Virtual Open Innovation Collaborative Environment for Safety (VOICES) Distributed Testing Pilot Test 1

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FOREWORD

Since 2020, the U.S. Department of Transportation (USDOT) has funded the Virtual Open Innovation Collaborative Environment for Safety (VOICES) initiative, which is aimed at creating a distributed research environment for testing interoperability of surface transportation technologies. Initially awarded to the Federal Highway Administration's Saxton Transportation Operations Laboratory (STOL), the project focused on advancing cooperative driving automation (CDA) applications through collaborative, distributed testing. Each test series conducted by FHWA and its research partners sought to demonstrate incremental and cumulative development of distributed testing capabilities.

The Pilot 1 test campaign described in this report was executed by FHWA's STOL with partners from the University of California Los Angeles (UCLA), Econolite®, and Nissan®, and aimed to integrate diverse cosimulation environments and tools for the first time. The test campaign pursued objectives in cosimulation and CDA, emphasizing interoperability among different simulation models and tools. Ultimately, Pilot 1 sought to establish a collaborative framework across government, private sector, and academic entities to inform CDA standards and foster innovation in surface transportation technologies.

Carl Andersen
Technical Director, Office of Safety and Operations
Research and Development

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16. Abstract This report documents the results and technical performance analysis of the Pilot 1 test for the FHWA Virtual Open Innovation Collaborative Environment for Safety (VOICES) project. Pilot 1 furthered the development of tools and software used for distributed testing and added new test partners to the distributed testing community. This test expanded and enhanced distributed testing functionality and proved that performing distributed testing is possible nationwide in realtime using diverse simulated models for a relatively low cost.		
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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

AGP	assured green period
API	application programming interface
BSM	basic safety message
C-ADS	connected automated driving system
CDA	cooperative driving automation
DOD	Department of Defense
FHWA	Federal Highway Administration
IP	Internet protocol
IT	information technology
KML	Keyhole Markup Language
LVC	live, virtual, and constructive
mph	miles per hour
ms	millisecond
N/A	not applicable
OM	object model
SDO	stateful distributed object
SIT	systems integration test
SPaT	signal phase and timing
SRC	Scientific Resource Corporation
Std. Dev.	standard deviation
STOL	Saxton Transportation Operations Laboratory
TCA	TENA CARLA adapter
TDCS	TENA Data Collection System
TENA	Test and Training Enabling Architecture
TFHRC	Turner-Fairbank Highway Research Center
TJ2735A	TENA J2735 adapter
TLEG	Traffic Light Entity Generator
TSC	traffic signal controller
UCLA	University of California, Los Angeles
UDP	user datagram protocol
UPER	Unaligned Packed Encoding Rules
USDOT	U.S. Department of Transportation
VOICES	Virtual Open Innovation Collaborative Environment for Safety
VPN	virtual private network
V2X	vehicle-to-everything

CHAPTER 1. VOICES PILOT 1 OVERVIEW

PURPOSE OF THIS DOCUMENT

This document is a test report for the Virtual Open Innovation Collaborative Environment for Safety (VOICES) distributed testing Pilot Test 1, referred to as Pilot 1, performed on a prototype secure network. This document details the results of tests conducted for VOICES Pilot 1 and how the results relate to the test objectives. This test report also discusses the performance analysis results in the context of this test and the scope of the larger project.

BACKGROUND

VOICES Program

VOICES is an effort funded by the U.S. Department of Transportation (USDOT) to develop a distributed research environment that tests interoperability of surface transportation technologies.(1)

In 2020, USDOT awarded the Federal Highway Administration's (FHWA) Saxton Transportation Operations Laboratory (STOL) an initial VOICES project to develop and test prototype distributed testing technologies.(2) This project has focused on identifying and demonstrating useful applications of collaborative, distributed testing, in particular, for advancing research in cooperative driving automation (CDA). The first major demonstration test, Systems Integration Test 1 (SIT-1), was conducted in August and September 2022 and is described in detail in the corresponding technical report.(3) Pilot 1 was conducted about seven months later and is described in this report.

In parallel, one of USDOT's goals has been to transfer some of the distributed testing technologies outside of the Government. To this end, in fall 2022, USDOT awarded MITRE Corporation a contract to build and operate the VOICES platform, which was still under development at the time of Pilot 1 testing.

Distributed Testing Technologies

Collaborative, distributed testing enables participating entities (e.g., State and local governments, private sector organizations, academic institutions) to collaborate in a distributed virtual environment for research and interoperability testing of prototype CDA and connected transportation applications.(1)

Distributed testing leverages the Test and Training Enabling Architecture (TENA) technologies, originally developed by the Department of Defense (DOD), to facilitate distributed testing of blended live, virtual, and constructive (LVC) simulation.(4,5) Live simulations refer to simulation instances with real roadway infrastructure, real vehicles, or other real roadway entities. The real vehicles can be operated either by human drivers or CDA systems. Virtual simulations refer to simulation instances with real human road users in a simulated travel environment. Constructive simulations refer to simulation instances with simulated vehicles and/or other road users operating in simulated environments that follow predefined driving logics. TENA carries out distributed LVC simulations through common object models (OMs) that enable semantic interoperability and through a high-performance communication infrastructure (i.e., the TENA middleware) for real-time data exchange.(4,6) Instances of TENA OMs are called stateful distributed objects (SDOs), which persist and carry data that describe relevant attributes of the objects in LVC simulations.(5,6) TENA messages are another way for one LVC simulation to send data to other LVC simulations.(5,6) TENA adapters are necessary to convert data from individual LVC simulations to TENA SDOs and TENA messages for consumption by other LVC simulations in a distributed test, and vice versa.(5,6)

Another key enabling technology of distributed testing is a secure testing network. Eventually, the MITRE-built VOICES platform will fulfill this function. For Pilot 1 testing, a commercial off-the-shelf cloud-based network (Twingate™) was leveraged since the MITRE-built VOICES platform was under development and therefore not available for the duration of Pilot 1 testing.(7)

From Systems Integration Test (SIT) 1 to Pilot 1 Test

In August and September 2022, the VOICES program at FHWA conducted its first systems integration test, referred to as SIT-1.(3) TENA OMs specifically for surface transportation were developed by Department of Defense (DOD) partners through STOL's initial VOICES project.(1,2,6) SIT-1 included four simulation nodes hosted at three geographically distributed sites.(3) Two prototype CDA applications were featured in SIT-1: work zone and platooning—both implemented using FHWA's open-source CARMA℠ suite of CDA tools.(3,8) SIT-1 successfully demonstrated the feasibility and potential benefits of distributed and collaborative interoperability testing of CDA technologies and applications.(3)

To make further progress toward the goals of transferring some of the distributed testing technologies outside of the Government, VOICES Pilot 1 aimed to cultivate new test partners outside of FHWA for CDA research who might be using a diverse set of cosimulation environments, tools, or models. To this end, Pilot 1 was planned and executed by FHWA's STOL with test partners from the University of California, Los Angeles (UCLA), Econolite®, and Nissan®.

SIT-1 revealed opportunities for performance improvement in the TENA OMs and adapters developed and used in previous testing.(3) For Pilot 1, the STOL team developed new TENA OMs and adapters that aim to reduce computational overhead by streamlining the encoding and decoding of SAE™ J2735® Vehicle-to-Everything (V2X) messages.(6,9)

PILOT 1 TEST

Starting in 2022, the VOICES program began pursuing two parallel development tracks: the Office of the Assistant Secretary for Research and Technology oversaw MITRE's development and maturation of the VOICES test platform, while FHWA guided Leidos' efforts to identify and demonstrate CDA applications that would benefit from distributed, collaborative testing. FHWA's Pilot 1 test was planned and conducted to demonstrate how distributed and collaborative testing could connect CDA research communities from different sectors.

Test Objectives

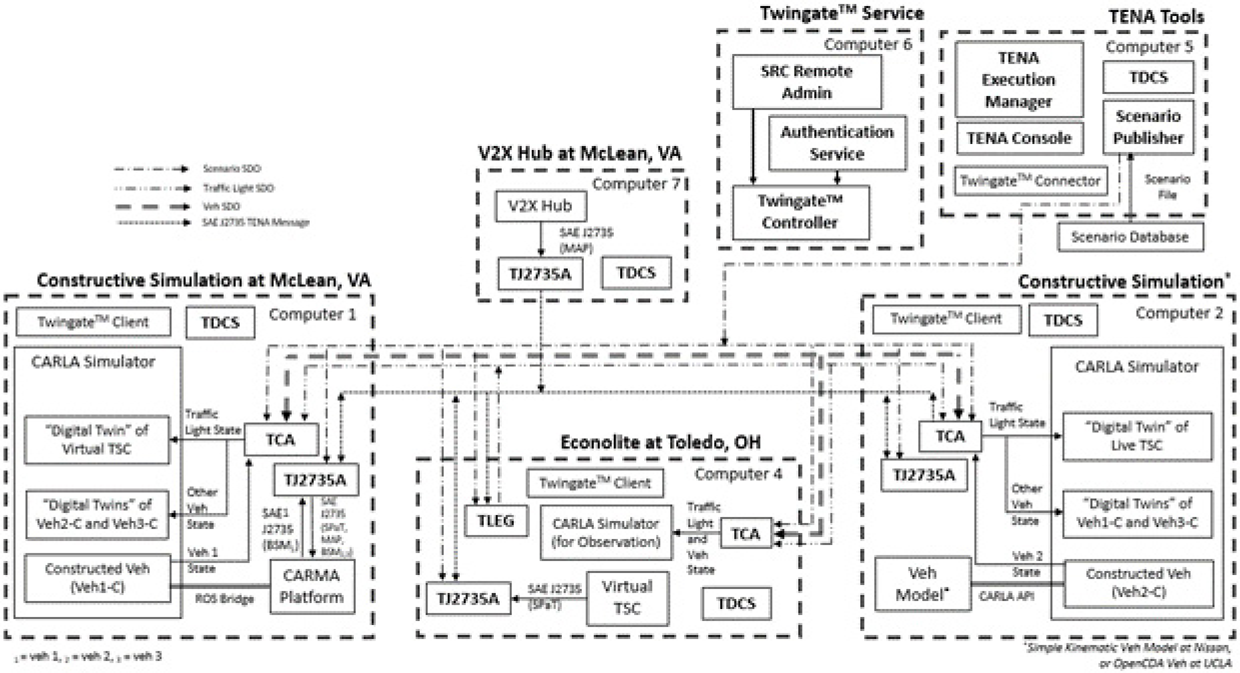
Pilot 1 test objectives fell into two categories—cosimulation and CDA. While the outcomes of the CDA functionalities were important to the test campaign, the successful integration of new and diverse simulation environments, tools, and models from new test partners was equally, if not more, important to the success of Pilot 1 because this type of cosimulation had never been done before for surface transportation applications. Pilot 1 included the following objectives:

