SUMMARY

Next Generation Communications for ITS

U.S. Department of Transportation

UNITED STATES DEPARTMENT OF TRANSPORTATION (U.S. DOT)

Test Plan and Test Procedures Summary: Testing Long-Term Evolution Vehicle-to-Everything (LTE-V2X) Radio Performance Capabilities within the 5.9 GHz Safety Band

Background

On May 3, 2021, the Federal Communications Commission (FCC) published in the *Federal Register* a [First Report and Order] (R&O)[1] that became effective on July 2, 2021. This R&O has significant implications for transportation safety. The new rules set forth in the R&O reduce the radio spectrum band that the FCC had previously dedicated for transportation uses. The R&O reallocated 45 MHz of the 5.850 to 5.925 GHz spectrum band (commonly called the "Safety Band") to unlicensed Wi-Fi uses, leaving 30 MHz remaining for transportation purposes (specifically, 5.895 to 5.925 GHz). These new rules also include the following changes:

- The FCC shifted the vehicle-to-everything (V2X) communications technology in the remaining 30 MHz. FCC chose 4G long-term evolution V2X (or LTE-V2X), which is part of an emerging cellular V2X (C-V2X) set of technologies.
- The "guard band" that had existed between the lower end of the original Safety Band and the unlicensed Wi-Fi band has been removed, raising concerns about potential out-of-band emissions (OOBE) from unlicensed Wi-Fi operating just below the new (30 MHz) V2X band (5.895 to 5.925 GHz).
- The FCC proposes to remove the priority for the safety-of-life and public safety messages, raising concern over how such messages may be affected by other V2X messages or by unlicensed Wi-Fi transmissions.
- Similarly, because safety-critical V2X communications must now operate at the upper end of the original Safety Band, adjacent band interference from unlicensed devices operating just above the new V2X band (in the 5.925-7.125 GHz band, also termed the "6 GHz band") may also cause interference with V2X. The FCC recently re-allocated this 6 GHz band for Wi-Fi operations.[2]

Test Goals

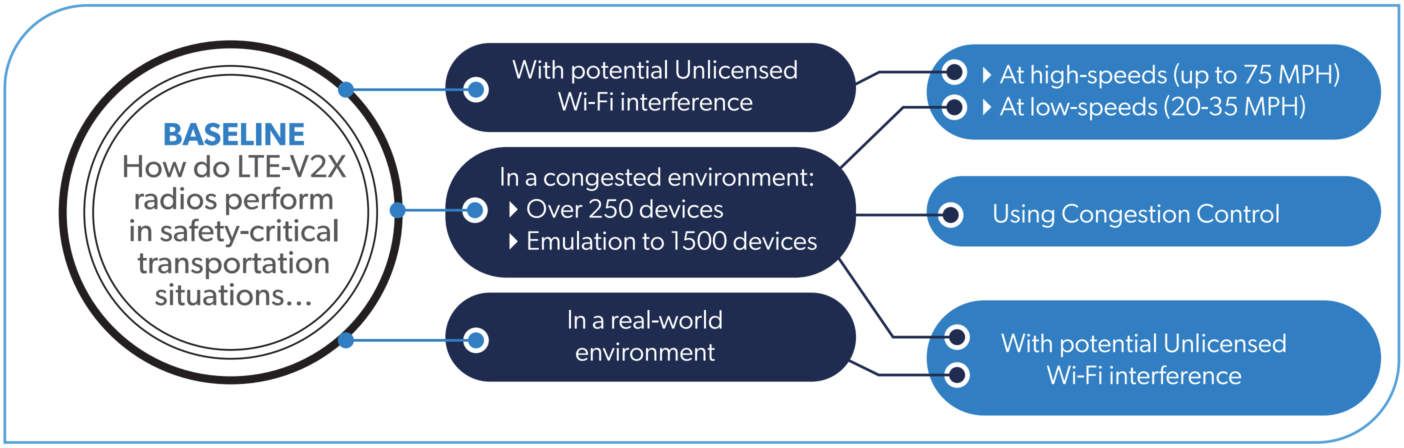
Safety is the top priority in the mission of the U.S. Department of Transportation (U.S. DOT). Therefore, the choice of a new technology and new set of rules must be informed by safety considerations. The U.S. DOT testing is designed to provide this assessment.

