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Development and Testing of a Prototype Connected Vehicle Wrong-Way Driving Detection and Management System

Technical Report 0-6867-01-1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
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16. Abstract

The primary objective of Phase II was to develop a prototype connected vehicle wrong-way driving detection and management system at the Texas A&M University Respect, Excellence, Leadership, Loyalty, Integrity, Selfless Service (RELLIS) campus. The purpose of the prototype system was to test and fine-tune the system components and operations at an off-roadway, closed-course facility prior to installing them on an actual roadway. As part of the prototype development, the research team generated a detailed system design of the system based on requirements that were established in Phase I. The research team then procured the hardware components needed to build the prototype system. Furthermore, the research team developed detailed system architecture, integrated hardware and software components, performed validation testing, and conducted a demonstration of the system.

In Phase II, the research team also conducted human factors studies to investigate the in-vehicle information needs of right-way drivers when a wrong-way driving event occurs. Researchers conducted a formal task analysis to identify critical stages where right-way drivers could make a better decision if information was provided to them through connected vehicle technology. Researchers then used structured interviews and surveys to identify the information needs of right-way drivers and evaluate comprehension and preference of message wording and timing.

The research team recommends the installation of a model field deployment of the connected vehicle wrong-way driving system on State Highway 47 (in conjunction with the ongoing development of a smart connected corridor). This real-world application will allow researchers and the Texas Department of Transportation to further prepare for the approaching connected vehicle environment and its ability to improve wrong-way detection, more quickly notify public agencies and law enforcement, and alert right-way drivers.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT.

This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Melisa D. Finley, P.E. (TX-90937).

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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LIST OF ABBREVIATIONS

Acronym	**Definition**
BSM	Basic Safety Message
CADET	Critical Action and Decision Evaluation Technique
COTS	Commercial Off-the-Shelf
CV	Connected Vehicle
CVDriver	Connected Vehicle Driver
CVS	Connected Vehicle Subsystem
DMS	Dynamic Message Sign
DPS	Department of Public Safety
DSRC	Dedicated Short-Range Communication
FHWA	Federal Highway Administration
IEEE	Institute of Electrical and Electronics Engineers
IRB	Institutional Review Board
ITIS	International Traveler Information Systems
ITS	Intelligent Transportation System
LED	Light-Emitting Diode
MAC	Media Access Control
NHTSA	National Highway Transportation Safety Administration
OBU	Onboard Unit
PCMS	Portable Changeable Message Sign
POD	Portable Onboard Device
PtMP	Point-to-Multi-point
RELLIS	Respect, Excellence, Leadership, Loyalty, Integrity, Selfless Service
RSA	Roadside Alerts
RSU	Roadside Unit
SAE	Society of Automotive Engineers
SwRI	Southwest Research Institute
TAPCO	Traffic and Parking Control Co., Inc.
TxDOT	Texas Department of Transportation
TMC	Traffic Management Center
TMX	Transportation Message eXchange
TTI	Texas A&M Transportation Institute
UDP	User Datagram Protocol
USDOT	United States Department of Transportation
UTC	University Transportation Center
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
WAVE	Wireless Access in Vehicular Environments
WWD	Wrong-Way Driving
WWM	Wrong-Way Monitor
WWV	Wrong-Way Vehicle

CHAPTER 1: INTRODUCTION

In 2015, the Texas A&M Transportation Institute (TTI) and Southwest Research Institute (SwRI) began working with the Texas Department of Transportation (TxDOT) to develop connected vehicle (CV) applications that detect wrong-way vehicles, notify traffic management agencies and law enforcement, and alert affected travelers. In Phase I of this project (*1*), the research team reviewed the state of the practice regarding intelligent transportation systems (ITS) and CV technologies being applied as wrong-way driving (WWD) countermeasures. The research team then identified user needs associated with the implementation of a CV WWD system, assessed motorist understanding of wrong-way driver warning messages posted on dynamic message signs (DMSs), and ascertained preliminary ways to connect with law enforcement. Phase I culminated in the development of a concept of operations, functional requirements, and high-level system design for a CV test bed for WWD applications. In addition, the research team recommended the development of a prototype system at an off-roadway location before implementing a model field deployment on an actual roadway in Texas.

PHASE II OBJECTIVES

The primary objective of Phase II of the project was to develop a prototype CV WWD detection and management system at the Texas A&M University Respect, Excellence, Leadership, Loyalty, Integrity, Selfless Service (RELLIS) campus. The purpose of the prototype system was to test and fine-tune the system components and operations at an off-roadway, closed-course facility prior to installing them on an actual roadway. In Phase II, the research team also conducted human factors studies to investigate the in-vehicle information needs of right-way drivers when a WWD event occurs.

CONTENTS OF THIS REPORT

Chapter 2 documents the tasks conducted to develop a prototype CV WWD detection and management system on a closed course. The chapter describes the four deployment scenarios, system design, validation testing, and demonstration of the system. Chapter 3 describes investigation of the in-vehicle information needs of right-way drivers when a WWD event is detected or reported. The chapter describes how researchers evaluated motorist comprehension and interpretations of existing data elements (i.e., wording) available to generate in-vehicle alerts about approaching wrong-way vehicles. Chapter 4 documents the next steps for the CV WWD system considering challenges with deploying CV technology, additional research efforts, and potential locations for a Phase III model field deployment.

CHAPTER 2: PROTOTYPE CV WWD SYSTEM

As part of the prototype development, the research team generated a detailed system design of the CV WWD system based on requirements that were established in Phase I of the project. The research team then procured the hardware components needed to build the prototype system at the Texas A&M RELLIS campus. Furthermore, the research team developed detailed system architecture, integrated hardware and software components, and performed validation testing. On August 16, 2017, the research team conducted a physical demonstration of the prototype system for select visitors, including local media.

SYSTEM ARCHITECTURE

The research team developed software components to enable the system functionality via two methods:

- A Lonestar® integrated demonstration version.
- A standalone version that resides in the field on the roadside unit (RSU) to demonstrate the WWD system functionality.

The use of the Lonestar® demonstration version follows the traditional architecture that has all components sending and receiving messages through a traffic management center (TMC). The use of a standalone version that resides on the RSU allowed researchers to show how such a system would operate outside a TMC region and the future potential for components to communicate directly with each other.

Integrating the CV WWD System with Lonestar®

Figure 1 shows the high-level system component architecture for the Lonestar® demonstration system. The Lonestar® ActiveITS software provides the intelligence behind the detection and alerts, and integrates the existing traditional technology with additional functionality for CVs. In addition, Lonestar® provides a map to allow traffic management operators to interact with the system.

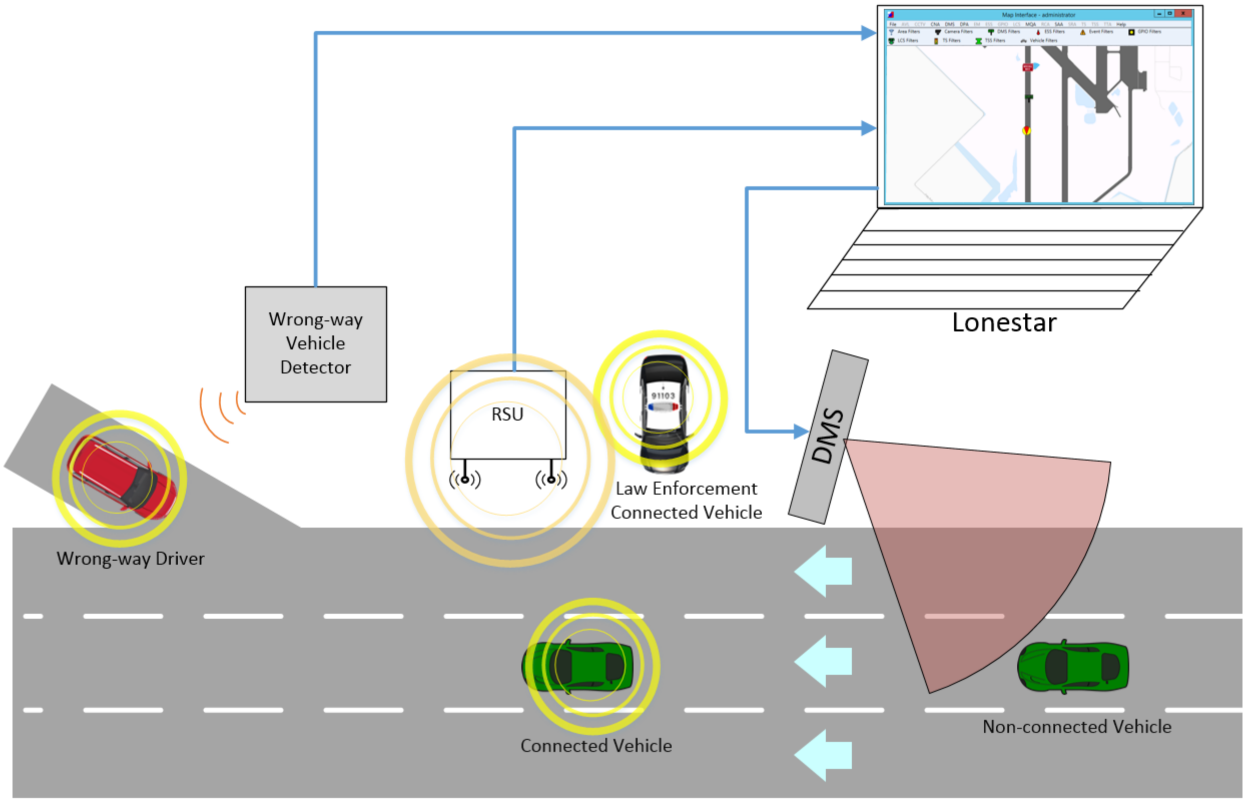


Figure 1. Lonestar® Demonstration System Components.

Hardware Components

The hardware components included in the test bed system boundaries are as follows:

- Lonestar® computer—The Lonestar® software operates on a single or multiple computers in a traditional deployment at a TMC. In the test bed, the Lonestar® demonstration version ran on a laptop with sufficient computing and networking capabilities to support running as the standalone computing for the intelligence and integration.
- Onboard unit (OBU)—OBUs in multiple vehicles (i.e., wrong-way, right-way, and law enforcement) provide dedicated short-range communication (DSRC) capabilities. The research team purchased multiple DSRC units from a variety of vendors to research interoperability. The OBUs were mounted in portable onboard devices (PODs) in order to provide for easy storage and transportation of the equipment. The OBUs transmit Society of Automotive Engineers (SAE) Standard J2735 DSRC Message Set Dictionary–compliant basic safety messages (BSMs) and receive

roadside alerts (RSAs) that indicate the presence of a wrong-way vehicle. Figure 2 shows an example of one of the PODs.