- **Cosimulation objectives:**
    - 1.1—Conduct a test using a cloud-hosted distributed network. Continue collecting data to better understand network performance.
    - 1.2—Demonstrate a mix of cosimulated environments or tools, including successful interoperation of CARMA tools and non-CARMA tools.(8)
    - 1.3—Test the first TENA adapters developed by USDOT.
- **CDA objectives:**
    - 2.1—Demonstrate a CDA application that tests interactions between infrastructure and vehicles. Collect CDA research data.
    - 2.2—Demonstrate a partnership among government, private sector, and academia that could potentially produce data to inform a CDA-standards effort.
    - 2.3—Develop new digital assets (e.g., maps, scenarios, etc.) and tools (e.g., TENA OMs and adapters for surface transportation interoperability testing) that will be of value to the CDA research community.
    - 2.4—Explore interoperability issues among the models or tools from VOICES testing partners that warrant further study and resolution.

High-Level Functional Architecture

Pilot 1 included the first non-CARMA automated vehicle platform with UCLA running its OpenCDA vehicle model and Nissan running a simple kinematic vehicle model.(10) The test also included a fully virtual traffic controller developed and hosted by Econolite. FHWA's STOL participated using its CARMA Ecosystem℠ tools, a suite of open-source software for CDA research that includes both infrastructure and vehicle elements.(11)

Figure 1 shows the high-level functional architecture for Pilot 1, with five constructive simulation nodes hosted at four geographically distributed sites, connected through a secure, commercial off-the-shelf, cloud-based, virtual private network (VPN) called Twingate.(7) All nodes across all sites were joined into the test platform and coordinated using TENA adapters and TENA middleware.(6)



Source: FHWA.

API = application programming interface; BSM = basic safety message (per SAE International J2735); CDA = cooperative driving automation; ROS = robotic operating system; SDO = stateful distributed object; SPaT = signal phasing and timing; SRC = scientific research corporation; TDCS = TENA Data Collection System; TCA = TENA-CARLA adapter; TENA = testing and training enabling architecture; TJ2735A = TENA SAE J2735 message adapter; TLEG = traffic light entity generator; TSC = traffic signal controller; UCLA = University of California, Los Angeles; V2X = vehicle-to-everything; Veh = vehicle; VOICES = Virtual Open Innovation Collaborative Environment for Safety.

Figure 1. Diagram. Pilot 1 functional architecture.

Secure Network

Pilot 1 used the secure network product, Twingate, and TENA technologies to connect multiple geographically isolated research and development sites to each other, allowing distributed testing of prototype ecosystems from various stakeholders.(4,7) Twingate is a cloud-hosted, commercial off-the-shelf, zero-trust VPN.(7)

The Twingate product includes the cloud-based configuration and authentication functionalities provided to the network.(7) Scientific Research Corporation (SRC) acted as the remote network administrator responsible for the configuration of the network. Each simulation site had to be authenticated to connect to the network. This authentication was carried out through an instance of the Twingate client software installed at each site, the Twingate controller in the cloud, and the Twingate cloud-based authentication service.(7)

Constructive Simulation Nodes

The "Constructive Simulation Node" box in figure 1 represents the two constructive simulation nodes, one at UCLA in Los Angeles, CA, and the other at Nissan in Farmington Hill, MI. Each node used the CARLA® simulation platform to render their respective vehicle models.(12) Both vehicle models, UCLA's OpenCDA and a simple kinematic model used by Nissan, were integrated into CARLA using the CARLA Python® application programming interface (API).(10,12) Since neither vehicle model was able to directly handle encoding and decoding of J2735 messages following Unaligned Packed Encoding Rules (UPER), both used the CARLA Python API to obtain traffic light state and vehicle information from their local instance of CARLA's world model.(9,12,13) Each of the two constructive simulation nodes also ran their local instances of two TENA adapters—the TENA-CARLA adapter (TCA) and the TENA J2735 adapter (TJ2735A). The TCA publishes relevant entity SDOs from the local simulation node to the secure network, subscribes to other entity SDOs from the secure network, and updates the states of the associated "digital twins" in the local CARLA simulator.(6,12) Since neither the constructive vehicles at the UCLA or the Nissan nodes generate their own J2735 V2X messages, the TCA also directly generate J2735 basic safety messages (BSMs) using information collected from CARLA.(9,12) The TJ2735A instances run at these two nodes, along with the TENA Data Collection System (TDCS), were used for data collection purposes. The TJ2735A essentially functions as an onboard unit or a roadside unit in the real world, facilitating the exchange of SAE J2735 V2X messages among entities across various simulation sites.(9,14,15) The TJ2735A is further discussed in the following subsection, *TENA Tools and Adapters*. Readers interested in the TCA are referred to appendix B in the SIT-1 report.(3)

The constructive simulation node at McLean, VA, is located at FHWA's STOL. The node features FHWA's CARMA Platform℠, a full stack software-defined connected automated driving system (C-ADS), as a software-in-the-loop simulation of a CDA vehicle in CARLA.(16,12) Same as in SIT-1, the constructive simulation node at FHWA's STOL leveraged the CARMA-CARLA integration—developed by STOL and now a part of FHWA's CDASim—for Pilot 1.(17) The constructive simulation node at FHWA's STOL site also ran its local instances of the TCA and the TJ2735A.

The box titled "V2X Hub at McLean, VA", in figure 1, illustrates a second constructive simulation node hosted at FHWA's STOL site. This node ran the FHWA STOL's V2X Hub℠ as software in-the-loop to simulate additional infrastructure-to-vehicle communication needed for the testing sequences.(18) More specifically, the V2X Hub instance published the SAE J2735 MAP message for the intersection of interest to all simulation nodes in the distributed simulation through the local instance of the TJ2735A.(18,9)

The constructive simulation node at Econolite in Toledo, OH (figure 1), ran an instance of the Econolite virtual traffic signal controller (TSC) as a standalone software application executing a two-phase, fixed-time traffic signal plan. Researchers ran an instance of the CARLA simulator at the Econolite site for observation purposes only.(12) The Econolite site ran an instance of the TJ2735A that publishes the J2735 signal phase and timing (SPaT) message received from the Econolite virtual controller to the secure network.(9) Additionally, the Econolite site included a TENA Traffic Light Entity Generator (TLEG) that subscribes to the J2735 messages, decodes the J2735 SPaT message, and uses relevant data fields in the J2735 SPaT message to update the traffic light SDO in Pilot 1.(9) It should be noted that only one instance of the TENA Traffic Light Entity Generator is needed across multiple sites. This can be hosted anywhere in the network.

TENA Tools and Adapters

The "TENA Tools" box in figure 1 shows that the core TENA components (TENA Execution, TENA Console, Scenario Publisher, and TDCS) were run on computer 5 located at FHWA's STOL site.(6) Note that these TENA tools can run from any site. Additionally, each simulation node ran an instance of the TDCS for data logging and analysis purposes.(6) All instances of TDCS subscribed to all TENA data.(6)

The core architecture for CDA messaging for Pilot 1 (and the associated TENA adapters) was completely overhauled from SIT-1.(3,6) The key difference is the introduction of a TENA message that corresponds to the J2735 V2X messages in Pilot 1, referred to as the J2735 TENA message hereafter.(3,9) This architecture change created a delineation between functional CDA messages (J2735 TENA messages) and simulation messages (traffic light SDOs and vehicle SDOs).(6) Functional CDA messages are sent between infrastructure and vehicles to share status information. These messages should be kept as simple and lightweight as possible to enable reliable and fast delivery of important information at high frequencies. Simulation messages are the second level of data—usually derived from a functional CDA message—used to update the simulated world. These simulation messages should be in a clear format that all parties can understand and contain all the information that is required to update all simulations.

This architecture change led to two new TENA adapters—namely the TENA J2735 adapter (TJ2735A) and the Traffic Light Entity Generator—developed by FHWA's STOL.

TENA J2735 Adapter

The TJ2735A replaced several TENA adapters used in SIT-1, streamlining the V2X message packaging process and enabling lightweight messages to be exchanged across the secure network.(3) These replaced adapters include the V2XHub-TENA-SPaT-Plugin, the V2XHub-TENA-BSM-Plugin, the V2XHub-TENA-Mobility-Plugin, the V2XHub-TENA-Traffic-Control-Plugin, and the CARMA-Platform-TENA-Adapter.(3)

In SIT-1, encoded CDA messages such as the J2735 BSM and SPaT were received via user datagram protocol (UDP) by a message-specific adapter at the site where the messages originated.(3,9,20) These messages were then decoded, packed into an SDO, and published to the secure network by the message-specific adapters.(3) These message-specific adapters, together with other TENA adapters, also subscribed to relevant SDOs published from other sites.(3) Once SDO updates were received by these adapters, any relevant V2X messages were then encoded again and sent via UDP to the destination device.(3,20) While this approach enabled detailed logging and data tracking, it was inefficient due to the added decoding and encoding computational overhead as the destination devices wanted the V2X messages in the original encoded format according to the J2735 asn.1 specification.(21) This decoding and encoding process also created opportunity for errors when the data were packed and unpacked.

This process was simplified with the introduction of a TENA message that corresponds to the J2735 V2X messages in Pilot 1.(9) The J2735 TENA message included a Message Type field containing the J2735 message type information and an array of the exact bytes of the message payload. This J2735 TENA message enabled a streamlined packaging process, and the lightweight message could be created and distributed faster due to the message being simpler and smaller.

