable road user.

- **SDSM** (SAE J3224™ standard) contains details about objects detected by a vehicle.

- **Emergency vehicle response message** (custom) indicates a vehicle's actions in response to an approaching emergency vehicle such as "Cannot move over."

- **Emergency vehicle acknowledgment message** (custom) acknowledges receipt of an emergency vehicle response message.



Applications	Message Sets				
Eco-Approach and Departure	Map Message	Signal, Phase, and Timing			
Cooperative Adaptive Cruise Control	Basic Safety Message				
Platooning	Mobility Operations Message	Mobility Request Message	Mobility Response Message		
Speed Harmonization	Traffic Control Request	Traffic Control Management			
Road Weather Management	Traffic Control Request	Traffic Control Management			
Traffic Incident Management	Mobility Operations Message				
Work Zone Navigation (Signals)	Signal, Phase, and Timing				
Work Zone Navigation (Data Exchange)	Traffic Control Request	Traffic Control Management	Roadside Safety Message		
All-Way Stop	Basic Safety Message	Mobility Operations Message	Mobility Path Message		
Freight Port Drayage	Mobility Operations Message				
Adaptive Signal Timing	Basic Safety Message	Map Message	Signal, Phase, and Timing	Mobility Operations Message	Mobility Path Message
Freight Work Zone	Traffic Control Request	Traffic Control Management	Mobility Operations Message		
Freight Emergency Response	Basic Safety Message	Emergency Vehicle Response	Emergency Vehicle Acknowledgement		
Yield and Situational Awareness	Mobility Operations Message	Mobility Response Message	Mobility Path Message		
Traffic Controls (Geofence) Updates	Traffic Control Request	Traffic Control Management			
Cooperative Perception	Basic Safety Message	Personal Safety Message	Sensor Data Sharing Message		

Source: FHWA.

Figure 1. Illustration. Mapping of V2X messages to the CDA applications that use them.

CHAPTER 3. CDA SCENARIOS

To determine spectrum needs for the applications described in chapter 2, the project team conceived several scenarios. In each scenario, the team considered various factors that would create an environment in which the demand for spectrum would be high. One or more applications are active in each scenario, and a high number of participants (e.g., road users and infrastructure elements) exist. For the most part, the applications follow the framework defined by SAE International for automated driving systems (SAE International 2021) and CDA (SAE International 2020b). This chapter describes the scenarios considered for the analysis.

GENERAL ASSUMPTIONS

A set of assumptions was created to frame each scenario. Assumptions specific to each scenario are outlined within that scenario's description. Table 1 lists the general assumptions that apply to all scenarios.

Table 1. General assumptions that apply to all scenarios.

Item	Description	Value
Vehicle length	Length of each vehicle on the roadway, which is a determining factor in traffic density	5 m
Standstill gap	Distance from the rear bumper of the preceding vehicle to the front bumper of the following vehicle, which is a determining factor in traffic density	3 m
Vehicle headway (typical)	Difference in arrival time between the front bumper of the preceding vehicle and the front bumper of the following vehicle, which is a determining factor in traffic density	1.2 s
CAV penetration rate	Ratio of CAVs to nonconnected and/or nonautomated vehicles on the roadway	100 percent
Vehicle acceleration	The vehicles in each scenario, which are assumed to be in steady state and so, traveling at a constant speed	0 m/s^2

In general, a highway will have six lanes traveling in the same direction and six lanes traveling in the opposite direction, with a median in the middle. The speed of all vehicles will be constant and is the main parameter that changes in these tests. Conversely, an arterial will have three lanes traveling in the same direction. To simplify the calculation, vehicles traveling east to west will have the green light and will travel at a constant speed. Vehicles traveling north to south will have the red light and will be stopped. The queue length will be half the distance to the prior intersection.

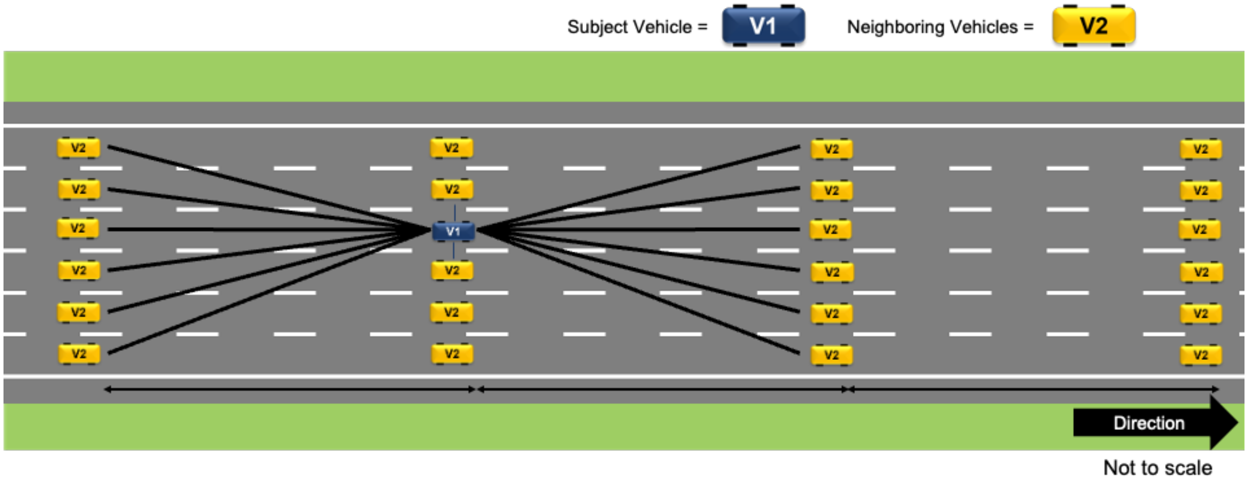
A vehicle's headway is nominally set to 1.2 seconds, vehicle length is 5 m, and standstill gap is 3 m. The total number of vehicles in the communication range calculated is based on vehicle length, standard gap, and vehicle headway to the other vehicle.

In addition to the scenario-specific messages, it is assumed that all vehicles are broadcasting a standard BSM.

SCENARIO 1: COOPERATIVE PERCEPTION

In this scenario, cooperative perception is running on each vehicle driving on a highway. It is assumed that vehicles traveling on the highway are uniformly distributed in straight lines, parallel with one another to allow for a clear view of a maximum number of surrounding vehicles. It is also assumed that the median in between the two opposing traffic lanes will block additional object detections from the opposite side. The assumptions simplify the number of objects detected to 14 or 13 for each vehicle, depending on whether the subject vehicle is traveling in a middle lane or an outer lane. Each vehicle can detect six vehicles in front, six vehicles behind, and one or two adjacent vehicles—on the left and/or right—depending on which lane the vehicle is in. Figure 2 illustrates in more detail both that scenario and total number of objects detected.

The messages pertaining to this scenario are SDSMs, which contain object detection information, BSM, mobility path message, and mobility operations message. No roadside unit (RSU) is present in this scenario.



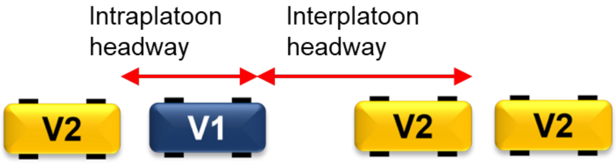
Source: FHWA.

Figure 2. Illustration. Distribution of vehicles considered in the cooperative perception scenario and the lines of sight to neighboring vehicles.