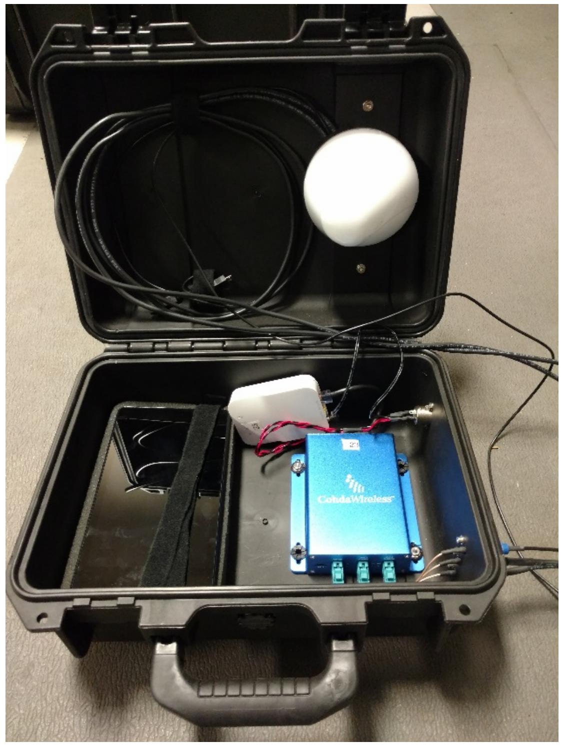


Figure 2. POD Containing a DSRC Radio, Dual-Band Antenna and Global Positioning System, Tablet, and Wi-Fi Access Point.

- RSU—The RSU is the infrastructure component of the system that receives BSMs from CVs and transmits messages over DSRC channels to nearby CVs. In the integrated demonstration version, the RSU provided all BSMs to the Lonestar® software, and Lonestar® provided properly formatted RSAs to the RSU to send out to CVs. The research team purchased multiple DSRC units from a variety of vendors to research interoperability.
- Portable changeable message signs (PCMSs)—Currently, warning messages displayed on DMSs are the primary method for communicating WWD events to right-way motorists. For the prototype system, the research team used a PCMS. However, the recommended WWD warning message (Figure 3) did not fit on the available PCMS (*1*, *2*). For the demonstration, the research team displayed the general warning message shown in Figure 4.

Figure 3. Recommended WWD Event Warning Message for DMSs.

Figure 4. A PCMS Displaying a Warning about the Existence of a Wrong-Way Driving Vehicle.

- Wrong-way vehicle detection and warning system—This system represents non-DSRC devices traditionally used for detecting wrong-way vehicles and alerting TMC staff. Currently, these types of systems trigger an alert when a vehicle drives through a predetermined area of the sensor's field of view going the wrong direction and sends a message through a backhaul connection to Lonestar®. In the test bed, the research team used a Traffic and Parking Control Co., Inc., (TAPCO) system with a camera, dual radar detectors, and light-emitting diode (LED) border-illuminated WRONG WAY sign.

For execution on the closed course, RSU equipment was mounted on portable trailers that also served to provide power to the devices (Figure 5a). The trailers offered 120-VAC power while recharging the integrated batteries using dual solar panels. The trailers included a 30-ft telescoping pole that could be used to provide a wide area of coverage for antennas that need line of sight (Figure 5b). Three such trailers were available to the research team for mounting and powering any devices for the project.

a) Trailer for Powering and Temporarily Mounting an RSU.

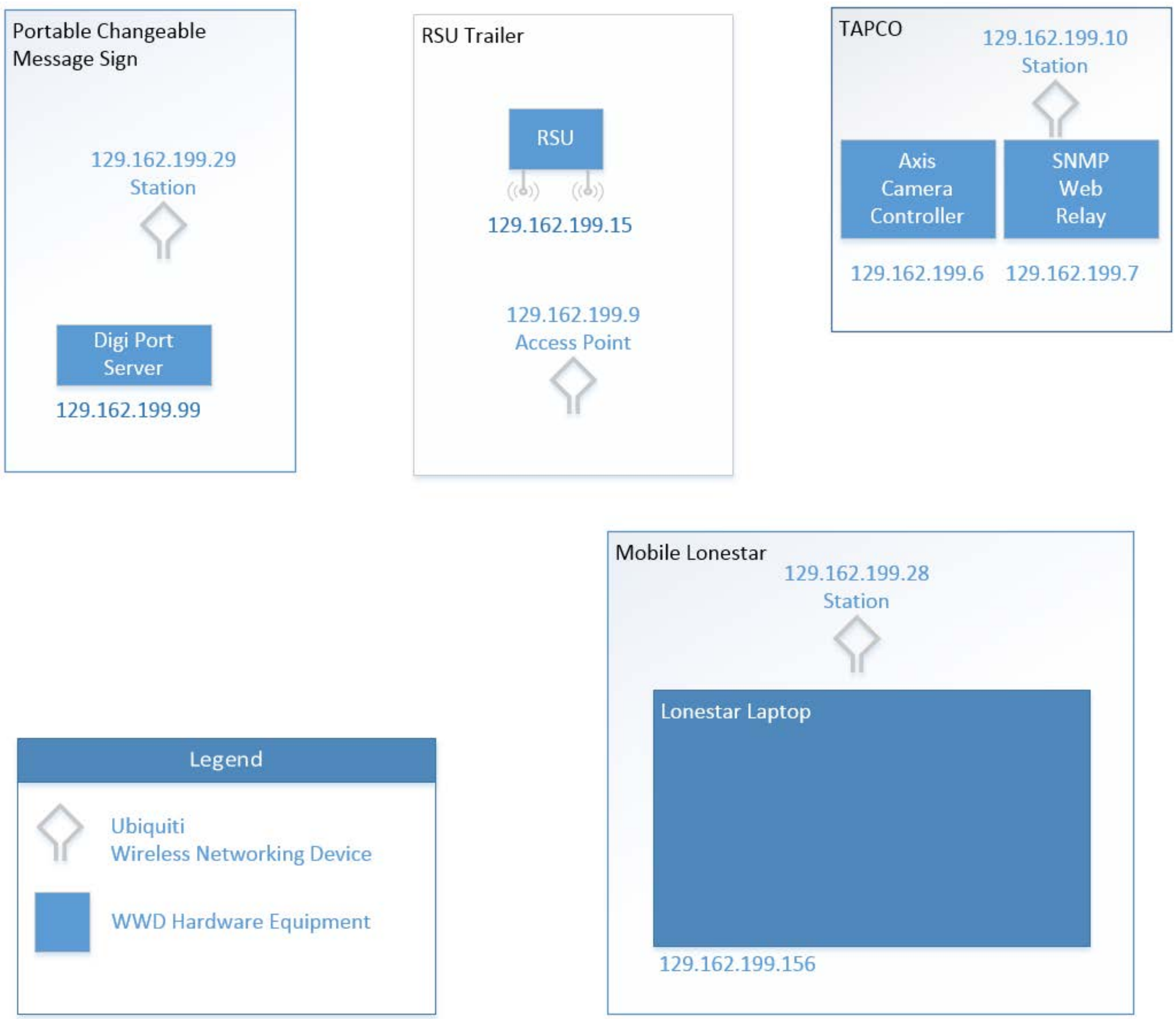
b) Trailer with a Pole-Mounted RSU and Communication Antenna (Foreground) and TAPCO Detectors (Background).

Figure 5. Portable Trailers with RSUs.

The research team mounted the TAPCO camera and dual radar detectors on a separate semi-permanent pole typical to a field installment (Figure 5b). The TAPCO system was powered by batteries included within the equipment cabinet and recharged by a dedicated solar panel. The border-illumined WRONG WAY sign was mounted on one trailer.

Communication Design

Using the three trailers allowed the research team the option to distribute multiple RSUs and other equipment such that coverage was guaranteed for the distance of the closed course. Additionally, the TAPCO equipment and the PCMS were strategically located along the closed course to support the necessary functionality and placement. In order to provide communication between the different components, wireless networking capabilities were enabled through the use of point-to-multi-point (PtMP) wireless network antennas, available from Ubiquiti (Figure 5b). This replaced the functionality that would otherwise be available from existing TxDOT connections such as a fiber backhaul network or cellular modem wireless connections. Figure 6 illustrates the network diagram of the communications equipment used. The introduction of wireless network antennas raised concern about introducing unreasonable latency; however, the validation testing proved that this additional latency was negligible.



NOTE: SNMP = simple network management protocol.

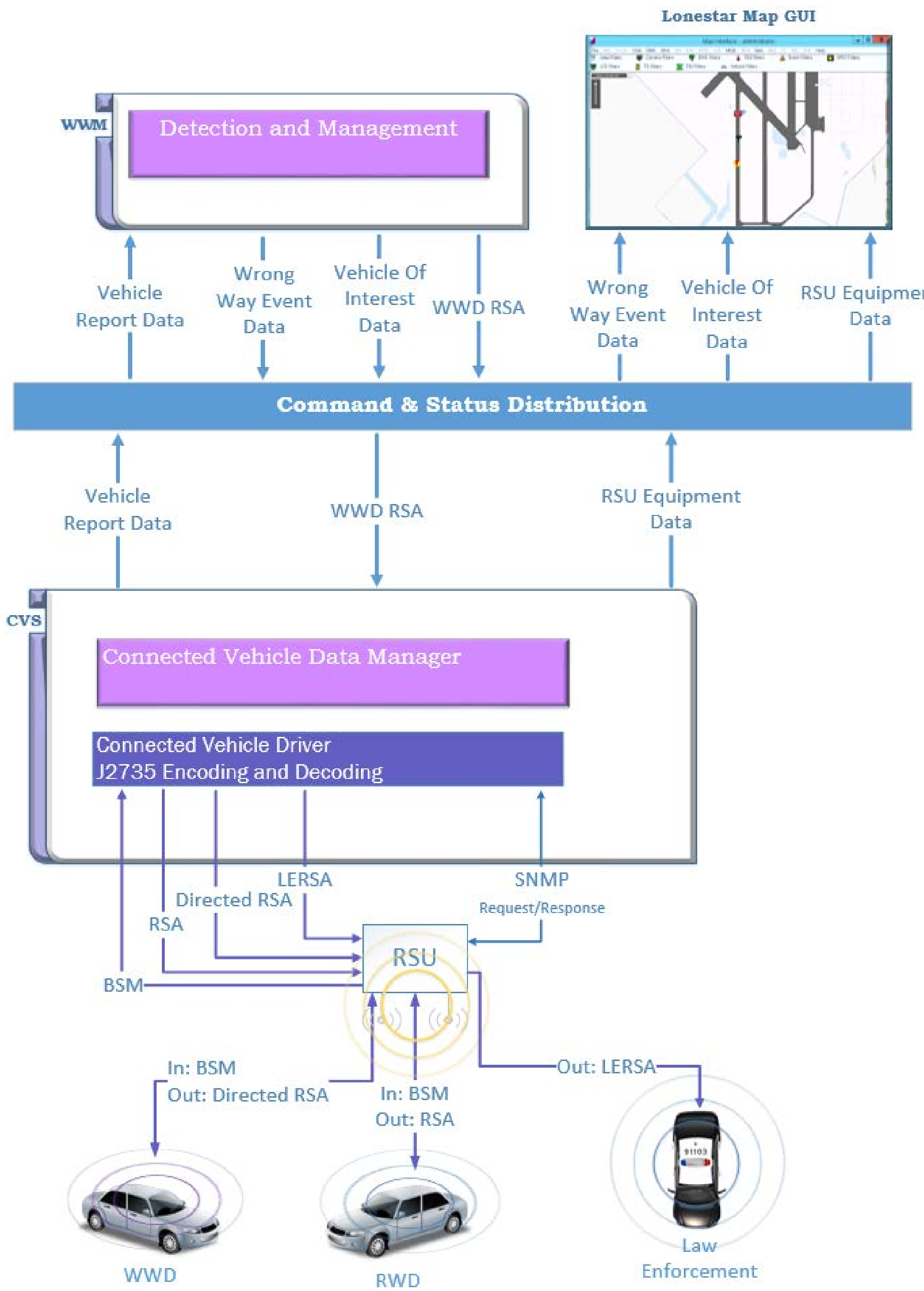
Figure 6. Network Diagram for WWD System Hardware.