With the introduction of the J2735 TENA message, the TJ2735A receives UPER-encoded J2735 messages through UDP and generates corresponding J2735 TENA messages and vice versa.(13,20)

Traffic Light Entity Generator

Removing the V2XHub-TENA-SPaT-Plugin resulted in no application generating traffic light SDOs, which are the simulation messages used to update traffic signals in the Pilot 1 distributed testing cosimulation.(3) To resolve this dilemma, the TLEG was created to receive J2735 TENA messages that correspond to J2735 SPaT messages, decode the payload, and package it into traffic light SDOs.(9)

CHAPTER 2. PILOT 1 TEST METHODOLOGY

Pilot 1 consisted of four test sequences that were each designed to examine various elements and capabilities of the integrated system under test gradually and cumulatively. Each test sequence was performed and reviewed to ensure all test elements performed as expected before systematically progressing to the next sequence. All vehicle route planning used waypoint-following controls, which were heavily reliant on waypoints defined in the maps.

Testing was conducted on two different maps—one of the default CARLA maps and one CARLA map developed by UCLA based on a real-world intersection in Los Angeles, CA.(12)

TEST SEQUENCE 1

Test sequence 1 was executed using the default CARLA Town4 map and included three constructive simulation nodes: Econolite with its virtual TSC, Nissan with a simple kinematic vehicle model, and FHWA's STOL with the V2X Hub constructive simulation node.(22)

Nissan ran a simple kinematic vehicle model starting from rest at various distances from the test intersection. The simple kinematic vehicle model would instantly accelerate to a predefined speed when the traffic light for its approach turned yellow, and then travel through the intersection with constant speed.

The V2X-Hub℠ broadcasted MAP messages, but these were not received or processed by the simple vehicle model.(9,18)

Nissan ran the simple vehicle model through five scenarios: 30 m at 25 miles per hour (mph), 30 m at 35 mph, 30 m at 45 mph, 50 m at 45 mph, and 50 m at 60 mph. The simple vehicle model was initiated only once, and scripts automatically ran through each of the scenarios in quick succession. For each run, the distance to the intersection was displayed on the user interface.

At Nissan's constructive simulation node, the TCA generated BSMs for the simple vehicle model, and the TJ2735A received J2735 SPaT from the Econolite virtual traffic controller.(9) The simple vehicle model was visible and updated for all participating simulations.

TEST SEQUENCE 2

This sequence tested integration of a different, more complex vehicle model with the same infrastructure test element. Test sequence 2 was executed using the default CARLA Town4 map and included two constructive simulation nodes: Econolite with its virtual TSC, UCLA with its OpenCDA vehicle model, and FHWA's STOL with the V2X Hub constructive simulation node.(22,10,18)

The UCLA's OpenCDA vehicle started from rest at a varying distance from the test intersection.(10) The vehicle started to accelerate toward the intersection at the beginning of a red phase for its approach and stopped at the red light. It remained at the red light until the light turned green and then accelerated through the intersection where it finished its route in the exit lane. The UCLA OpenCDA vehicle followed the OpenCDA waypoint following algorithm.(10)

At UCLA's constructive simulation node, the TCA generated BSMs for the OpenCDA vehicle, and the TJ2735A received J2735 SPaT from the Econolite virtual traffic controller.(9,10) The UCLA OpenCDA vehicle was visible and updated for all participating simulations.

TEST SEQUENCE 3

Test sequence 3 combined the previous two test sequences by simultaneously operating the simple kinematic vehicle model used by Nissan and the UCLA OpenCDA vehicle model with the Econolite virtual TSC in the same test event.(10) Test sequence 3 was executed using the default CARLA Town4 map and included four constructive simulation nodes: Econolite with its virtual TSC, Nissan with a simple kinematic vehicle model, UCLA with its OpenCDA vehicle model, and FHWA's STOL with the V2X Hub constructive simulation node.(12,10,18)

The UCLA OpenCDA vehicle and the Nissan simple kinematic vehicle model were initiated on two approaches to the intersection that are perpendicular to each other.(10) Both vehicles were initiated at prespecified distances to the intersection. At the beginning of its red phase, the UCLA OpenCDA vehicle model began to move.(10) Executing the OpenCDA waypoint following algorithm, the UCLA OpenCDA vehicle approached and stopped at the test intersection on red.(10) On the cross street, the Nissan simple kinematic vehicle model accelerated toward and passed through the intersection on its green light. Afterward, the light changed to green for the OpenCDA vehicle, and the vehicle continued through the intersection.(10)

At both constructive simulation nodes at UCLA and Nissan, the local instance of TCA generated BSMs for the OpenCDA vehicle and the simple kinematic vehicle, respectively.(10) The local instance of TJ2735A at both nodes received J2735 SPaT from the Econolite virtual traffic controller.(9) The Nissan simple vehicle model and the OpenCDA vehicle model were visible and updated for all participating simulations.(10)

TEST SEQUENCE 4

Test sequence 4 significantly increased the complexity from previous test sequences by involving a full-stack C-ADS (CARMA Platform) vehicle as software-in-the-loop and moving all test elements from a fictional CARLA map to a map of a real-world intersection in Los Angeles, CA, provided by UCLA (see figure 2).(16,12) Test sequence 4 included four constructive simulation nodes: Econolite with its virtual TSC, UCLA with its OpenCDA vehicle model, FHWA's STOL with its CARMA Platform software-in-the-loop vehicle, and FHWA's STOL with the V2X Hub constructive simulation node.(16,18)

The UCLA OpenCDA and CARMA Platform vehicles were initialized in the same travel lane (that travels from the bottom of the figure to the top in figure 2), with the CARMA Platform vehicle in front of the OpenCDA vehicle. After both vehicles were initialized, at the beginning of a red phase for their approach, the test sequence called for the two vehicles to begin moving in the same direction toward the intersection, stop on red at the intersection, and move through the intersection after the light turned green.

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Figure 2. Illustration. CARLA view of the real-world intersection used in test sequence 4.(12)

PILOT 1 TEST EXECUTION ENTRY AND EXIT CRITERIA

The following list provides the entry criteria for Pilot 1 and how those criteria were met:

- All required hardware shown under the Test Environment section in the Pilot 1 test plan is available and configured with the specified software. All hardware is configured with the specified software at Turner-Fairbank Highway Research Center (TFHRC), UCLA, Nissan, a cloud-based network, and Econolite sites.

- All participant sites submitted in writing that the planned network test configuration complies with their organization’s information technology (IT) security policies. All participating sites confirmed they received the appropriate approval from their appropriate IT (if necessary) to conduct the testing specified in the Pilot 1 test plan.

- All devices connected to the Pilot 1 network are time synced using the network time protocol servers provided.(23) All sites are time synced using the chrony tool and reported time synchronization within 20 ms.(24)

    - All sites successfully participated in a joint connectivity test prior to the actual test event and unloaded network ping testing has been conducted and recorded.

    - All sites had previously verified connectivity and basic functionality before the official tests were conducted.

The following list provides the exit criteria for Pilot 1:

- Test sequence 1 data collection has been satisfactorily completed for three predefined setpoints.
- All test data are collected, the metadata sheet is created, and data are uploaded to the appropriate destinations.

The entry and exit criteria both centered around collecting, organizing, and storing data. These criteria were met, and details are provided in chapter 4 and appendix A of this report.

CHAPTER 3. HIGH-LEVEL ASSESSMENT OF TEST OBJECTIVES AND REQUIREMENTS

The following sections detail the Pilot 1 objectives and how they were met with respect to the test results.

COSIMULATION OBJECTIVES

Objective 1.1 Conduct a test using a cloud-hosted distributed network; continue collecting data to better understand network performance.

Researchers successfully met objective 1.1. Pilot 1 was conducted on the cloud-hosted, zero-trust VPN platform Twingate.(7) Each site established connections to every other site by authenticating and gaining authorization from the Twingate controller hosted on a cloud-based network.(7) This platform allowed each site to connect directly with minimal configuration. More information can be found in the Pilot 1 network overview and network diagram documents. Network performance data were collected, and results are detailed in chapter 4 and appendix A.

Objective 1.2 Demonstrate a mix of cosimulated environments or tools, including the successful interoperation of CARMA tools and non-CARMA tools.

Researchers successfully met objective 1.2. The Pilot 1 test included Econolite's Virtual TSC, CARMA Platform, UCLA's OpenCDA vehicle, and a simple kinematic vehicle model run by Nissan.(10) Pilot 1 was conducted on a fictional CARLA Town 04 map, as well as one CARLA map developed by UCLA based on a real-world intersection in Los Angeles, CA.(22)

Pilot 1 revealed opportunities for both FHWA's CARMA Platform and UCLA's OpenCDA to further improve and enhance interoperability.(16,10) Through integration testing of test sequence 4, the project team determined that initializing the OpenCDA vehicle model first would lead to more reliable interactions between the OpenCDA and CARMA Platform vehicles.(10,1) Additionally, the project team identified several improvement areas where the trajectory planning logic of the two constructive vehicles could further cooperate. This finding highlighted the value and effectiveness of distributed and collaborative testing to identify and address interoperability issues across various CDA entities, applications, and models.(1) For more discussions, please see appendix B.

Objective 1.3 Test the first TENA adapters developed by DOT.

Researchers successfully met objective 1.3. During the SIT-1 test, many TENA adapters were built by DOD partners.(3) Pilot 1 marked the first time anyone outside DOD had developed TENA-based objects. Two new TENA adapters and one new TENA message type were developed for Pilot 1. Some adapters and OMs were also modified to enable using the new TENA message and accomplish the Pilot 1 objectives and requirements. All development was completed by FHWA's STOL team. With the completion of this test, the team became familiar with the process and effective practices in developing and modifying TENA OMs, messages, and adapters for future exercises.

CDA OBJECTIVES

Objective 2.1 Demonstrate a CDA application that tests interactions between infrastructure and vehicles. Collect CDA research data.