SCENARIO 2: LARGE-SCALE PLATOONING

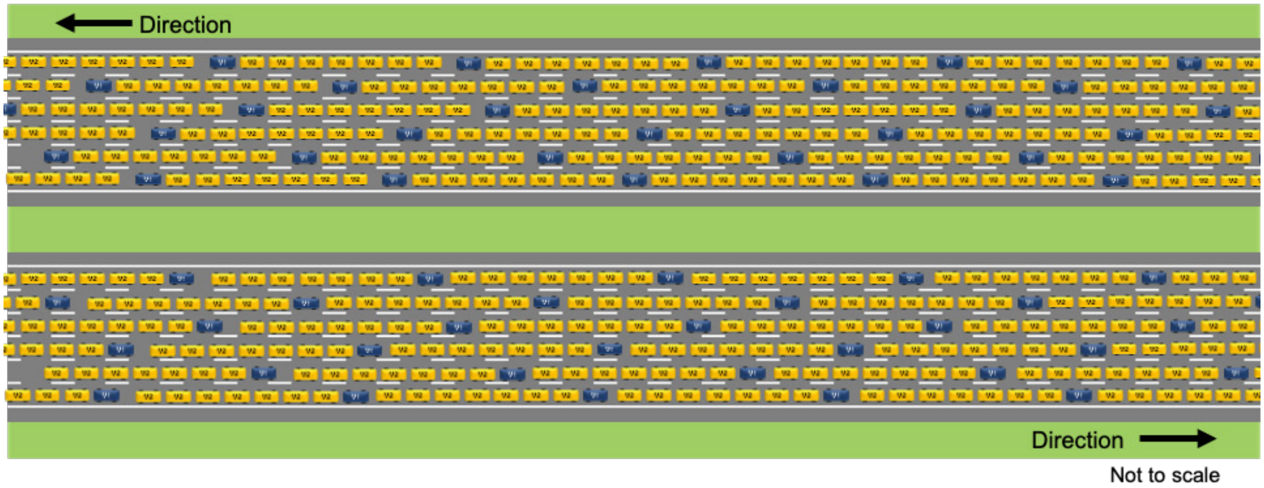
In this scenario, platooning was running on every vehicle driving on a highway as shown in figure 4. It is assumed that every vehicle on the highway is a part of a platoon as either the leader or a follower and that the maximum size of each platoon is eight vehicles. Eight vehicles are considered an average platoon length on a stretch of highway that allows 10-vehicle platoons. For these vehicles, the interplatoon headway is set to 1.2 seconds, while the intraplatoon headway is 0.6 seconds. That difference between intra- and interplatooning is illustrated in figure 3.

The messages pertaining to this scenario are BSM, mobility path message, and mobility operation message. No RSU is present in this scenario.



Source: FHWA.

Figure 3. Illustration. Types of headways considered in the platooning scenario.



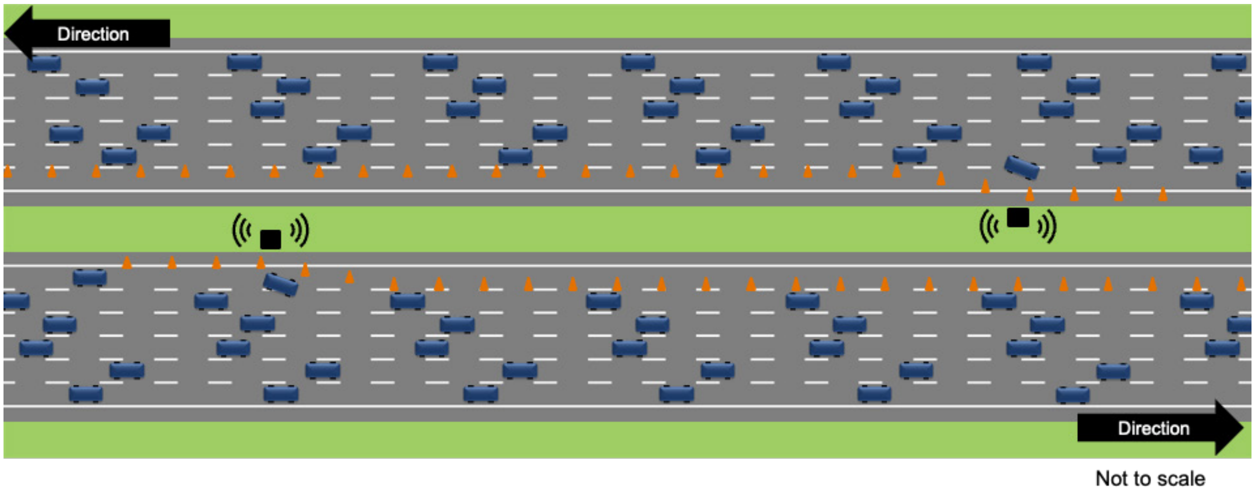
Source: FHWA.

Figure 4. Illustration. Distribution of vehicles considered in the platooning scenario.

SCENARIO 3: WORK ZONE WITH SPEED HARMONIZATION

In this scenario, a work zone is positioned so that it closes the inner lane alongside the median on each side of a highway. As a result of the lane closure, the six lanes in each direction have been reduced to five lanes in each direction, as illustrated in figure 5. For the length of the work zone, the roadway has a reduced speed limit that applies to the entire area of interest. Two RSUs are positioned in the median toward the beginning of the work zone on each side of the highway. The RSUs communicate to the vehicles the messages from CARMA Streets about the geofence, which closes one lane on the highway and imposes a speed reduction for all vehicles traveling on the highway.

The messages pertaining to this scenario are BSM, TCR message, TCM, mobility path message, and mobility operation message. Two RSUs are present in this scenario.



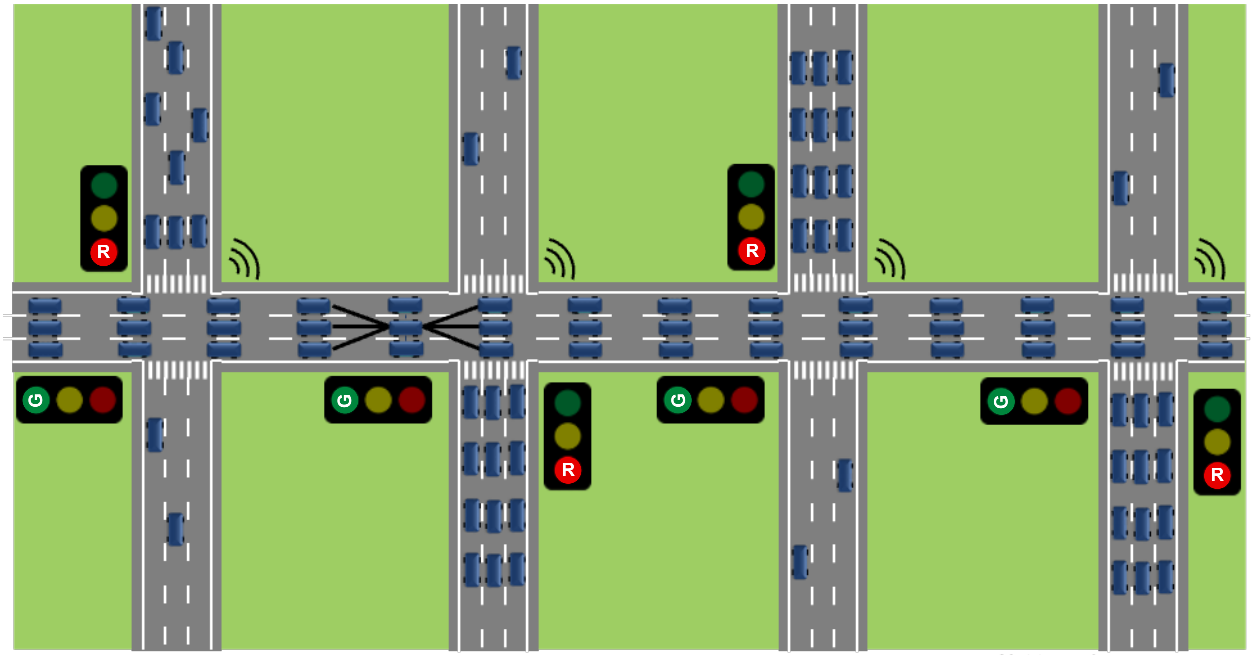
Source: FHWA.

Figure 5. Illustration. Distribution of vehicles considered in the work zone scenario.

SCENARIO 4: DENSE URBAN

The dense urban scenario consists of a grid of roads. Each road has multiple lanes with a single direction of travel. Vehicles traveling north to south or south to north are stopped at a red light, while vehicles traveling east to west or west to east are traveling in free flow through a green light. Vehicles stopped at a red light have a queue length that is half the distance to the intersection behind it. Vehicles traveling east to west are traveling at 30 mph with standard headway distances. This gridlike pattern is repeated in each direction until the maximum range from an RSU positioned at the center. The length between intersections from east to west is the same as the length between intersections from north to south. The grid spacing was selected from a survey of U.S. cities and from guidance from the Signalized Intersections Informational Guide (Chandler et al. 2013).

The messages pertaining to this scenario are BSM, SPaT message, MAP message, TCR message, TCM, mobility path message, and mobility operation message. In this scenario, every intersection is equipped with an RSU.