Lonestar® Software

Prior to the efforts for this project, the Lonestar® ActiveITS software package supported the necessary capabilities for interacting with a DMS or PCMS. Additionally, alerts from TAPCO detectors were processed within existing Lonestar® software components, although the information was only provided to TMC operators. In order to integrate existing components and CV technology, the research team created two new subsystems: the Wrong-Way Monitor (WWM) subsystem and the Connected Vehicle Subsystem (CVS). The CVS also contains the necessary logic to interact with the RSU hardware and the J2735 message parsing, called the Connected Vehicle Driver (CVDriver). The software architecture diagram in Figure 7 depicts the components that enabled the integrated WWD detection and mitigation functionality. The responsibilities of the new software components were:

- WWM—The WWM was responsible for detecting wrong-way vehicles and sending alerts to drivers. Detection of CV-enabled WWD vehicles was accomplished through a comparison of the heading and position of BSMs with established geometric regions (or paths) and the expected direction of travel. Detection of non-equipped vehicles was accomplished by integrating alerts from traditional detectors in this software component. Once a WWD vehicle was identified, this subsystem initiated and managed a WWD event. This subsystem was responsible for providing an appropriately generated RSA and managing the timing of outgoing messages. When a WWD event was verified or canceled through interaction with the user interface, the WWM modified the event information, wrong-way vehicle information, and RSA.
- CVS—The CVS integrated the CV equipment information, such as location and expected status, with the incoming messages. The CVS also directly transferred the BSMs to the WWM since BSMs have an extremely high data rate (10 Hz per CV). This rate can also be limited through intelligent filtering implemented in the CVS.
- CVDriver—The CVDriver software component managed the networking communication that connects Lonestar® to any RSUs used in the system and integrated the necessary software libraries in order to interact with RSU messages. This driver was responsible for providing high-level status information about each RSU, filtering incoming messages, decoding incoming messages following the appropriate standard, and transmitting outgoing messages over the network

connection. The driver incorporated the libraries that interact with RSU messages that correspond to the J2735 standard including the Abstract Syntax Node One (ASN.1) codecs (from 2009 and 2016, as well as a specific codec for this project based on the 2016 version).



NOTE: GUI = graphic user interface; LERSA = law enforcement roadside alert; SNMP = simple network management protocol; RWD = right-way driver

Figure 7. Lonestar® Software Components and Interactions.

- Graphical user interface (GUI) map plug-ins for CVS and WWM—The research team created two additional GUI map plug-ins for this project. The CVS plug-in provided information to the Lonestar® operator regarding the status of RSU equipment. The WWM plug-in provided a visual representation of wrong-way vehicles and the status of WWD events. DMS equipment status was provided through an existing separate plug-in.

Connected Vehicle Software

The CV software used for this test bed used the standardized J2735 BSM and RSA. A customized RSA for law enforcement vehicles was also generated and transmitted with additional details. Software running on the OBUs communicated with an Android tablet that provided a visual user interface for the vehicle. While not directly interfacing with a specific vehicle's infotainment unit, the tablet allows any vehicle to represent an integrated solution. A visual representation of the necessary information was presented to occupants depending on the role of the CV. The display in the WWD vehicle contained an alert similar to static wrong-way signs (Figure 8). Consistent with the human factors studies performed in Task 4, right-way driving CVs received a warning about a WWD vehicle nearby (Figure 9). Law enforcement officers received information that provided additional vehicle information to assist them in addressing the WWD event. When used in a connected law enforcement vehicle, the tablet displayed the speed of the WWD vehicle (Figure 10).

Propagation of RSAs from one receiving vehicle to another vehicle extends the communication range of the CV test bed. In order to enable propagation, a CV POD was customized to repeat any RSAs that were received to any vehicles that were within range. With the limited space and clear line of sight available in the test bed, testing this functionality was a challenge. The research team either used an obstruction or drove the receiving vehicle far off course in order to no longer receive RSA messages directly from the RSU. The propagating CV POD (while remaining within range of the RSU) was then driven within range of the receiving CV. The results successfully proved the capability to propagate messages from the RSU through an intermediate CV, thus extending the range of RSUs.

Figure 8. Wrong-Way Driver In-Vehicle Alert.

Figure 9. Warning Message That Appears on Right-Way Driving Vehicle's Tablet.

Figure 10. Information Displayed to Connected Law Enforcement Vehicle.

RSU Software

While the typical usage of DSRC is for multicast (broadcast) application information, the applicable Institute of Electrical and Electronics Engineers (IEEE) 1609.x standards facilitate unicast (directed) messaging between DSRC radios. This is accomplished by including a target media access control (MAC) address to the wireless access in vehicular environments (WAVE) stack when an application sends a message to be transmitted. The United States Department of Transportation (USDOT) RSU 4.1 Specification defines high-level requirements for the inclusion of a WAVE stack proxy that facilitates receiving messages over DSRC and forwards them to a specified user datagram protocol (UDP) interface, and also receives a message over UDP to be forwarded over DSRC. The requirements for this proxy application do not include transmitter/receiver MAC address information, which limits communication to multicast messages. The designed implementation used for this project leveraged the unicast capabilities of IEEE 1609.3 in order to use as much native, low-level interface code as possible to reduce the application layer requirements. Due to the lack of unicast support in the vendor-supplied WAVE proxy, a custom proxy was developed that implemented the MAC address handling. This extended WAVE proxy is relatively basic, minimizing software complexity; however, it requires custom development for each vendor's WAVE stack application programming interface.

System Functionality

Within the Lonestar® software, regions were defined that provided boundaries for the areas that the WWM subsystem was monitoring for potential WWD events. Each region contained an expected direction of travel (Figure 11). The BSMs received by the WWM subsystem were checked against the regions and the expected heading, and any BSMs that did not match triggered a WWD event.

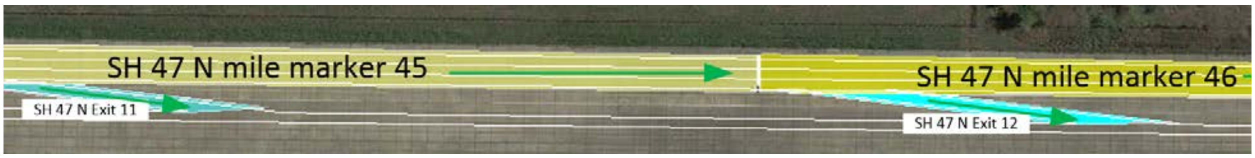


Figure 11. Visual Depiction of Wrong-Way Regions within Lonestar®.

When a BSM was identified as traveling in the wrong direction within a region, an alert was generated and the WWD vehicle was represented as a vehicle of interest on the Lonestar® map user interface (depicted as a red arrow on a yellow background in Figure 12). The interface continually displayed the position and heading of the vehicle of interest (in Figure 12 the WWD vehicle is located in the middle of the closed course and is headed south).

In addition to recognizing WWD events that were triggered by CV detection or traditional vehicle detectors, users of the Lonestar® map interface were able to create WWD events manually. This option would be needed for WWD events reported through calls to 911 and in cases where technology is not present to detect wrong-way vehicles. The Lonestar® operator would right-click on the map in the area where the event was reported, and a wrong-way event would be created (Figure 13).

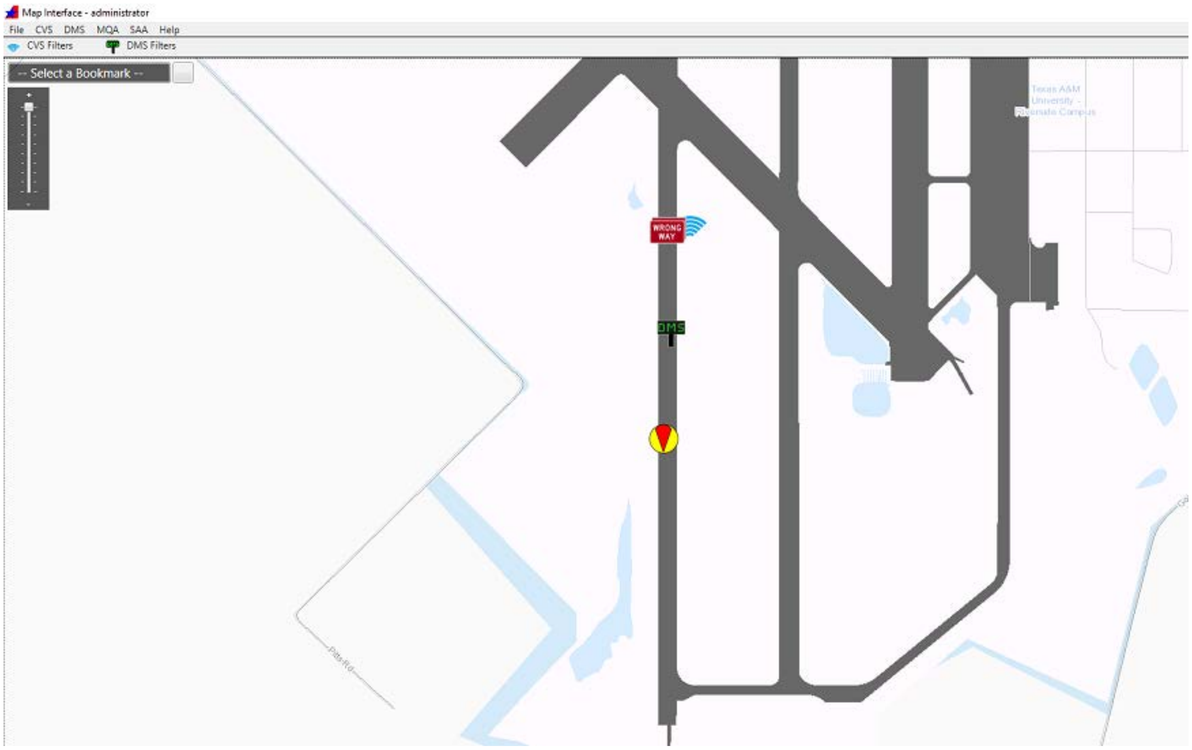


Figure 12. Active WWD Event with a CV.

a) Context Menu Enabling an Operator to Create Events.

b) WWD Event Icon after Creation.

