CAMP LLC

Vehicle to Infrastructure (V2I) Consortium

Vehicle-to-Infrastructure Program

V2I Safety Applications

Connected Work Zone Warning Application Deployment Guideline

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Federal Highway Administration (FHWA)

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Executive Summary

This report describes the work completed during Task 13 of the Vehicle-to-Infrastructure Safety Applications (V2I-SA) Project. This task addresses functionality, data needs and lessons learned from field deployment and testing efforts of work zone mapping procedure and Reduced Speed Zone Warning with Lane Closure (RSZW/LC) application for Connected Work Zone (CWZ) on the I-35 corridor in coordination with Texas Transportation Institute (TTI) and the Texas Department of Transportation (TxDOT). A section of I-35 will be expanded from four-lane freeway sections to six-lane sections in rural areas and expanded to eight-lane sections in Temple and Waco in Texas.

The RSZW/LC application uses V2I communication to inform or warn drivers as appropriate of a transient reduction in speed limit ahead due to roadway configuration change in a work zone such as lane closure or when the workers are present. The application supports both Reduced Speed (RS) Zone and Lane Closure (LC) ahead use cases. One of the key functions of the on-board RSZW/LC application is to accurately determine the vehicle's lane-level position using the work zone geometry received from the infrastructure. A Road-side Unit (RSU) broadcasts high-fidelity work zone map data elements in a wireless message that includes geometry of the work zone for each lane, start and end of tapers for lane closure(s), zone(s) where workers are present and posted speed limit(s) in the work zone.

Traditionally, for V2I applications, lane geometry is constructed by converting surveyed points to proper format as described in SAE J2735 [2] specification. Alternately, lane geometry can be generated by selecting points using a mapping software tool such as Google Earth Pro and then converting to the appropriate format.

One of the key elements of the in-vehicle application is to determine the vehicle's lane position. The lane matching algorithm uses two consecutive node points of the lane geometry and the lane width information to create a virtual bounding box. For a curved lane segment, the placement of consecutive waypoints is critical and may result in portions of the virtual bounding box being located outside the physical lane causing the algorithm to produce incorrect lane determination.

As described in the Task 14 [1] Interim Report, a "software toolchain" was developed to map a lane level digital maps in standard format for work zone for over-the-air transmission. The toolchain provides a mechanism for developing work zone map in a consistent manner.

The overall goal of the field deployment and testing efforts was to demonstrate the use of "software toolchain" for mapping procedures and receipt of information in the RSWZ/LC application status in a real-world situation. Additionally, there was a need to develop information and provide guidance as to how Infrastructure Owners and Operators (IOO) could plan to incorporate these procedures and applications in future work zones. In addition to testing the mapping process, a further objective of the work effort was to test the RSWZ/LC application. The IOOs however, differ in their approach to work zone testing, information distribution, and the level of traffic management software sophistication. Technical discussions amongst the research team led to the development

and testing of two approaches for CWZ application testing: High-Fidelity and Low-Fidelity. The High-Fidelity approach utilizes the full-lane-level digital map while the Low-Fidelity approach utilizes only a subset of the available information such as "left lane is closed ahead."

The experiences detailed in this report demonstrate conclusively that the process of broadcasting work zone information in a connected vehicle environment is valid and can be accomplished. The overall takeaway, however, is that the process of the connected work zone information broadcast cannot be directly adapted for the current practices used by the IOOs and needs to address several items prior it being ready for widespread use. The following lessons are apparent from the conclusion of this work effort.

- <u>Field Hardware Maturity</u> – The current state of field hardware utilized suffer from a lack of maturity and adherence to standards. Overall, significant diligence must be taken prior to field hardware procurement to ensure that the equipment meets all required specifications.
- <u>Test Vehicle Hardware</u> - The hardware components and application software used for building a reference test vehicle require manual configuration for testing the application and not integrated with the vehicle system. It would be ideal to have commercial off-the-shelf plug-and-play equipment. However, none is available at this time.
- <u>GPS Positioning Issue</u> - GPS position offset was encountered in one out of four test runs conducted. A preliminary investigation of the two GPS receivers used for work zone mapping and RLVW/LC application testing indicated approximately 67 centimeters position offset between the two receivers. No further detailed investigation was conducted. It is very likely that although the two receivers are from the same manufacture, but the different models require different configurations for offset adjustment.
- <u>Work Zone Mapping</u> - One of the most vexing problems to solve may well be the mapping requirements since the work zone deployments differ by state and perhaps even by region within any given state. The level of sophistication required to digitally maintain dynamic work zone setup may vary significantly by the agencies. Unless the required level of system to associate a mapped work zone and detailed lane closure information is addressed, there will be an impediment to wide-spread application deployment.
- <u>Availability of Lane Closure Information</u> - Some IOOs do not even require their contractors to submit individual lane closure information on a routine basis. The standardization of work zone information elements required to support the RSWZ/LC application will be necessary for future, broad-scale application.

- Desired Level of Broadcast Information - Conversations with multiple IOOs during this work effort indicate no universal support for either the high- or low-fidelity approach. Neither model is right or wrong but rather is an individual IOO choice that depends on multiple factors.

Overall, the process of alerting drivers in a work zone environment is a complex system integration effort. Operating a work zone connected vehicle environment without a traffic management software system would be highly manual task prone to significant effort. These realities limit the overall implementation arena and point to the potential need for multiple integration efforts across the nation to different software solutions.

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List of Acronyms

ASN.1	Abstract Syntax Notation One
CAMP	Crash Avoidance Metrics Partners LLC
CCTV	Closed-circuit Television Camera
CDCS	Corridor Data Collection Subsystem
CPMS	Corridor Performance Metrics Subsystem
CSW	Curve Speed Warning
CTIS	Construction Traveler Information Subsystem
CVMB	Connected Vehicle Message Builder
CWZ	Connected Work Zone
DOTs	Departments of Transportation
DSRC	Dedicated Short-Range Communications
DVI	Driver Vehicle Interface
eGUI	Engineering Graphical User Interface
EXER	eXtended XML Encoding Rules
FHWA	Federal Highway Administration
GNSS	Global Navigation Satellite System
I2V	Infrastructure-to-Vehicle
IATC	Infrastructure Application Technical Committee
ID	Identification Number
IMNS	Incident Messaging Notification Subsystem
IOO	Infrastructure Owners and Operators
LC	Lane Closure
LCAS	Lane Closure Assessment Subsystem
MAP	SAE J2735 Map Message
NB	Northbound
OBU	Onboard Unit
PCNS	Planned Closure Notification Subsystem
POE	Power over Ethernet

RS	Reduce Speed
RSM	Road Safety Message
RSU	Roadside Unit
RSUs	Roadside Units
RSZW/LC	Reduced Speed Zone Warning / Lane Closure
SAE	Society of Automotive Engineers
SB	Southbound
SwRI	Southwest Research Institute
TIED	Trav. Info. Email Dissemination Subsystem
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
UPER	Unaligned Packed Encoding Rules
V2I	Vehicle-to-Infrastructure
V2I-SA	Vehicle-to-Infrastructure Safety Applications (Project)
WZ	Work Zone
XML	Extensible Markup Language

1 Introduction

This document describes the functionality, data needs and lessons learned from implementing the Reduced Speed Zone Warning with Lane Closure (RSZW/LC) application for Connected Work Zone (CWZ) in coordination with Texas Transportation Institute (TTI) and the Texas Department of Transportation (TxDOT). The application is developed under the Vehicle-to-Infrastructure Safety Applications (V2I-SA) Project conducted by the Crash Avoidance Metrics Partners LLC (CAMP) V2I) Consortium. The project is sponsored by the Federal Highway Administration (FHWA) through Cooperative Agreement DTFH611H0002, Work Order 0003.

V2I applications potentially address scenarios that require information from the infrastructure for which vehicle on-board sensors alone may not be sufficient to provide the driver or system with information needed to take appropriate action in a timely manner. Proper and accurate infrastructure maps are crucial for the desired functioning of many V2I applications. V2I applications can employ any suitable technology or method to transmit infrastructure related information.

The objective of the RSZW/LC application is to leverage V2I communication to inform or warn drivers as appropriate of a transient reduction in speed limit ahead due to roadway configuration change such as lane closure when the workers are present. These conditions are frequently associated with active work zones. A Road-side Unit (RSU) broadcasts work zone data elements in a wireless message from the infrastructure that include:

1. Geometry of the work zone represented by waypoints that describe the layout for each lane
2. Lane closure location(s) – Start and end of tapers for lane closure(s) in the work zone
3. Workers present location(s) – area(s) where the workers are present in the work zone
4. Posted speed limit(s) in the work zone

The in-vehicle application receives work zone related information from the infrastructure and combines it with on-board Global Navigation Satellite System (GNSS) data for vehicle position determination and vehicle dynamics data to alert the driver appropriately when:

1. Lane closure(s) require the driver to change lanes
2. Vehicle speed is higher than the work zone speed limit

The in-vehicle RSZW/LC application relies on a Road Safety Message (RSM) transmitted from the infrastructure that includes a work zone map containing data elements specified in the SAE J2735 DSRC Message Set Dictionary [2] standard and specification being defined in SAE J2945/4 (Road Safety Applications). In this project, the RSM transmission from the infrastructure was limited to wireless communication using 5.9 GHz Dedicated

Short-Range Communication (DSRC). Field testing in an active work zone was needed to evaluate the work zone map data generated and transmitted over DSRC by the local Infrastructure Owners / Operators (IOO) using their typical practices and contractors against the in-vehicle RSZW/LC application performance.

Pilot field testing was conducted in conjunction with the TxDOT and their partners, Texas Transportation Institute (TTI) and Southwest Research Institute (SwRI) on selected section(s) of the I-35 corridor under construction. The goal was to understand the local IOO's ability to generate and maintain the desired work zone map and to refine/update the in-vehicle application to adapt to variations in map generation capabilities and work zone configurations. The outcome of the effort is a guidance document to assist other IOOs in deploying work zone mapping and data transmission and a refined in-vehicle RSZW/LC application.

2 The RSZW/LC Application for CWZ

When a connected vehicle equipped with DSRC approaches a zone that requires reduced speed and/or presents a change in roadway configuration, the RSZW/LC application evaluates vehicle speed and position against data received from the roadside to inform the driver they are approaching a reduced speed zone and, if necessary, warn them to take appropriate action. In the case of a work zone, the vehicle's On-Board Unit (OBU) receives RSM transmitted from the work zone RSU containing reduced speed limit(s), presence of workers, and geometric configuration including lane closure information, and combines this with vehicle-based data to execute the RSZW/LC function.

Experience has shown that effectiveness of this application is dependent upon timely information, which may require frequent infrastructure information updates as the work zone configuration and the presence of workers change. Figure 1 provides several examples of scenarios which illustrate the variability in work zone configurations the system should address.

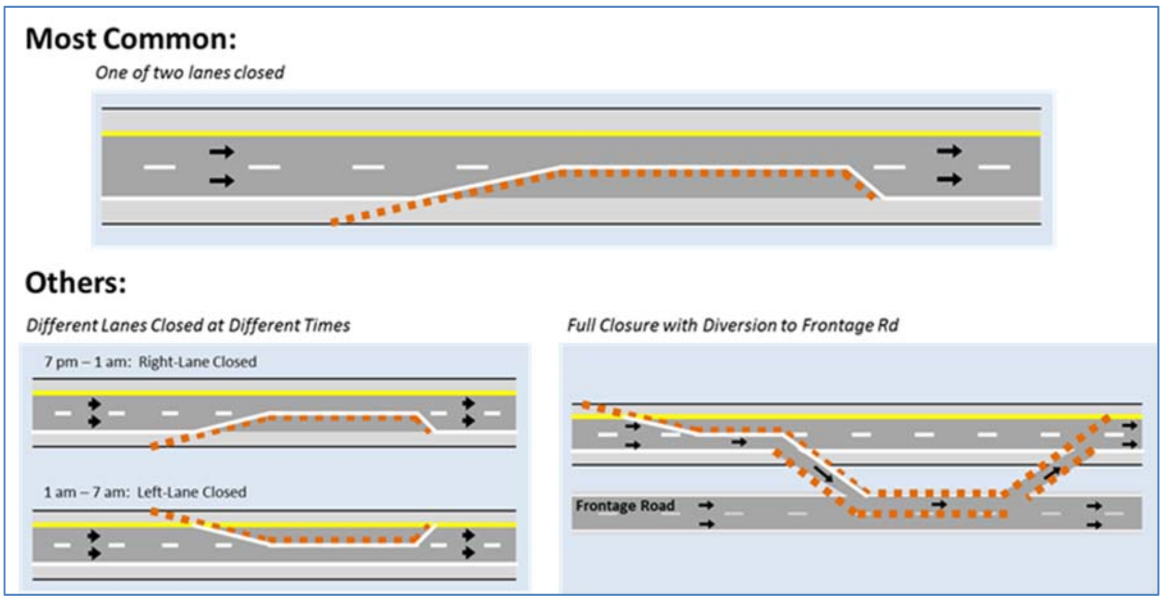


Figure 1: Examples of Work Zone Configuration

The RSZW application supports two different use cases:

1. Reduced Speed (RS) Zone: When approaching a RS zone, the application displays an RS Inform message on the Driver Vehicle Interface (DVI) at a configurable distance corresponding to typical response time and comfortable deceleration rate of 0.3g (does not account for weather and pavement conditions) for the driver to reduce speed before entering a work zone.
2. Lane Closure (LC) Ahead: In this case of a LC ahead, the application issues a LC Inform or Warning message to the driver based on the vehicle's travel lane and location relative to the reference point (start of the work zone). Initially the LC Inform message is displayed on the DVI at a configurable distance ahead of the

lane closure. If the driver continues to travel in the closing lane a LC Warning will be issued, which is also based on distance to the start of taper for the lane closure in the work zone.

The RSZW/LC application concept is illustrated in Figure 2 and the supporting information flow is shown in Figure 3.

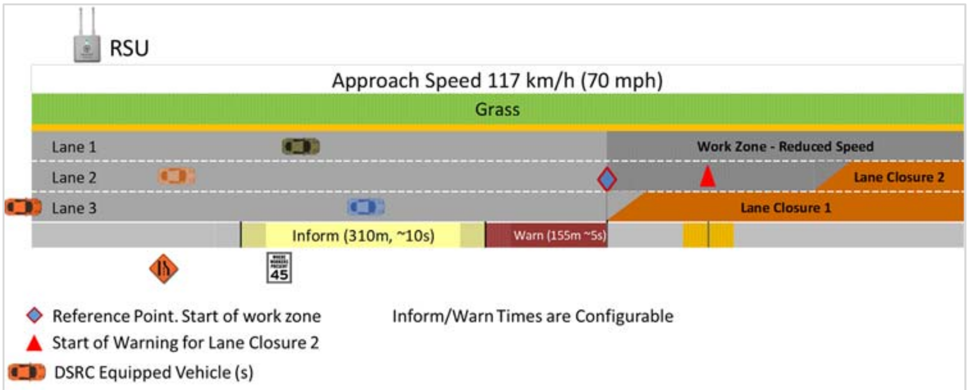


Figure 2: RSZW/LC Application Concept

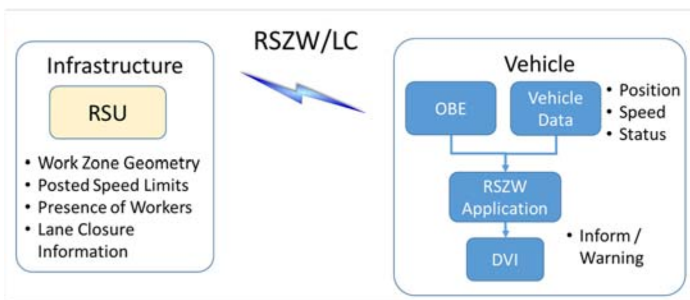


Figure 3: Information Flow between RSU and OBU

The work zone RSU broadcasts the information shown in Table 1 at a frequency of 1 Hz in RSM format.