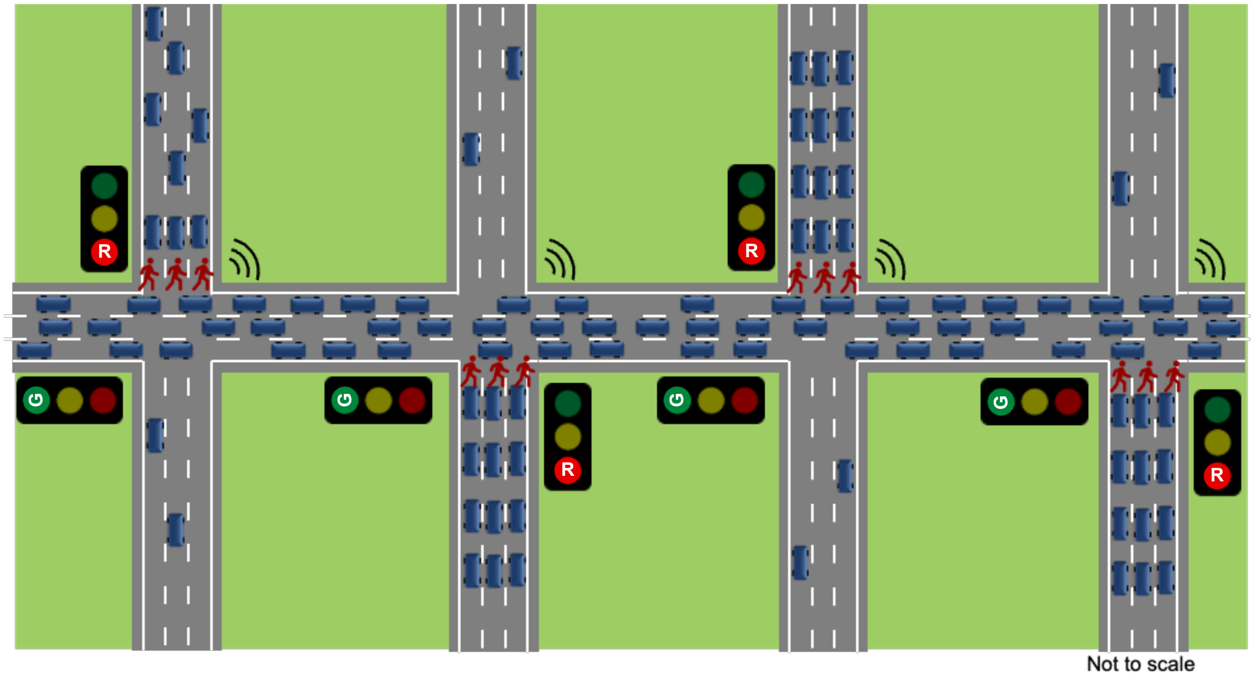
Source: FHWA.

Figure 6. Illustration. Distribution of vehicles considered in the closely spaced intersection scenario.

SCENARIO 5: COMBINED SCENARIO: DENSE URBAN AND COOPERATIVE PERCEPTION

In this scenario, cooperative perception is running on each vehicle present in the dense urban model in scenario 4. All assumptions in scenario 4 are kept in this scenario, particularly pertaining to the intersection setup and vehicle locations. The assumptions in scenario 1 are similar in this scenario, but because the lanes have been reduced from six to three in this scenario, the number of vehicles detected for each vehicle has changed accordingly. An added assumption in this scenario is that 15 pedestrians are in the crosswalk at every red intersection, which increases the number of objects detected by the first row of vehicles sitting at the red light at each intersection. The scenario also assumes that each vehicle traveling in the outer lane of the east–west road can also detect the pedestrians, which can be assumed for all vehicles in one single lane, because a vehicle that did not detect the pedestrians in the previous intersection should be able to detect the pedestrians at the next intersection. This scenario and number of pedestrians are illustrated in figure 7.

The messages pertaining to this scenario are BSMs, SPaT messages, MAP messages, TCR messages, TCMs, SDSMs, mobility path messages, and mobility operation messages. In this scenario, an RSU is placed at every intersection.



Source: FHWA.

Figure 7. Illustration. Vehicle distribution considered in the combined closely spaced intersection and cooperative perception scenario.

CHAPTER 4. ANALYSIS OF SPECTRUM NEEDS

METHODOLOGY

This study performs a quantitative analysis of the spectrum needs of CDA applications developed at STOL. The analysis relies on characteristics of the messages used in those applications. This section outlines the processes used in compiling and addressing the data presented in preceding chapters.

After compilation of the list of applications and messages and development of the scenarios, the spectrum usage within those scenarios could be calculated. The project team considered a limited number of variables in the analysis, shown in table 2. To limit the scope of the analysis, the team limited the number of permutations of these variables to one or two options.

Table 2. Assumptions made for analysis.

Variable	Value	Effect
Message size	Typical maximum	Message size relates to how much bandwidth an over-the-air packet consumes—larger messages use more bandwidth.
Message transmit interval	Typical	Message transmit interval relates to how often messages are sent—shorter interval uses more bandwidth, and vice versa.
Modulation coding scheme (MCS)	MCS 7 or 11 (IEEE 2021)	MCS determines the capacity of the channel and is generally inversely proportional to the range—higher MCS index yields lower signal-to-noise ratio and shorter range. (FCC 2016)
Signing	Yes	Signing adds Institute of Electrical and Electronics Engineers (IEEE) 1609.2 security content to the over-the-air packet. (IEEE 2016)
Transmit power	23 decibel-milliwatts	Transmit power will affect the reception range of the message and is a key factor in how many transmitters will be considered in a given scenario.
Hybrid automatic repeat request (HARQ)	Yes	HARQ repeats the message to increase the packet success ratio but generally doubles the required spectrum.
Congestion mitigation	No	Congestion mitigation algorithms are responsible for reducing the spectrum needs under congested conditions by increasing transmit interval, reducing power, or applying other methods.
Communication technology	C-V2X (SAE 2022)	C-V2X is the primary channel allocated by the FCC for V2X communication going forward (Qualcomm 2019).

In the foregoing scenarios, the project team calculated the number of vehicles present in two different environments: highway model and dense urban model. For both models, a vehicle length of 5 m and a vehicle standstill gap of 3 m were used. For stationary vehicles—like those present at intersections in scenarios 4 and 5—those two numbers alone determined how many vehicles occupied the available space, which was selected to be half the distance to the next intersection.

For vehicles traveling at a constant speed along a road, a vehicle's headway was used. The team calculated headway distance for each vehicle based on the distance each vehicle would travel during the headway time at its current speed. The total space within a lane that each vehicle occupied is the sum of headway distance, vehicle length, and standstill gap. The team calculated the total number of vehicles based on total length of the roadway within the communication range multiplied by the number of lanes divided by the total space each vehicle used.

After finding the total number of vehicles present in each scenario, the team had to calculate the number of messages per vehicle. The different messages used in each scenario are described in the scenario sections in chapter 3. The size and frequency of messages of the same type are assumed to be the same, and the values used in this calculation can be found in table 3. One exception is SDSM, because the content of that message depends on the number of objects that surround the vehicle. The size of an SDSM is approximately 50 bytes for the header plus 30 bytes per object detected.

By means of total number of vehicles in a scenario and number of messages per vehicle, the total number of messages per scenario can be calculated. A similar process was repeated for RSUs. Figure 8 and figure 9 give the number of vehicles per meter and total number of vehicles in the highway model, respectively.

$$Veh\_per\_m = \frac{1}{5 + 3 + headway * speed}$$

Figure 8. Equation. Number of vehicles per meter in the highway model.

$$Veh\_in\_roadway = Veh\_per\_m * radio\_radius * 2 * num\_lanes$$

Figure 9. Equation. Number of total vehicles in one RSU range in the highway model.

Figure 10 and figure 11 give the number of vehicles per meter and total number of vehicles in the dense urban model, respectively.

$$stopped\_Veh/m = Veh\_per\_m(speed = 0) * (\frac{intersection\_spacing}{2} - intersection\_width)$$

Figure 10. Equation. Number of vehicles per meter stopped at the intersection.

$$Veh\_in\_intersection = Veh\_per\_m * intersection\_spacing + stopped\_Veh/m$$

Figure 11. Equation. Number of total vehicles in one RSU range in the dense urban model.

The following list describes the calculations for message sizes in each case:

- Calculation for message size per vehicle for cooperative perception: Each vehicle sends out BSMs at 10 Hz, mobility path messages at 10 Hz, TCR messages at 1 Hz, and SDSMs for detections at 10 Hz. Each SDSM has 13 detections for vehicles in the outer lanes and 14 detections for vehicles in the inner lanes.

- Calculation for message size per vehicle for platooning: Each vehicle sends out BSMs at 10 Hz, mobility path messages at 10 Hz, mobility operation messages at 10 Hz, and TCR messages at 1 Hz.