Figure 13. WWD Event Manually Created in the Lonestar® User Interface.

Validation Testing

The research team developed the prototype CV WWD system around the following four deployment scenarios:

- A CV-enabled vehicle drives the wrong way—the case where the wrong-way vehicle has an OBU with DSRC capabilities and is driving in a zone that is covered by a RSU.
- The CV warning propagates—the case where an alert from an RSU is received by a CV-enabled vehicle (using an OBU with DSRC capabilities) and that alert is sent between CV-enabled vehicles, effectively extending the communication range of the RSU.
- Non-DSRC infrastructure-based sensors detect a wrong-way vehicle—the case where a non-equipped wrong-way vehicle is detected by an infrastructure-based sensor (not DSRC).
- A 911 caller reports a wrong-way vehicle—the case where the WWD vehicle is reported to emergency personnel through a call to 911.

The validation testing did not include the 911 scenario since the communication between law enforcement agencies and TMCs was out of scope for this project. In addition, the communication between the RSU, CV-enabled vehicles, and PCMS for the 911 scenario is the same as the non-DSRC infrastructure-based sensor scenario, which was tested. Over the course of the project, each of the remaining scenarios were verified to authenticate appropriate functionality and to establish metrics on the performance of the system. From the validation testing, the research team established the following metrics (additional testing results are located in the appendix):

- Lonestar® received and processed 99.8 percent of the BSMs transmitted by CV-enabled wrong-way vehicles.
- The system reported zero false positives from CV-enabled right-way driving vehicles.
- Alerts took less than 100 milliseconds for the total round trip, from the transmission of a CV-enabled WWD BSM to right-way drivers receiving an RSA. This includes any networking latency incurred by using PtMP wireless networking equipment, verifying that any delays were negligible.

- Updates to RSAs occurred within 200 milliseconds after the initial alert was triggered.
- CV-enabled wrong-way vehicles traveled less than 20 ft at highway speeds between RSA updates. This is comparable to the accuracy required for reporting the positioning in a BSM, and is sufficient for further relative localization reporting through CVs.
- CV-enabled wrong-way vehicles received 98.1 percent of RSAs transmitted by Lonestar®.
- CV-enabled right-way vehicles received 99.2 percent of RSAs transmitted by Lonestar® as broadcast messages.
- Propagation of RSAs did not incur any additional processing delays beyond the networking delays (less than 100 milliseconds).
- A 10-Hz update rate on BSMs was confirmed for all CV equipment included in the test bed (both Cohda and Savari™ equipment were verified).
- The cancelation of a WWD event was recognized within 5 seconds.

In order to test whether the CV WWD system could be device agnostic, the research team purchased at least one RSU, one OBU, and the associated software development kits from three vendors (i.e., Cohda Wireless America, LLC; Savari,™ Inc.; and Lear Corporation). In preliminary testing, the research team verified that the Savari™ and Lear RSUs supported the multicast WAVE proxy defined in the USDOT RSU 4.1 specification, which enabled basic forwarding of a vehicle's BSMs through the backhaul to a TMC. However, the WAVE proxy in these two RSUs did not support unicast messaging, which is required for sending directed messages to a specific vehicle (e.g., a WWD vehicle). As such, these two RSUs could not be used for the applications implemented in the test bed system, which required access to the unicast messaging capabilities defined in IEEE 1609.3. Therefore, the prototype CV WWD system only used Cohda RSUs.

While testing OBUs, the research team found that the Savari™ OBU transmitted BSMs without reconfiguration, although they were sent with valid, but unexpected, IEEE 1609.2 headers. The research team was able to identify this early and modify other processes to support the different security header, allowing the Savari™ OBU to be used for interoperability testing. The Lear OBU did not transmit BSMs initially. After some reconfiguration, the unit did transmit them. However, other units were unable to correctly parse the messages sent by the Lear OBU. The team was unable to determine the exact cause of the issue in the time available. Therefore, the research team used OBU radios from Cohda and Savari™ for limited interoperability verification. While both performed appropriately, one notable metric for the Savari™ equipment was the unusually long startup time (on the order of 3 to 5 minutes, compared to approximately 30 seconds for Cohda equipment). Additional investigations regarding contributing factors would be necessary to understand this difference.

Integrating the CV WWD System with the Federal Highway Administration Vehicle-to-Infrastructure Hub Platform

The standalone local CV WWD detection system was a plug-in module that resided on the Federal Highway Administration (FHWA) Vehicle-to-Infrastructure (V2I) Hub, which was designed to support the deployment of roadside applications in a CV environment. The V2I Hub gave applications the ability to broadcast SAE J2735 messages to CVs via a DSRC RSU connected to the V2I Hub. At the same time, it gave the roadside applications access to the BSMs received from CVs in range of the RSU. Figure 14 shows the basic architecture of the standalone application.

Hardware Components

The hardware components of the standalone implementation were almost the same as the Lonestar® implementation, except that the research team replaced the Lonestar® computer with the FHWA V2I Hub to identify wrong-way vehicles using BSMs received from CVs or through local alerts received from a non-DSRC WWD detection system. The V2I Hub is a software system that acts as a translator and data aggregator/disseminator for infrastructure components of a CV deployment (*3*). It is designed specifically to allow custom CV applications to run on an industrial computer located on the roadside. This architecture allowed the research team to move all processing functions that would have normally occurred in the TMC to the field. This eliminated the need for a high-speed communication link (e.g., fiber connection or dedicated link) back to the TMC. The V2I Hub was also used to generate and broadcast RSA messages to CVs through the local RSU, display alerts on the PCMS, and send alerts back to a TMC using a cellular modem connection or similar communications link.

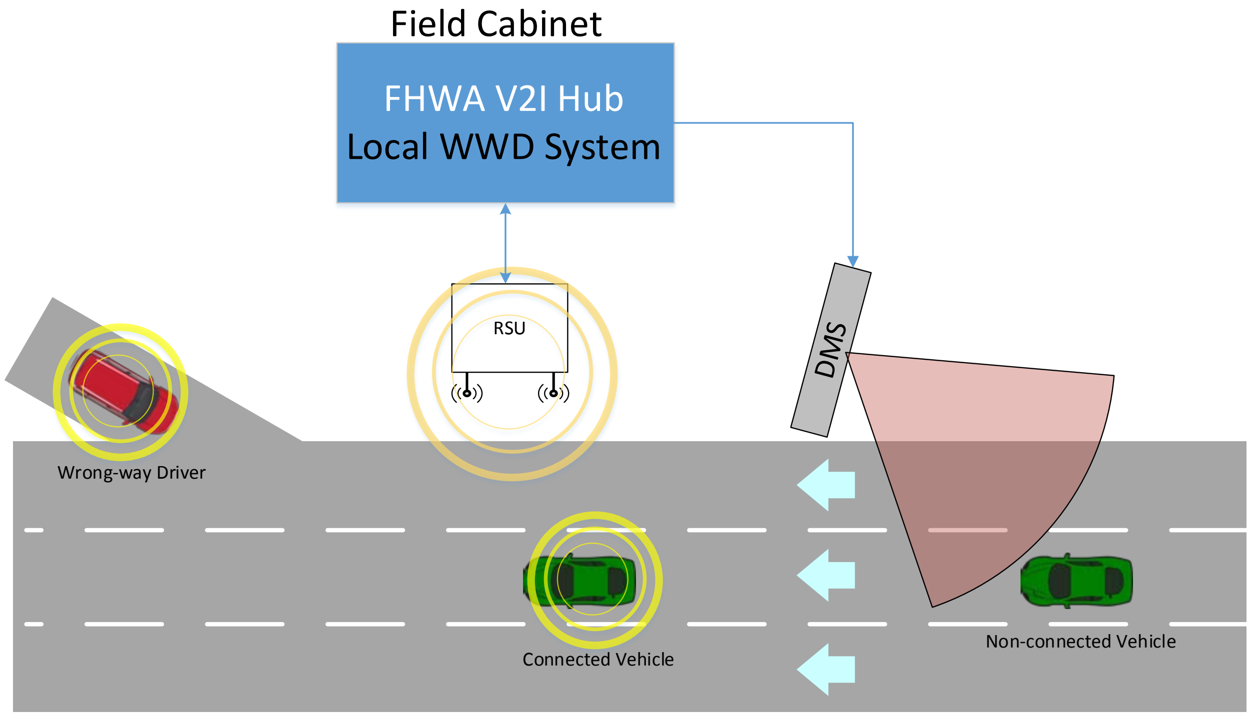


Figure 14. Layout of the Standalone Local CV WWD System.

V2I Hub Software

The V2I Hub software is an open-source software developed by FHWA to support field implementation of CV technologies. It is available for use through the FHWA Open Source Application Development Portal. It contains a suite of plug-ins designed to handle specific functions on the roadside. The V2I Hub is not the same as an RSU. The RSU is the radio that communicates the messages between the infrastructure and vehicles and vice versa (i.e., infrastructure to vehicle and V2I). The V2I Hub, in contrast, supports a large number of interfaces for communication between other infrastructure components, vehicles, and traffic management systems. The V2I Hub not only exchanges data but also processes and handles messages. In this application, the research team made use of the following existing interfaces and message handlers built into the V2I Hub (Figure 15):

- The BSM/approaching vehicle aggregator—used to collect and process BSMs from CVs.
- The transportation message eXchange (TMX) core—used to generate and broadcast J2735 RSA messages to vehicles from the infrastructure.

- The roadside signage DMS arbitrator—used to display wrong-way alert messages on the PCMS.