The U.S. DOT's 5.9 GHz Spectrum Team is assessing the radio performance and communications quality of the LTE-V2X technology under the new FCC rules and within test scenarios that mimic both typical and challenging crash avoidance conditions—the type of conditions that result in some of the most common crashes. Further, the number of V2X devices transmitting within reception range of each other may exceed several hundred devices in many congested traffic conditions. Therefore, it is important to examine the radio environment and V2X performance in such congested conditions.

In terms of understanding how LTE-V2X supports dense traffic environments, we note the theoretical maximum spectrum occupancy rate of a 20 MHz channel is reached when approximately 250 devices are operating within reception range of each other. However, because congestion control features built into V2X devices limit transmission rates as device density increases, the U.S. DOT's test plan includes test scenarios for the theoretical maximum occupancy rate, as well as emulating even higher levels of traffic (over 1000 vehicles) to assess congestion control performance.

Test Objectives

Test LTE-V2X communications under varying conditions. Each test case helps to assess the effects of each factor on the performance of LTE-V2X radios.



Test Progress

Due to the implementation timelines for the new spectrum allocations in the R&O, the U.S. DOT has compressed a typical three year test period into one year. As LTE-V2X devices became commercially available in 2020, the U.S. DOT released a Broad Agency Announcement to procure test devices. Laboratory characterization of devices proceeded from August 2020 through May 2021, when the U.S. DOT made the decision to advance to controlled-track testing. Vendors confirmed the firmware and software updates.

Testing is underway at various partner facilities, based on the test scenario:

- Laboratory and small-scale testing at the U.S. DOT-Federal Highway Administration (FHWA) Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA
- Laboratory testing at the National Telecommunications and Information Administration (NTIA)/Institute for Telecommunications Sciences in Boulder, CO (ITS-Boulder)
- Controlled track testing at the Decommissioned Naval Air Base (NAB) in Willow Grove, PA
- Controlled track testing at the Summit Point Motor Sports Park in Summit Point, WV
- Real-world environment testing at a U.S. DOT Connected Vehicle Pilot Site: Tampa-Hillsborough Expressway Authority (THEA) in Tampa, FL.

Laboratory, controlled test track, and real-world testing, as well as the data analysis, are being performed in parallel and iteratively as early data analysis has resulted in observations that have necessitated additional testing for further investigation.

Initial reporting of observations (accompanied by raw data) is expected in Spring 2022. The U.S. DOT expects that both the initial findings and the full report will assist in informing decision-makers regarding options for V2X deployments in the context of the new rules in the R&O. The information is also intended to support investment and installation decisions by infrastructure owners/operators (IOOs) and vehicle manufacturers who have operational deployments, or who are in the planning stages and require information for investment, transition, and installation decisions; as well as to provide information to vehicle and device manufacturers and other interested parties.

Summary of Test Approach

Test set-ups in use allow for testing of V2X communications link quality and consistency:

- Under a variety of both average and challenging spectrum, interference, and scalability conditions
- In a safe, controlled environment with vehicles moving at high speeds, varying speeds, and with line-of-sight blockages (*i.e.*, buildings, foliage, other vehicles)
- With collection of data that assists in illustrating the consistency and quality of the propagation of the basic safety messages (BSMs) throughout an *ad hoc* LTE-V2X environment.

Test methodology includes:

- **Laboratory Device Performance Characterization** to quantify the baseline performance of the devices for comparison to performance under test conditions
- **Device/System Integration Testing** to ensure that all systems (including data collection systems and test command and control systems) are operating correctly with properly calibrated measurement equipment
- **Controlled Track Testing** using two basic scenarios that can scale to over 250 LTE-V2X transmitting and receiving devices (with an ability to emulate up to 1500 devices), including moving vehicles and generation of unlicensed Wi-Fi transmissions
- **Small-Scale Real-World Testing** to gather data on communications under conditions such as typical reflectivity and obstructions that complicate the RF environment (*i.e.*, buildings, overpasses, and other elements of a built environment).