Researchers successfully met objective 2.1. The UCLA OpenCDA vehicle successfully stopped at a traffic signal controlled by an Econolite virtual TSC in multiple tests. The UCLA OpenCDA vehicle also navigated around the CARMA vehicle, showing that the UCLA OpenCDA vehicle was aware of the CARMA vehicle.(10) Finally, data from the simple vehicle model run by Nissan were collected from test sequence 1 to support the development of the SAE J3305 standard on assured green period (AGP) capabilities.(25) Data for all tests were collected, and details are provided in chapter 4 and appendix A.

Objective 2.2 Demonstrate a partnership between government, private sector, and academia that would ideally produce data to inform a CDA standards effort.

The researchers successfully met objective 2.2. Pilot 1 was a team effort between FHWA (government organization), Nissan (private automotive company), UCLA (university), Econolite (private intelligent transportation systems solutions company), and Scientific Research Corporation (DOT and DOD contractor).

The collaboration between UCLA (with its OpenCDA vehicle) and Econolite (with its virtual TSC) allowed them to validate the functionalities with applications developed by other organizations.(10)

The simple vehicle model run by Nissan demonstrated the capability to rapidly test and collect data to support the development of the SAE J3305 standard on AGP.(25) AGP is meant to decrease the probability of a vehicle being in a connected intersection during a red signal. It aims to improve red light violation warning applications by enhancing existing problem zone protection at signalized junctions with advanced detection.(26) One test partner, Nissan, is involved in the SAE AGP standard development and leveraged Pilot 1 to collect data to support the standard development.(25) The pilot was used to prove that data collection using models was possible as Nissan used their simple kinematic vehicle model to collect data. However, as the model was simple, it did not reflect real-world vehicle dynamics.

All parties involved in Pilot 1 contributed time and resources and shared their applications. The success of this collaboration demonstrates the effectiveness of these relationships and the potential for existing and additional relationships in the future.

Objective 2.3 Develop new digital assets (e.g., maps, scenarios, etc.) and tools (e.g., TENA OMs and adapters for surface transportation interoperability testing) that will be of value to the CDA research community.

Researchers successfully met objective 2.3. Pilot 1 was conducted on two different maps: the CARLA fictional Town 04 and one CARLA map developed by UCLA based on a real-world intersection in Los Angeles, CA.(22) The success of Pilot 1 establishes these maps as assets for use in future tests and demonstrations.

Objective 2.4 Explore interoperability issues among the models or tools from distributed testing partners that warrant further study and resolution.

This objective was successfully met. Pilot 1, especially test sequence 4, demonstrated interoperability among all participants and specifically aimed to begin testing out conflicts between road actors. While all tests incorporated the Econolite virtual TSC, test sequence 4 included vehicle-to-vehicle interaction between the OpenCDA vehicle and the CARMA Platform vehicle.(10,16) These interactions could help wring out certain interactive behaviors (e.g., OpenCDA vehicle's maneuver to overtake the CARMA vehicle), demonstrating the value distributed testing brings to the landscape of connected transportation. For more discussions, please see appendix B.

TEST REQUIREMENTS ASSESSMENT

Table 1 lists the requirements that Pilot 1 was tested against and how they were met during testing. These requirements are grouped based on functionality and participants.

Table 1. Pilot 1 requirements.

Identifier	Requirement Text	Objective	Test Case	Result	Result Notes
GEN-01	Pilot 1 shall include multiple vehicles controlled by different automated driving systems.	1.2	All	Pass	Pilot 1 included CARMA Platform, UCLA OpenCDA, and the Nissan simple vehicle model.(10)
GEN-02	Pilot 1 shall integrate a remotely hosted virtual traffic controller to control a traffic signal in CARLA.(12)	1.2, 1.3	All	Pass	Pilot 1 included an Econolite virtual traffic controller.
GEN-03	Pilot 1 shall collect data from all sites for postanalysis for simulation accuracy and network performance.	1.1, 1.3	All	Pass	Pilot 1 collected data for all sites. See the "Network Performance Analysis Results" section for results.
TJA-01	The TENA J2735 adapter shall receive J2735 UDP packets at a configurable IP and port, identify the J2735 message type, package the payload into a TENA J2735 message, and broadcast it to the TENA execution.(9,20)	1.5, 2.2	All	Pass	All sites utilized a TENA J2735 adapter to receive J2735 data. Information on the data and analysis can be found in the "Analysis Results" section.(9)
TJA-02	The TENA J2735 adapter shall subscribe to TENA J2735 messages, assemble received messages payloads into a UDP packet, and send that packet to a configurable IP and port.(9,20)	1.5, 2.2	All	Pass	All sites utilized a TENA J2735 adapter to receive J2735 data. Information on the data and analysis can be found in the "Analysis Results" section.(9)

Identifier	Requirement Text	Objective	Test Case	Result	Result Notes
TTEG-01	The TENA TrafficLight Entity Generator shall subscribe to TENA J2735 messages, decode messages with the SPaT type, assemble a TrafficLight SDO with the decoded data, and broadcast the TrafficLight SDO.(9)	1.5, 2.2	All	Pass	The TENA J2735 TrafficLight Entity Generator was hosted by Econolite for Pilot 1 and received J2735 messages generated by the Econolite TJ2735 adapter and converted them to TrafficLight SDO updates.(9)These SDO updates could be seen visually as traffic light state changes on all participating simulations as well as in the data collected. Information on the data and analysis can be found in the "Analysis Results" section.
NET-01	Pilot 1 shall utilize a cloud-hosted networking solution that enables participants to connect their devices and connect to other participants devices.	1.1	All	Pass	Pilot 1 was conducted on a cloud-hosted zero-trust VPN platform by Twingate.(7) Each site established connections to every other site by authenticating and gaining authorization from the Twingate controller hosted on a cloud-based platform.(7)
NET-02	The Pilot 1 network shall require individual user authentication to connect and allow for per-user configuration of authorization of access to specific resources.	1.1	All	Pass	Twingate requires user-level authentication as well as authorization of specific resources.(7)

Identifier	Requirement Text	Objective	Test Case	Result	Result Notes
NIS-01	The Nissan site shall host CARLA simulation, a simple vehicle model constructive vehicle, a TENA CARLA adapter, and a TENA J2735 adapter.(12)	1.2, 2.1	Tests 1, test 3	Pass	The Nissan site hosted the simple vehicle model, a TENA CARLA adapter, and a TENA J2735 adapter.
NIS-02	The Nissan simple vehicle model shall drive in a straight line from its start point to end point without changing speed or direction.	1.3, 2.3	Tests 1, test 3	Pass	The simple vehicle model traveled from start point to end point without changing speed or direction.
NIS-03	The Nissan simple vehicle model shall receive J2735 BSMs and J2735 SPaT from the TENA J2735 adapter via UDP packet.(9,20)	1.3, 1.4	Tests 1, test 3	Pass	The simple vehicle model received J2735 SPaT and BSMs and was collected in the inbound packet capture.(9)
ECO-01	The Econolite site shall host a virtual traffic controller, which sends J2735 SPaT messages for the Test Intersection to a local TENA J2735 adapter.(9)	1.2, 2.1, 2.3	All	Pass	The Econolite site hosted a virtual traffic controller, which sends J2735 SPaT.(9)
ECO-02	The Econolite site shall host a TENA J2735 adapter, which shall receive the J2735 SPaT from the Econolite virtual traffic controller and convert it to TENA J2735 messages.(9)	1.3	All	Pass	The Econolite J2735 adapter received J2735 SPaT and converted it to J2735 TENA messages as seen in the outbound packet capture and TDCS data.(9)

Identifier	Requirement Text	Objective	Test Case	Result	Result Notes
ECO-03	The Econolite site shall receive J2735 BSMs from the TENA J2735 adapter via UDP packet.(9,20)	1.3, 1.4	All	Pass	The Econolite site received J2735 BSMs from the TENA J2735 adapter as seen in the inbound packet capture.(9)
ECO-04	The Econolite site shall host a TENA TrafficLight Entity Generator, which converts TENA J2735 messages of type SPaT into TrafficLight SDOs.(9)	1.3, 1.5	All	Pass	The Econolite site hosted a TENA TrafficLight Entity Generator and generated TrafficLight SDOs as seen in the TDCS data.
UCLA-01	The UCLA site shall host a CARLA simulation, an OpenCDA constructive vehicle, a TENA CARLA adapter, and a TENA J2735 adapter.(12)	1.2, 2.1, 2.3	Test 2, test 3, test 4	Pass	The UCLA site hosted host a CARLA simulation, an OpenCDA constructive vehicle, a TENA CARLA adapter, and a TENA J2735 adapter.(12,10)
UCLA-02	The Nissan simple vehicle model shall receive J2735 BSMs and J2735 SPaT from the TENA J2735 adapter via UDP packet.(9,20)	1.3, 1.4	Test 2, test 3, test 4	Pass	The UCLA site received J2735 BSMs and SPaT from the TENA J2735 adapter as seen in the inbound packet capture.(9)

GEN = general requirements for the Pilot 1 system; TJA = requirements for the TENA J2735 adapter; TTEG = requirements for the TENA TrafficLight Entity Generator; NET = network-based requirements; NIS = requirements for the functionality at the Nissan site; ECO = requirements for the functionality at the Econolite site; UCLA = requirements for the functionality at the UCLA site; IP = Internet protocol.

CHAPTER 4. NETWORK PERFORMANCE ANALYSIS RESULTS

DATA COLLECTED

This section describes the specific data collected using the TENA TDCS and details how the data were used for troubleshooting and data analysis. All collected data were organized into a metadata sheet. The metadata sheet referenced specific files for each data type for each test case and run. Table 2 shows the type of data obtained from Pilot 1 testing.

Table 2. Pilot 1 data.