- Calculation for message size per vehicle for work zone: Each vehicle sends out BSMs at 10 Hz, mobility path messages at 10 Hz, and TCR messages at 1 Hz. Each vehicle also receives TCMs from the RSU at 1 Hz.

- Calculation for message size per vehicle for arterial or intersection: Each vehicle sends out BSMs at 10 Hz, mobility path messages at 10 Hz, and TCR messages at 1 Hz. Each vehicle also receives SPaT messages at 10 Hz and MAP messages at 1 Hz from each RSU in range.

Figure 12 gives the total number of intersections, which was calculated by dividing the area of the RSU range by the area taken up by each intersection grid square. The calculation does not compute exactly the number of intersections located in each specific RSU range circle but, rather, computes the average number of intersections covered by each RSU. The calculation also accounts for the fact that there may be intersections just outside the circle with vehicles still inside or vice versa.

$$num\_intersections = \frac{\pi * radio\_radius^2}{intersection\_spacing^2}$$

Figure 12. Equation. Number of intersections within the RSU's range in the dense urban model.

- Calculation for message size per vehicle for CP + intersection: Each vehicle sends out BSMs at 10 Hz, mobility path messages at 10 Hz, TCR messages at 1 Hz, and SDSMs for detections at 10 Hz. Each vehicle also receives SPaT messages at 10 Hz and MAP messages at 1 Hz from each RSU in range.

Because the number of detections for each vehicle is more complicated in this example, the drivers have been divided into the following five groups for simplification:

- Vehicles in the outer lanes of the east–west road detect vehicles waiting at the stop bar on the north–south road in addition to vehicles in the surrounding travel lanes, as in the cooperative perception scenario. These vehicles also detect 15 pedestrians in each crosswalk.
- Vehicles in the middle lanes of the east–west road detect vehicles in the surrounding travel lanes, as in the cooperative perception scenario.
- Vehicles waiting at the stop bar of the north–south road detect all the vehicles in the closest lane on the east–west road driving in front of them and the 15 pedestrians in the crosswalk in front of them. They also detect vehicles behind them stopped in the surrounding lanes.
- Vehicles in the outer lanes of the north–south road—not including the front row—detect vehicles stopped in the surrounding lanes, as in the cooperative perception scenario.
- Vehicles in the inner lanes of the north–south road—not including the front row—detect vehicles stopped in the surrounding lanes, as in the cooperative perception scenario.

Message Characteristics

To calculate channel usage for a given scenario, the project team determined the message characteristics for each application by surveying the STOL development team. The project team used logs from prior testing or analysis based on message structure and contents to estimate minimum, maximum, and typical messages’ sizes and minimum, maximum, and typical transmit intervals. For this study, the typical and maximum message sizes and typical transmit intervals were used to obtain a more conservative estimate of demand (table 3). This same analysis was conducted for each scenario but only for safety messages—to find the minimum required channel usage needed.

Table 3. V2X message characteristics.

Message Type	Typical Transmit Frequency (Hz)	Typical Size (bytes)	Maximum Size (bytes)	Safety Message
TCR	1	90	90	No
TCM	1	130	130	No
SPaT	10	320	1,400	Yes
MAP	1	500	1,400	No
BSM	10	320	1,400	Yes
Personal safety message	10	320	1,400	Yes
SDSM	10	370	1,400	Yes
Mobility path	10	500	500	No
Mobility request	10	200	200	No
Mobility response	10	100	100	No
Mobility operation	10	200	200	No
RSM	1	To be determined (TBD)	TBD	No
Emergency vehicle response	Not applicable	TBD	TBD	No
Emergency vehicle acknowledgment	Not applicable	TBD	TBD	No

Note: Emergency vehicle response messages and emergency vehicle acknowledgment messages are still in development and are not transmitted at regular intervals.

Channel Capacity

For this study, a single, 20-megahertz (MHz) C-V2X channel was considered, which is the primary allocation currently provided by the FCC. The capacity of the channel is driven by various factors laid out within the 3rd Generation Partnership Project and IEEE standards. The MCS used by the radios is a primary driver of the capacity, and the MCS index describes the density of data within the channel. Under the best channel conditions (i.e., high signal-to-noise ratio), MCS 11 may be used, which allows 135 megabits per second (Mbps)—theoretically. As channel conditions degrade, radios may fall back to a lower MCS index to achieve better range. In addition to MCS 11, this study considered MCS 7, which gives a theoretical capacity of 81 Mbps. In practice, lower coding schemes may also be used.

In addition to the MCS index, the use of HARQ affects channel capacity. With HARQ enabled, each message is sent twice, which increases the packet success rate but doubles the number of spectrum resources consumed by a given message. Since this study considers HARQ to be enabled in all cases, the effective capacity is reduced to 67.5 Mbps for MCS 11 and by 40.5 Mbps for MCS 7.

Communication Range

The communication range used in each test case is based on values given by industry and confirmed through limited testing at STOL (Rayamajhi et al. 2020). Those values are provided in table 4. Although the nominal range of a V2X device is usually considered to be 100 m, the practical range has been seen to be much larger depending on the environment. Thus, the values in table 4 reflect that performance.

Table 4. Typical communication range of V2X devices in different environments.

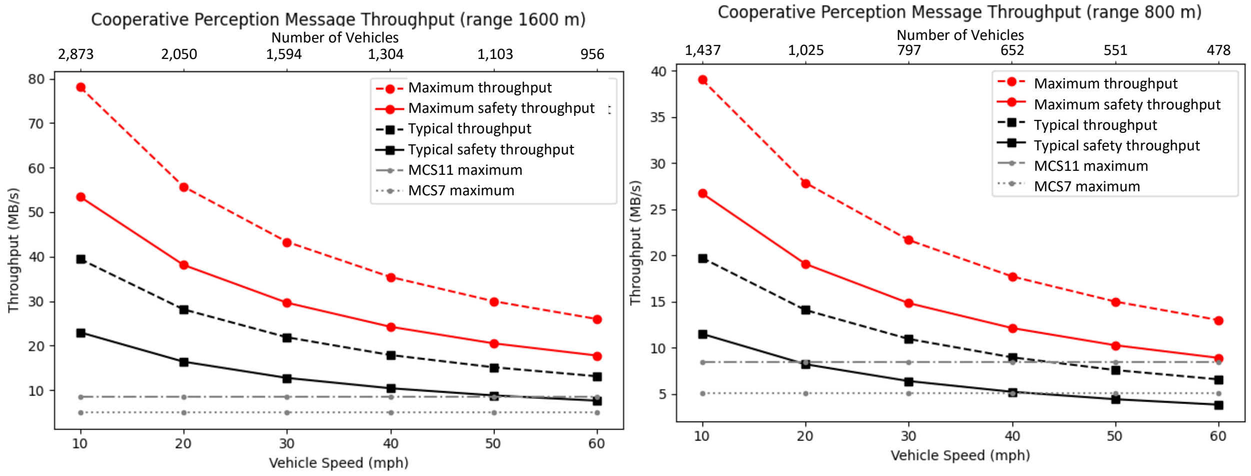
Environment	Line-of-Sight Range (m)	Non-Line-of-Sight Range (m)
Highway	1,600	800
Urban	400	230

RESULTS

This section provides the spectrum demand for scenarios 1–5. In general, the traces in the graphs are functions of the density of the vehicles on the roadway. In the highway case, traffic density increases as speed increases since the time headway is taken to be a constant value. The same is true in an arterial or intersection case, but since those scenarios consider a portion of vehicles stopped at red lights, traffic density increases as density of intersections increases. For each scenario, the maximum message size and the safety message size are plotted along with the maximum throughput. The safety messages, as defined in table 3, are considered the minimums required for each scenario to operate safely.

Cooperative Perception Scenario

Figure 13 shows expected demand for spectrum from the cooperative perception highway scenario. Four traces are shown: the red, dashed line with circles uses the maximum expected message size; the red, solid line with circles uses the maximum safety message size; the black, dashed line with squares uses the typical safety message size; and the black, solid line with squares uses the typical message size. Both the dotted and dash-dotted lines show the available bandwidth for MCS index 7 and 11, respectively. In both cases, more spectrum is demanded than is available, except for the 800-m communication range using MCS 11, shown in figure 13-B. Since the scenario is based on a highway environment, the results at lower operating speeds are not as relevant as those at freeway speeds. When the cooperative perception concept is being considered, data sharing at lower speeds on a limited-access roadway is not as important as data sharing at higher speeds.



Source: FHWA.
MB/s = megabytes per second.