SCENARIO 1: High-Speed Moving Vehicles with Non-Line-Of-Sight (NLOS) in Midst of Congestion, Communicating with Each Other and with Surrounding Static Vehicles

Scenario 1 Overview

- Establish baseline LTE-V2X performance with over 250 operational devices
- Measure NLOS radio performance in situations not previously addressed by industry testing
- Assess variations in communications between and among vehicles operating up to and over 75 mph while surrounding onboard units (OBUs) are stationary (*e.g.*, similar to idling traffic at an intersection) because the LTE- V2X technology uses different modulations based on vehicle speed.

Scenario 1 test design (see Figure 1) includes:

- Vehicles approaching each other at high speed amidst over 250 OBU devices set to transmit BSMs, including accurate current location and time elements with variations
- Using each device's own settings based on draft SAE J3161/1 parameter settings, including use of the 20 MHz Channel 183 and an operational congestion mitigation algorithm
- Over 10 roadside units (RSUs) set to transmit MAP (intersection geometry) messages, using larger (approximately 1,400 byte) MAP messages.

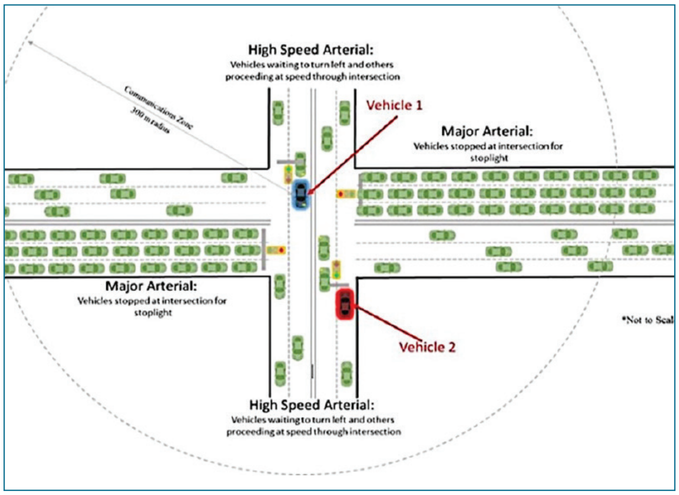


Figure 1: Test Track Scenario 1 Set-up

Scenario 1 Parameters

Scenario 1 LTE-V2X and Line-of-Sight/NLOS Test Parameters and the Range of Variations:

Number of OBUs	250+
Number of RSUs	10+
Payload	365 Byte (V2V) / 1400 Byte (I2V)
Hybrid Automatic Repeat Request (HARQ)	ON
LTE-V2X Channels	183 (for both OBUs and RSUs)
LTE-V2X Transmit Power	20 dBm
Obstructing Vehicle	YES / NO
High-Speed Vehicle Congestion Mitigation	ON / OFF
High-Speed Vehicle Transmit Time Interval (TTI) Setting	AUTOMATIC / 100 ms
250+ Stationary Devices Congestion Mitigation	ON / OFF
250+ Stationary Devices TTI Setting	AUTOMATIC / 100 ms / 300 ms / 600 ms

Scenario 1 LTE-V2X Test Case Notes:

- **Obstructing Vehicle:** A large box truck is used to create an NLOS scenario between the moving vehicle and the stationary vehicles opposite of the truck positioned in the center of the array.
- **Congestion Mitigation ON** means SAE J3161/1 congestion mitigation algorithm is activated.
- **Transmit Time Interval (TTI)** was set manually to 100 ms, 300 ms, or 600 ms when the congestion control algorithm was turned off.

Scenario 1 Dedicated Short-Range Communications (DSRC) Test Case Parameters:

Number of OBUs	250+
Number of RSUs	10+
Payload	365 Byte (V2V) / 1400 Byte (I2V)
DSRC Transmit Power	20 dBm
DSRC High-Speed Vehicle Congestion Mitigation	ON
DSRC High-Speed Vehicle TTI Setting	AUTOMATIC
DSRC Channels	172 / 180 / 184
LTE-V2X Channel for 250+ Stationary Devices	183
LTE-V2X 250+ Stationary Devices Congestion Mitigation	ON
250+ Stationary OBU Devices TTI Setting	AUTOMATIC
Obstructing Vehicle	YES / NO

Scenario 1 DSRC Test Case Notes:

*Note the inclusion of testing DSRC in the presence of LTE-V2X. This interference testing is included given the possible situation that, as existing DSRC installations move to the upper 30 MHz, a nearby LTE-V2X installation may be desired by a State or local DOT before DSRC operations are required to cease. In addition, in the FCC's Further Notice of Proposed Rulemaking (FNPRM), questions remain regarding the spectral and/or geographic separation requirements that might be necessary to prevent harmful interference between the two types of operations. These test runs will produce data to help understand the potential for interference between devices using these different technologies.