Data Type	Description	Use
CARMA Platform rosbag(16)	Contains all Robot Operating System (ROS) messages sent and received by a CARMA Platform instance.(16,27)	Verify messages sent and received by CARMA Platform are properly decoded; troubleshoot CARMA Platform issues.(16)
CARMA Platform logs(16)	Contains all logs for a CARMA Platform instance.(16)	Troubleshoot CARMA Platform issues.(16)
CARMA Platform inbound PCAP(16)	Packet capture of all messages inbound to a CARMA Platform instance.(16)	Verify messages are being sent to CARMA Platform and validate the contents against TENA SDO data.(16,4)
CARMA Platform outbound PCAP(16)	Packet capture of all messages outbound from a CARMA Platform instance.(16)	Verify messages are being sent from CARMA Platform and validate the contents against TENA SDO data.(16,4)
V2X Hub message receiver inbound PCAP(18)	Packet capture of all messages inbound to V2X Hub.(18)	Verify messages are being received by V2X Hub and validate the contents against TENA SDO data.(18,4)
V2X Hub message receiver outbound PCAP(18)	Packet capture of all messages outbound from V2X Hub.(18)	Verify messages are being sent by V2X Hub and validate the contents against TENA SDO data.(18,4)
TENA adapter logs(4)	Log output from the TENA adapter.	Troubleshoot issues with the TENA adapters.
Pilot 1 TDCS database capture	Pilot 1 TDCS database of all TENA SDOs and TENA messages sent and received in the TENA execution.(4)	Verify TENA SDO and TENA message data are being generated and validate contents against packet captures.(4)
Screen recordings	Recording of the screens of various components of the Pilot 1 LVC environment.(5)	Visualize the Pilot 1 simulation and demonstrate LVC components working together.(5)

PCAP = packet capture.

KEY FINDINGS

The shift from individual message-specific TENA OMs (e.g., BSM Track OM in SIT-1) to a J2735 TENA message simplified the analysis process and led to similar performance for all data types.(3) The following takeaways can be drawn from the detailed data analysis results (see appendix A).

First, J2735 TENA messages can be generated from J2735 UDP packets within 0.1–0.2 ms.(9,20) J2735 SPaT and BSM as TENA messages were generated in this range by the local instances of TJ2735A at the Econolite and V2X-Hub constructive simulation nodes, respectively (measurement steps 1 and 2 in figure 3 and figure 4) in appendix A.(18) The only exception to this were MAP messages for test sequence 1, which were skewed by a single message generation outlier of 232 ms.(9) This single outlier has a large effect on the average, as MAP messages are only sent every 1 s.(9)

Second, the time measurement anomaly for TENA message to J2735 UDP packet persists from SIT-1, which results in negative latency values.(3) This anomaly occurred when the team measured the time between when an adapter receives a TENA message or SDO update, and when the respective UDP packet is generated. The UDP packet is regularly timestamped before the TENA SDO or message time of receipt.(20) This results in a negative latency value, which was verified by manually cross-checking data points and calculating the latency by hand. The source of this anomaly is still unclear: the timestamp recording process, the packet capture process, or the inaccuracy caused by approximating adapter data receipt by using TDCS all could be incorrectly timestamped. More discussion on this anomaly can be found in the SIT-1 report under BSM latency results.(3)

However, zero packets were dropped during all tests, and during the test segments analyzed, no dropped packets were found. The only packets missing from one dataset to another were found at the end of the file and were caused by datasets being clipped in slightly different places during collection or analysis.

The process for creating the J2735 MAP messages for the fictional CARLA Town 04 proved to be difficult, as there was no real-world location to use as a reference.(9,22) More information on this difficulty can be found in the “Lessons Learned” section in chapter 5.

Test results were also affected by slow internet connectivity at TFHRC. While all applications hosted at TFHRC were affected, connectivity issues were most evident in the data collected from V2X Hub during test sequence 4.(18) CARMA Platform data were likely also affected, but its data were not saved during this particular test sequence.(16) TFHRC leverages a bonded cellular internet connection that showed significantly higher jitter during the receipt of data (30–50 ms as opposed to 10–20 ms for other sites) but showed better than average outbound data transfer jitter (less than 10 ms). This behavior may indicate the cellular connection had faster upload speed than download speed, as speed tests regularly showed 90–110 megabits/s for the upload speed versus 60–80 megabits/s for the download speed.

There were also issues found specifically in test sequence 4. Multiple sources of data were not collected during test execution, including all V2X-Hub data and outbound TFHRC J2735 messages.(18,9) Instead, only SPaT from Econolite to UCLA and Econolite to TFHRC were collected, as well as BSMs from UCLA to TFHRC and UCLA to Econolite.(9)

The data transmission results appear to show that the clocks for all sites were out of sync. The average transmission time for TENA J2735 messages from Econolite to UCLA was 4.559 ms, and the reverse was 139.045 ms. Under the assumption that the upload and download speeds for each site are the same, both values should be approximately equal. The fact that they are not means a clock is skewed in at least one of the sites. However, if these values are averaged (such that the clock skew is canceled out), the resulting latency is 71.8 ms, which is very close to the value seen in test sequences 1–3. Additionally, the V2X Hub clock time was off from all other sites by 4–5 s.(18) All message latencies to or from V2X-Hub were between ±4,000–5,000 ms. This excessive latency was attributed to the V2X-Hub clock not being synchronized before execution. This issue can be corrected by synchronizing all clocks (manually or automatically) at the start of every test event. Again, this result stresses the importance of ensuring all clocks are synchronized at the start of all test events.

SIT-1 AND PILOT 1 LATENCY COMPARISON

SIT-1 sent J2735 data by using a TENA SDO that decoded J2735 data, repackaged them into separate BSM and SPaT messages, then encoded them on the transmitting end.(3,9) On the receiving end, data were decoded again, then repackaged into a single J2735 for use by CDA algorithms.(3) This messaging architecture was created by developers who had TENA experience but no domain knowledge, resulting in the inefficiency of the architecture.

For Pilot 1, FHWA developed the adapters in-house using its newly acquired knowledge of the TENA data language. Pilot 1 changed the messaging architecture by passing the full encoded J2735 messages directly, without any decoding or repackaging. This resulted in greatly reduced test latencies, as listed in table 3.(9) The results for BSM and SPaT latency were compared to the SIT-1 results to determine if the change to using TENA J2735 messages had an impact on measured test latencies.(9,3) The reference times are slightly different, owing to the different TENA objects used. Table 4 and table 5 show some analogous SIT-1 performance results for BSM and SPaT, respectively.(3)

Table 3. SDO generation results comparison.

Test	Origin	Destination	Latency (ms)	Comments
SIT-1	J2735 UDP receipt (BSM)	SDO update	0.75	N/A
SIT-1	J2735 UDP receipt (SPaT)	SDO update	0.75	N/A
Pilot 1	J2735 UDP receipt (BSM)	J2735 TENA message creation	0.1–0.2	N/A
Pilot 1	J2735 UDP receipt (SPaT)	J2735 TENA message creation	Inconclusive	Analysis resulted in a negative latency value, similar to SIT-1 results shown in table 5.

N/A = not applicable.

For message creation performance, from origination to receipt, Pilot 1 BSM and SPaT J2735 creation for Pilot 1 was between 0.1 and 0.2 ms.(9) Similar BSM message creation measurements from SIT-1 were 0.75 ms.(3) Similar SPaT generation results were inconclusive due to a negative calculated latency. Table 3 provides a summary of this information.

Based on the valid data collected, it can be concluded that creating messages using the new TENA J2735 adapter was almost four to five times faster than using the SIT-1 SDO update. This latency measurement captures only the message generation time, which is a small fraction of overall end-to-end test latency and is dominated by network latency between sites. Nonetheless, the research team recommends that prospective distributed testing users conducting CDA testing use the new adapter to minimize test latency.

Data transmission is difficult to compare between SIT-1 and Pilot 1. These tests not only involved almost all different sites, but also used completely different network architectures. To achieve a comparison, tests would need to use both the same sites and the same network architecture. As a result, only BSM and SPaT latency were compared between tests.

Table 4. SIT-1 BSM latency results for experiment 3, run 3, Augusta, GA (SRC), to McLean, VA (MITRE)*.

Steps	Average (ms)	Minimum (ms)	Maximum (ms)	Jitter (ms)	Std. Dev. (ms)
SDO message creation from J2735 (Augusta, GA)	0.753552	0.185013	16.293049	N/A	1.546494
SDO network transmission (from Augusta, GA, to McLean, VA)	10.411779	9.355068	33.188820	1.157521	N/A
J2735 message creation from SDO (McLean, VA)	3.463692	−8.454084	1,671.032906	N/A	67.930768

*Table 18 in SIT-1 report.(3)
Std. Dev. = standard deviation.

Table 5. SIT-1 SPaT latency results for experiment 3, run 3, live simulation node to constructive simulation node at SRC (Augusta, GA)*.

Steps	Average (ms)	Min (ms)	Max (ms)	Jitter (ms)	Std. Dev. (ms)
NTCIP message transmission (TSC to V2X Hub)	—	—	—	—	—
SDO creation (TFHRC V2X Hub Computer)	−1.459694	−67.244053	123.282194	N/A	14.474051
SDO network transmission (from TFHRC to Augusta, GA)	14.792430	10.411978	78.141928	4.147593	N/A

*Table 19 in SIT-1 report.(3)
—No data.

CHAPTER 5. LESSONS LEARNED AND CONCLUSION

LESSONS LEARNED

Adapter and Object Model Development Fundamentals

Pilot 1 was the first time the project team participated in the software development of TENA adapters and OMs. The team combined its transportation domain knowledge and its new understanding of TENA to improve test execution using TENA tools. Pilot 1 fundamentally changed the messaging approach for most CDA testing data exchanges by directly passing encoded J2735 payloads using TENA message adapters, as opposed to decoding and encoding them on either end.(9) This simplification of data exchange significantly decreased the latency of message exchange as the data being passed was smaller, and the process by which it was passed involved less processing. Ultimately the project team developed the J2735 TENA message, the TENA J2735 adapter, and the TENA Traffic Light Entity Generator as new components. The team also modified the scenario publisher, scenario SDO, and TENA CARLA adapter. The Pilot 1 team gained skills and confidence in TENA development during Pilot 1 development that will be useful for future collaborative, distributed testing tasks.

Streamlined Configuration Management

Configuration management becomes increasingly complex as the number of participants and types of participating applications increase. The Pilot 1 system contained multiple levels of configuration for each site and each application at each site. A configuration management plan needs to be carefully considered so that each site can quickly, easily, and effectively manage sites on initial setup and between updates. To streamline this process, the team made numerous enhancements to the Pilot 1 configuration management. Most notably, Pilot 1 managed scenario configuration and site configuration separately.