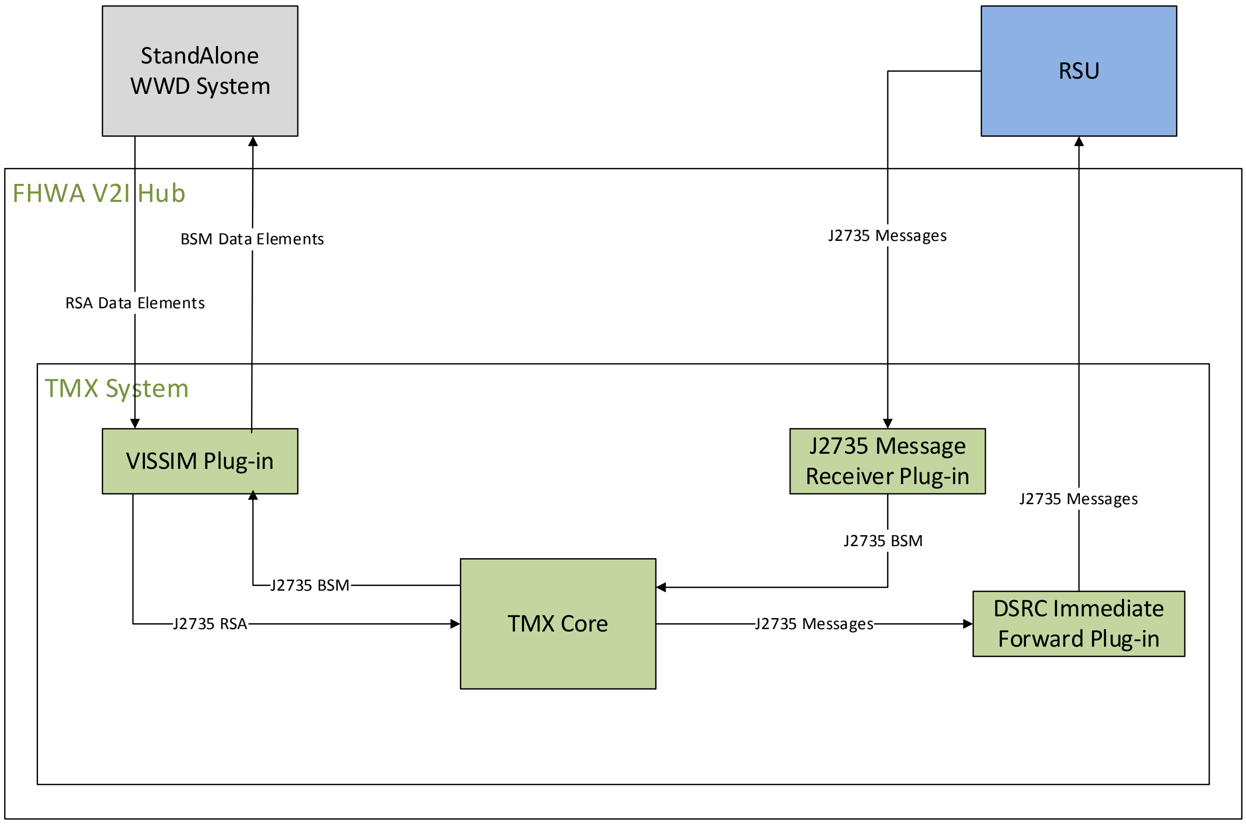


Figure 15. V2I Hub Plug-Ins Used in the Development of the Standalone CV WWD System.

WWD Software

In addition to the message handlers discussed previously, the research team deployed specific wrong-way detection and messaging software on the V2I Hub. The V2I Hub used an RSU radio to receive BSMs from CVs. The V2I Hub then decoded the BSMs and created a string of data that was passed to the on-site computer running the standalone WWD detection roadside application. The software took the BSM data, parsed the data into different variables, and checked the variables for an indication of wrong-way behavior. The research team created a virtual wrong-way detection area, representing the region of interest (e.g., exit ramp) using a set of vertices consisting of latitude and longitude coordinates. The detection area was a polygon that could be altered to include more vertices if needed. Detection was accomplished using a ray-casting method to determine if the latitude and longitude point from the BSM was contained within the vertices of the detection zone. More specifically, the ray-casting method compared the value of the BSM location to the location of the detection zone vertices to determine how many of the lines drawn between the vertices would be crossed by a ray drawn to the BSM location. If the BSM was in the virtual detection area, the algorithm checked to see if the reported heading in the BSM was incorrect for that location. If the software found the heading to be inappropriate, it populated a program file with text indicating a wrong-way vehicle was detected. Otherwise, no entry was included in the program file. When the software detected a wrong-way vehicle, it triggered alerts to right-way vehicles via a PCMS and a J2735 RSA message broadcast via the RSU.

Validation Testing

The research team tested the standalone system at the Texas A&M RELLIS campus. As discussed previously, the research team defined a zone of interest for wrong-way vehicle detection. The research team then drove a vehicle equipped with an OBU in the region of interest. This vehicle traveled in both the correct (right-way) and incorrect (wrong-way) directions multiple times. The system successfully detected each time the vehicle was driven the wrong-way and generated alerts. The validation testing of the secondary standalone system was not as extensive as the testing of the primary Lonestar® system.

DEMONSTRATION

The research team conducted a physical demonstration of both CV WWD systems for select visitors, including some local media, on August 16, 2017, at the Texas A&M RELLIS campus. There were approximately 35 attendees, plus research team staff. The demonstration began with a brief overview of the WWD issue in Texas. The research team then described the components and operation of the CV WWD systems. Attendees were then encouraged to ride in the wrong-way and right-way vehicles, as well as observe the mock TMC operator station and law enforcement vehicle. The event included demonstrations of the Lonestar® system's functionality to:

- Detect a CV-enabled wrong-way vehicle via DSRC, notify a TMC, and alert a CV-enabled right-way vehicle and CV-enabled law enforcement vehicle.

- Detect a non-equipped wrong-way vehicle via an infrastructure-based device, notify a TMC, and alert a CV-enabled right-way vehicle and CV-enabled law enforcement vehicle.
- Show interoperability between two types of OBUs.
- Propagate an RSA between two CV-enabled right-way vehicles.

The research team also explained the standalone local system.

SUMMARY

The research team developed and tested a prototype CV WWD detection and management system in a closed-course environment. Verification of the Lonestar® system confirmed the reliability and real-time alerting available to right-way and wrong-way CVs. The research team also showed that CV-enabled law enforcement vehicles were able to receive and leverage additional real-time information available from the Lonestar® system. In addition, the Lonestar® system provided TMC operators with additional insight into WWD events as they occurred. The research team also successfully implemented and tested a secondary standalone system. Overall, the success of the validation testing and demonstration of the prototype CV WWD system in a closed course demonstrates the viability of a model field deployment on a real roadway.

CHAPTER 3: IDENTIFICATION OF INFORMATION NEEDS FOR RIGHT-WAY DRIVERS

Researchers investigated in-vehicle information needs of right-way drivers when a WWD event is detected or reported. Researchers also evaluated motorist comprehension and interpretations of existing data elements (i.e., wording) available to generate in-vehicle alerts about approaching wrong-way vehicles. Since car manufacturers are independently developing their driver interfaces and the National Highway Transportation Safety Administration (NHTSA) has an active research program for driver-vehicle interface design, this research did not consider the design of the driver interface (e.g., visual, audio, or haptic) for these messages. Instead, the studies documented herein focused on content, terminology, and timing of the in-vehicle messages rather than how the message is displayed to the driver.

First, researchers conducted a formal task analysis to determine the steps a right-way driver must go through in order to respond safely to a WWD event. The purpose of the task analysis was to identify critical stages of the detection, decision, and response steps where right-way drivers could make better decisions if information was provided to them through CV technology, roadway signs, or other communication methods.

Researchers then used two human factors activities to identify the information needs of right-way drivers and evaluate comprehension and preference of message wording and timing. First, researchers conducted individual structured interviews with 65 drivers from the Dallas/Fort Worth, Houston, and San Antonio areas. Researchers derived the structured interview questions directly from the task analysis. These one-on-one interviews allowed researchers to gain a deep understanding of a driver's decision-making process and what information drivers would like to receive about a WWD event dependent upon where they were located relative to a wrong-way vehicle. The structured interviews also permitted researchers to ask follow-up questions to gauge areas of misunderstanding, comprehension, trust, and preference in more detail than can be done with a survey or focus group.

The structured interview results prompted the development and conduct of a short survey using tablet computers with 361 drivers from the same geographic areas (Dallas/Fort Worth, Houston, and San Antonio). Researchers designed the survey to address specific areas of confusion and disagreement on preference for message types identified in the structured interviews. For the surveys, drivers were shown a series of photos of a typical in-dash video screen containing various in-vehicle messages. Along with each photo were questions aimed at determining comprehension and preference of the in-vehicle message wording.

TASK ANALYSIS

The human factors profession has developed a variety of methods to conduct task analyses. The research team selected a method best suited for a cognitive task (as opposed to tasks that are more simple action oriented). The method selected, the Critical Action and Decision Evaluation Technique (CADET), is often used in analyzing complex industrial plant operations where an operator must detect an abnormal state, consider alternative actions, seek further information, and make a decision (*4*). This method is built on a step ladder model of decision making first introduced in the field of human machine interaction by Rasmussen (*5*). It has been embraced widely in many application areas, especially the aviation field where it is used by the Federal Aviation Administration to examine pilot decisions in critical situations (*6*).

The task analysis steps through each stage of a WWD event. The actual decision and response execution depends on where the right-way driver is relative to the wrong-way driver. But for this task analysis, the focus is on what kinds of information a right-way driver would need in order to make decisions. So the task analysis should apply to every vehicle in the vicinity, even those who may be on parallel frontage roads and not really threatened by the wrong-way driver. Even a driver on the frontage road may want information in order to determine that he or she is safe and no evasive action is needed.

A task analysis does not consider how the driver would receive the information desired. The task analysis answers solely the "what" information questions. The task analysis can be thought of as a way to formalize questions drivers would ask themselves once they become aware of a wrong-way driver.

Table 1 provides a summary of the decision-making stages and the associated common sources of error used with the CADET. A WWD alert system should try to address these sources of error. Because this technique is typically applied to operators responding to critical events in processes, such as responding to an alert at an oil refinery control board, not all of the error sources will be directly applicable to the WWD situation. But in most cases, analogues can be found in a WWD event, and it is valuable to use this formal method to organize the analysis.

Table 1. Summary of the CADET.

Process Stage	Common Sources of Error
Initial Alert Detect initial stages of the problem	Distraction, absent-mindedness, low alertness
Observation Either directly observe or observe alerts of a distant event	Unjustified assumptions, violation of expectations
Identification Identify the system state	Information overload, time delay
Interpretation Interpret what has happened and its implications	Failure to consider alterative causes, fixation on the wrong cause
Evaluation Evaluate and select alternative goals	Failure to consider side effects, focus on the main event exclusively
Planning Plan a success path	Selection of the wrong task due to shortcuts in reasoning and stereotyped response to a familiar state
Procedure Selection Choose or formulate a procedure to achieve the required objective	Procedural steps omitted or executed in the wrong order
Execution Execute the chosen procedure	Reversal of direction or sign when carrying out an action, habit intrusion
Feedback Observe the change of state of the system to indicate the correct outcome	Feedback ignored or misinterpreted

Source: adapted from (*4*)

Using the stages and error sources identified in the CADET, researchers analyzed a WWD event from the perspective of a right-way driver in the area. This analysis is presented in Table 2. Researchers used these findings to derive the structured interview questions.