Table 1: Work Zone Information from Infrastructure

1. Work Zone Geometry
o Reference Point: Indicate start of the work zone (e.g., location where the taper for lane closure begins). The work zone warning application in vehicle uses distance from the reference point for generating appropriate alerts/warnings for the driver. o Approach lanes: Define lanes that lead to the work zone o Work zone lanes: Define lanes within the work zone o Total length of the work zone
2. Lane Closure / Open Information
o Start of taper to indicate start of lane closure o End of taper to indicate end of closed lane / start of lane open o Indicate lane for possible lane change for a closed lane
o Workers Presence Zone
o Presence / absence of workers in the section(s) of the work zone where a lower speed limit applies
3. Posted Speed Limits (in the work zone)
o Normal speed limit o Speed limit in the work zone o Speed limit in the work zone when workers are present

3 Mapping a Work Zone

A work zone map defines the layout and configuration of the lanes approaching the work zone and available lanes for traveling in the work zone. Figure 4 illustrates a map that shows three approach lanes leading to the work zone and lanes in a work zone. The work zone begins at the marked reference point. It should be noted that the start of work zone is not always at the start of lane closure. As shown, lane geometry in the work zone has two lane closures. Lane closures and path through the work zone is defined by lane geometry. Lane numbers are designated from left to right in the direction of travel with left lane being the lane number 1.

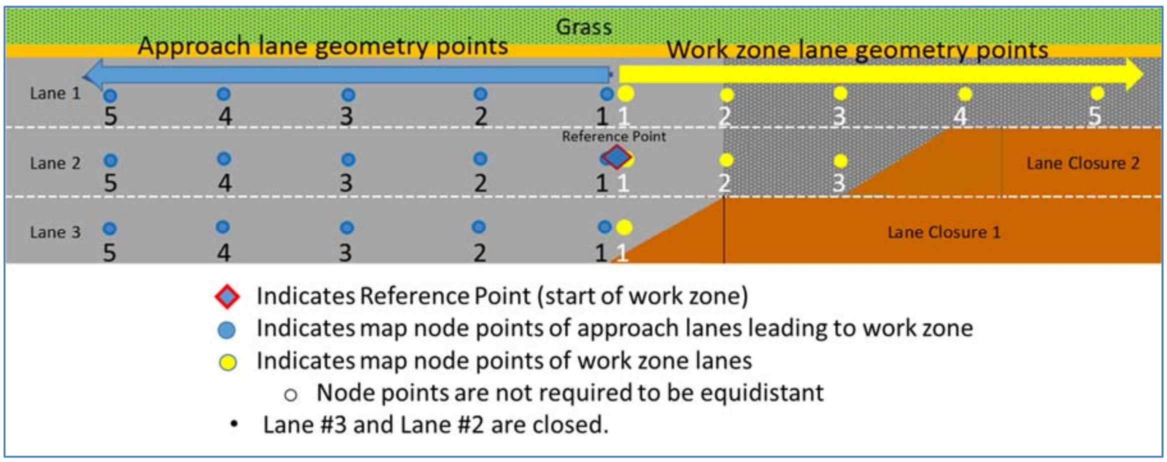


Figure 4: Illustrative Work Zone Map – 3 Lanes with 2 Lanes Closures

One of the key functions of the in-vehicle RSZW/LC application is to accurately determine the vehicle's lane-level position using the work zone geometry transmitted from the infrastructure. The selection of waypoints to represent work zone lane geometry, as defined in the SAE J2735 and J2945/4 documents, has direct implications on the performance of the vehicle map matching algorithm in determining the vehicle's position at a lane-level.

Traditionally, for V2I applications, waypoints (node points) for lane geometry are constructed by conducting a survey of lanes with fixed distance points. The surveyed points are then converted to proper format as described in SAE J2735 message set data dictionary. Such practice of conducting a survey can be costly and time consuming. It may also be necessary to conduct such survey multiple times since the road configuration, such as lane closures, invariably change several times during the roadway construction.

Alternately, waypoints for lane geometry can be generated by selecting points using a mapping software tool such as Google Earth Pro that provides latitude, longitude and elevation to define waypoints for lane geometry and then converts the waypoints to the appropriate format. For long roadway construction segments, this method can be very slow and prone to errors and may produce highly inaccurate lane geometry that would be insufficient for meeting V2I application map matching requirements. In cases where new roadway is being constructed, Google Map may not be available to define lane geometry.

3.1 Placement of Lane Geometry Waypoints for Lane Level Map Matching

Figure 5 shows a map matching algorithm concept that uses waypoints for a lane geometry and vehicle position using GNSS receiver. A virtual bounding box equal to the lane width (shown using a blue dashed line) is created using two consecutive waypoints or node points of the lane geometry. When the vehicle position is within the virtual bounding box, it is determined to be within the lane. The placement of consecutive waypoints (node points) may result in portions of the virtual bounding box being located outside the physical lane, particularly for a curved lane segment. In such cases, the map matching algorithm may produce either a false-positive result, indicating the vehicle is in lane when it is not (shown by the green crosshatched area in the figure), or a false-negative result, indicating the vehicle is out of the lane when it is in the physical lane (red crosshatched area).

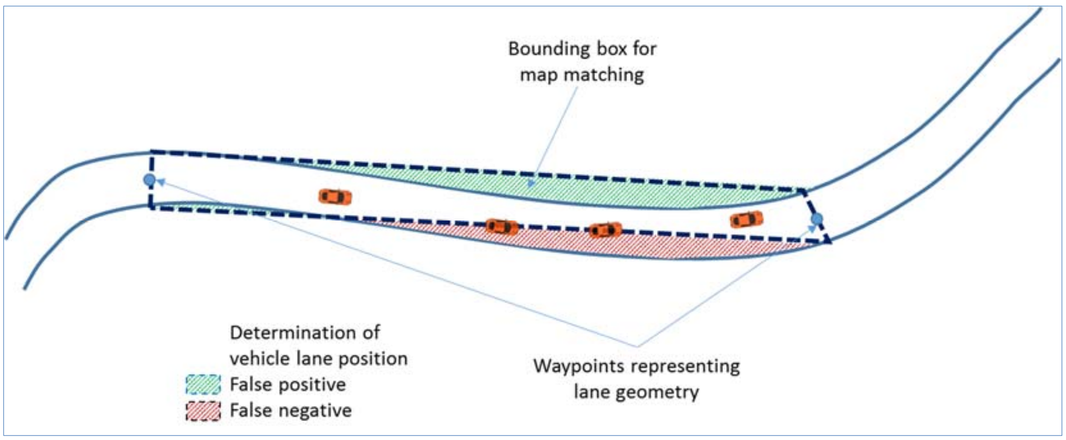


Figure 5: Vehicle Map Matching Using A Bounding Box

As illustrated in Figure 6, as the distance between the placement of the consecutive waypoints increases along a curved road segment, more and more portions of the virtual bounding box, as shown by dashed line, falls outside the physical lane, which increases potential for false positive and false negative errors in the map matching.

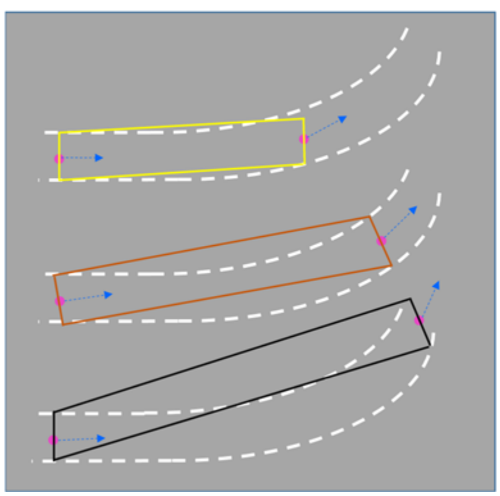


Figure 6: Placement of Lane Geometry Waypoints Based on Fixed Distance

As shown in Figure 7, lane geometry can be described by placing waypoints at a very close distance such that the virtual bounding box fully covers the physical lane segment. However, for a long work zone, it is very likely that the number of waypoints needed to represent the lane geometry could be greater than 63 waypoints (upper limit set in SAE J2735 specification) and would require splitting the lane geometry into multiple segments requiring multiple messages to represent the work zone thus resulting in loss of efficiency.

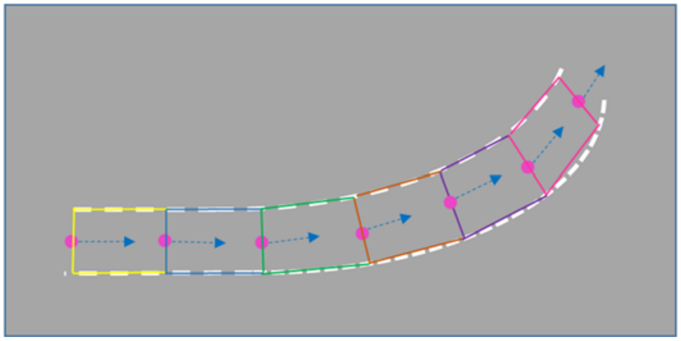


Figure 7: Lane Geometry Waypoints Based on Close Fixed Distance

To alleviate the issue described in previous section, the lane geometry waypoints need to be closer on curved lane segments while they can be further apart on straight segments such that the virtual bounding box for two consecutive waypoints maximizes the coverage of the lane area. As shown in Figure 8, the distance between waypoints can be varied as lane curvature changes to better accommodate straight and curved lane segments.

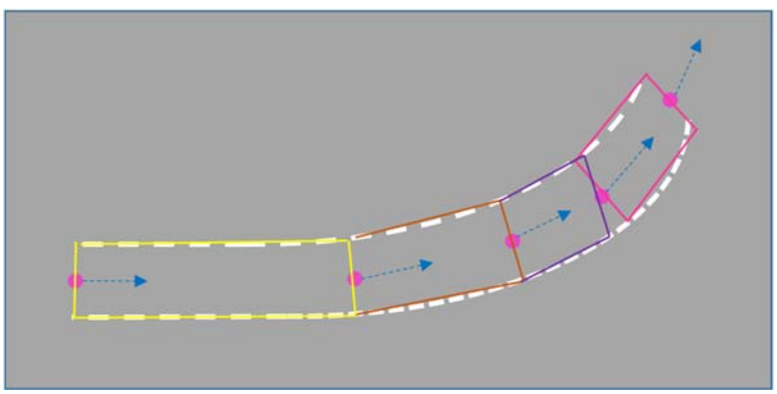


Figure 8: Lane Geometry Waypoints Based on Variable Distance

The following guidelines in Table 2 are established to generate a work zone map. The guidelines are based on ASN.1 schema defined for RSM as proposed in SAE J2945/4 document, SAE J2735 data dictionary and requirements for on-board application.

Table 2: Guidelines for Generating Lane-level Map

Guidelines for Generating Lane-level Map for a Work Zone	
1	Start of a work zone is designated by the "Reference Point" placed in the middle of the overall road cross section. The reference point is represented by latitude, longitude in degrees and altitude in meters.
2	Lane numbers are designated from left to right in the direction of travel with left lane being lane number 1.
3	Lane geometry waypoints (node points) are always in sequence starting from the "Reference Point" and moving away as shown in Figure 4. For the approach lane(s), waypoints (node points) are sequenced opposite to the direction of travel and for the work zone lane(s) sequenced that follows in the direction of the travel.
4	For each lane, geometry waypoints (node points) are represented in an X and Y offset from the prior waypoint. For simplicity, the waypoints can be defined by their latitude, longitude in degrees and altitude in meters at the center line of the lane. Each waypoint is then converted into DF_NodeXY using a software as defined in the SAE J2735 standard from the previous waypoint. Representing the waypoint as an offset from the previous waypoint reduces over-the-air message payload size. NOTE: A post processing software module to convert each waypoint into DF_NodeXY offset is incorporated into the "message builder" portion of the work zone mapping and message building software toolchain [3] as described later in this document.
5	The distance between the "Reference Point" and the 1st geometry waypoint (node point) for both the approach lane and the work zone lane should be equal to or less than the lane width to maintain map matching continuity from approach to work zone by the in-vehicle application.

Guidelines for Generating Lane-level Map for a Work Zone

6 The distance between geometry waypoints may vary and is dependent on the geometry of the lane/road curvature. For a straight segment, the distance between the two consecutive waypoints can be as much as 327.67m (see item #5 in this table. Waypoint offset is represented as xy offset in centimeter using a 16-bit integer value), apart, however, for a curved section the xy offset distance should be as specified. See Table 3 following the analysis graph shown in Figure 9 for suggested range of distance between waypoints for a curved segment. The ideal distance between the waypoints is highlighted by a dash line in the graph in Figure 9. The bounded area of blue colored line different colored square shows percentage error from ideal value.

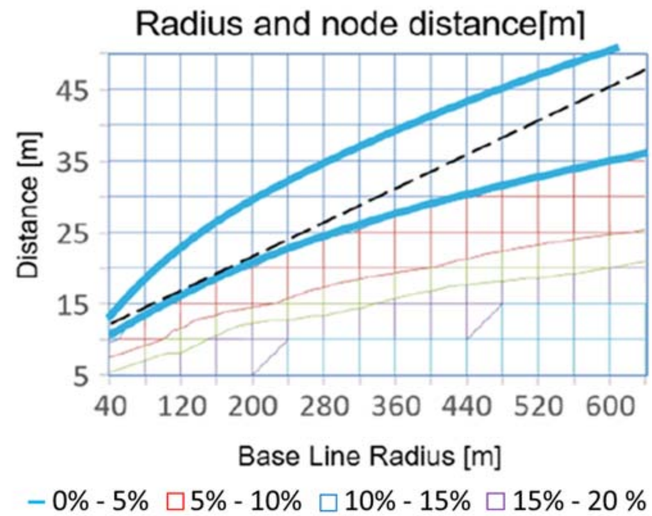


Figure 9 : Radius of Curvature and Distance between Nodes

Table 3: Radius of Curvature vs. Distance (Range) Between Waypoints

Radius of Curvature (m)	Distance (Range) Between Waypoints (m)
< 100	15 - 20
101 to 200	22 - 30
201 to 300	25 - 35
301 to 400	30 - 38
401 to 500	32 - 45
501 to 600	35 - 52

7 It is recommended that all approach lanes contain map data covering a distance equivalent to a minimum of 20 seconds of vehicle travel at the posted speed limit. This is needed by the in-vehicle application to determine vehicle position at lane level and generate inform / warn messages for the driver to take appropriate action. For example,

Guidelines for Generating Lane-level Map for a Work Zone	
	to support a vehicle approaching a work zone at a speed of 117 kph (70 mph), approach lanes should contain a minimum 626 meters (2054 ft) of map data.
8	Start of a lane closure (lane taper) distance in work zone is defined as an offset in meters from the "Reference Point."
9	Lane geometry for each lane in the work zone should be provided for the entire length of the work zone.

In Figure 10, waypoints of a representative map of a work zone is shown. As described earlier in the document, the reference point indicates the start of work zone where the effective speed limit change is applied for the work zone. In this example, the closure of lane #4 is at the start of the work zone and stays closed until the end of the work zone. Lane #3 closure starts later and ends before the end of the work zone. Lane #1 has a zone where the workers are present which may require change in speed limit within the work zone. The colored dots in the figure indicate waypoints that describe the lane level geometry of the work zone. Each waypoint may have associated one or more attributes to indicate for example start or end of lane closure, workers present and change of speed limit.