Previously, if a scenario's adapter version had been updated, that numerical version change needed to be propagated to all configuration files for each site. With the new scenario configuration files, such a change is applied to a central scenario configuration file to which all sites point. Other enhancements to the configuration architecture include changing the site configuration file link to the user's home directory to prevent accidental commits and/or consolidation of configuration parameters. The configuration management structure for executing collaborative, distributed tests will continue to evolve and improve with each additional test experience as opportunities to streamline the configuration process are identified.

Testing with External Models

Pilot 1 was the first time that the project team conducted distributed testing with heterogeneous models, as SIT-1 only used CARMA Platform.(3,16) The Pilot 1 test events integrated with UCLA's OpenCDA platform, which required the project team to adapt their practices to integrate with OpenCDA as well as assist the OpenCDA team to modify their capabilities to integrate with the distributed testing system.(10) This collaborative effort on both sites allowed both systems to become more interoperable. For the simple vehicle model run by Nissan, the project team worked together with Nissan engineers to develop a model from scratch that fit their needs. This was a learning experience for both teams that enhanced their understanding of CARLA and how it interacts with the distributed testing system.(12)

Planning, Coordination, and Time Management

When different complex systems come together for the first time, the amount of time required to troubleshoot can be difficult to estimate. Sometimes integration goes smoothly, but often it takes extensive troubleshooting of subsystems to get all parts working together. Because the components of Pilot 1 were managed and operated by many different parties, scheduling and logistics were among the biggest hurdles. It became important to use all planned time as efficiently as possible to give all teams the best chance for success. The project team quickly determined which components it could prep and test before the partners connected to the network while full collaborative testing meetings focused on distributed integration and coordination. There was a renewed emphasis on automated tools to execute a test, as well as analyzing the results. Scripting ensures tests and analyses could be conducted quickly and consistently. Through this process, the project team better grasped the true level of effort for integrating external platforms to improve planning for future integration efforts. Generating a more accurate level of effort and estimating timelines earlier in the project can help all parties plan and coordinate more effectively.

Mapping Simulated Worlds Can Be Difficult

Due to schedule constraints, most of the Pilot 1 test sequences had to be conducted using the CARLA Town 04 map instead of a CARLA map of any real-world place.(22) This was the first test of the system involving a fictional location with the use of CARLA's Town 04.(22) This simple example town was centered around 0 degrees latitude and 0 degrees longitude (i.e., 0, 0), with no correlation to a physical place on Earth. This made it difficult to create a J2735 MAP message (used in mapping SPaT message states to a vehicle's current approach) for this location.(9)

The standard process for developing a J2735 MAP message is to use the Intersection Situation Data (ISD) Message Creator, which allows the user to draw the appropriate configuration on top of satellite imagery.(9,28) Without satellite imagery, the project team could not draw the roadway geometry and relationships. The team worked around this by converting the XODR file format for Town 04 to a Keyhole Markup Language (KML) file format and importing the KML file into the ISD Message Creator.(See references 28, 22, 29, and 27.) This process created an outline of Town 04 in the appropriate location (0, 0).(22) With this, the team was able to draw the appropriate configuration and generate a J2735 MAP message.(9) This process was effective, but more elegant solutions could be explored. With the increased interest in simulation, it is likely this challenge with fictional towns will surface again.

CONCLUSION

VOICES Pilot 1 successfully integrated many new components, a new network architecture, and new TENA messaging structures while collaborating with public and private partners. The ability to quickly prototype and collaborate with diverse partners is what makes collaborative, distributed testing important. Pilot 1 strengthened relationships across government, industry, and academia; cultivated valuable TENA development experience; and expanded and enhanced system functionality. The Pilot 1 test proved that it is possible to perform distributed testing across the country in realtime using diverse simulated models at relatively low cost. Test outcomes should provide value to external stakeholders and foster relationships for future collaboration and development.

APPENDIX A. DETAILED MESSAGE LATENCY RESULTS

The Pilot 1 data analysis focused on three areas: comparing the performance of Pilot 1 BSMs with SIT-1; comparing the performance of Pilot 1 SPaT with SIT-1; and determining the performance of MAP messages.(3,9) These three metrics served as both regression tests of the system against previous tests and tested new functionality added for Pilot 1.

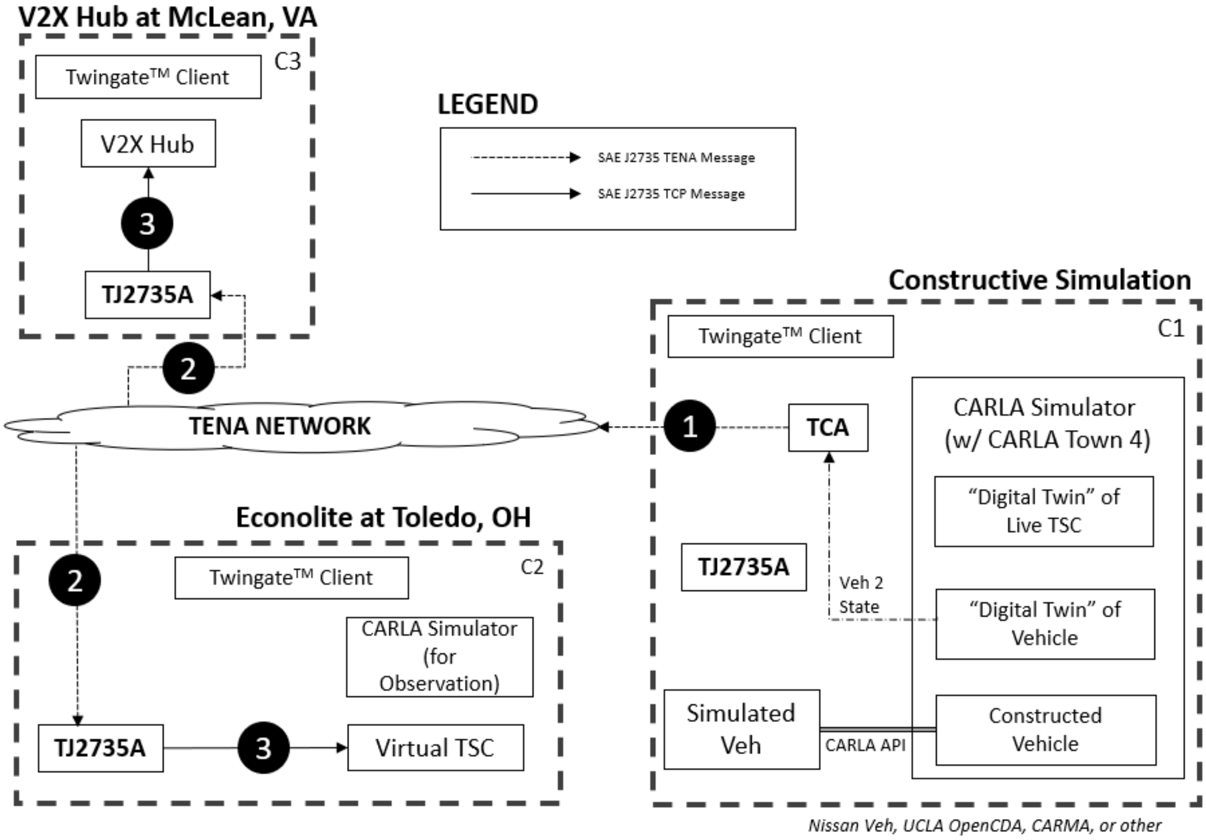
The main change between the SIT-1 and Pilot 1 test execution dataflows was the use of TENA message adapters instead of SDOs for each J2735 message type.(9)

The J2735 TENA message adapter simply packaged and sent the entire encoded J2735 payload.(9) Whereas, in SIT-1 testing, relevant adapters decoded messages, packed the fields into an SDO, and then broadcasted the SDO data.(3) Upon receipt, the SDO data had to be unpacked before use. The updated Pilot 1 approach reflected a greater understanding of how to efficiently conduct a test using TENA tools. This new approach saved compute time and resources at each end because the messages could be directly passed back and forth instead of decoding and encoding on each end.

The new dataflow contained three types of data generation and transmission: TENA message generation from J2735 UDP (or TENA message commit), TENA message network transmission, and J2735 UDP generation from J2735 TENA message. To measure these processes, data were collected as UDP packets outbound from the source application, as TENA data at the source site, as TENA data at the destination site, and as UDP packets to the destination application.(20) Some dataflows originated as TENA data and therefore did not have outbound UDP data, nor did they measure the TENA message generation from J2735 UDP step.(9,20) Specifics for each data type are detailed in the following sections along with results. Each analysis contained minimum, maximum, and mean for latency. Analysis was also performed for data transmission jitter as well as standard deviations for data generation times.

BSM DATA LATENCY PERFORMANCE RESULTS

The UCLA and Nissan vehicles did not produce their own J2735 BSMs; therefore, the TENA-CARLA adapter was responsible for generating them using CARLA data (similar to virtual vehicles in SIT-1).(3) This dataflow is shown in figure 3. Each data collection point in the process is numbered in the order of the dataflow. The results are shown in table 6, table 7, table 8, and table 9.



Source: FHWA.

Figure 3. Diagram. TENA J2735 BSM dataflow.

Table 6. Pilot 1, Test sequence 1, BSM data latency performance results.

Measurement Steps	Source	Destination	Minimum (ms)	Maximum (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1–2	Nissan	Econolite	53.790	108.118	64.245	4.792	NA
2–3	Econolite	Econolite	-44.982*	8.637*	-0.570*	NA	2.023
1–2	Nissan	V2X-Hub	4,970.096**	6,314.941**	5,066.811**	33.382	NA
2–3	V2X-Hub	V2X-Hub	-668.634	641.583	-3.351	N/A	84.406

N/A = not applicable.

*The time measurement anomaly for TENA message to J2735 UDP packet persists from SIT-1, which results in negative latency values.(3) See the "Network Performance Analysis Results" section for more information.