For purposes of this analysis, researchers assumed that the right-way driver had become aware of the wrong-way driver either by directly observing the event or by receiving notification from roadway signs, in-vehicle warnings, or media reports. In other words, the Initial Alert and Observation stages were complete. For direct observation, a right-way driver may see any of these events in order to identify a wrong-way driver:

- The wrong-way vehicle coming toward them.
- The right-way vehicles downstream swerving.

- Someone entering the freeway the wrong way on a ramp.
- Police cars in the area, though this could be due to another incident.

Table 2. CADET Applied to WWD Events.

Process Stage	Information Element	Comments
Identification	Is the source of the notification reliable? Do I trust this alert and/or observation?	Drivers will consider the source and the wording of the alert message in determining the urgency of the situation.
Identification	Is the wrong-way driver really on my side of the road?	For non-observable events (e.g., too far away), the drivers must be able to know which road they are on and their direction of travel in order to determine if they are directly threatened. For some drivers, this may require messages using landmarks and local terms as opposed to route numbers and cardinal directions (for instance, a wrong-way driver “just passed Ikea heading toward Beltway 8 on the Katy Freeway” as opposed to “heading west on I-10 just east of Antoine Street”). For non-specific warnings of a wrong-way driver in the vicinity, a driver may not be able to identify which side of the road the wrong-way driver is on.
Interpretation	Is that location on my intended path?	In addition to understanding where the wrong-way driver was last reported, right-way drivers must be able to place themselves on a mental map relative to that wrong-way driver. This can be very difficult for many people, especially those unfamiliar with the area.
Interpretation	Is there somewhere I can get off the freeway between the wrong-way driver and me?	Depending on their familiarity with the area, drivers may know of intervening exit points.

Table 2. CADET Applied to WWD Events (Continued).

Process Stage	Information Element	Comments
Evaluation	Should I change lanes? Which direction (laterally) should I move? Should I keep going but slow down and be on the lookout? Should I exit the freeway? Should I turn around and drive away? Should I stop? Which side of the road should I pull onto if I am going to stop? What are other vehicles doing?	The basic options for action are to: • Change lanes but continue moving. • Change lanes and stop. • Stop in the current lane. • Continue moving in the current lane. • Exit the freeway (either legally or illegally crossing a median or frontage road divider). • Turn around and drive the wrong way. Information provided at this stage can help drivers consider unintended consequences of their action. For instance, if a driver chooses to pull over and stop, he or she may have just parked in the path of the oncoming WWD.
Planning	Are there other vehicles around me that I'm going to cut off if I change lanes, exit the freeway, or stop? Do I see a good place to pull over (e.g., wide pavement, lit, and no debris)? Am I going to get stuck there for a long time if I stop? Will I get stuck in traffic if I exit? How do I know when it is safe to get back on the freeway?	The planning stage happens in quick succession or possibly in parallel with the evaluation of options.

Table 2. CADET Applied to WWD Events (Continued).

Process Stage	Information Element	Comments
Procedure Selection	When should I start moving over, exiting the freeway, or stopping? How far away is the wrong-way driver? Will the police have stopped the wrong-way driver before I meet the wrong-way driver?	The actual selection of the procedure may be influenced by the level of inconvenience and the perceived risk. The perceived risk could depend on how far away the wrong-way driver is (in terms of time or distance). Some drivers may select a procedure based on their estimation of how likely it is that the police will have stopped the wrong-way driver before they meet the wrong-way driver, particularly if the reported location is a greater distance away.
Execution	Should I do this really quickly and drive erratically, or do I have time to slow down and safely change lanes?	The actual execution could depend on the presence of passengers. The vehicle type would affect the execution phase as well in terms of expected braking and acceleration performance. The proximity of the wrong-way driver would affect the selection of braking or steering as a response.
Feedback	Have the police stopped the wrong-way driver yet? Did the wrong-way driver crash into anybody? Was that vehicle I just saw go by the wrong-way driver that I got the alert about? Do I trust the source of the information that the wrong-way driver has been stopped and/or cleared?	Receiving feedback about the time and location of the end of the WWD event will help drivers learn from their experience. If they were able to exit and observe the wrong-way driver going past them, for instance, they will know they made the right decision to exit even though it was an inconvenience. They will also gain trust in the alert system and know that it was not a false alarm.

STRUCTURED INTERVIEWS

Data Element Categories

The goal of the structured interviews was to identify what information drivers would like to receive about a WWD event depending on where they are located relative to the wrong-way vehicle. The interviews also helped to determine when in the course of their encounter with the WWD event they would like to receive that information.

In order to assist the structured interviews, the researchers identified key message data elements to be investigated that correspond to DMS message design, as well as other units of information pertinent specifically to WWD events. These data elements consisted of:

- Urgency.
- Problem.
- Location.
- Lanes affected.
- Action.
- Validation.

The open-answer nature of the survey allowed the respondents to add to the types of data elements. After speaking to the first few participants, researchers added the following data elements to the interview script:

- Speed of the wrong-way vehicle.
- Details of the wrong-way vehicle.
- Reaction time.
- Warn others.

Table 3 describes the data elements used and what key words were tied to that data element.

Table 3. Data Element Category Descriptions and Key Words Used.

Data Element	Description	Key Words/Phrases
Urgency	Audio or visual attention grabber (flashing symbol or beeping noise)	Warning, flashing, alarm, alert, beep, severity
Problem	Identify that there is a wrong-way vehicle detected	Wrong-way driver or vehicle, problem, car coming
Location	Where the wrong-way vehicle is located; either by name of the facility, time, or distance to the vehicle	On US 75, 100 yards ahead of you, in your vicinity, on the same freeway, on a cross street, 20 seconds ahead
Lanes affected	Telling which lane the wrong-way vehicle is currently traveling in	In my lane, left lane, what lane he or she is in
Action	Which action the right-way driver should take; a command instructing what you should do	What to do, exit now, do not enter, pull over, suggestion, options, tell me what to do
Validation	Some way to tell that the message is coming from a reliable source and is currently relevant	From TxDOT, time stamp, authority
Speed of the wrong-way vehicle	The current speed of the wrong-way vehicle	His or her speed, how fast
Details of the wrong-way vehicle	Information known about the make, model, and/or color of the wrong-way vehicle; also includes specific information about the driver	Color of the vehicle, what type of car, driver intoxicated, is the driver drunk, if the driver is impaired
Reaction time	How much time until a collision would occur with the wrong-way vehicle	Reaction time, how much time before a collision
Warn others	Right-way vehicles should flash lights or notify others that there is a wrong-way vehicle ahead	Flash my lights, warn others

Researchers developed the interview questions in a format similar to those that would be used in a focus group. However, researchers chose to conduct individual interviews in order to go into more depth with each participant and not have them influenced by other people's comments. Researchers used a table-top display (Figure 16) to illustrate a wrong-way vehicle and other possible vehicles in the area to aid in the conversation. The large-format color line drawing showed vehicles in the same and opposing directions of travel on the freeway and adjoining frontage roads, as well as on cross streets. The freeway and cross street names were changed to correspond to the area near where the surveys were conducted.

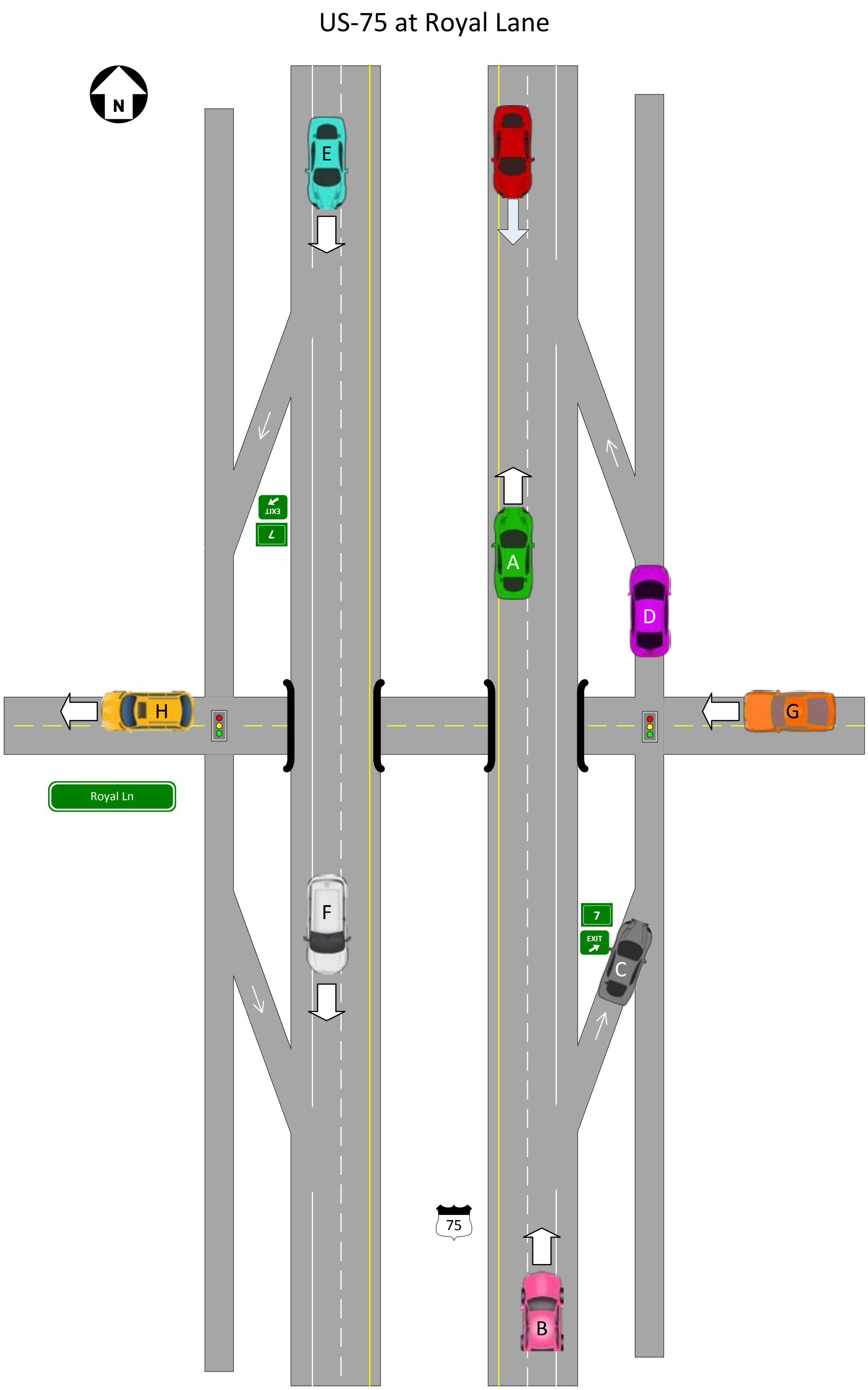


Figure 16. Illustration Used in Structured Interviews.