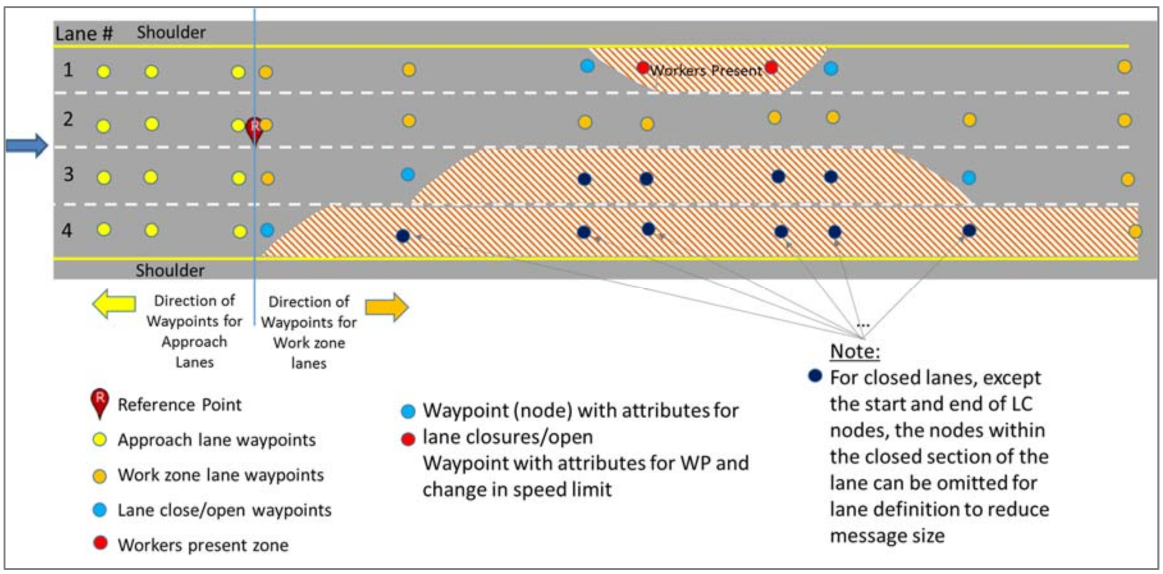


Figure 10: Representative Example of Waypoints

4 Road Safety Message

The message and data structures used in the RSM are designed to form a framework that enables multiple potential Infrastructure to Vehicle (I2V) applications and to address both static and dynamic events. The message consists of a common container that addresses information requirements across multiple applications and an application-specific container providing additional information to be included in the message as needed. Individual use cases within a given application may or may not require the application container. For example, a RSZW that supports school zones does not require an application container while one that supports work zones does require an application container. The common and application containers concept is illustrated in Figure 11. At the time of writing this document, under SAE Infrastructure Application Technical Committee (IATC), a J2945/4 Road Safety Message is being developed using the container concept. The application container for RSZW is in addition to other application container.

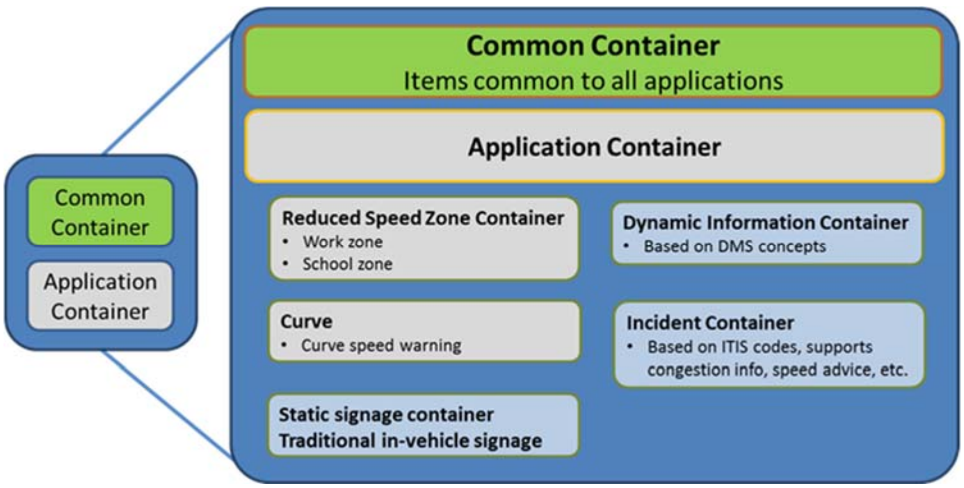


Figure 11: Common and Application Container Concept

4.1 Connected Vehicle Message Builder

The Connected Vehicle Message Builder (CVMB) [4] tool provides an automated software-based solution to convert an XML schema into Unaligned Packed Encoding Rules (UPER)-encoded RSZW/LC and Curve Speed Warning (CSW) messages compliant with the ASN.1 representation of RSM. The CVMB accepts work zone map generated in eXtended XML Encoding Rules (EXER) format and translates into UPER ready for over-the-air transmission. All messages are based on the ASN.1 schema for the RSM and the SAE J2735 (March 2016) data dictionary. The generated UPER encoded message is the communication medium agnostic for message transmission.

A detailed user guide v1.4 for the CVMB tool is provided in a separate document. The user guide provides:

1. Using XML to Formulate a Message
    - How to Formulate EXER-encoded Message

- XML Message Representation Detail
- Example XML Representation of the RSM

2. Use of optional fields
   - ASN.1 Definition of RSM
   - Encoding of Geometric Waypoint (node point) Latitude, Longitude and Elevation

3. Software Installation and Operating Instructions for CVMB
   - System Requirements
   - CVMB software installation and to run it in command window

4. J2735 editing instructions for updating the standard J2735 ASN.1 file (J2735_201603DA.asn) to include support for the RSM

5 Description of In-vehicle Application

The RSZW/LC application is designed to "Inform" the driver when approaching the work zone and "Warn" the driver when vehicle speed is higher than the posted work zone speed limit or a lane change is required due to a lane closure ahead. The application generates the Inform and Warn based on the vehicle velocity, lane placement and distance to the reference point (start of work zone). An "Inform" is generated at configurable time 't_{inform}' (currently 15 seconds) and "Warn" is also generated at configurable time 't_{warn}' (currently 5 seconds) prior to reaching the Reference Point. High-level vehicle-application logic is described in Table 4.

Table 4: Vehicle Application Logic

Vehicle Application Logic	
1	When the vehicle is approaching a work zone (WZ reference point) the application generates "Inform" indicating work zone ahead at t_{inform} allowing the driver to adjust the vehicle speed to the work zone speed.
2	When the vehicle is on the approach lane that is closing ahead in the work zone, an "Inform" indicating lane closure ahead is generated at t_{inform} seconds prior to the start of the lane closure.
3	When the vehicle continues in the closing lane, a "Warn" is generated at t_{warn} seconds prior to the start of the lane closer (taper) indicating immediate action is required. If the appropriate vehicle turn signal is activated or the lane is changed, the "Warn" is suspended.
4	When the vehicle speed in the work zone is above the posted speed limit plus a configurable hysteresis of between 6.43 to 11.26 km/h (4 to 7 mph) is used (to allow for vehicle to maintain speed limit closed to posted speed limit and to avoid frequent generation of the warning just above the posted speed limit), a work zone warning will be generated. When the vehicle speed is below the posted speed limit in the work zone, warning is suppressed, however, the "Inform" indicating "active work zone" continues until the end of the work zone.

The initial step of the algorithm is to calculate the appropriate "Inform" distance and "Warn" distance based on the vehicle's current speed. This is done using the following formulas:

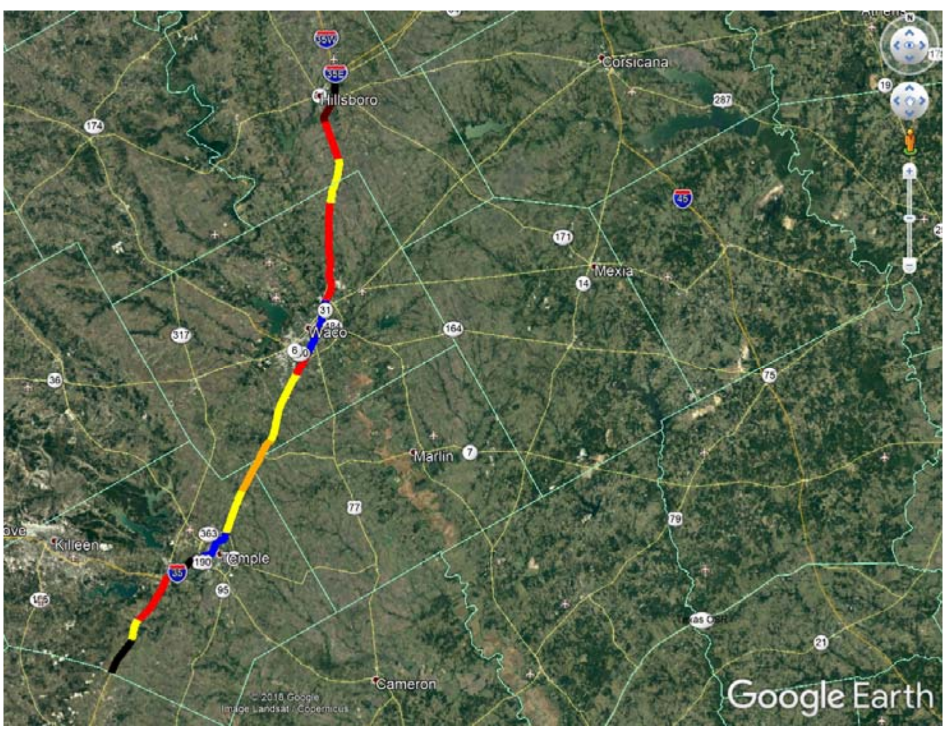
$$d_{inf} = v * t_{inform}$$
$$d_{warn} = v * t_{warn}$$

6 Field Deployment and Testing

The overall goal of the field deployment and testing efforts completed under this work task was to demonstrate the mapping procedures and receipt of information in the RSWZ/LC application status in a real-world situation. Additionally, there was a need to develop information and provide guidance as to how IOO's could plan to incorporate these procedures and applications in future work zones.

6.1 Field Testing Environment

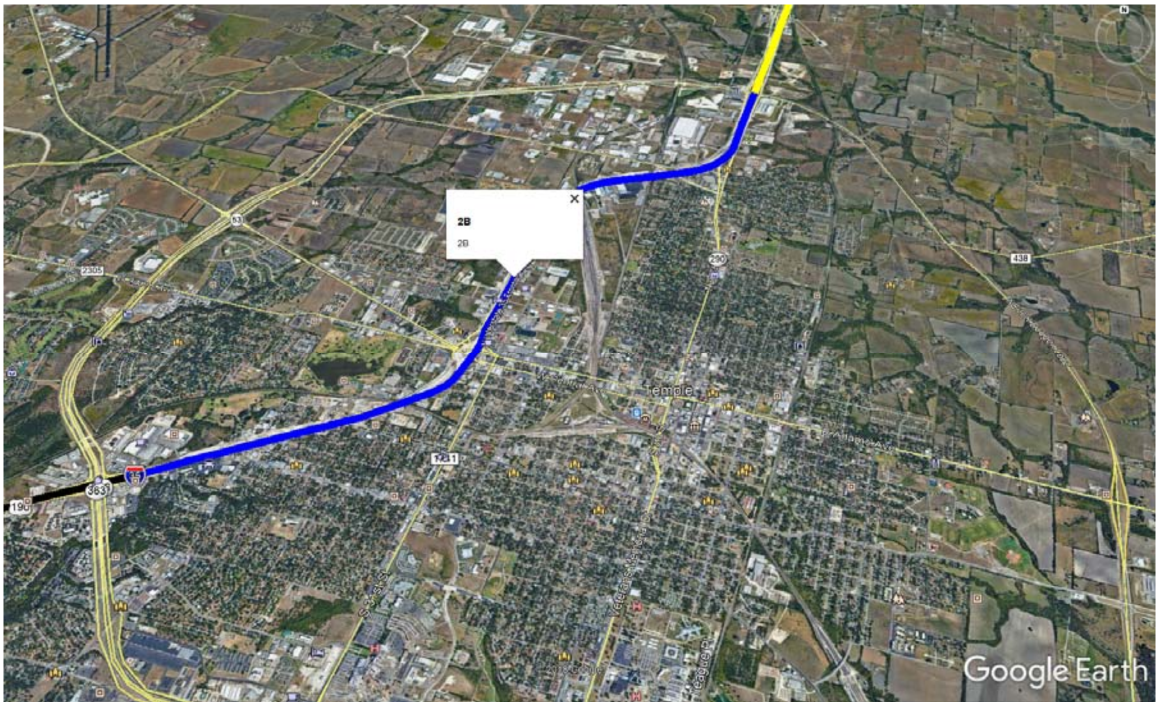
As illustrated in Figure 12, the Texas Department of Transportation (TxDOT) is implementing planned improvements to 96 miles of the I-35 corridor through Hill, McLennan, Falls, and Bell counties within the Waco district. This section of I-35 will be expanded from four-lane freeway sections to six-lane sections in rural areas and expanded to eight-lane sections in Temple and Waco. In addition, continuous north- and south-bound frontage roads will be constructed throughout this section of I-35. With the lengthy limits of construction, the rural and urban settings, and the large number of jurisdictions along and adjacent to I-35, maintaining regional traffic operations, local mobility, and an informed traveler creates unique challenges. TxDOT wanted to embrace the use of innovative intelligent transportation systems to provide traveler information during this multi-year reconstruction. TxDOT contracted with the Texas A&M Transportation Institute (TTI) to develop and implement a pioneering traveler information system for I-35 corridor travelers impacted by this construction.



Source: Map image from Google Earth. Used with permission.
Plotted data from Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 12: I-35 Corridor in Texas Showing Construction Sections

Figure 13 illustrates construction section 2B, located in Temple, Texas. The section covers North Loop 363 to South Loop 363, a distance of slightly more than five miles. As part of the existing data collection systems in place between the loop to monitor the construction activities, the section is covered by four Bluetooth readers for computing travel times, as well as a Wavetronix radar detector for recording volumes and classification. Two additional radar detectors are located slightly outside the loop on either end as well as additional Bluetooth readers.

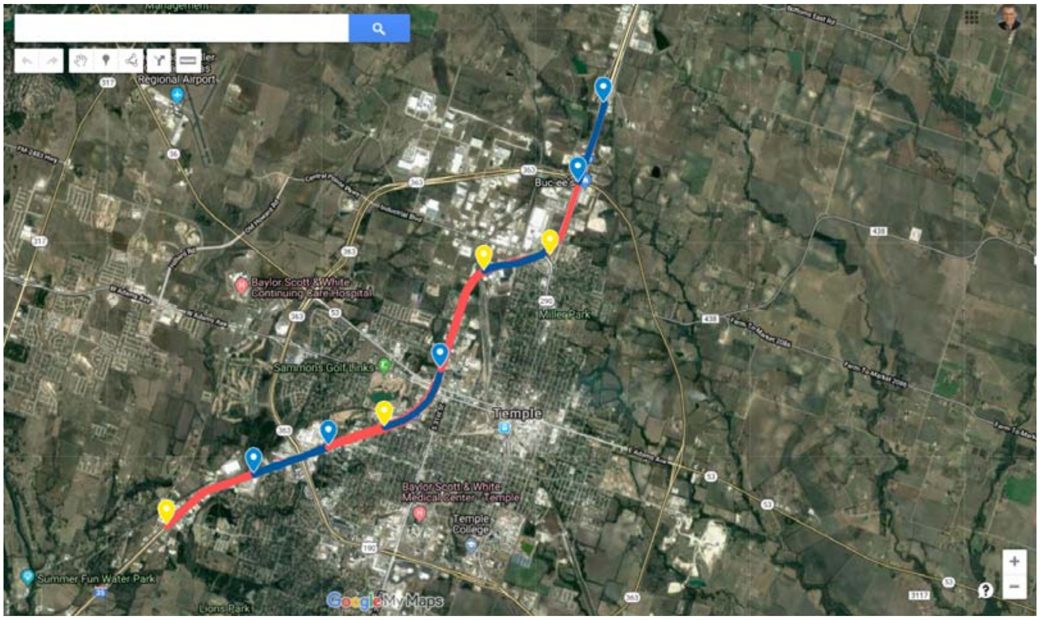


Source: Map image from Google Earth. Used with permission.
Plotted data from Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 13: I-35 In Temple, Texas

Figure 14 shows the RSU sites deployed to support the field testing based on the availability of power for field equipment. In the figure, the blue push pins indicate where RSUs were located on permanent infrastructure while yellow indicates that a temporary infrastructure solution of a wooden pole was utilized. There were five permanent sites and 4 temporary sites, for a total of nine RSU locations, spaced at approximately one mile. The overall extents of the test area extended beyond Loop 363 on both sides so that a variety of testing scenarios could be conducted.