- The obstructing vehicle is used to create NLOS conditions within the Scenario 1 test track set-up.
- Congestion Mitigation **ON** for DSRC devices means SAE J2945/1 congestion mitigation algorithm is activated; and SAE J3161/1 is activated for LTE-V2X devices.
- DSRC OBUs transmit over 10 MHz channel width.

SCENARIO 2: High-Speed Moving Vehicles in Midst of Congestion, Communicating with Each Other and with Surrounding Static Vehicles

Scenario 2 Overview

- Assess communications between high-speed vehicles, among high-speed vehicles and surrounding stationary vehicles as congestion increases, and without and with Unlicensed Wi-Fi transmissions. Scenario 2 can help assess the suitability of LTE-V2X communications to support crash-imminent safety applications (*i.e.*, Intersection Movement Assist, Do Not Pass, Lane Change Warnings—including when vehicles in stopped/slow traffic enter high-speed lanes).
- Measure unlicensed Wi-Fi OOBE and assess the effects on LTE-V2X communications.

Scenario 2 test design (Figure 2) includes:

- Vehicles approaching each other at high speed
- Over 250 OBU devices set to transmit BSMs, including accurate current location and time elements with variations
- Using each device's own settings based on draft SAE J3161/1 parameter settings, including use of the 20 MHz Channel 183 and an operational congestion mitigation algorithm
- Over 10 RSUs set to transmit MAP (intersection geometry) messages, using larger (approximately 1,400 byte) MAP messages.

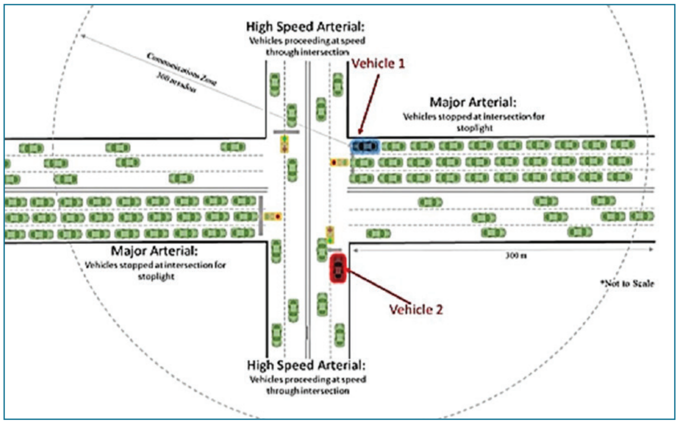


Figure 2: Test Track Scenario 2 Set-up

Scenario 2 Parameters

Scenario 2 Test Parameters and Variations:

Number of LTE-V2X OBUs	250+
Number of LTE-V2X RSUs	10+
Payload	365 Byte (V2V) / 1400 Byte (I2V)
HARQ	ON
LTE-V2X Channels	5.915 MHz-183 (for both OBUs and RSUs)
LTE-V2X Transmit Power	20 dBm
High-Speed Vehicle Congestion Mitigation	ON
High-Speed Vehicle TTI	AUTOMATIC
250+ Stationary Devices Congestion Mitigation	ON / OFF
250+ Stationary Devices TTI Setting	AUTOMATIC / 50 ms / 100 ms / 600 ms
Unlicensed Wi-Fi Channel	OFF / 5.885 MHz (CH 177) / 5.895 MHz
Unlicensed Wi-Fi Effective Isotropic Radiated Power (EIRP)	OFF / 13 dBm /33 dBm / Max OOBE

Scenario 2 LTE-V2X Test Case Notes:

- The unlicensed Wi-Fi configurations shown in the table above represent the "bounding case" used in testing; lower power and loading settings are also being tested.
- Congestion Mitigation **ON** means SAE J3161/1 congestion mitigation algorithm is activated.
- TTI is manually set to value indicated in table when congestion mitigation is turned **OFF**.