For discussion purposes, the scenarios were grouped together and presented to the participants in three groups: same side of the road, opposite side of the road, and cross-street traffic. So three separate, simplified diagrams were actually used in the initial questioning. At the end of the interview, researchers used the illustration showing all vehicles (Figure 16) to summarize and review. The following is a description of the three vehicle groups and what each participant was told about each vehicle location in that particular group.

Vehicles on the Same Side of the Road

Vehicles A, B, C, and D were located on the same side of the freeway as the wrong-way vehicle. Vehicle A (the green car) was in the immediate vicinity of the wrong-way vehicle; thus, the driver of Vehicle A could see the wrong-way vehicle. Vehicle B (the pink vehicle) was located further upstream than Vehicle A. Therefore, the driver of Vehicle B could not see the wrong-way vehicle, and he or she had the option to exit the freeway as illustrated. Based on initial participant responses, researchers added questions about the case where the driver of Vehicle B did not have an option to exit the freeway. Vehicle C (the gray vehicle) had just exited the main lanes upstream of the wrong-way vehicle and was not getting back on the freeway. The driver in Vehicle C could not see the wrong-way vehicle. Vehicle D (the magenta vehicle) was about to enter the main lanes upstream of the wrong-way vehicle. The driver of Vehicle D could not see the wrong-way vehicle.

Vehicles on the Opposite Side of the Road

Vehicles E and F were located on the opposite side of the road from the wrong-way vehicle. Based on the initial discussions, researchers divided this group into two different situations:

- Traveling on a four-lane, divided freeway with no median barrier (i.e., the wrong-way vehicle could cross the median).
- Traveling on a four-lane, divided freeway with a median barrier (i.e., the wrong-way vehicle could not cross the median).

Vehicle E (the turquoise vehicle) was in the immediate vicinity of the wrong-way vehicle, and thus the driver of Vehicle E could see the wrong-way vehicle. Vehicle F (the white vehicle) was ahead of the wrong-way vehicle. Therefore, the driver of Vehicle F could not see the wrong-way driver.

Cross-Street Traffic

Vehicles G and H were both located on the cross street. Vehicle G (the orange vehicle) was traveling on the cross street approaching the intersection with the frontage road. Participants were told that the in-vehicle system would not necessarily know where Vehicle G was going. Instead, the in-vehicle system might only know where Vehicle G was at any given moment in time. Vehicle H (the yellow vehicle) was also traveling on the cross street; however, this vehicle was leaving the intersection. Neither vehicle driver on the cross street could see the wrong-way vehicle.

Study Methods

Locations

Researchers conducted a pilot of the structured interviews in the Bryan/College Station area with eight participants. Based on the pilot findings, TTI researchers revised the interview guide, as noted previously. Researchers then conducted 23 structured interviews in Dallas/Fort Worth, 21 in Houston, and 21 in San Antonio (65 total). These three TxDOT districts had the highest percentage of WWD crashes from 2010 to 2014.

Participants

Researchers recruited approximately 20 individuals from the TTI subject list in each selected city by phone or email. The requirements for participation were:

- Be 18 to 85 years of age.
- Have a valid driver’s license.
- Be able to read and speak English.

If the potential participants met these criteria and agreed to participate, a researcher scheduled a time for them to complete the interview at the local TTI office.

Table 4 contains the demographic sample obtained compared to the 2013 Texas driving population (*7*). While the gender and age attainment for the interviews was slightly different from the 2013 Texas driving population, researchers believe that the survey sample still represents Texas drivers reasonably well.

Table 4. Demographics of Texas Drivers and of the Study Sample.

Sample	Male (38%)			Female (62%)			Total
	18–39	40–54	55+	18–39	40–54	55+	
Study sample (n=65)	15%	15%	8%	23%	17%	22%	100%
Texas data (*7*)	19%	14%	15%	20%	14%	16%	98%[a]

[a] 2 percent were licensed drivers under the age of 18.

Study Procedure

This activity was considered human subjects research by the Texas A&M Office of Human Subject Protection. For this reason, all participant recruiting materials and interview questions were reviewed and approved by the Texas A&M Institutional Review Board (IRB) before conducting the interviews. This review included assurances of confidentiality of responses and reporting in a way that does not identify the respondent.

The structured interviews began with a researcher describing the overall scenario to each participant. The researcher also explained, in basic terms, how future in-vehicle technology would be able to receive information from outside sources (i.e., TxDOT) and provide warnings about nearby hazards, such as a WWD event. The researcher assured the participants this technology would not be able to track the participants' movements, nor would it have the ability to know their destination. It was emphasized that this technology would be very accurate and reliable. Each interview lasted 45 to 60 minutes and was conducted by the same researcher. A second researcher took notes. For each vehicle group (i.e., same side, opposite side, and cross street), the participants were asked the following questions:

- Which right-way vehicle locations need to be notified of the WWD event? Participants indicated by pointing at vehicles on the illustration.
- For each individual vehicle on the illustration, the researcher then asked a series of questions, beginning with "What types of information would you want to receive, and when would you like to receive that information?" The participants were given an opportunity to respond freely, and then the researcher followed up with these questions:

- How far upstream of the wrong-way driver would you want to start receiving in-vehicle alerts?
- Should the in-vehicle alert contain some type of information or symbol that conveys the urgency of the situation? Why or why not?
- Should the in-vehicle alert become more frequent and/or more urgent as you get closer to the wrong-way driver? Why or why not?
- Should the in-vehicle alert contain information about the problem? Why or why not?
- Should the in-vehicle alert contain information about the location of the wrong-way driver? Why or why not? If so, should relative locations be expressed in units of time or units of distance?
- Should the in-vehicle alert contain information about the lanes affected? Why or why not?
- Should the in-vehicle alert contain information about the action you should take? Why or why not? If so, what action(s) do you think should be provided?
- Should the in-vehicle alert contain information that validates the message? Why or why not? If so, in what ways would that change your thinking or action?

After going over each vehicle, the researcher asked the following general questions about in-vehicle alerts:

- Which piece of information would you need in order to trust the in-vehicle alert?
- If you get an in-vehicle wrong-way driving alert, would you assume police are responding?
- Once a wrong-way driving event is detected or reported by authorities, how soon do you think you should get an in-vehicle alert message?
- Once you get an in-vehicle alert message, how long would you assume it is valid for?
- Should an all-clear message be broadcast to let you know the event/alert is over? Why or why not?

Next, participants prioritized their selected desired information from most to least important using pre-printed notecards with likely response categories. During the individual vehicle discussion, the researcher taking notes pulled out the appropriate notecard as the participant responded. For instance, if the participant responded, “I’d want to know what lane the wrong way driver was in," the note taker pulled out the "lane information" pre-printed card. If the participant said something that the research team had not anticipated, the note taker created a new notecard.

Finally, the researcher ended the interview with several questions that compared the use of in-vehicle alerts to DMS messages (i.e., roadside signs) during a WWD event:

- Which type of device do you have more confidence in: roadside signs or in-vehicle alerts?
- What advantages do you see for in-vehicle alerts versus roadside signs to convey wrong-way driver alerts?
- What disadvantages do you see for in-vehicle alerts versus roadside signs to convey wrong-way driver alerts?
- What if the roadside signs and the in-vehicle alert had different content?
    - For example, what if you receive an in-vehicle alert about a wrong-way driver but the roadside sign is blank? How would that affect your confidence in the in-vehicle alert system?
    - What if you see a wrong-way driver message on a roadside sign but do not receive an in-vehicle alert? How would that affect your confidence in the in-vehicle alert system?
    - What if you personally witness a wrong-way driver but never got an in-vehicle alert? How would that affect your confidence in the in-vehicle alert system?

Results

During the one-on-one discussions, several different types of situations were addressed. In addition, participants frequently discussed more than one vehicle or information need at a time. Therefore, the researchers grouped the results somewhat differently than the previously discussed guide. The results are divided into the following five sections:

- Vehicle locations identified as needing WWD alert information.
- Specific information needed based on vehicle location.
- Follow-up discussion about in-vehicle alerts.
- Most critical information needs.
- In-vehicle versus DMS alerts.

Vehicle Locations Needing WWD Alerts

Figure 17 shows the percent of participants that wanted information regarding the WWD event for each vehicle location. A majority of the participants (94 percent or higher) indicated they would like to receive in-vehicle information about the WWD event for Vehicles A, B, D, and G. For Vehicles B and D, all of the participants felt there would be an adequate amount of time for them to receive a warning and perhaps advice about what driving action they should take. In contrast, a small percentage of participants (6 percent) thought that an in-vehicle alert for Vehicle A was not relevant since the driver of Vehicle A could see the wrong-way vehicle and needed to focus on the driving action needed to avoid a collision. Participants thought Vehicle G should receive an in-vehicle alert in case the driver was planning to turn onto the frontage road and enter the freeway. In addition, participants noted the possibility of the wrong-way driver exiting the freeway and driving the wrong way on the frontage road.

Although a researcher had informed the participants that Vehicle C was exiting the freeway and would not re-enter the freeway, 60 percent of participants thought this vehicle should receive an in-vehicle alert about the WWD event. Researchers believe that participants understood that the system would not know where each vehicle was heading, so in reality Vehicle C could possibly re-enter the freeway.

For Vehicles E and F, the desire for in-vehicle information regarding the WWD event varied based on whether or not a median barrier (i.e., physical obstacle between opposing lanes of travel) was present. When researchers indicated that a median barrier was present, only 52 and 37 percent wanted in-vehicle information about the WWD event for Vehicles E and F, respectively. Most participants thought that the vehicles on the opposite side of the road did not need information about an event that would not directly affect them. However, some participants felt that looking over into the opposite lane and seeing someone traveling in their direction would startle them and make them question whether they themselves were going in the right direction. When the researcher asked participants if they would change their answers if a median barrier was not present, those wanting in-vehicle information about the WWD event increased to 86 and 60 percent for Vehicles E and F, respectively. Most participants thought that this scenario would increase the possibility of the wrong-way driver crossing onto their side of the freeway.