In all cases, the RSUs were installed with solar power and cellular communications as the backhaul. At all locations, the cabinet solution utilized a 24V power over Ethernet (POE) solution. Some sites had collocated equipment such as a Bluetooth, radar detector, and/or a closed-circuit television camera (CCTV). The RSU make and model were specified by CAMP as listed in Table 5 to be compatible with previous testing. Figure 15 shows a typical RSU deployment on a temporary pole.



Source: Map image from Google. Used with permission.
Plotted data from Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 14: RSU Sites for Deployment in Temple, Texas

Figure 15: Typical RSU Deployment

6.2 Vehicle Testing Environment

At the time of the testing, no vehicles equipped with connected vehicle technology direct from the original equipment manufacturer were available to the research team. Additionally, the testing requirements dictated the need for a mobile unit that could be transported easily and installed in whatever vehicle was available for testing. Except for the case, connectors, and an external tablet or viewing mechanism, the make and model of all equipment for the vehicle, including external antennas was specified by CAMP to be compatible with development and previous testing. Table 5 details the equipment specified for purchase.

Table 5: List of Equipment for Vehicle

Item	Component / Cable Description	Supplier
1	**DSRC On-Board Unit (OBU)**	DENSO International
1.a	WSU 5001 Kit consists of following:	
1.b	Single DSRC Radio WSU-5001 with SD card installed	
1.c	WSU-5001 Power Cable	
1.d	Ethernet Cable	
1.e	U-blox M8N Receiver Evaluation Kit (EVK)	
1.f	Cables included in Kit	
	WSU to Router (Ethernet) WSU to Vehicle Power and Ignition Sense WSU to Ublox (GPS Receiver) Power	
2	**DSRC, GPS magnetic mount shark fin antenna**	Hirschmann Car Communication
2.a	HDSC-M2-0104A-02 with following 2 pig tails for DSRC and GPS 1. RG 174 LL600mm +/- 10 mm for DSRC (FAKRA Z Female) 2. RG 174 LL600mm +/- 10 mm for GPS (SMA Male)	
2.b	Extension Cable: HCBL-EX-01 - 6000 mm Length - DSRC (FAKRA Z Male)	
2.c	Extension Cable: HCBL-EX-02 - 6000 mm Length - GPS (SMA Female)	

Figure 16 illustrates the overall connectivity diagram for the equipment while Figure 17 shows a complete suitcase unit that could be installed in any vehicle. Power was supplied through a connection to the vehicle's cigarette lighter.

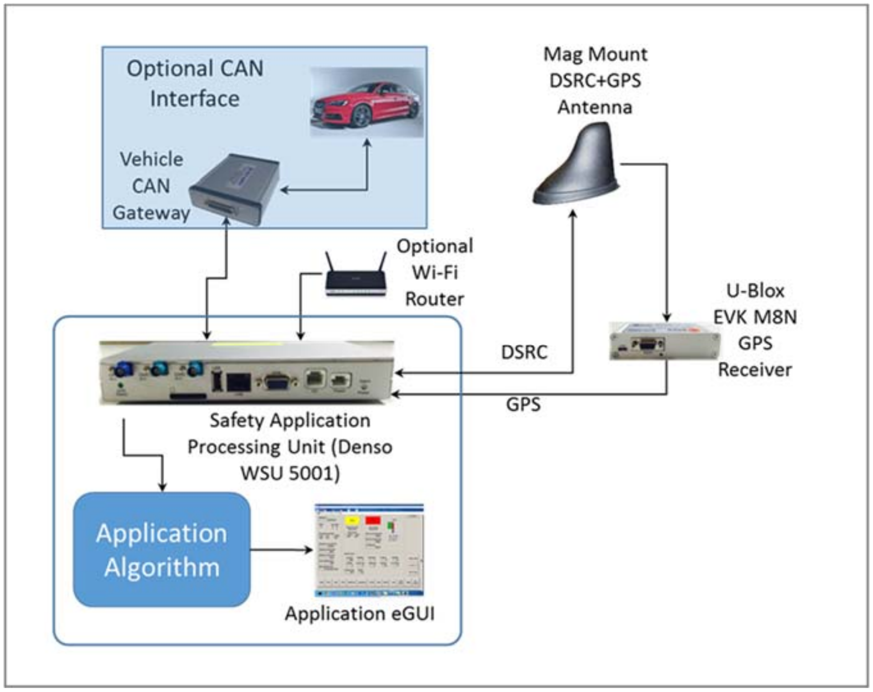


Figure 16: Vehicle Equipment Diagram

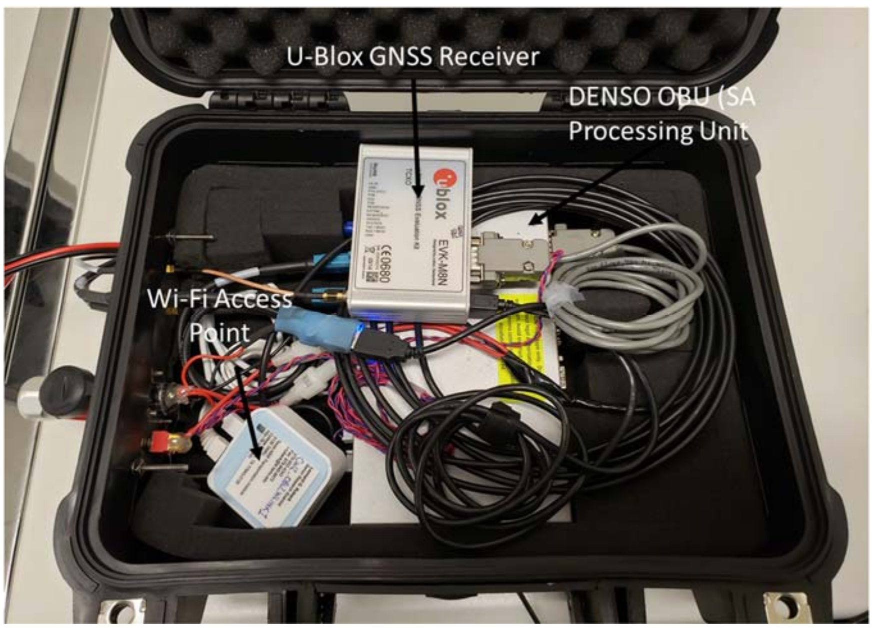


Figure 17: Portable OBU Installation Developed for Testing

6.3 Software Testing Environment

Figure 18 illustrates the high-level functionality of the traveler information system. A foundational aspect of this traveler information system is a comprehensive lane closure database identified as 'Planned Closure Notification Subsystem (PCNS) in Figure 18. The systems also included as the significant field data collection sites (identified as the Corridor Data Collection Subsystem (CDCS).) The availability of this information and assets made the I-35 area uniquely available for supplemental deployments to support a connected vehicle environment and perform comprehensive testing of the CAMP developed procedures and application.

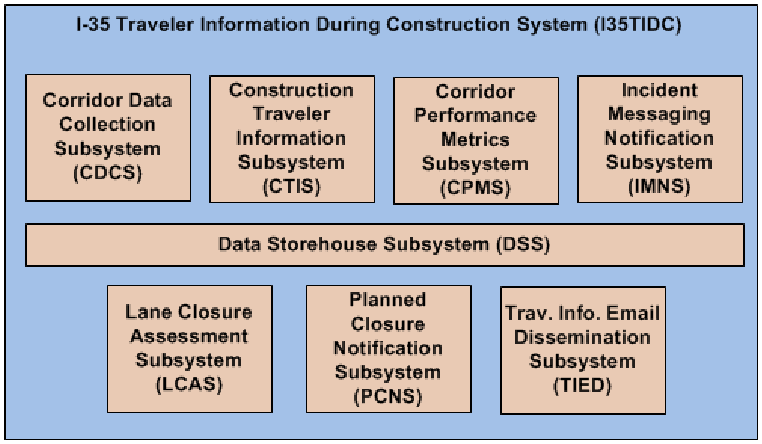


Figure 18: Overview of I-35 Traveler Information System

Figure 19 illustrates the data flows in the Traveler Information System. Lane closures originate with the Construction Contractor submitting the information to the System Operator, which in this case is TTI. TTI personnel then enter the information into the PCNS which has linkages to multiple other aspects of the system, including the data storage subsystem (DSS). As indicated in the diagram, data in the DSS flows to the Waco District Freeway Management System, which is commonly referred to as the Lonestar™ Traffic Management System.

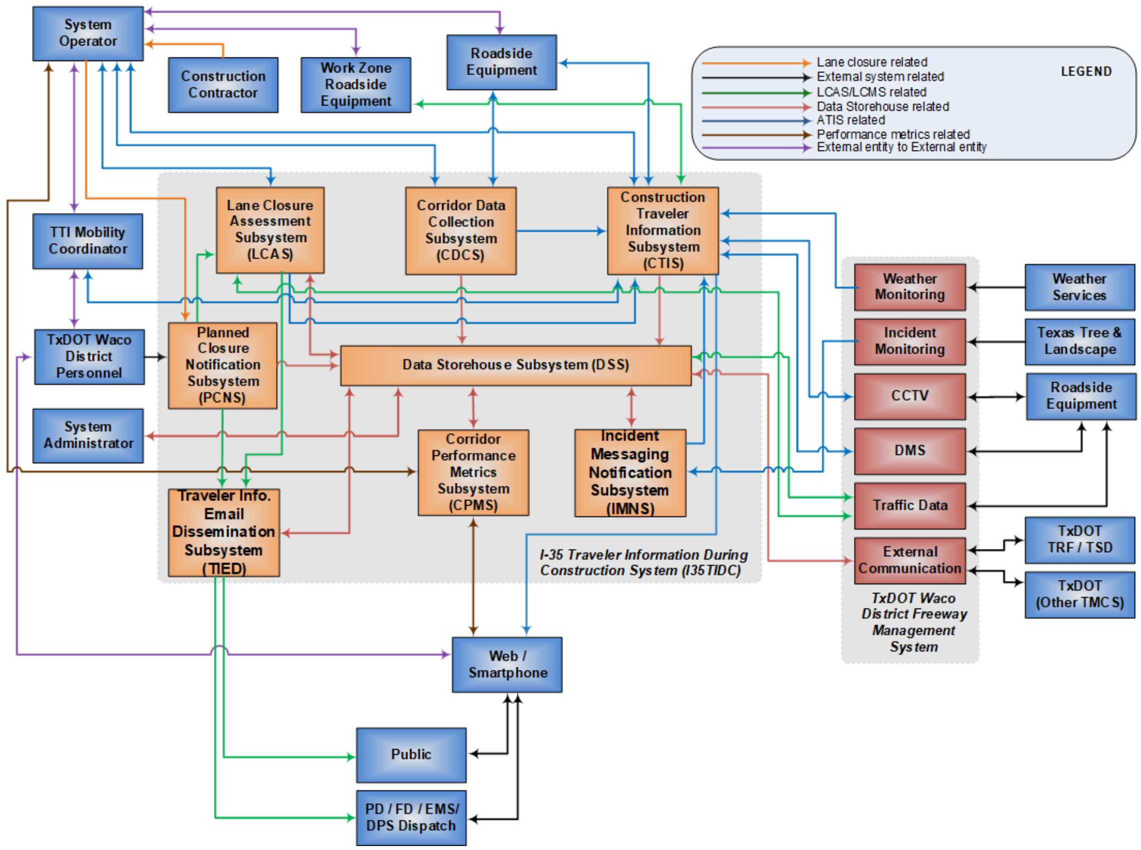


Figure 19: Traveler Information System Detail Diagram with Data Flow

The plan for the field testing was to utilize the Lonestar system to produce RSMs, based on an overlay of the baseline mapping information and the available lane closure information in PCNS; transmit to the field RSU infrastructure via cellular connectivity; and receive the information via the OBU RSWZ/LC application in an equipped vehicle.

6.4 Work Zone Mapping

The CAMP supplied process for mapping a work zone was outlined in Table 2 and is encapsulated in the 'Connected Work Zone Software Toolchain User Guide'[3] document. TTI followed these guidelines while preparing the baseline work zone mapping and this section overviews those procedures without going into the extensive details contained in the user guide.

The Northbound (NB) and Southbound (SB) directions of the Temple work zone were mapped across the entire RSU deployment area. Throughout the course of the testing timeframe (January 2019 through April 2019), the work zone configuration changed as construction progressed. This led to the need to occasionally remap the work zone in one or both directions. Additionally, due to the lane phasing, it was sometimes not possible to stay in a consistent lane throughout the entire deployment area. In that event, the work zone was broken up into more discrete mapping sections where the travel lane remained consistent.

Configuring the software environment for the installation and run-time operation of the mapping process is a non-trivial manner. There are several program support environments, scripts, directory structures and application executables which must be correctly installed and configured to enable the software application. Although the initial process took some time, the CAMP supplied instructions and links proved sufficient to set up the operating environment. It should be noted however, and will be discussed in the lessons learned, that this step could prove daunting to a user unfamiliar with these development environments.

Figure 20 illustrates the initial step in the mapping process which is Vehicle Path Data Acquisition. In this step, the software interfaces with the GPS unit to capture data at 10 Hertz (Hz) while the vehicle is driving in the work zone and maintaining a consistent lane and speed. Note that the GPS unit is the same as was discussed in Section 6.2.

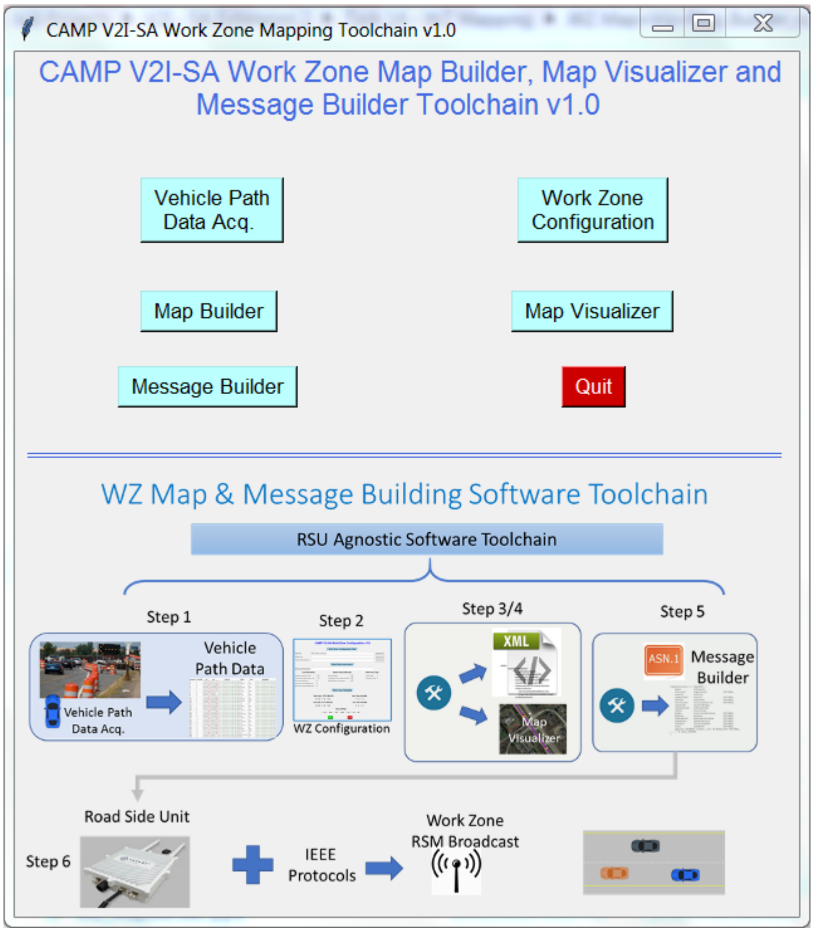


Figure 20: Opening Screen of Software Tool Chain - Work Zone Mapping Procedure

Throughout the mapping process, the operator can visually mark several points of interest, including the reference point, indications for lanes open and closed, and indications for workers present. The software was developed with the largest roadways in mind, allowing for up to nine lanes of travel in one direction. Figure 21 illustrates this aspect of the software toolchain.