SCENARIO 3: Testing in a real-world environment

Scenario 3 Overview

Using a Connected Vehicle Pilot site as a real-world location for communications performance testing, U.S. DOT is testing in an environment that offers buildings and reflectivity, urban canyon effects, overpasses, foliage, and weather variation, among other typical conditions. The dataset will allow for a fuller understanding of the propagation performance of LTE-V2X technologies outside of controlled conditions. The objectives are to understand:

- Patterns of LTE-V2X vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) transmissions in different conditions (weather, times of day) as a baseline and then in the target area where unlicensed Wi-Fi interference will be generated.
- Communications effectiveness between the two test vehicles in various real-world road segment situations: first without interference as a baseline; then, under various interference parameters as described in the test procedures.
- Communications effectiveness between moving vehicles, between moving vehicles and roadside infrastructure (RSUs), and between moving vehicles and a stationary vehicle located near the central intersection of focus (and close to the interference point) to allow observation of RF propagation for vehicle height (1.5 m/5 ft) antennas.

Figure 3: Test Track Scenario 3 Set-up

- Effects of interference (if any) on communications between the two vehicles and between the test vehicles and RSUs.

Scenario 3 test design (Figure 3) includes:

- Two vehicles operating in real-world traffic, with one stationary vehicle parked near roadside infrastructure and an interference point.
- Three OBU devices set to transmit and receive BSMs, including accurate current location and time elements with variations.
- Using each device's own settings based on draft SAE J3161/1 parameter settings, including use of the 20 MHz Channel 183 and an operational congestion mitigation algorithm.
- One RSU set to transmit MAP messages, using larger approximately 1,400-byte MAP messages.

Scenario 3 LTE-V2X Test Case Notes:

After establishing a baseline to understand the regularly occurring noise present in the environment in and near the 5.9 GHz band (using RF scanning equipment and a spectrum analyzer), testing will include three scenarios:

1. Two moving vehicles drive north and south, both approaching and moving away from the roadside infrastructure and interference point.
2. Two moving vehicles drive east and west, both approaching and moving away from the roadside infrastructure and interference point.
3. Two moving vehicles continue onto the Reversible Entrance Lanes to the north of the intersection. That route extension includes traveling under a highway overpass located near the intersection and interference point.

The stationary vehicle will be used to both capture data (*e.g.*, receive messages from the moving vehicles) and act as another vehicle sending messages to understand whether the vehicles in motion can consistently "hear" this third vehicle.

Scenario 3 Unlicensed Wi-Fi Test Case Notes:

A Vector Signal Generator is used to produce simulated Unlicensed Wi-Fi over-the-air data units. The system is placed adjacent to the intersection to generate the simulated Wi-Fi interference. The Unlicensed Wi-Fi operations are tested in the adjacent and next-adjacentbchannel from the LTE-V2X transmissions from the vehicles, allowing for assessment of interference with no guard band for protection, as per the rules in the R&O.

Criteria for generating **Unlicensed Wi-Fi indoor interference** include:

- Unlicensed Wi-Fi is set up as IEEE 802.11ax with various channel- loading levels (*e.g.*, 60 percent and 10 percent), supported by a 20 dB amplifier.
- Revised FCC maximum indoor power levels: 36 dBm EIRP over frequency band in use (maximum power spectral density must not exceed 20 dBm EIRP in any 1-megahertz band, which translates to maximum of 33 dBm in a 20 MHz channel).
- Adjusted attenuation of the signal generator to emulate "indoor" operation, as estimated in the FCC R&O (note: this setting is 13 dBm EIRP to account for 33 dBm maximum power level and FCC's assumed building loss of 20 dB).

Criteria for generating **Unlicensed Wi-Fi outdoor interference** include:

- Same as above except set the generator to the proposed Unlicensed Wi-Fi "outdoor" power level of 33 dBm for 20 MHz channel.