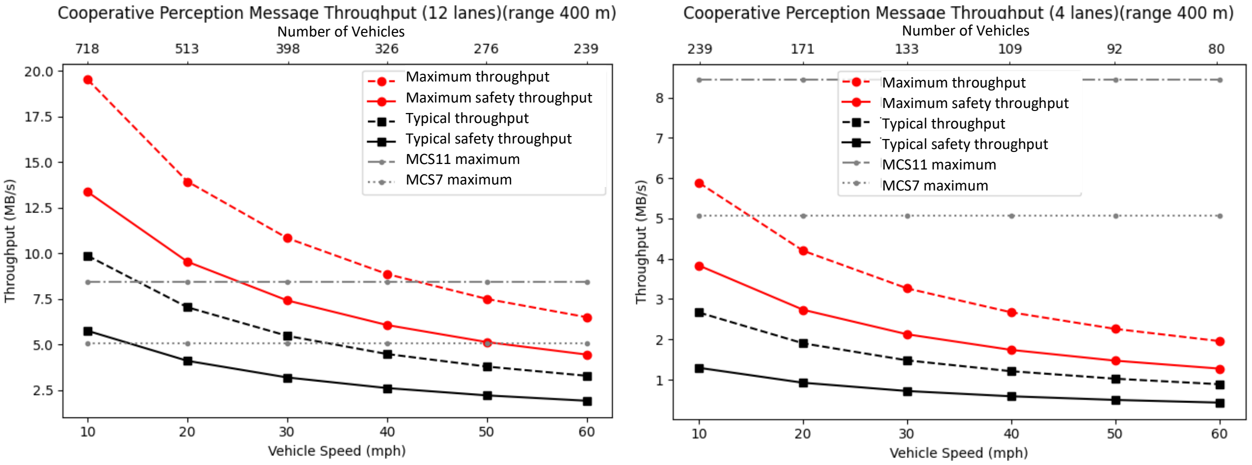
Source: FHWA.

A. Scenario 1 results: 12 lanes, 1,600 m.

B. Scenario 1 results: 12 lanes, 800 m.

Figure 13. Graphs. Expected spectrum demand for the cooperative perception scenario for range of 1,600 m (A) and 800 m (B).

Figure 14 shows how this scenario could function within the bandwidth constraints with adjusted parameters. The lanes would have to be reduced from 12 (6 lanes in each direction) to 4 (2 lanes in each direction), and the RSU's communication range would have to be reduced to 400 m. With those adjustments to the scenario, every line was under the MCS 7 maximum, except the maximum throughput, which was between the MCS 11 maximum and MSC 7 maximum at only 10 mph and below the MSC 7 maximum for 20 mph.



Source: FHWA.

Source: FHWA.

A. Scenario 1 results: 12 lanes, 400 m.

B. Scenario 1 results: 4 lanes, 400 m.

Figure 14. Graphs. Expected spectrum demand for the cooperative perception scenario with reduced lane number, four lanes, and communication range of 400 m.

The research team incrementally adjusted the initial parameters for this scenario and stopped after reaching reasonable initial conditions that allow for typical throughput messages to be within safety standards. The results of the preceding plots have been simplified to show when all messages in the scenario and only the safety messages are within MCS 11 and MCS 7 standards for message throughput for typical message size, shown in table 5, and maximum message size, shown in table 6.

Table 5. Conditions that support cooperative perception at typical throughput.

Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 1,600	None	None	Speed >50 mph	None
Six lanes in each direction; comm range 800	Speed >40 mph	None	Speed >20 mph	Speed >40 mph
Six lanes in each direction; comm range 400	Speed >14 mph	Speed >34 mph	All speeds	Speed >13 mph
Two lanes in each direction; comm range 400	All speeds	All speeds	All speeds	All speeds

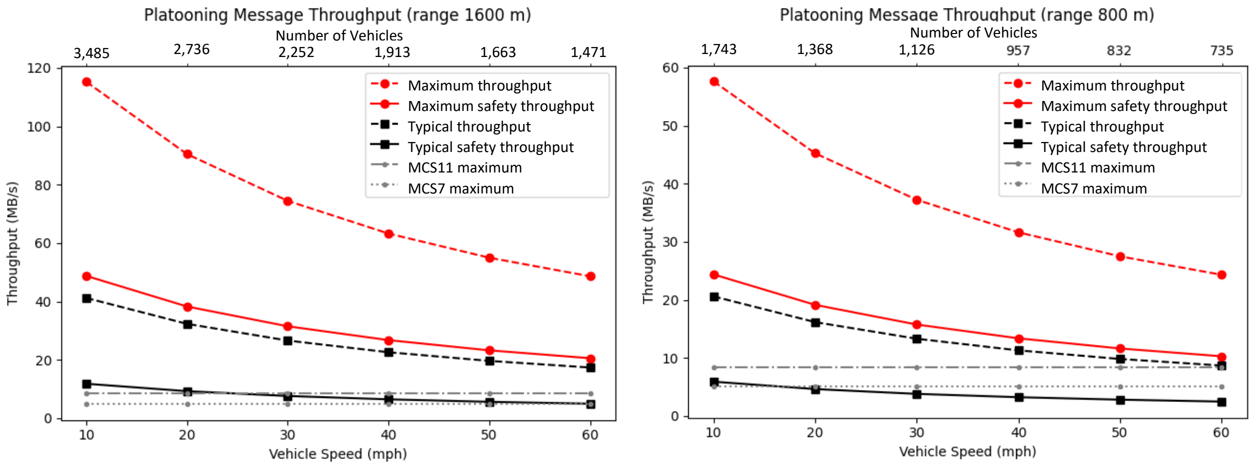
comm = communication.

Table 6. Conditions that support cooperative perception at maximum throughput.

Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 1,600	None	None	None	None
Six lanes in each direction; comm range 800	None	None	Speed >60 mph	None
Six lanes in each direction; comm range 400	Speed >42 mph	None	Speed >25 mph	Speed >50 mph
Two lanes in each direction; comm range 400	Speed >15 mph	All speeds	All speeds	All speeds

Large-Scale Platooning Scenario

Figure 15 shows the expected demand for spectrum from the platooning highway scenario. Four traces are shown: the red, dashed line with circles uses the maximum expected message size; the red, solid line with circles uses the maximum safety message size; the black, dashed line with squares uses the typical safety message size; and the black, solid line with squares uses the typical message size. The dotted and dash-dotted lines both show the available bandwidth for MCS index 7 and MCS index 11, respectively. In both cases, more spectrum is demanded than is available. Because the scenario is based on a highway environment, the results at lower operating speeds are not as relevant as those at freeway speeds.



Source: FHWA.

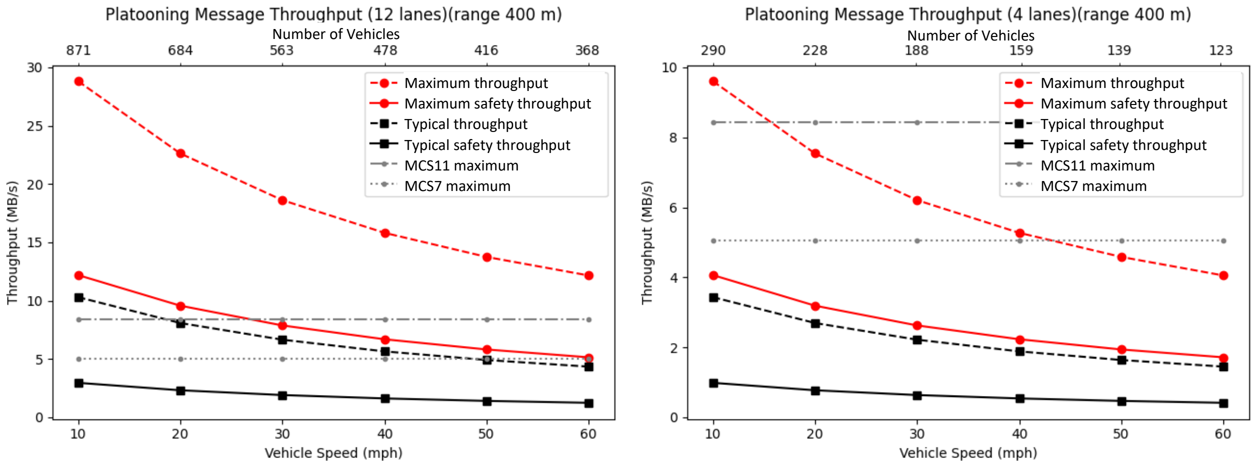
Source: FHWA.