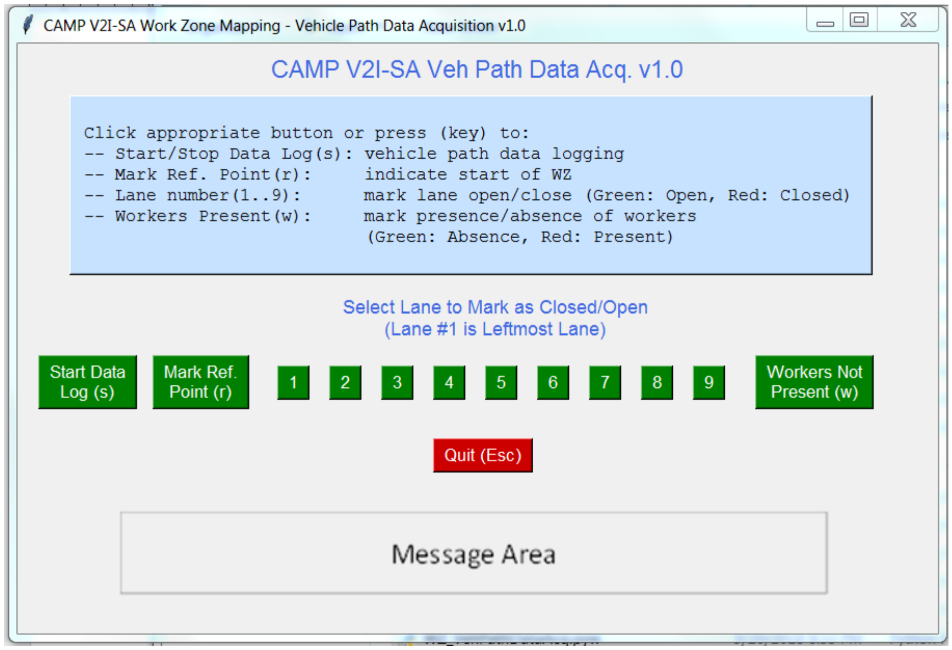


Figure 21: Vehicle Path Acquisition Data

Upon completion of the physical mapping, the next step in the process is the Work Zone configuration, where baseline information such as locations of vehicle path data files, speed limits, lane widths, number of lanes, lane driven during the mapping run and work zone schedule are entered.

After the baseline work zone information is entered, the software conversion of the mapping data can begin. Figure 22 illustrates the dialogue is simple and comprised of entering a location for the work zone configuration file and telling the tool chain to build the WZ map.

Figure 23 showcases one of the real strengths of the software tool chain. In this process, the vehicle mapping data is overlaid onto satellite imagery from Google Earth. The purple dots represent the data acquired by the GPS during the mapping run with each point indicating a $1/10^{th}$ of a second of travel. The visualization is dynamic, allowing for the user to zoom in and out to see different extents of the area and details associated with each collected vehicle path data point.

The caveat to this visualization, however, is that it relies on updated satellite imagery. Construction often alters road geometry dramatically as new alignments are put into place. It is therefore quite possible, depending on the construction project, phasing, and geometric changes, as well as the date of the most recent satellite capture, that the visualization may not line up over a road on the underlying imagery. This is not a problem with the tool chain software, however, as it can only utilize the most recently publicly available information.

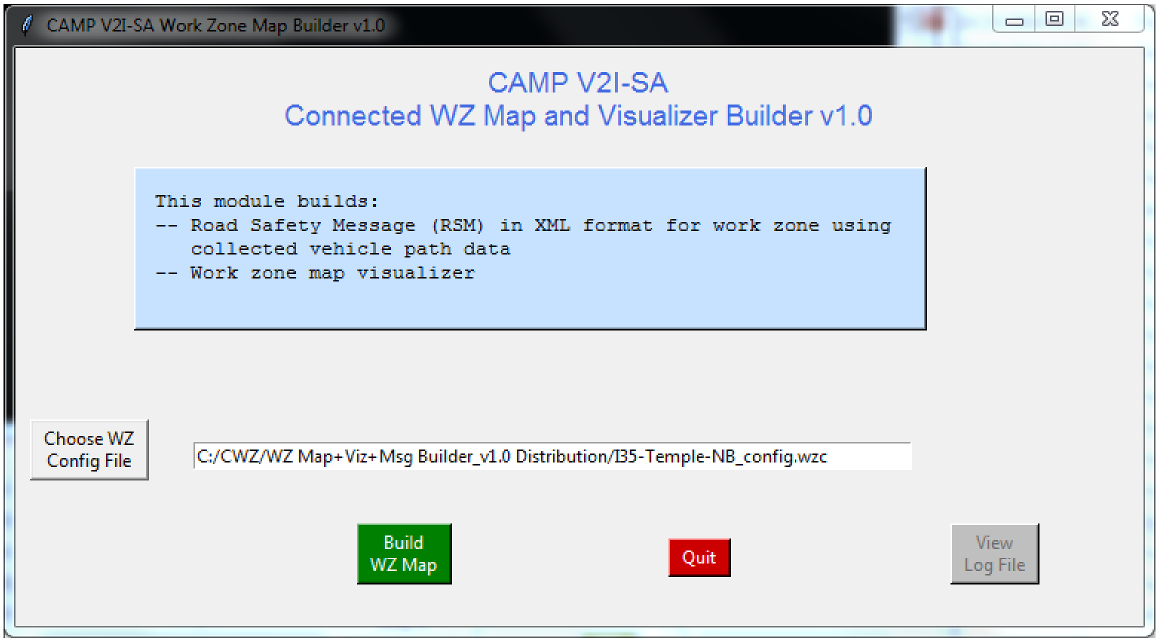
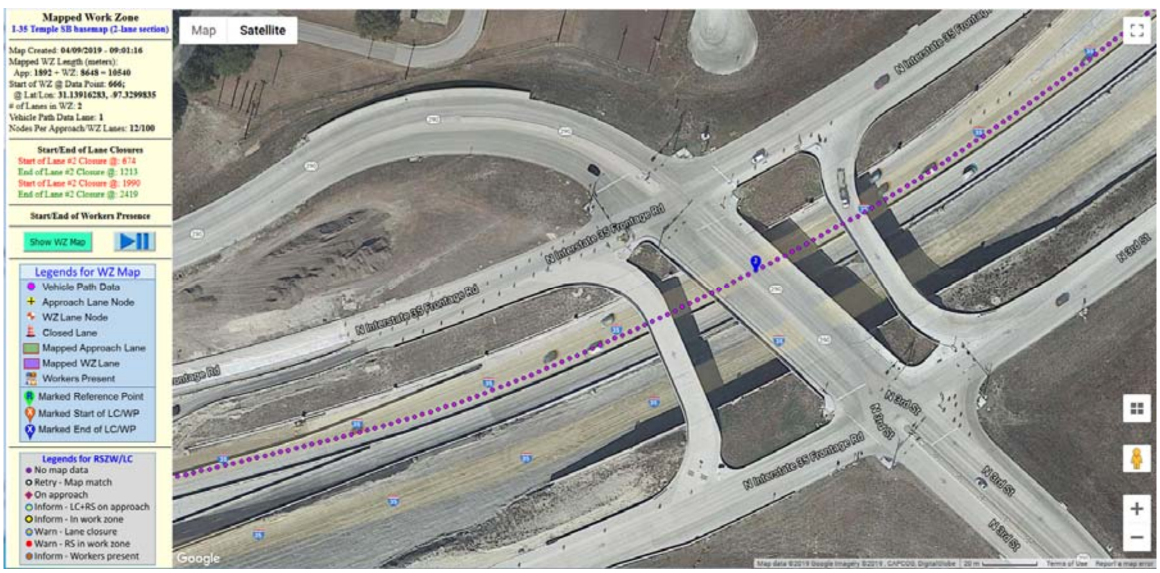


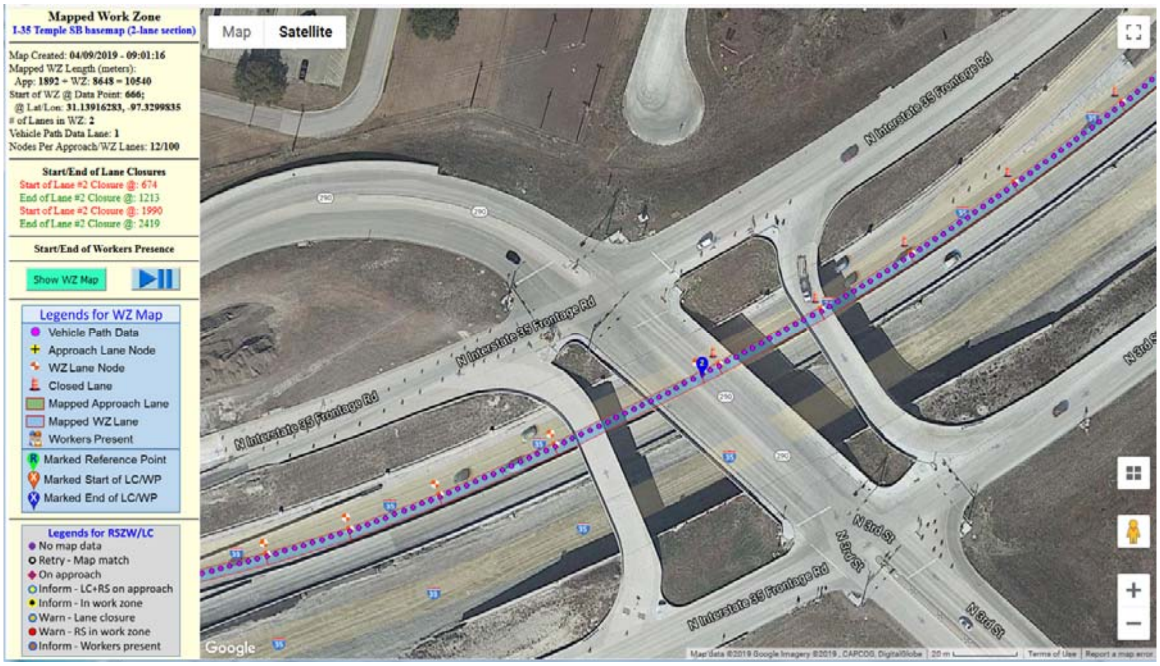
Figure 22: Build Mapping Visualization



Source: Map data©2019 Google Imagery © 2019, CAPCOG, DigitalGlobe. Used with permission.
Plotted data from Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 23: Mapping of Work Zone Visualization

Figure 24 illustrates the completion of the work zone mapping visualization process. In the figure, the mapped lane is shown with a purple overlay with offsets to other lanes appearing as orange and white circles. The completed visualization shows icons for the closed lane and indications of workers present. Overall, the visualization is an extremely helpful check on the validity of the data acquisition, with the previously noted caveat that it may not align with available imagery.



Source: Map data©2019 Google Imagery © 2019, CAPCOG, DigitalGlobe. Used with permission.
Plotted data from Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 24: Completed Work Zone Map Visualization

At this point in the mapping process, the software tool chain is intended to create the RSM messages for upload into the RSUs. However, it is at this point that consideration must be given to the IOO end-user needs and consider alternative approaches. These alternatives will be examined in the following section.

6.5 RSWZ/LC Testing

In addition to testing the mapping process provided by the software tool chain, a further objective of the work effort was also to test the RSWZ/LC application. However, it is readily apparent that IOOs differ in their approach to work zone testing, information distribution, and the level of traffic management software sophistication. Technical discussions amongst the research team led to the development of two approaches for testing: High Fidelity and Low Fidelity.

The High-fidelity approach was envisioned to utilize the full information load available in the CAMP application and transmit a detailed RSM message to an RSU for broadcast to a vehicle OBU. Likewise, the Low-fidelity approach was envisioned to utilize only a subset of the available information and provide limited detail for broadcast. The High-fidelity application was developed by CAMP whereas the Low-fidelity application was developed by SwRI. The real-world testing within this task desired to test both approaches.

In use, the High-fidelity approach would alert drivers of an upcoming work zone lane closure and the need to change lane only if they were in the closed lane. Once all drivers were in the open lane(s) within the work zone, the application would provide all pertinent information, such as speed drops tied to the presence of workers. Conversely, the Low-fidelity approach would alert all drivers of an impending work, regardless of the lane the driver was in approaching the work zone.

6.5.1 High-fidelity Testing Process

The desired process for the High-fidelity application testing is shown in Figure 25. By utilizing the output of the mapping procedure and sending that digital representation to Lonestar, the traffic management software could then make an association with the known lane closure information from the available traveler information system. This would allow Lonestar to generate RSMs and send those files to the appropriate RSUs. When an equipped vehicle passed by an RSU broadcasting an RSM message, the CAMP OBU application would receive the message and issue alerts, as per the prior discussion of what lane the vehicle was in, in relation the lane closure.

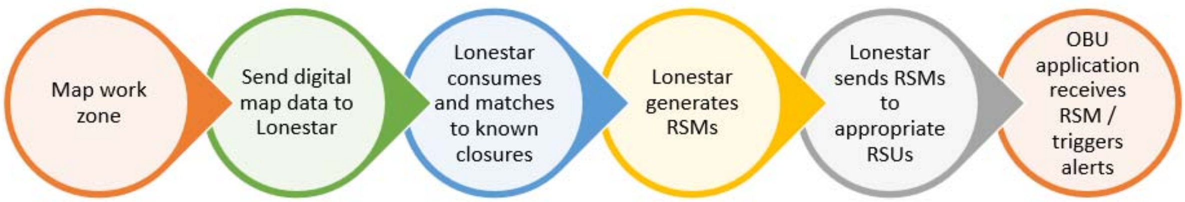


Figure 25: Desired High-fidelity Process

Ultimately, this process was not able to be completed in an end-to-end fashion. The development process for allowing Lonestar to consume a digital representation at the 10Hz level of detail, associate lane closure information that was represented at a resolution of a per mile basis and create detailed RSMs proved to be too difficult to accomplish within the available time and resources. Additionally, Texas as an IOO with a statewide traffic management software had to determine the efficacy of allocating resources to provide such high-resolution data compared to the current level of maturity of the connected vehicle arena.

In order to mimic the process of this information transfer through Lonestar and still test the High-fidelity application, a revised procedure was created, as illustrated in Figure 26. Figure 27 provides more detail on the steps necessary to mimic the distribution of RSMs through the RSU for the High-fidelity approach.