**The V2X-Hub clock time was off from all other sites by 4–5 s. See the "Analysis Results" section for more information.

Table 7. Pilot 1, Test sequence 2, BSM data latency performance results.

Measurement Steps	Source	Destination	Minimum (ms)	Maximum (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1–2	UCLA	Econolite	73.151	105.587	77.345	3.382	N/A
2–3	Econolite	Econolite	-5.838*	20.012*	-0.024*	NA	1.921
1–2	UCLA	V2X-Hub	4,959.772**	5,149.015**	4971.199**	9.824	N/A
2–3	V2X-Hub	V2X-Hub	-125.102*	176.415*	-0.638*	N/A	18.187

*The time measurement anomaly for TENA message to J2735 UDP packet persists from SIT-1, which results in negative latency values.(3) See the "Analysis Results" section for more information.

**The V2X-Hub clock time was off from all other sites by 4–5 s. See the "Analysis Results" section for more information.

Table 8. Pilot 1, Test sequence 3. BSM data latency performance results.

Measurement Steps	Source	Destination	Minimum (ms)	Maximum (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1–2	Nissan	Econolite	58.417	102.513	65.987	5.787	N/A
2–3	Econolite	Econolite	-9.727*	7.119*	-0.267*	N/A	1.758
1–2	Nissan	UCLA	45.134	57.412	50.743	1.987	N/A
2–3	UCLA	UCLA	-6.985*	0.269*	-0.051*	N/A	0.782
1–2	Nissan	V2X-Hub	4,973.732**	5,701.432**	5,066.243**	40.833	N/A
2–3	V2X-Hub	V2X-Hub	-621.060*	176.211*	-17.006*	N/A	71.243
1–2	UCLA	Econolite	71.140	107.484	76.029	3.715	N/A
2–3	Econolite	Econolite	-5.421*	5.113*	-0.327*	N/A	1.294
1—2	UCLA	Nissan	28.652	33.432	30.928	0.377	N/A
2–3	Nissan	Nissan	13.319*	18.537*	15.846*	N/A	0.629
1–2	UCLA	V2X-Hub	4,955.922**	5,508.892**	5,002.491**	32.261	N/A
2–3	V2X-Hub	V2X-Hub	-244.996*	266.163*	-1.537*	N/A	29.082

*The time measurement anomaly for TENA message to J2735 UDP packet persists from SIT-1, which results in negative latency values.(3) See the “Analysis Results” section for more information.

**The V2X-Hub clock time was off from all other sites by 4–5 s. See the “Analysis Results” section for more information.

Table 9. Pilot 1, Test sequence 4, BSM Data latency performance results.

Measurement Steps	Source	Destination	Minimum (ms)	Maximum (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1–2	UCLA	Econolite	135.4241***	205.2190***	139.0445***	2.8490	N/A
2–3	Econolite	Econolite	-143.8041*	7.8590*	-1.5354*	N/A	12.6398
1–2	UCLA	TFHRC	237.0179***	910.2919***	276.9412***	25.9875	N/A
2–3	TFHRC	TFHRC	-244.7331*	14.5352*	-4.0504*	N/A	24.8826

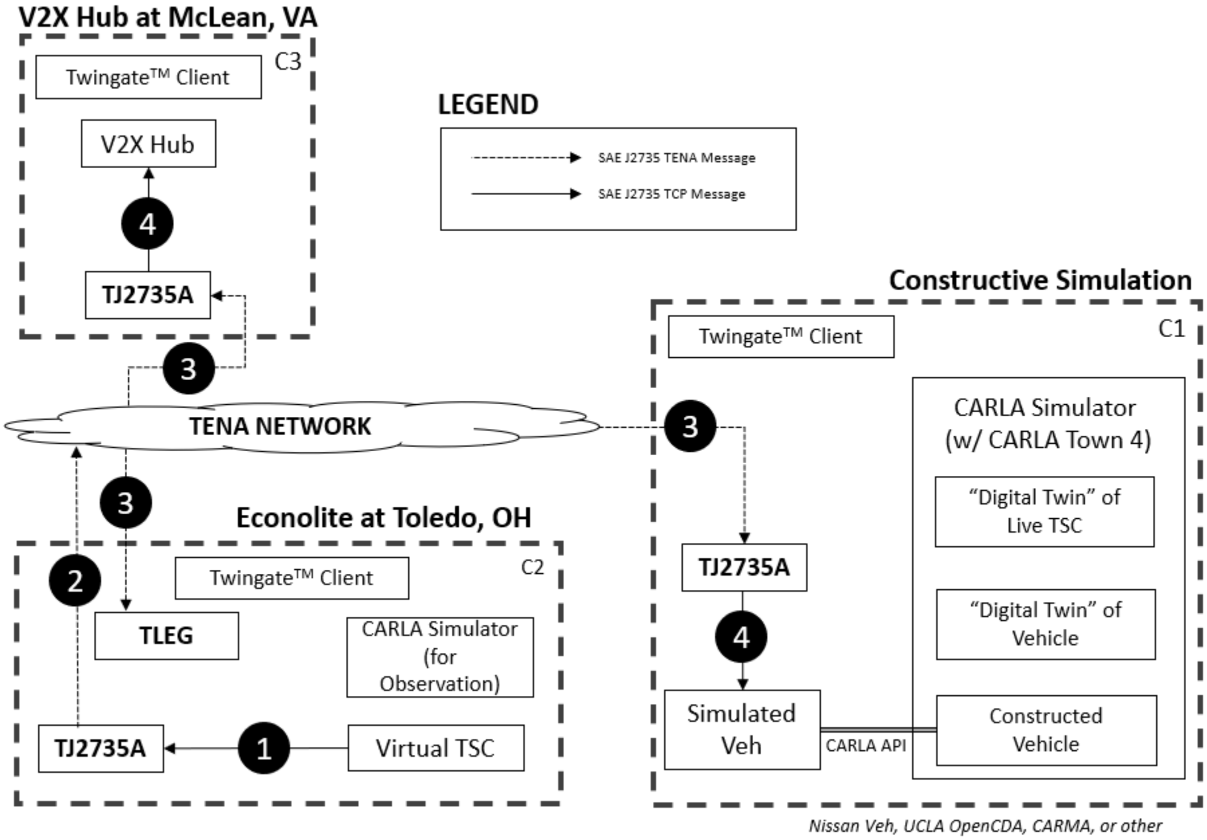
*The time measurement anomaly for TENA message to J2735 UDP packet persists from SIT-1, which results in negative latency values.(3) See the “Analysis Results” section for more information.

**The V2X-Hub clock time was off from all other sites by 4–5 s. See the “Analysis Results” section for more information.

***All time clocks during test 4 appear to be out of sync. See the “Analysis Results” section for more information.

SPAT DATA LATENCY PERFORMANCE RESULTS

J2735 SPaT data were transmitted from the Econolite virtual traffic controller by converting the J2735 UDP data to a TENA J2735 message and back using the TENA J2735 adapter on both ends.(9,20) Each data collection point in the process is numbered in the order of the dataflow. Figure 4 shows the TENA J2735 SPaT dataflow. Table 10, table 11, table 12, and table 13 show the TENA J2735 SPaT performance results for all tests.



Source: FHWA.

Figure 4. Diagram. TENA J2735 SPaT Dataflow.

Table 10. Pilot 1, Test Sequence 1, TENA J2735 SPaT data latency performance results.

Measurement Steps	Source	Destination	Min (ms)	Max (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1-2	Econolite	Econolite	0.059	3.674	0.125	N/A	0.163
2-3	Econolite	Nissan	38.096	110.107	55.504	10.557	N/A
3-4	Nissan	Nissan	-52.541*	50.154*	-6.723*	NA	11.778
2-3	Econolite	V2X-Hub	4,980.624**	6,514.449**	5077.848**	32.526	NA
3-4	V2X-Hub	V2X-Hub	-711.649*	1,010.795*	-5.929*	N/A	77.666

*The time measurement anomaly for TENA message to J2735 UDP packet persists from SIT-1, which results in negative latency values.(3) See the "Analysis Results" section for more information.

**The V2X-Hub clock time was off from all other sites by 4–5 s. See the "Analysis Results" section for more information.

Table 11. Pilot 1, Test Sequence 2, TENA J2735 SPaT data latency performance results.

Measurement Steps	Source	Destination	Min (ms)	Max (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1-2	Econolite	Econolite	0.062	2.829	0.137	N/A	0.210
2-3	Econolite	UCLA	50.401	104.323	61.821	9.422	N/A
3-4	UCLA	UCLA	-45.063*	34.101*	-1.667*	NA	11.176
2-3	Econolite	V2X-Hub	4,988.704**	5,147.433**	5,017.170**	17.044	N/A
3-4	V2X-Hub	V2X-Hub	-147.177*	34.751*	-9.538*	N/A	16.551

*The time measurement anomaly for TENA message to J2735 UDP packet persists from SIT-1, which results in negative latency values.(3) See the "Analysis Results" section for more information.

**The V2X-Hub clock time was off from all other sites by 4–5 s. See the "Analysis Results" section for more information.

Table 12. Pilot 1, Test Sequence 3, TENA J2735 SPaT data latency performance results.

Measurement Steps	Source	Destination	Min (ms)	Max (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1-2	Econolite	Econolite	0.048	1.894	0.125	N/A	0.162
2-3	Econolite	Nissan	41.361	123.884	59.092	14.400	N/A
3-4	Nissan	Nissan	-46.444*	50.074*	-7.046*	N/A	14.937
2-3	Econolite	UCLA	53.305	123.010	69.531	15.766	N/A
3-4	UCLA	UCLA	-44.123*	35.939*	-4.711*	N/A	12.717
2-3	Econolite	V2X-Hub	4,982.280**	5,709.105**	5,086.639**	50.044	N/A
3-4	V2X-Hub	V2X-Hub	-693.610*	100.137*	-22.078*	N/A	74.690

*The time measurement anomaly for TENA message to J2735 UDP packet persists from SIT-1, which results in negative latency values.(3) See the “Analysis Results” section for more information.

**The V2X-Hub clock time was off from all other sites by 4–5 s. See the “Analysis Results” section for more information.

Table 13. Pilot 1, Test Sequence 4, TENA J2735 SPaT data latency performance results.