A. Scenario 2 results: 12 lanes, 1,600 m.

B. Scenario 2 results: 12 lanes, 800 m.

Figure 15. Graphs. Expected spectrum demand for the platooning scenario for communication range of 1,600 m (A) and 800 m (B).

Figure 16 shows how this scenario could function within the bandwidth constraints with adjusted parameters. The lanes would have to be reduced from 12 (6 lanes in each direction) to 4 (2 lanes in each direction), and the RSU's communication range would have to be reduced to 400 m. With those adjustments to the scenario, every line was under the MCS 7 maximum, except the maximum throughput, which was between the MCS 11 maximum and MSC 7 maximum for all speeds up to 50 mph.



Source: FHWA.

Source: FHWA.

A. Scenario 2 results: 12 lanes, 400 m.

B. Scenario 2 results: 4 lanes, 400 m.

Figure 16. Graphs. Expected spectrum demand for the platooning scenario with reduction in number of lanes and communication range.

The research team incrementally adjusted the initial parameters for this scenario and stopped after reaching reasonable initial conditions that allow for the typical throughput messages to be within safety standards. The results of the preceding plots have been simplified to show when all messages in the scenario and only the safety messages are within MCS 11 and MCS 7 standards for message throughput for typical message size, shown in table 7, and maximum message size, shown in table 8.

Table 7. Conditions that support platooning at the typical throughput.

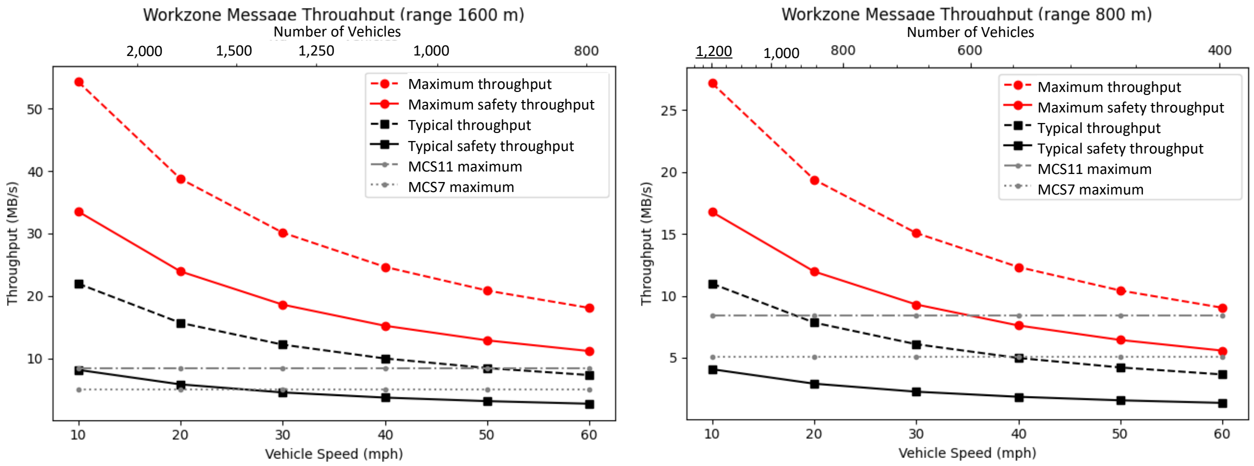
Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 1,600	None	None	Speed >26 mph	Speed >59 mph
Six lanes in each direction; comm range 800	Speed >60 mph	None	All speeds	Speed >16 mph
Six lanes in each direction; comm range 400	Speed >18 mph	Speed >49 mph	All speeds	All speeds
Two lanes in each direction; comm range 400	All speeds	All speeds	All speeds	All speeds

Table 8. Conditions that support platooning at maximum throughput.

Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 1,600	None	None	None	None
Six lanes in each direction; comm range 800	None	None	None	None
Six lanes in each direction; comm range 400	None	None	Speed >26 mph	Speed >60 mph
Two lanes in each direction; comm range 400	Speed >16 mph	Speed >43 mph	All speeds	All speeds

Work Zone with Speed Harmonization Scenario

Figure 17 shows the expected demand for spectrum from the work zone highway scenario. Four traces are shown: the red, dashed line with circles uses the maximum expected message size; the red, solid line with circles uses the maximum safety message size; the black, dashed line with squares uses the typical safety message size; and the black, solid line with squares uses the typical message size. The dotted and dash-dotted lines both show the available bandwidth for MCS index 7 and MCS index 11, respectively. In both cases, using the maximum expected message size demands more spectrum than is available, except for safety messages only with the 800-m communication range. However, with the typical message size and 800-m communication range, MCS 11 provides enough bandwidth for all vehicles present, as shown in figure 17-B, and the typical safety message size and 1,600-m range, as shown in figure 17-A.



Source: FHWA.

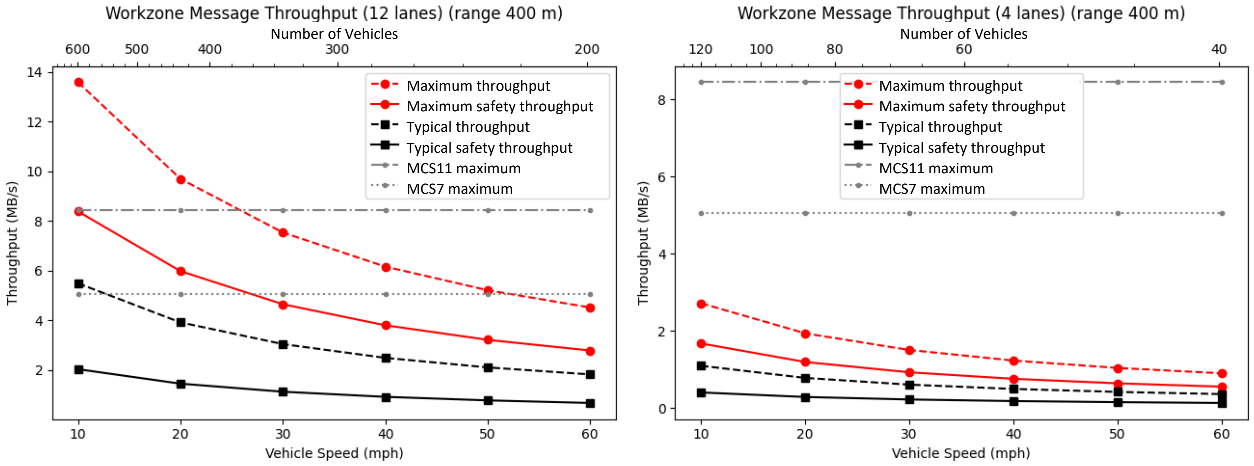
Source: FHWA.

A. Scenario 3 Results – 12 lanes, 1600 m

B. Scenario 3 Results – 12 lanes, 800 m

Figure 17. Graphs. Expected spectrum demand for the work zone scenario for communication range of 1,600 m (A) and 800 m (B).

Figure 18 shows how this scenario could function within the bandwidth constraints with adjusted parameters. With the lanes reduced from 12 (six lanes each direction) to four (two lanes each direction), most points fall within the capacity for MCS 11, as shown in figure 18-A. Going a step further and reducing the RSU's communication range to 400 m, every line was under the MCS 7 maximum, as shown in figure 18-B.



Source: FHWA.

Source: FHWA.

A. Scenario 3 Results – 12 lanes, 400 m

B. Scenario 3 Results – 4 lanes, 400 m

Figure 18. Graphs. Expected spectrum demand for the work zone scenario with reduction in number of lanes and communication range.

The research team incrementally adjusted the initial parameters for this scenario and stopped after reaching reasonable initial conditions that allow for the typical throughput messages to be within Safety Standards. The results of the preceding plots have been simplified to show when all messages in the scenario and only the safety messages are within MCs 11 and MCS 7 standards for message throughput for typical message size, shown in table 9, and maximum message size, shown in table 10.

Table 9. Conditions that support work zone at typical throughput.

Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 1,600	Speed >50 mph	None	All speeds	Speed >27 mph
Six lanes in each direction; comm range 800	Speed >17 mph	Speed >39 mph	All speeds	All speeds
Six lanes in each direction; comm range 400	All speeds	Speed >13 mph	All speeds	All speeds
Two lanes in each direction; comm range 400	All speeds	All speeds	All speeds	All speeds

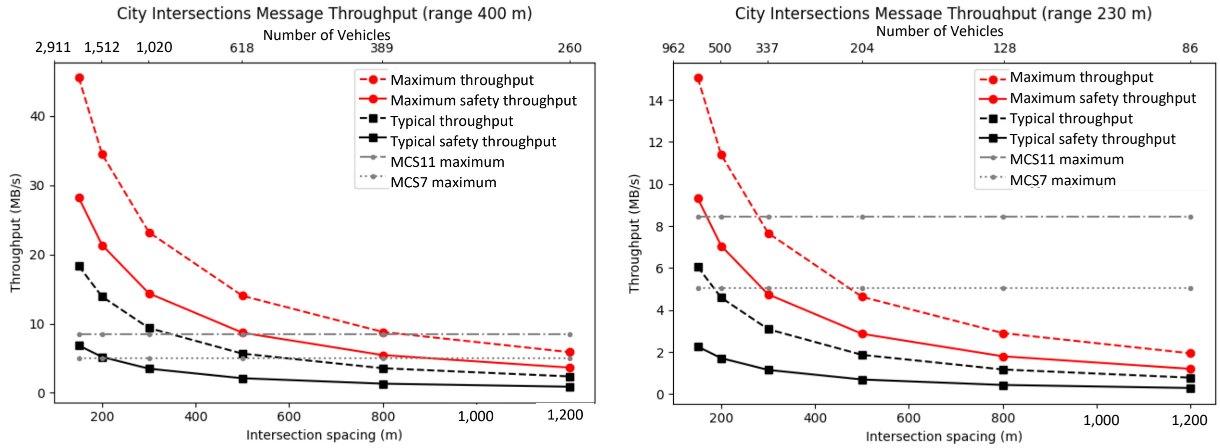
Table 10. Conditions that support work zone at maximum throughput.

Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 1,600	None	None	None	None
Six lanes in each direction; comm range 800	None	None	Speed >36 mph	None
Six lanes in each direction; comm range 400	Speed >26 mph	Speed >52 mph	Speed >10 mph	Speed >27 mph
Two lanes in each direction; comm range 400	All speeds	All speeds	All speeds	All speeds

Dense Urban Scenario

Figure 19 shows the expected demand for spectrum from the dense urban scenario. Four traces are shown: the red, dashed line with circles uses the maximum expected message size; the red, solid line with circles uses the maximum safety message size; the black, dashed line with squares uses the typical safety message size; and the black, solid line with squares uses the typical message size. The dotted and dash-dotted lines both show the available bandwidth for MCS index 7 and 11, respectively. For the larger 400-m communication range, MCS 11 can accommodate most of the wireless traffic at the typical message size—above roughly 360-m intersection spacing—and MCS 7 can accommodate most of the wireless traffic at the typical safety message size—above 200-m intersection spacing. For the smaller, 230-m communication range, MCS 7 can accommodate most of the wireless traffic for the typical message size, and

MCS 11 can accommodate most of the wireless traffic for the maximum message size. The recommended minimum spacing for signalized intersections is 400 m, although city blocks as short as 160 m, or shorter, exist.



Source: FHWA.

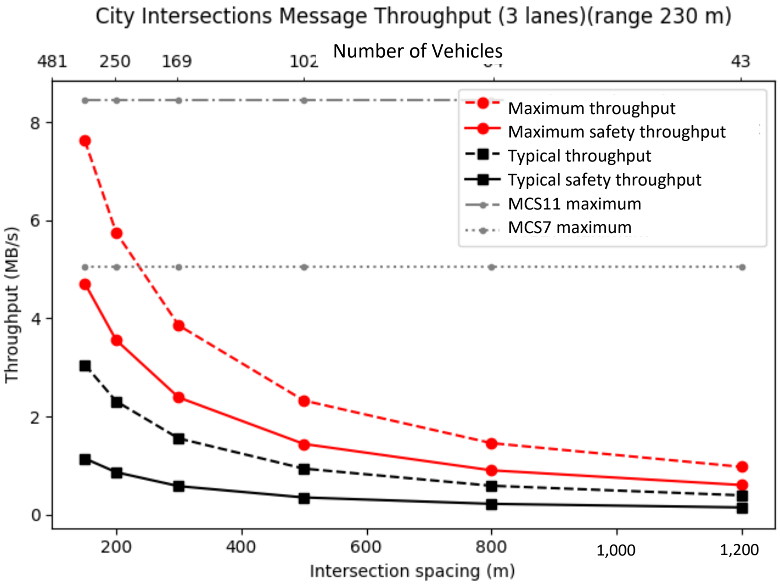
Source: FHWA.

A. Scenario 4 Results – 6 lane, 400 m

B. Scenario 4 Results – 6 lane, 230 m

Figure 19. Graphs. Expected spectrum demand for the dense urban scenario for communication range of 400 m (A) and 230 m (B).

Figure 20 shows how this scenario could function within the bandwidth constraints with adjusted parameters. The lanes would have to be reduced from six to three, and the RSU's communication range would have to be reduced to 230 m. With these adjustments to the scenario, every line was under the MCS 7 maximum, except maximum throughput—which was above the MCS 7 capacity for intersection spacing below 250 m.



Source: FHWA.

Figure 20. Graph. Expected spectrum demand for the dense urban scenario with reduction in number of lanes.

The research team incrementally adjusted the initial parameters for this scenario and stopped after reaching reasonable initial conditions that allow for the typical throughput messages to be within Safety Standards. The results of the preceding plots have been simplified to show when all messages in the scenario and only the safety messages are within MCS 11 and MCS 7 standards for message throughput for typical message size, shown in table 11, and maximum message size, shown in table 12.

Table 11. Conditions that support dense urban at typical throughput.

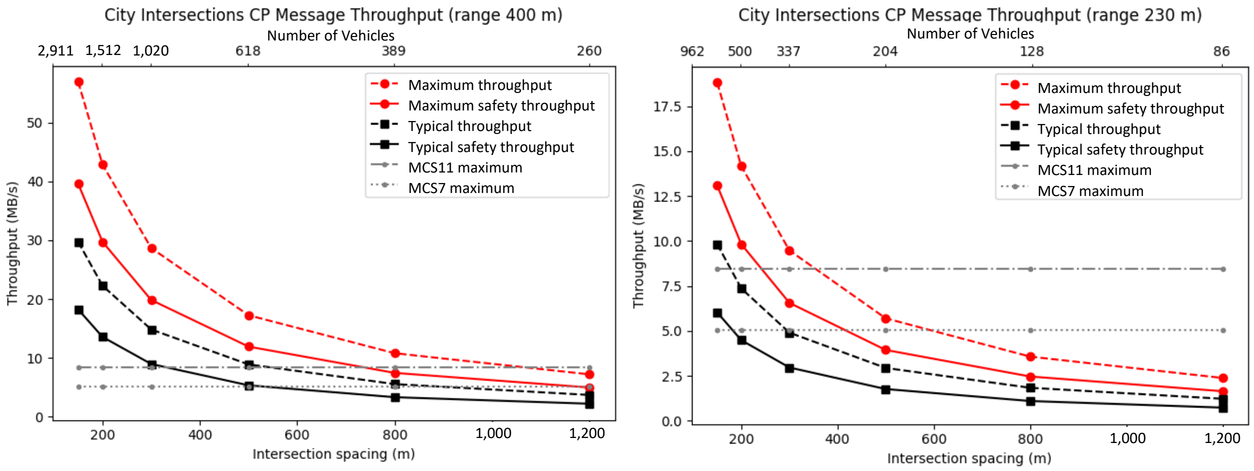
Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 400	Spacing >330 m	Spacing >590 m	All spacing	Spacing >20 m
Six lanes in each direction; comm range 230	All spacing	Spacing >180 m	All spacing	All spacing
Three lanes in each direction; comm range 230	All spacing	All spacing	All spacing	All spacing

Table 12. Conditions that support dense urban at maximum throughput.

Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 400	Spacing >81 m	None	Spacing >500 m	Spacing >850 m
Six lanes in each direction; comm range 230	Spacing >290 m	Spacing >490 m	Spacing >170 m	Spacing >290 m
Three lanes in each direction; comm range 230	None	Spacing >240 m	All spacing	All spacing

Combined Cooperative Perception/Dense Urban Scenario

Figure 21 shows the expected demand for spectrum from the combined cooperative perception/arterial/intersection scenario. Two traces are shown: the dashed line uses the maximum expected message size and the solid line uses the typical message size. The dotted and dash-dotted lines both show the available bandwidth for MCS index 7 and 11, respectively. For the larger 400-m communication range, MCS 11 can accommodate wireless traffic at the typical message size only above roughly 500-m intersection spacing. For the smaller 230-m communication range, MCS 7 can accommodate most of the wireless traffic for the typical message size, and MCS 11 can accommodate most of the wireless traffic for the maximum message size.



Source: FHWA.