Figure 26: Implemented High-fidelity Process

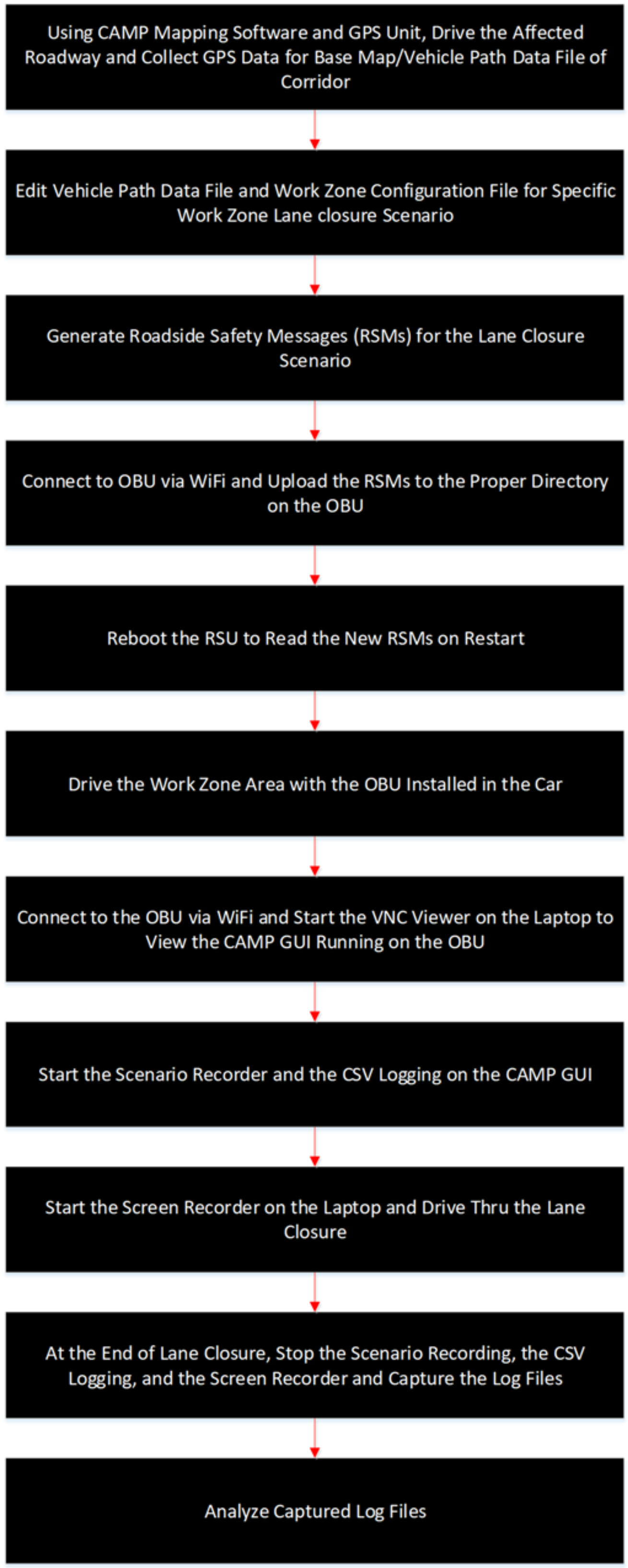
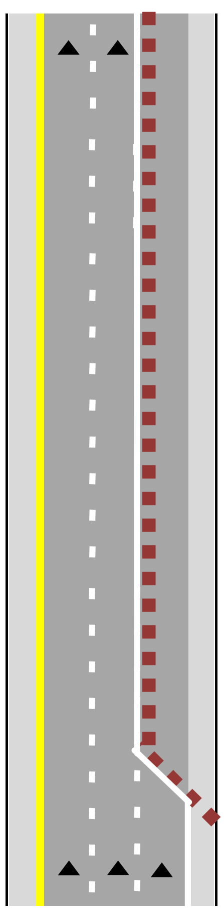
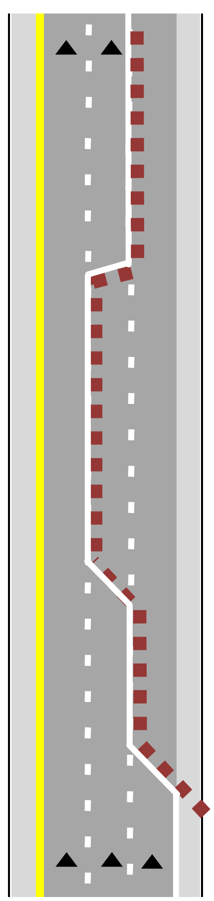
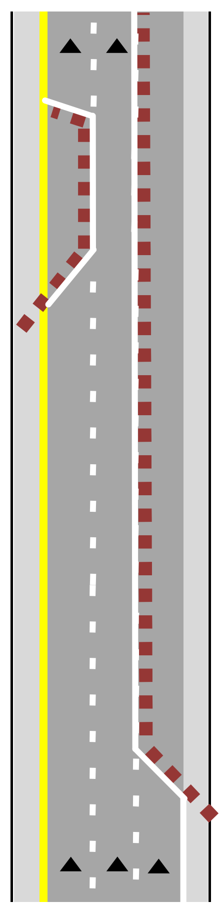
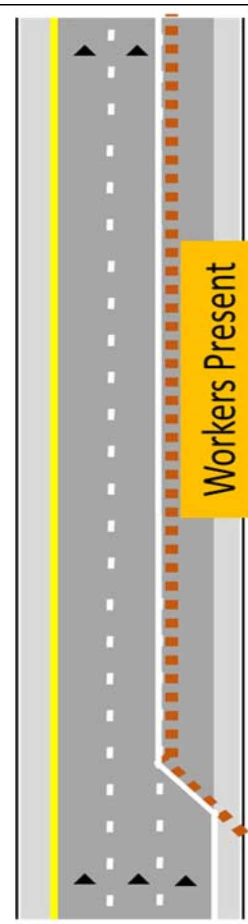


Figure 27: Detailed Steps to Mimic Lonestar RSM Generation and Transmission to OBU

6.5.2 High-Fidelity Testing Scenarios

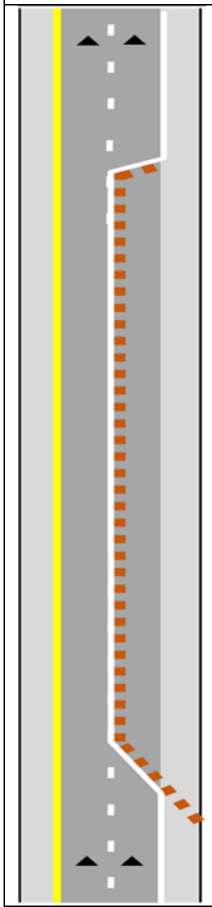
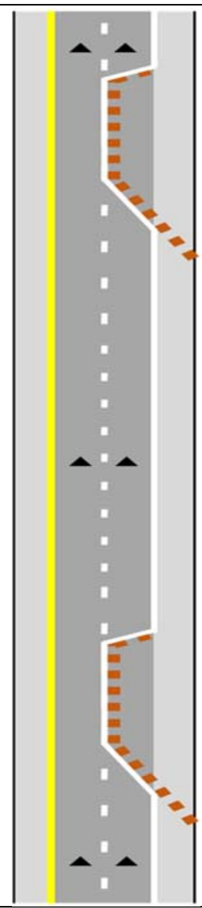
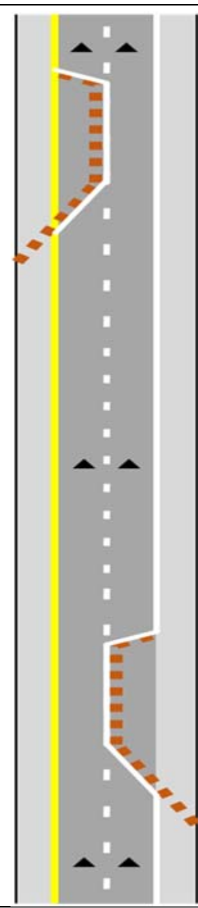
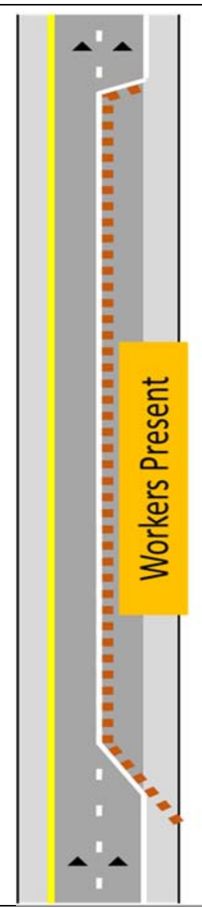
A variety of work zone scenarios encompassing both simple and complex arrangements were generated to test the CAMP application. Table 6 and Table 7 illustrate the four scenarios created for each direction of I-35 within the deployment area in Temple. In both cases, the last scenario is the same as the first, but with workers present. In the NB direction there were three lanes total, which afforded the opportunity to implement scenarios such as #2, which was an initial lane closure followed by a second lane closure. Scenario #3 was also created to illustrate a narrowed roadway cross section by having a long work zone closure in lane 3 and a shorter closure on lane 1.

Table 6: NB Testing Scenarios

I-35 NB in Temple, TX			
NB-1	NB-2	NB-3	NB-4
			

In the SB direction, there were only two lanes available, so the implemented scenarios were slightly different. In total, 6 different scenarios were tested across the two directions.

Table 7: SB Testing Scenarios

I-35 SB in Temple, TX			
SB-1	SB-2	SB-3	SB-4
			

6.5.3 High-fidelity Testing Results

Table 8 and

Table 9 detail the results for NB and SB testing respectively. It should be noted that these summary tables represent the final runs conducted. Numerous testing runs were conducted over the course of several weeks as the processes explained for mapping and High-fidelity application testing were identified, tested, revised, and finalized.

Table 8: NB Testing Results

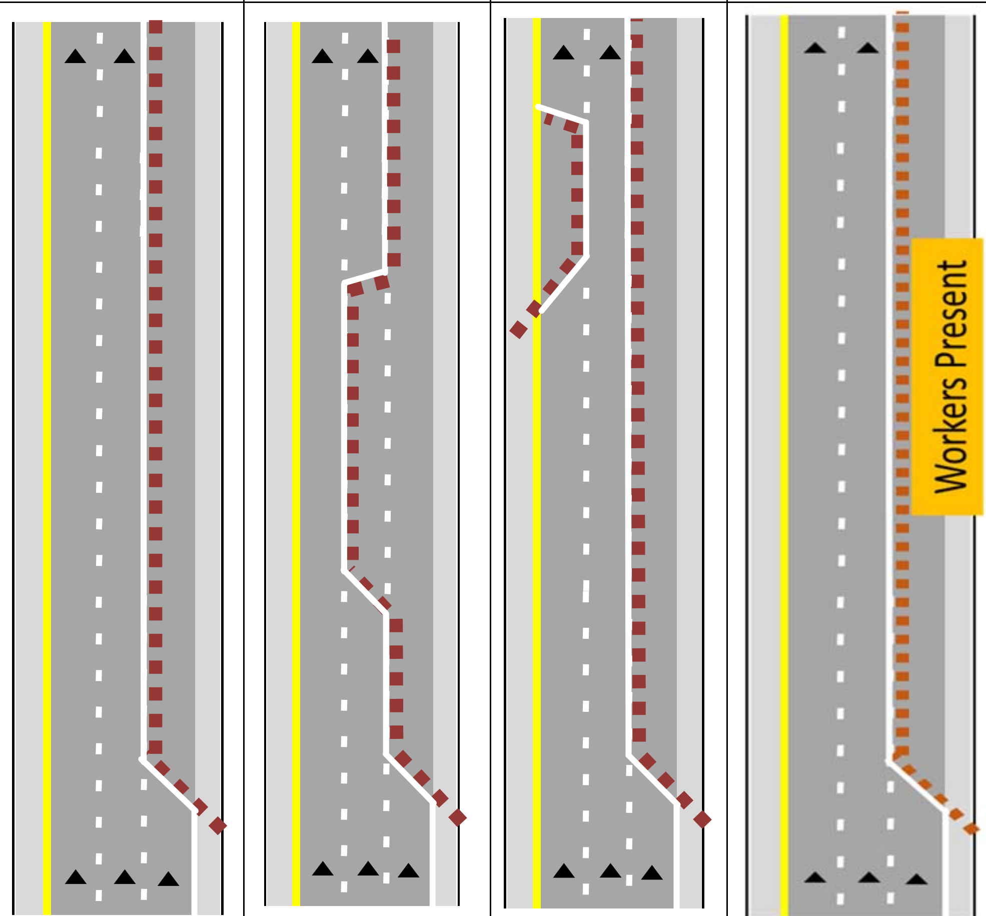
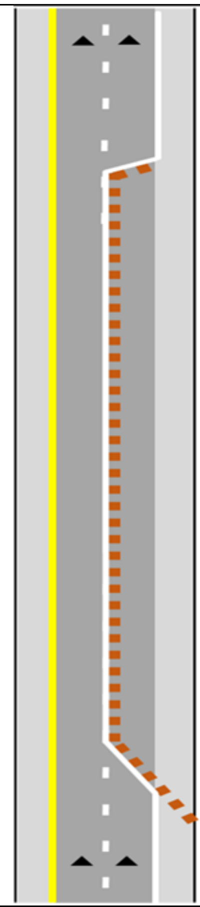
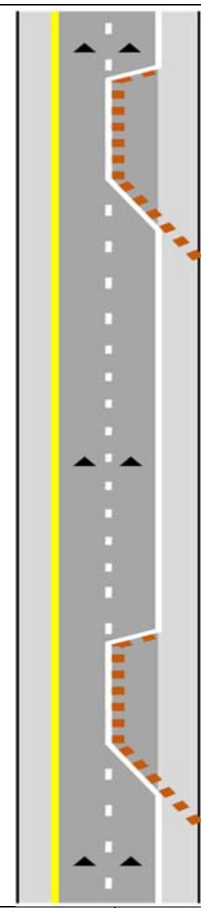
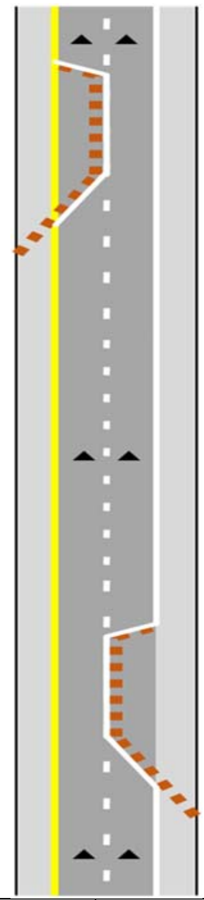
	I-35 NB in Temple, TX							
	NB-1		NB-2		NB-3		NB-4	
								
	NB-1.1	NB-1.2	NB-2.1	NB-2.2	NB-3.1	NB-3.2	NB-4.1	NB-4.2
Start in lane	Right	Center	Right	Center	Right		Right	
Reduced Speed Zone Inform	OK	OK	OK	OK	OK		OK	
Reduced Speed Zone Warning	OK	OK	OK	OK	OK		OK	
Lanes Closure Inform #1	OK	OK	OK	OK	OK		OK	
Lanes Closure Warning #1	OK	N/A	OK	N/A	OK		OK	
Stayed in/Moved to Lane	Center	Center	Center	Center	Left		Center	
Lanes Closure Inform #2	N/A	N/A	OK	OK	OK		N/A	
Lanes Closure Warning #2	N/A	N/A	OK	OK	OK		N/A	
Workers Present with reduced SL	N/A	N/A	N/A	N/A	N/A		OK	

Table 9: SB Testing Results

	I-35 SB in Temple, TX							
	SB-1		SB-2		SB-3		SB-4	
								
	SB-1.1	SB-1.2	SB-2.1	SB-2.2	SB-3.1	SB-3.2	SB-4.1	SB-4.2
Start in lane	Right	Left	Right		Right	Left	Right	Left
Speed Zone Inform	OK	OK	OK		OK	OK	OK	OK
Speed Zone Warning	OK	OK	OK		OK	OK	OK	OK
Lanes Closure Inform #1	OK	OK	**NO INFORM**		OK	**NO INFORM**	OK	OK
Lanes Closure Warning #1	OK	N/A	**NO WARNING**		OK	N/A	OK	**NO WARNING**
Stayed in/Moved to Lane	Left	Left	Left		Left	Left	Left	Left
Lanes Closure Inform #2	N/A	N/A	N/A		OK	**NO INFORM**	N/A	N/A
Lanes Closure Warning #2	N/A	N/A	N/A		OK	**NO WARNING**	N/A	N/A
Workers Present with reduced SL	N/A	N/A	N/A		N/A	N/A	OK	**OK**

Analyzing the results in Table 8 and
Table 9 show some scenarios which did not produce appropriate lane closure warning and/or information messages when they were needed. A detailed technical investigation was conducted to examine each failure as well as repeated runs to ensure that data

collection hardware, software, and processes were performing consistently and as expected. At the time of testing, the implemented RSZW/LC application on OBU did not support scenario - SB Scenario 2 consisting of multiple lane closures on the same lane. However, single lane closure on a different lane is supported by the application. It should be noted that there is no limitation set on the developed CVMB. The message builder does generate proper UPER encoded RSM and fully supports both multiple lane closures on the same level as well as on different lanes.