Measurement Steps	Source	Destination	Min (ms)	Max (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1-2	Econolite	Econolite	0.0491	5.7158	0.1880	N/A	0.4413
2-3	Econolite	UCLA	-18.1670***	69.0110***	4.5590***	19.5061	N/A
3-4	UCLA	UCLA	-59.4831*	50.9870*	-7.1993*	N/A	22.4370
2-3	Econolite	TFHRC	192.0249***	800.0131***	250.4067***	38.0263	N/A
3-4	TFHRC	TFHRC	-463.1970*	124.2740*	-2.3224*	N/A	43.5657

*The time measurement anomaly for TENA message to J2735 UDP packet persists from SIT-1, which results in negative latency values.(3) See the “Analysis Results” section for more information.

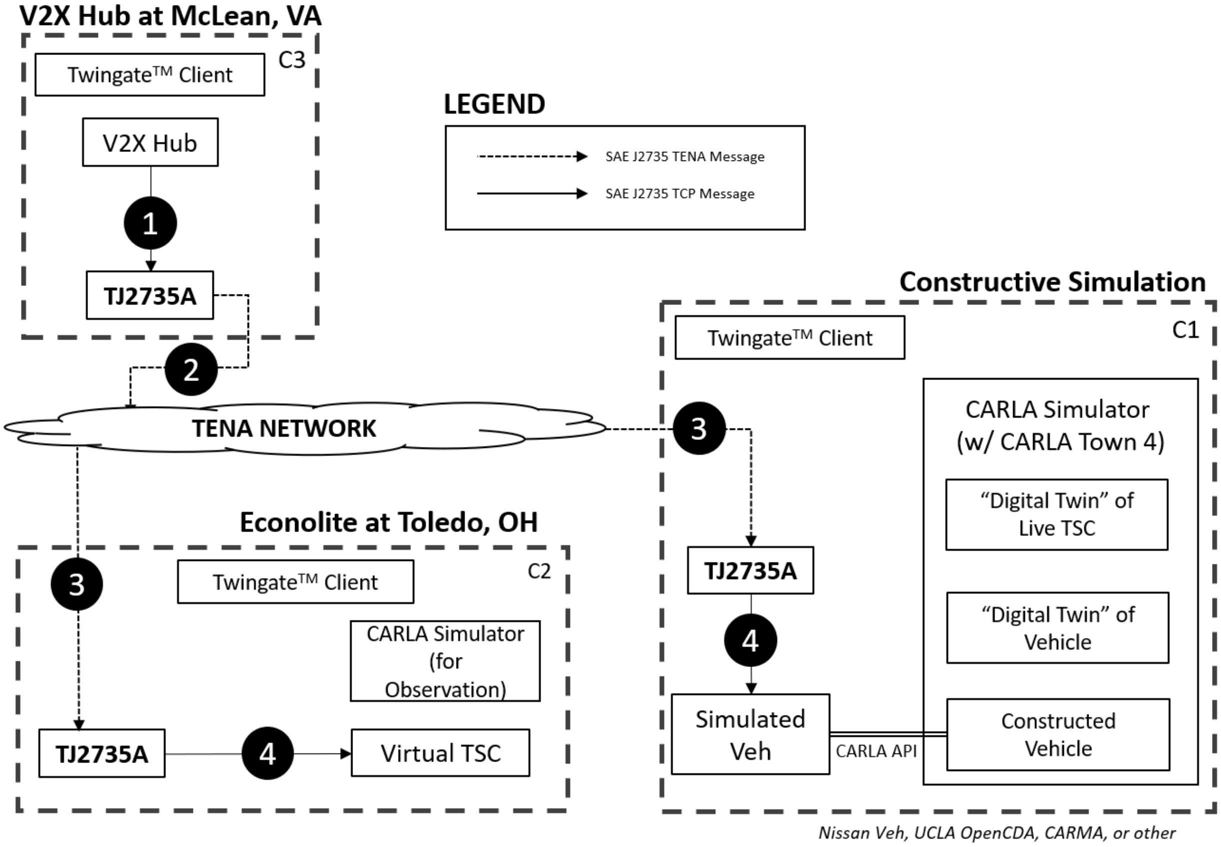
**The V2X-Hub clock time was off from all other sites by 4–5 s. See the “Analysis Results” section for more information.

***All time clocks during test sequence 4 appear to be out of sync. See the “Analysis Results” section for more information.

MAP DATA LATENCY PERFORMANCE RESULTS

J2735 MAP data were transmitted from the V2X Hub by converting the J2735 UDP data to TENA J2735 messages and back using TENA J2735 adapter on both ends.(9,18) Each data collection point in the process is numbered in the order of the dataflow. Figure 5 shows the TENA J2735 MAP dataflow. Table 14, table 15, and table 16 show the TENA J2735 MAP performance results for all tests.

Some TENA J2735 MAP messages were malformed and contained no data when decoded.(9) This is likely due to an improperly formatted UPER hex configuration in V2X Hub.(13,18)



Source: FHWA.

Figure 5. Diagram. TENA J2735 MAP Dataflow.

Table 14. Pilot 1, Test Sequence 1, TENA J2735 MAP data latency performance results.

Measurement Steps	Source	Destination	Min (ms)	Max (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1-2	V2X-Hub	V2X-Hub	0.057	232.521	1.736	N/A	19.436
2-3	V2X-Hub	Econolite	-4,787.552**	-3,344.581**	-4765.036**	27.598	N/A
3-4	Econolite	Econolite	1,570.536**	4,435.278**	2,999.553**	N/A	177.976
2-3	V2X-Hub	Nissan	-39.652**	230.914**	196.416**	7.939	N/A
3-4	Nissan	Nissan	-2,035.875**	-580.260**	-1,989.064**	N/A	126.139

**The V2X-Hub clock time was off from all other sites by 4-5 s. See the "Analysis Results" section for more information.

Table 15. Pilot 1, Test Sequence 2, TENA J2735 MAP data latency performance results.

Measurement Steps	Source	Destination	Min (ms)	Max (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1-2	V2X-Hub	V2X-Hub	0.069	0.374	0.136	N/A	0.078
2-3	V2X-Hub	Econolite	-4,786.426**	-4,751.058**	-4,774.702**	8.736	N/A
3-4	Econolite	Econolite	4,979.100**	5,033.372**	5,001.318**	N/A	10.915
2-3	V2X-Hub	UCLA	-4,843.291**	-4,817.143**	-4,828.866**	8.102	N/A
3-4	UCLA	UCLA	4,987.669**	5,026.016**	5,002.671**	N/A	8.869

Table 16. Pilot 1, Test Sequence 3, TENA J2735 MAP data latency performance results.

Measurement Steps	Source	Destination	Min (ms)	Max (ms)	Mean (ms)	Jitter (ms)	Std. Dev. (ms)
1-2	V2X-Hub	V2X-Hub	0.056	0.364	0.097	N/A	0.052
2-3	V2X-Hub	Econolite	-4,782.388**	-4,732.785**	-4,773.257**	8.247	N/A
3-4	Econolite	Econolite	4,962.930**	5,014.550**	5,000.218**	N/A	11.156
2-3	V2X-Hub	Nissan	-4,810.676**	-4,785.012**	-4,803.596**	5.045	N/A
3-4	Nissan	Nissan	4,975.838**	5,017.764**	5,001.147**	N/A	8.814
2-3	V2X-Hub	UCLA	-4,832.887**	-4,809.661**	-4,826.264**	5.247	N/A
3-4	UCLA	UCLA	4,979.092**	5,014.698**	5,002.020**	N/A	8.280

**The V2X-Hub clock time was off from all other sites by 4-5 s. See the "Analysis Results" section for more information.

APPENDIX B. TEST SEQUENCE 4 COOPERATIVE BEHAVIORS

The Pilot 1 test sequence 4 involved two constructive C-ADS vehicles—FHWA's CARMA Platform and UCLA's OpenCDA—that interacted with each other when traveling in the same lane toward the same intersection.(16,10) Both teams brought previously developed C-ADS capabilities to Pilot 1 test sequence 4. Since both C-ADS systems are research-grade software, it is expected that not all software functions, edge cases, or performances had been fully tested or smoothed out. Distributed testing is thus a highly useful capability that supports easy collaboration due to its distributed nature, as well as providing a safe and low-cost testing environment in simulation that avoids any risk of injury during testing.

Testing quickly revealed opportunities to improve the existing C-ADS capabilities in both systems to operate with other road elements. In initial testing, FHWA's CARMA Platform vehicle was intended to travel in front of the UCLA OpenCDA vehicle.(16,10) It was observed that FHWA's CARMA Platform vehicle did not stop at the traffic light properly in simulation at the time, although the functionality was tested and verified in the field as well as in simulation outside of this project. Moreover, the UCLA OpenCDA vehicle displayed aggressive overtaking behaviors that did not account for lane restrictions.

Further investigation revealed that the CARMA Platform vehicle did not stop at the red light during Pilot 1 due to a simulation time synchronization issue with the SPaT data and a MAP message that was misaligned with the actual high-definition map used by CARMA Platform.(16,9)

The UCLA OpenCDA vehicle attempted to overtake FHWA's CARMA Platform vehicle, when it caught up with the latter, and tried to pass in the left lane.(10,16) However, the left lane was a left-turn lane very close to the edge of the digital map. Since the vehicle was meant to travel straight through the intersection, the UCLA OpenCDA vehicle no longer had a prescribed path to its destination after it initiated its left turn. This conflict caused the UCLA OpenCDA vehicle to stop. In later test runs, the UCLA OpenCDA logic to initiate the passing maneuver was disabled, and the UCLA OpenCDA vehicle stopped behind the CARMA vehicle.(10,16) The UCLA OpenCDA vehicle used ground truth data from the CARLA API to identify when it got too close and needed to stop to avoid colliding with the CARMA vehicle.(10,12,16)

This testing highlighted previously unknown issues and enabled the team to better understand interactions between different road elements and types of connected and automated software. This finding highlighted the value and effectiveness of collaborative, distributed testing to identify and address interoperability issues across various CDA entities, applications, and models.

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