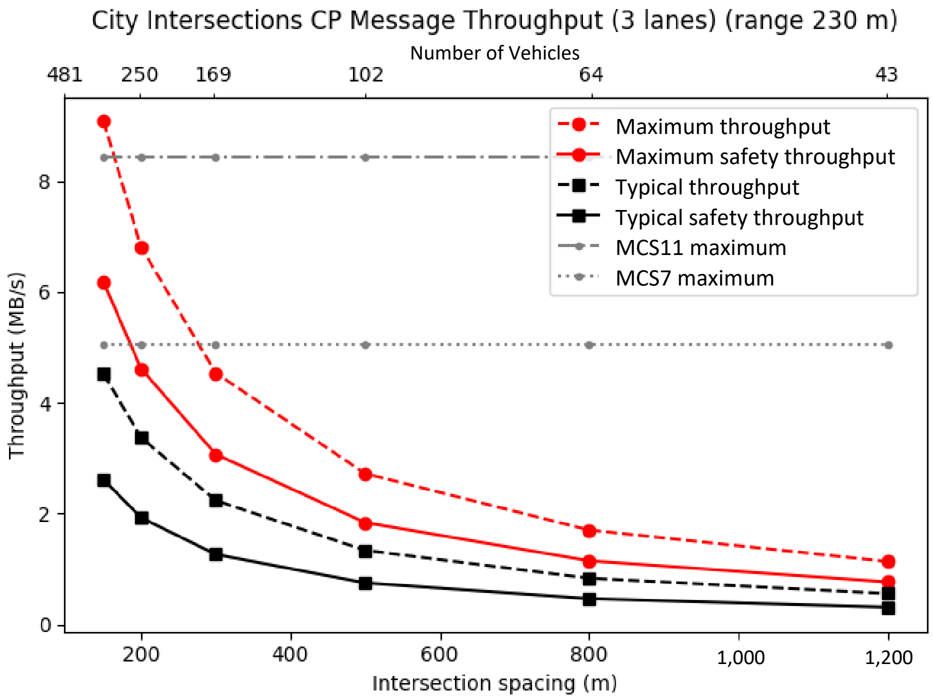
Source: FHWA.

A. Scenario 5 Results – 6 lane, 400 m

B. Scenario 5 Results – 3 lane, 230 m

Figure 21. Graphs. Expected spectrum demand for the combined cooperative perception/arterial/intersection scenario for communication range of 400 m (A) and 230 m (B).

Figure 22 shows how this scenario could function within the bandwidth restraints with adjusted parameters. The number of lanes would have to be reduced from six to three, and the RSU's communication range would have to be reduced to 230 m. With these adjustments to the scenario, every line was under the MCS 7 maximum, except maximum throughput—which was less than MCS 11 at 10 mph and less than MCS 7 at 20 mph for the case with all messages.



Source: FHWA.

Figure 22. Graph. Expected spectrum demand for the combined cooperative perception/dense urban scenario with reduction in number of lanes.

The research team incrementally adjusted the initial parameters for this scenario and stopped after reaching reasonable initial conditions that allow for the typical throughput messages to be within Safety Standards. The results of the preceding plots have been simplified to show when all messages in the scenario and only the safety messages are within MCs 11 and MCS 7 standards for message throughput for typical message size, shown in table 13, and maximum message size, shown in table 14.

Table 13. Conditions that support dense urban at typical throughput.

Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 400	Spacing >510 m	Spacing >850 m	Spacing >310 m	Spacing >500 m
Six lanes in each direction; comm range 230	Spacing >170 m	Spacing >300 m	None	Spacing >170 m
Three lanes in each direction; comm range 230	All spacing	All spacing	All spacing	All spacing

Table 14. Conditions that support dense urban at maximum throughput.

Scenario Conditions (m)	All Messages MCS 11	All Messages MCS 7	Safety Messages MCS 11	Safety Messages MCS 7
Six lanes in each direction; comm range 400	Spacing >1,050 m	None	Spacing >740 m	Spacing >1,200 m
Six lanes in each direction; comm range 230	Spacing >360 m	Spacing >590 m	Spacing >250 m	Spacing >400 m
Three lanes in each direction; comm range 230	Spacing >160 m	Spacing >280 m	All spacing	Spacing >190 m

CHAPTER 5. CONCLUSION AND FUTURE WORK

This study summarized an investigation into the spectrum needs for various CDA applications developed at STOL. The study began with a survey of applications developed during the past 7 yr that involved communication on the 5.9-GHz communication band. For each of the 17 applications documented, the V2X messages on which they rely were identified. The project team considered 14 unique messages in this study.

To perform the analysis, the team compiled key characteristics of each message— specifically, message size and transmit interval. Since most messages were used in multiple applications, the team recorded the minimum, maximum, and typical size and interval for each message. The data were fed into five scenarios crafted to place maximum demand on the wireless communication channel. For each scenario, the team considered two communication ranges based on prior research: first, a longer range, which is more typical of a location with good line of sight and which more conservatively estimates spectrum needs, and second, a shorter range, which is more typical of poor line of sight and a more realistic estimate of spectrum needs. Along with communication range, the team considered both typical and maximum message size and typical transmit interval.

When comparing spectrum needs for the five scenarios with the available spectrum, the team found that for the most part, the need greatly outpaced the available spectrum. In edge cases, such as the cooperative perception and platooning scenarios operating at 10 mph, spectrum demand was up to eight times the available bandwidth. However, a closer look at each scenario showed that the difference between supply and demand is not as stark—for a few reasons. First, for a given time headway, traffic density increases as speed decreases, while communication range remains constant. Thus, many more vehicles are within communication range of one another. However, that density is unrealistic for highway applications such as platooning, which are intended to run at freeway speeds.

Second, many messages in such applications as platooning and cooperative perception are relevant only to vehicles in the immediate vicinity of a transmitting vehicle. Thus, the transmit power can be reduced for messages associated with those applications, thereby reducing the range and the number of messages that occupy the airwaves.

Third, messages in such applications as work zone and speed harmonization may be suited to higher-latency communication such as cellular. Moving those messages to another band would free up space in the limited, 5.9-GHz band for important low-latency messages.

The results of this study suggest several avenues for further investigation into the use of V2X spectrum:

- This was a paper study that generalized many communication features and driving behaviors associated with the developed applications. A more detailed analysis that considers more practical vehicle distributions and communication characteristics could be performed and could take advantage of new and existing simulation tools available in STOL.

- Once the numbers have been solidified and better understood through simulation, a field study may be appropriate. While it is not practical to equip a large number of vehicles with the necessary hardware to complete a test at the same scale as the scenarios described in this document, a portion of one or more scenarios may be possible. For example, a dozen vehicles could be driven alongside one another to carry out part of the cooperative perception scenario. The data gathered during such a field test could be used to extrapolate the results to a larger number of vehicles.

- Based on the results presented in this document, potential spectrum demand outweighs available spectrum. Although this study was conservative in its estimates, it showed the potential for overloading of the remaining 20 MHz C-V2X channel. Thus, efforts to minimize usage would be worthwhile to pursue and could be accomplished by reducing message sizes through the elimination of unnecessary data, by being more efficient with data, or by sending data less frequently.

- This study considered only the messaging needs of applications developed at STOL. A future phase of this study could include the needs of other applications such as traffic optimization for signalized corridors or multimodal intelligent traffic signal systems.

Because of the numerous and complex factors involved in the performance of each scenario, even beyond those that were considered in this study, a simple yes or no answer is not possible with regard to whether a given application can be supported by C-V2X under all conditions. However, for a specific set of characteristics, support of a given application can be done and can give a sense of the kinds of capabilities that lie within the single channel of C-V2X. The following list describes a realistic and specific set of characteristics.

- The typical packet size from each scenario is considered, along with MCS 7, which is more robust than MCS 11.

- The half radio range for each scenario is considered, which limits the traffic that a given vehicle will see.

- The urban scenarios use 150-m intersection spacing, which is similar to those in New York.

- The freeway scenarios use 12 lanes, with vehicles traveling at 50 mph.

- Messages for both safety and mobility applications are considered.

For these characteristics, the simple answer in table 15 applies to each scenario.

Table 15. C-V2X support for applications with specific characteristics.

Scenario	Supported by C-V2X?
Cooperative perception	No
Large-scale platooning	No
Work zone with speed harmonization	Yes
Dense urban	No
Dense urban with cooperative perception	No

In summary, the 20-MHz band can support the scenarios explored in this document only under limited conditions. In general, the band is not sufficient to support large, saturated roadways with 100-percent market penetration.

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