Scenarios 3 and 4 also showed alerting errors within the application, although not consistently. The technical investigations revealed that the most likely cause of the error was the GPS unit indicating that the vehicle was out of the lane of travel. Since this was not physically the case and the antenna was verified to be in the middle of the vehicle roof. Further analysis of the collected test data indicated a continuous position offset reported by the test vehicle GPS unit indicating the vehicle is in adjacent lane. Though both GPS units used for work zone mapping and application were from the same supplier U-blox, the GPS unit used for mapping was configured using CAMP supplied configuration file while the GPS unit used for application testing was configured using a different configuration file. It is possible that the improper offset parameter is applied in the configuration causing fixed offset in the position information.

The TTI team conducted a preliminary short 30 minutes exercise to compare data from both GPS units to a known survey point (Smetana) on the Texas A&M RELLIS Campus by placing both units' antennas next to the survey point and collecting data for about 30 minutes. The data collected from both units was compared to the survey point location by calculating the distance from each point collected to the survey point geo-coordinates. On average there is approximately 1.2m difference between data points collected using the mapping GPS unit from the survey point location and an average difference of approximately 0.55 meters between data points collected using the GPS unit used for application testing from the survey point location. Since a 30 minute test is an extremely short time to determine a GPS performance systemic error, the obtained result is inconclusive and not reported here.

6.5.4 High-fidelity Messaging

The CAMP supplied RSZW/LC OBU application has a very detailed information loading that is available for viewing. Figure 28 illustrates the warnings that are available through the application and the conditions when they appear. Figure 29 through Figure 33 show the CAMP OBU application notices. This is the detailed visual for debugging and testing and is not representative of the amount of visual information that a driver would receive.

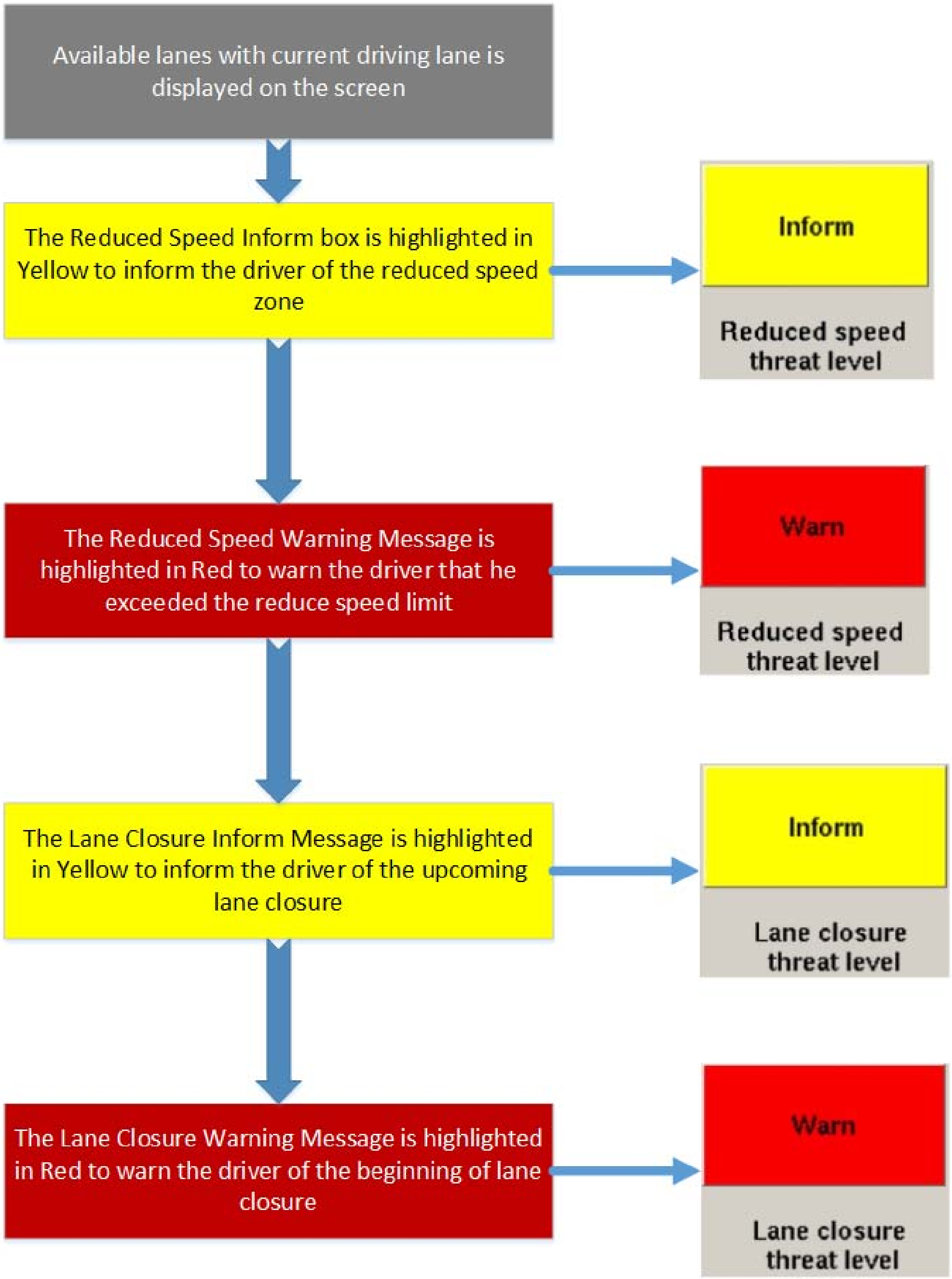


Figure 28: CAMP RSZW/LC Application Information Alerts

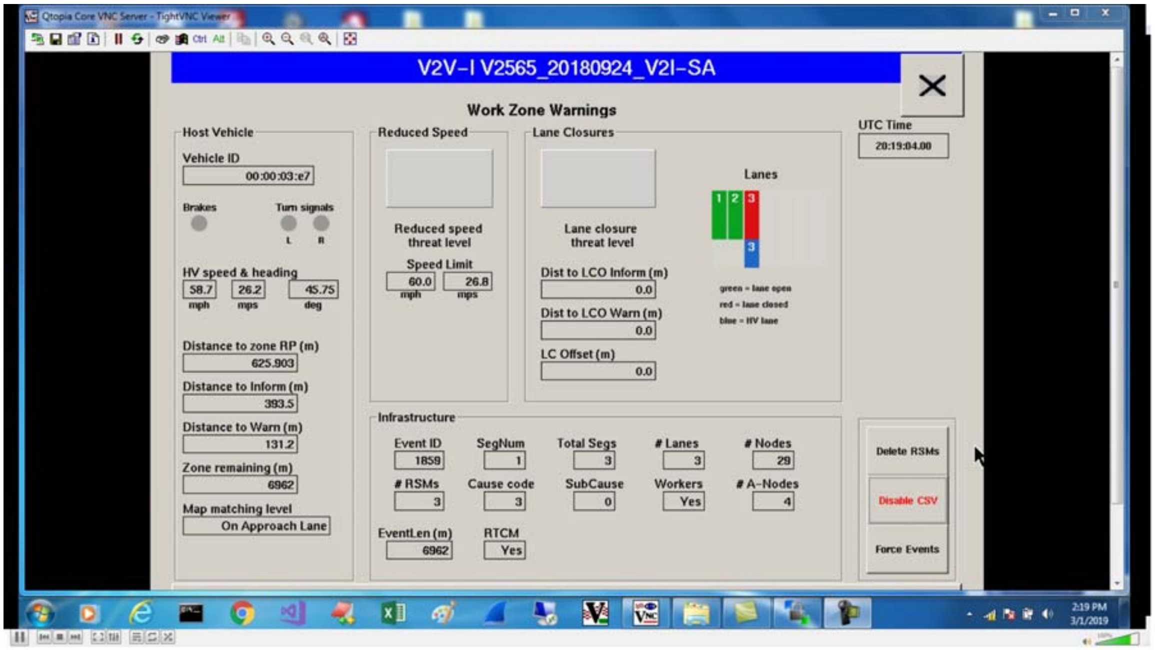


Figure 29: CAMP RSZW/LC Application – Current Lane of Vehicle (Blue) Lanes Available (Green) and Lane Closed (Red)

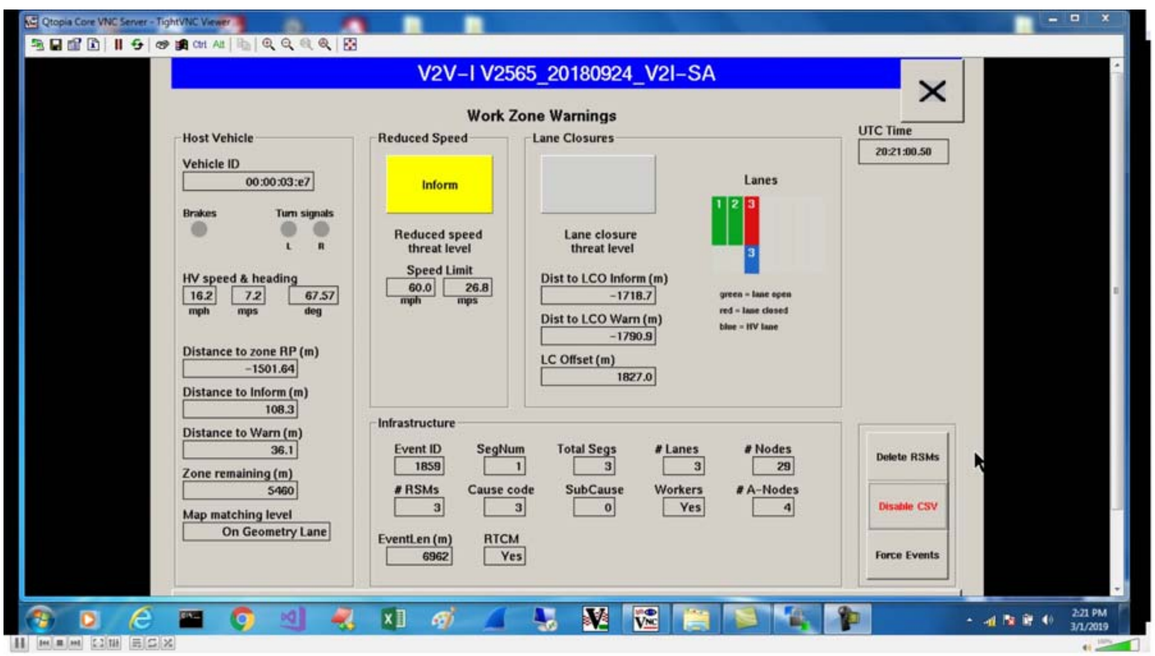


Figure 30: CAMP RSZW/LC Application – Reduced Speed Inform Notice

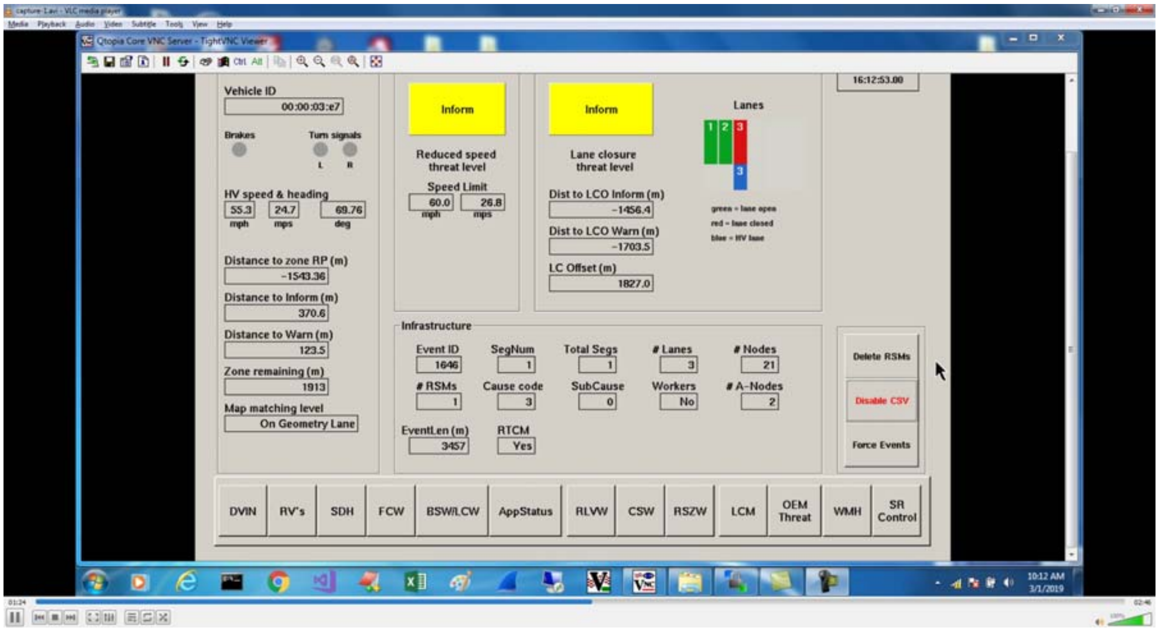


Figure 31: CAMP RSZW/LC Application – Reduced Speed Inform and Lane Closure Inform Notice

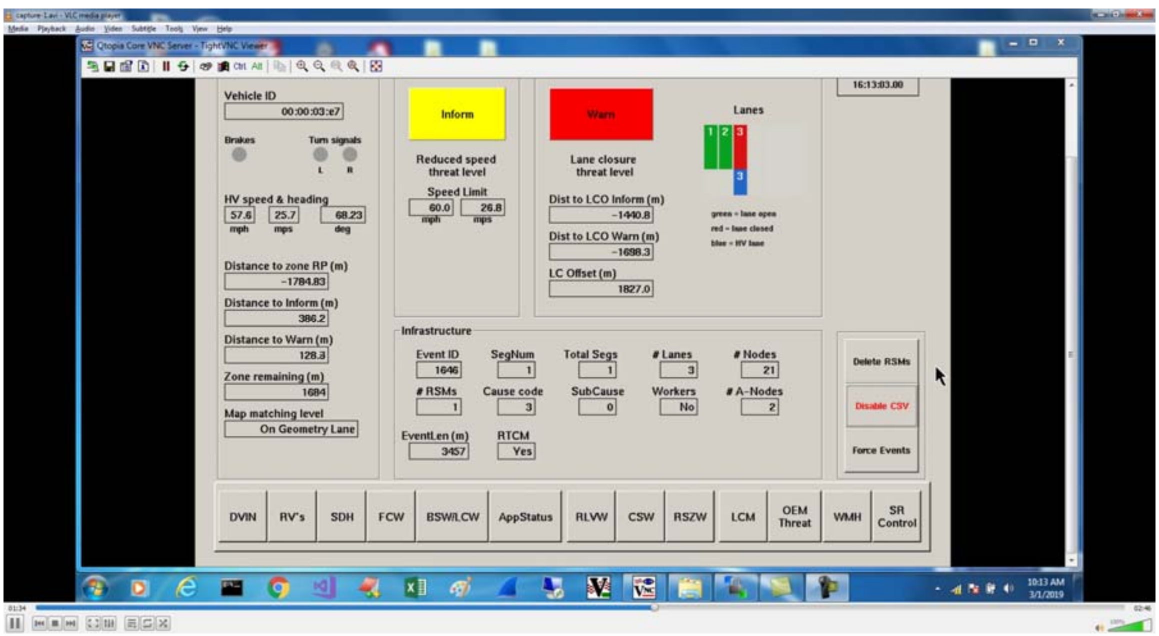


Figure 32: CAMP RSZW/LC Application – Reduced Speed Inform and Lane Closure Warn Notice