Scenario 3 Parameters

Scenario 3 Test Parameters and Variations:

Number of LTE-V2X OBUs / RSUs	3 OBUs, 1 RSU
Payload	365 Byte (V2V) / 1400 Byte (I2V)
HARQ	ON
LTE-V2X Channels	CH 183
LTE-V2X Transmit Power	20 dBm
Unlicensed Wi-Fi Channel	20 MHz channel centered at 5.895 MHz / Also in the next adjacent channel CH177 Unlicensed Wi-Fi
Unlicensed Wi-Fi EIRP	OFF / 13 dBm /33 dBm / Max OOBE

Assessment Metrics

"Pair-wise" communications for each of the devices will be performed, inclusive of the RSU locations at representative points within the set-up. This type of analysis will identify whether all devices consistently "hear" each other as congestion builds and how the congestion mitigation algorithms automatically adjust to the congestion.

Analysis will investigate whether all of the devices retain reliable communications under different dynamics, as these devices represent the nearby roadway threats and hazards; and how the transmissions provide data to the safety-critical applications especially, and including, the high-speed vehicles changing modulations based on speed.

Data analysis will result in observations using the following safety performance metrics:

- Packet error (PER) / packet completion rate (PCR)
- Consecutive packets lost
- Transmit time delays (TTI) / Information Age (IA)
- Interpacket gap (IPG)
- Channel busy ratio (CBR)
- Propagation of the signal.

Analysis of the test data is anticipated to address the following questions:

- **LTE-V2X Device Performance:** *What are the operational characteristics and how do they support V2V and V2I ad hoc communications? Can LTE-V2X remain operational with loss of GPS and thus loss of ability to "sync" with all surrounding devices to divide up/reserve the available spectrum resource blocks?*
- **Scalability/Congestion:** *Are there LTE-V2X technology performance gaps in high-density scenarios? How stable and consistent are the LTE-V2X ad hoc environments as more devices are added?*
- **Interference and Understanding the Usability of the 30 MHz at 5.895-5.925 GHz:** *Are any mitigations required to prevent harmful interference from unlicensed Wi-Fi OOBE above and below the Safety Band?*

- **Safety Performance:** *What is the potential for LTE-V2X radio performance to meet crash-imminent safety communications requirements in a non-network connected mode under varying average and challenging traffic, interference, and spectrum conditions?*

Industry Testing

In performing this testing, the U.S. DOT extends known industry testing with a focus on the communications quality and consistency under typical and congested conditions but using a greater number of physical devices as a means of assessing performance that may not be detected in analytical or simulation studies, or with a smaller number of devices. Using spectrum measurement equipment, the Spectrum Team is also able to examine the operation of the 20 MHz channel as well as to gather additional data on metrics beyond packet error rate. Industry test design and results that informed our test set-up include:

- 5GAA and member testing that focused on performance on a test track with 50 devices with transmit times at 100 and 600 ms to emulate up to 600 devices.[3]
- The Crash Avoidance Metrics Partnerssship LLC and industry partners that focused on in-vehicle interference between LTE-V2X and unlicensed Wi-Fi.[4]
- Recent international testing that is investigating the possibility of coexistence between DSRC and LTE-V2X in the same band, and further performing field-testing with available devices to compare DSRC and LTE-V2X performance, while also assessing performance under challenging GPS conditions.[5]

1. First Report and Order, Further Notice of Proposed Rulemaking, and Order of Proposed Modification In the Matter of Use of the 5.850-5.925 GHz Band https://docs.fcc.gov/public/attachments/FCC-20-164A1.pdf.
2. Unlicensed Use of the 6 GHz Band; Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz Report and Order at https://www.fcc.gov/document/fcc-opens-6-ghz-band-wi-fi-and-other-unlicensed-uses-0.
3. See studies and results at https://www.qualcomm.com/media/documents/files/c-v2x-congestion-control-study.pdf.
4. See studies and results at https://www.campllc.org/project-cellular-v2x-device-to-device-communication-c-v2x.
5. For instance, a recent set of European Commission tests that were also performed with China in a "twinning" exercise. See: https://5g-drive.eu/wp-content/uploads/2021/08/5GD-D4.4_Final-report-of-V2X-trials.pdf. Also, in China, testing is taking place with up to 180 devices in test track environments.

This summary document is posted on the U.S. Department of Transportation's Safety Band website at www.transportation.gov/content/safety-band. Further comments or questions can be sent to 5.9GHzSpectrum@dot.gov.