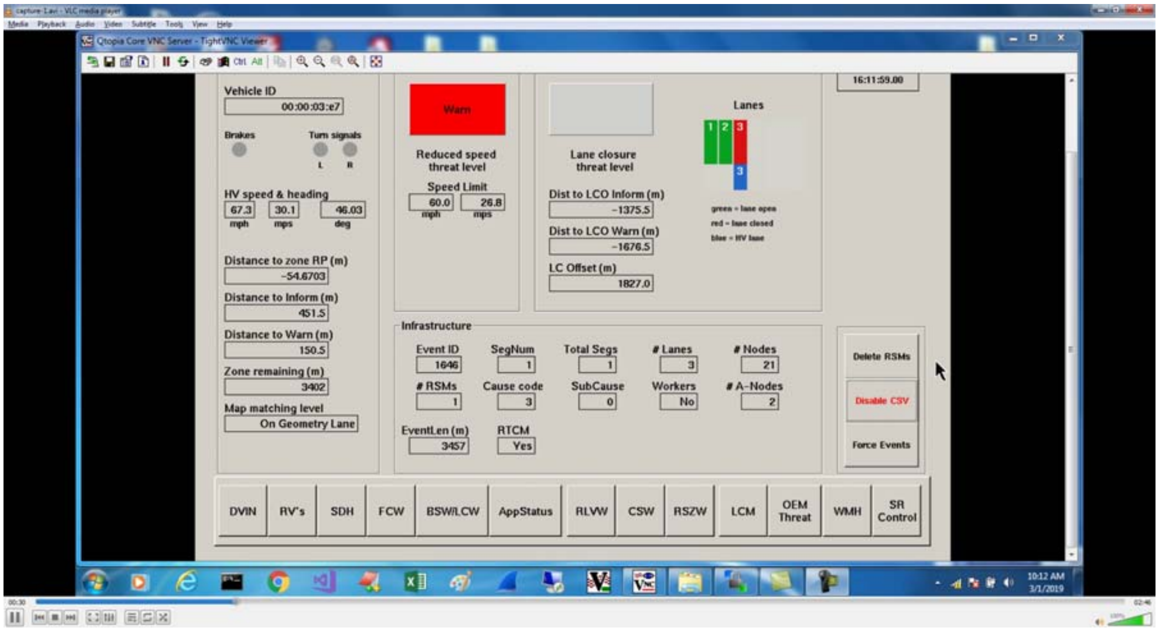


Figure 33: CAMP RSZW/LC Application – Reduced Speed Warn Notice

6.5.5 Low-fidelity Testing

The process for testing the Low-fidelity application from SwRI was the same as indicated in Figure 25. The sole difference is in the amount of detail contained within the RSM message sent to the RSUs. In this application, the desired outcome was simply to alert drivers of an upcoming work zone, regardless of lane position or work zone configuration. The message load contained in the RSM was much smaller and this level of RSM generation was able to be accomplished within the time and resources allocated to the project. Additionally, the OBU was switched to a Cohda Wireless unit as that was the development base for the SwRI application.

The deployed RSU equipment consisted of nine Savari units with the latest firmware, as per CAMP requirements for consistency with previous testing. The team tried to configure the Savari units in the Store-and-Repeat mode to broadcast the RSMs. In the Store-and-Repeat mode, the encoded RSMs are stored in a folder on the RSU and the RSU broadcasts the stored messages as per the dispatch information included with the RSMs. Dispatch information includes: the start time, end time, and the frequency for broadcasting the stored messages. However, the latest version of the Savari RSU firmware supported the broadcast of only one message in the Store-and-Repeat mode. This made it difficult to ascertain which messages should be on which RSUs to ensure full coverage throughout the work zone area. After consulting with Savari technical support, they indicated that they are working on modifying the firmware to support the broadcast of multiple messages in the Store-and-Repeat mode as the USDOT RSU Specification recommends.

The team switched to configure the RSUs to another mode called on the Savari RSUs as the Battelle mode. In the Battelle mode, the RSU is configured to receive a UDP message on a configured port from an external device. Anytime the RSU receives a UDP message on the configured port, it checks the validity of the message and for the dispatch information included in the received message on how often to broadcast the message and it immediately forwards the message to connected vehicles in the vicinity of the RSU. This mode is similar to the Immediate-Forward mode specified in the USDOT RSU specification.

After testing one of the RSUs in the lab and verifying that the SwRI Cohda OBU was able to receive the RSMs sent from an external laptop via the RSU, the team went ahead and configured the nine RSUs appropriately and conducted field tests using the SwRI OBU.

Multiple tests were conducted where an offline version of TxDOT's Lonestar software was used to receive work zone information from an online feed, Lonestar then generated RSMs for the work zone and sent the RSMs via the network to the nine RSUs installed along the I-35 corridor. At the same time, the TTI team and SwRI team were driving along the I-35 corridor to test the reception of the broadcast RSMs and the warnings generated by the SwRI software. A tablet that was communicating with SwRI Cohda Wireless OBU, running the SwRI software, was used to provide the driver with lane closure warnings.

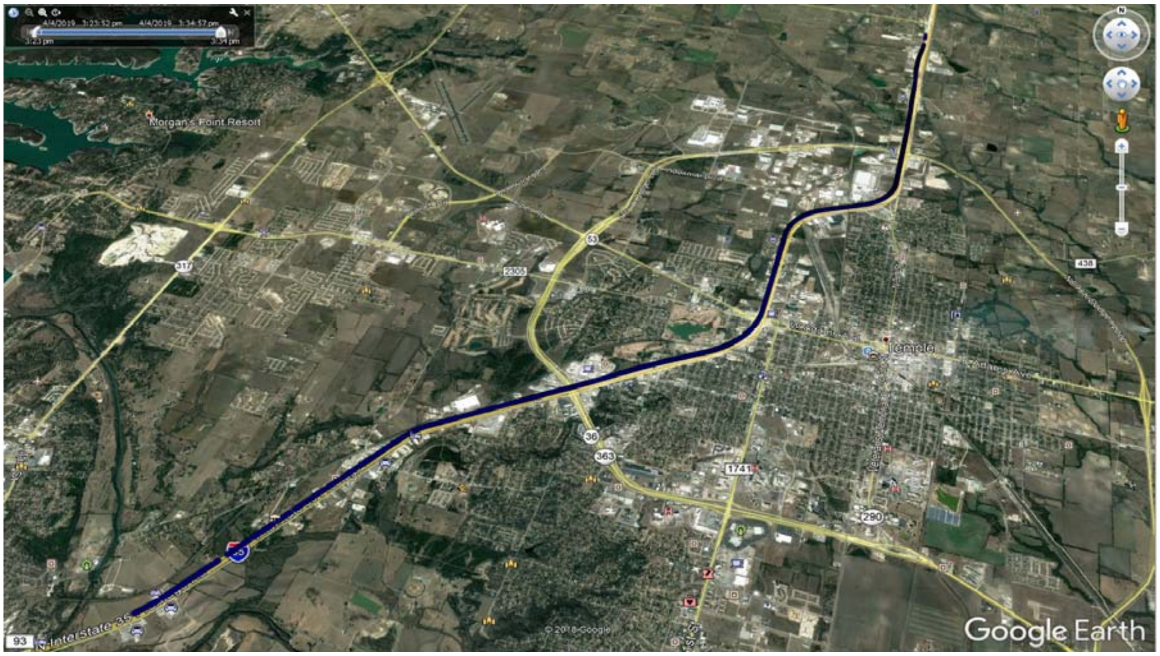
6.5.6 Low-fidelity Scenarios and Testing Results

Due to the SwRI RSWZ/LC application only alerting to the presence of an upcoming work zone, multiple testing scenarios were not required. During the timeframe of the testing, several software errors in the OBU application were encountered and fixed. The current application state is working as expected.

6.6 Deployment Area Coverage

One of the unknowns going into the deployment process was the extent of coverage that could be obtained. The team was limited in resources that could be planned and maintained in an active construction zone. Figure 34 shows the resulting plot of the RSU coverage at the approximately 1-mile spacing as discussed earlier. Except for a small gap at the very end of the deployed zone, the nine RSUs blanketed the entire deployment zone and provided very good coverage for RSU broadcast and OBU receipt of the RSM messages.

6.7 Deployment Area Coverage



Source: Map image from ©2018 Google. Used with permission.
Plotted data from Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium

Figure 34: RSU Coverage in Testing Zone

7 Lessons Learned

The experiences detailed in this guidance document demonstrate conclusively that the process of broadcasting work zone information in a connected vehicle environment is valid and can be accomplished. The overall takeaway, however, is that the work zone broadcast scenario is not yet ready for a production environment and several items need to be addressed prior to it being ready for widespread use. The following sections discuss individual areas where lessons are apparent from the conclusion of this work effort.

7.1 Field Hardware Maturity

Some of the hardware utilized in this deployment testing suffered from a lack of maturity and adherence to standards. This is not an unexpected result in a rapidly changing development environment with evolving standards. The adherence to standards also appears to vary widely between vendors of the same equipment type. There were also incompatibilities noted between hardware versions. *Overall, significant diligence must be taken prior to field hardware procurement to ensure that the equipment meets all required specifications*. This due diligence must fully document the status of the adherence to the required standards. As an example, RSUs not operating in a store-and-forward mode and only accepting one RSM are not operating according to current standards and had an impact on testing.

7.2 Vehicle Hardware

Individual component, connectors and interface assembled for the OBU and application testing under this work effort from the supplier are for R&D purposes and were built as a portable system and not as a cohesive platform integrated into a specific make and model of test vehicle. This allowed for ease of conducting tests using the hardware in different test vehicles. However, this required manual setup and configuration of the hardware to run and test the application. It is understood that vehicle manufactures will produce an OBU package for inclusion on future vehicles that is tightly integrated into the vehicle and requires no configuration from a user. *In the future, commercial off-the-shelf plug-and-play hardware would be ideal for building on-board test equipment to minimize effort needed to assemble, configure and debug the system.*

7.3 GPS Issues

During one of four tests conducted, an unexpected GPS position offset issue was encountered and remains unexplained. The GPS receiver used for mapping the work zone using collected vehicle path data and the receiver used for application testing are from the same manufacturer but different model. It should be noted that the GPS units utilized in this testing were highly sophisticated devices with configuration files that spanned hundreds of lines. It is certainly plausible that a minor misconfiguration or a mismatch between units could induce offset of the type seen. However, for an application environment that relies on being in a specific lane to issue a specific warning, a GPS error could be the difference between receiving an alert or not. The profession is still learning the degree of accuracy that applications in the connected vehicle environment will require. *Overall, the profession must understand the GPS accuracy required for operations and* *warnings to occur across a broad set of applications for the connected vehicle environment.*

7.4 Mapping Work Zone Deployments

It is well-known that work zone deployments differ by state and perhaps even regions within any given state. That alone imparts complexity into the task of designing a work zone warning application process that works in all situations. However, one of the most vexing problems to solve may well be the mapping requirements. Depending on the level of notice (i.e., what type and detail of work zone warnings) an IOO desires to provide, lane-level detailed mapping may be necessary. In states where work zones are set up and taken down nightly, this requirement can be onerous. While it is certainly possible to develop procedures where a mapping is done only when a lane or geometric shift is performed, it will require methodology and software to associate lane closures to the baseline mapping. *The level of software development to associate a mapped work zone and detailed lane closure information at the operating agencies level is in its infancy and is an impediment to wide-spread application.*

7.5 Availability of Lane Closure Information

One of the aspects that made testing on I-35 in Temple appealing was the level of detailed information available about all work zones. That information was available in a robust database with external data feeds that could be ingested by other processes for associating lane closures to other data elements necessary for producing work zone information and alerts. While this level of information is not unique, neither is it commonplace. Some level of information is a fundamental requirement for ensuring this process can produce messages. Some IOOs do not even require their contractors to submit individual lane closure information on a routine basis. *The standardization of work zone information elements required to support the RSWZ/LC application will be necessary for future broad-scale application.*

7.6 Desired Level of Broadcast Information

An additional aspect of the lane closure information problem is the level of information that individual IOOs desire to push out to consumers. This work effort developed and tested both a high-fidelity (e.g., a lane-level specific information application developed by CAMP) and low-fidelity approach (e.g. the general work zone broadcast information application developed by SwRI). *Conversations with multiple IOOs during this work effort indicate no universal support for either approach.* Neither model is right or wrong but rather an individual IOO choice that depends on multiple factors.

7.7 System Integration

Overall, the process of alerting drivers in a work zone environment is a complex system integration effort. Many IOOs do not have a statewide traffic management system. Furthermore, many IOOs do not even have complete regional ITS coverage of agency owned and operated roadways by a traffic management software. Operating a work zone connected vehicle environment without a traffic management software system would be a highly manual task prone to significant effort. *These realities limit the overall* *implementation arena and points to the potential need for multiple integration efforts across the nation to different software solutions.*

8 Summary

This task report describes 1) need, requirements and development of lane-level geometry mapping technique for a work zone to support RSZW/LC application for CWZ and 2) completed field deployment and testing efforts. Under this task, the team demonstrated the work zone mapping procedures and the RSWZ/LC application status and lessons learned in a real-world situation. The field tests were conducted by TTI and TxDOT in coordination with CAMP and SwRI on a section of the I-35 corridor which is expanded from four-lane freeway sections to six-lane sections in rural areas and expanded to eight-lane sections in Temple and Waco in Texas. Additionally, there was a need to develop information and provide guidance as to how IOO's could plan to incorporate these procedures and applications in future work zones.

The RSZW/LC application for connected work zone requires proper and accurate infrastructure maps to inform or warn drivers as appropriate of a transient reduction in speed limit ahead due to roadway configuration change such as lane closures. These conditions are frequently associated with active work zones.

Traditionally, for V2I applications, waypoints (node points) for lane geometry are constructed either by conducting a survey of the lane or by using an application such as Google Earth or similar software tool that provides latitude, longitude, elevation to create path consisting waypoints. In either case, with nearly equidistant waypoints and then converting to the proper format as specified in SAE J2735 message set dictionary. One drawback in representing lane geometry using nearly equidistant waypoints, the placement of the waypoints is not optimized to support lane-level map matching requirements to determine vehicle's lane position on curved roadway segments. It is essential that the distance between the consecutive waypoints be adjusted for curved versus straight roadway segments.

Both high- and low-fidelity approaches were utilized for the field setup and testing. The high-fidelity work zone map approach used CAMP-developed work zone mapping and message building toolchain to map both northbound and southbound sections of I-35 consisting of single and multiple lane closures, workers present zone and speed limit changes and generate UPER encoded RSM for broadcast from an RSU. Likewise, the low-fidelity approach developed by SwRI used only a subset of the available work zone information and provided limited detail for broadcast.

The experiences detailed in this guidance document demonstrate conclusively that the process of broadcasting work zone information in a connected vehicle environment is valid and can be accomplished. The overall takeaway, however, is that the work zone broadcast scenario is not yet ready for a production environment and several items need to be addressed prior to it being ready for widespread use.

Overall, the process of alerting drivers in a work zone environment is a complex system integration effort. Operating a work zone connected vehicle environment without a traffic management software system would be a highly manual task prone to significant effort.

These realities limit the overall implementation arena and points to the potential need for multiple integration efforts across the nation to different software solutions.

9 References

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