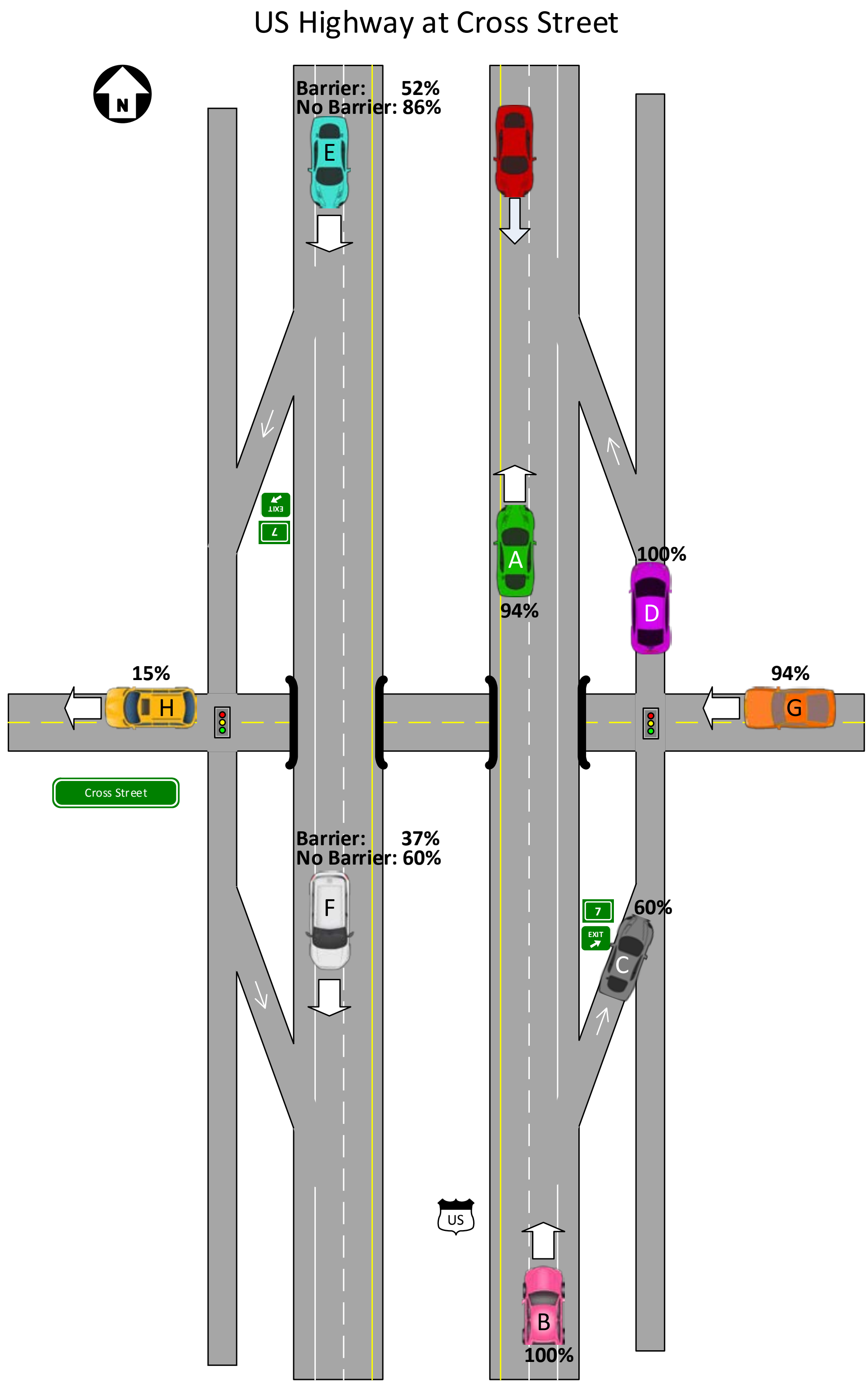


Figure 17. Percent of Participants That Wanted Information per Vehicle Location.

Only 15 percent of participants felt that Vehicle H needed in-vehicle information about the WWD event. Most participants thought the alert would not be applicable to Vehicle H since this driver was traveling away from the area impacted by the WWD event.

Specific Information Needed

In this section of the results, researchers identified the type of information participants felt they needed based on each vehicle location. Researchers combined the participants' initial open-ended responses with those received when the researcher asked more pointed follow-up questions. Table 5 contains a summary of the information desired by vehicle location.

Figure 18 shows the types of information participants wanted the in-vehicle alerts in Vehicles A and B to contain. Participants preferred information about the urgency (88 percent) and problem (83 percent) for Vehicle A. Most participants felt Vehicle A was too close to the wrong-way vehicle and thus would not have much time to receive and process a lot information.

Since Vehicle B was further upstream, participants thought that the driver of Vehicle B had more time to receive and process information. Therefore, participants preferred information about the problem (92 to 97 percent), action (88 to 92 percent), and urgency (83 to 85 percent). In addition, 77 to 82 percent of participants desired information about the location of the wrong-way vehicle. These findings reveal little difference in responses based upon whether or not Vehicle B could exit.

Table 5. Summary of Information Wanted.

Vehicle/Location	Urgency	Problem	Location	Lanes Affected	Action	Validation	Speed of WWV	Details of WWV	Reaction Time	Warn Others
Vehicle A—same side; in immediate vicinity	88%	83%	68%	46%	46%	48%	20%	9%	0%	2%
Vehicle B—same side; further upstream; can exit	85%	97%	82%	37%	92%	48%	18%	9%	3%	3%
Vehicle B—same side; further upstream; cannot exit	83%	92%	77%	38%	88%	46%	20%	9%	3%	3%
Vehicle C—just exited freeway; further upstream	43%	65%	62%	14%	40%	35%	6%	5%	0%	0%
Vehicle D—about to enter freeway upstream	91%	95%	85%	35%	97%	49%	14%	6%	0%	2%
Vehicle E—opposite side of freeway; in immediate vicinity; concrete median barrier	38%	57%	48%	5%	32%	28%	3%	2%	0%	2%
Vehicle E—opposite side of freeway; in immediate vicinity; grass median	65%	91%	77%	11%	57%	45%	14%	6%	0%	2%
Vehicle F—opposite side of freeway; downstream; concrete median barrier	29%	38%	35%	5%	23%	18%	2%	2%	0%	2%
Vehicle F—opposite side of freeway; downstream; grass median	46%	63%	57%	9%	35%	28%	8%	5%	0%	2%
Vehicle G—on cross street entering intersection	74%	92%	85%	28%	77%	48%	11%	6%	2%	0%
Vehicle H—on cross street leaving intersection	11%	15%	12%	2%	3%	9%	0%	0%	0%	0%

Note: WWV = wrong-way vehicle.

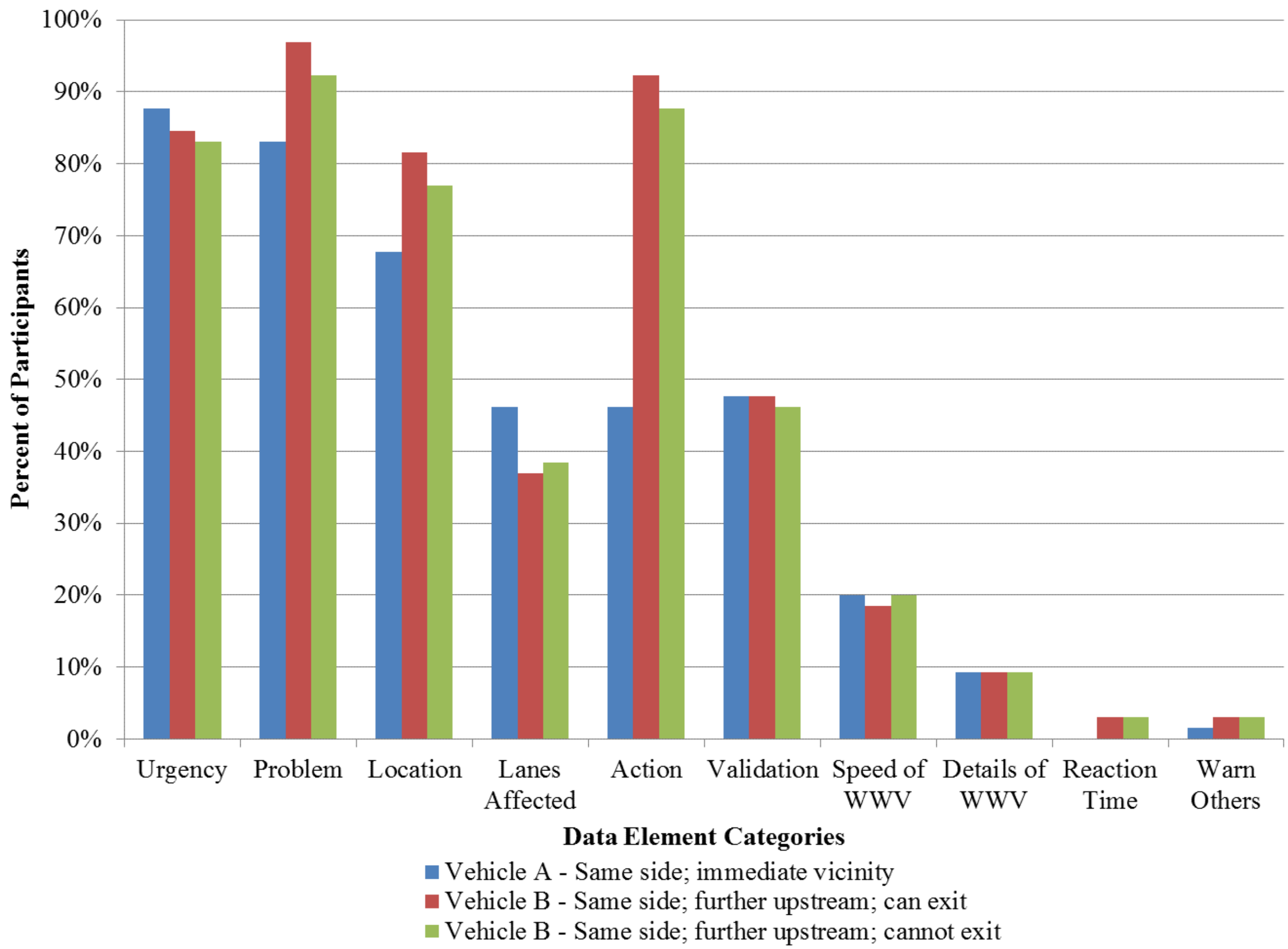


Figure 18. Information Wanted for Vehicles A and B.

Figure 19 illustrates the types of information wanted for vehicles C, D, G, and H. Since Vehicle D was about to enter the freeway in the vicinity of the wrong-way vehicle, participants wanted the in-vehicle alert to contain information about the action (97 percent), problem (95 percent), and urgency (91 percent). In addition, 85 percent of participants wanted information about the location of the wrong-way vehicle. Essentially, the information desired for Vehicle D was comparable to that for Vehicle B.

Similar to Vehicle D, Vehicle G was approaching the area affected by the WWD event. Participants thought the driver of Vehicle G would need information about the problem (92 percent) and its location (85 percent) in order to make an informed decision as he or she approached the intersection. Slightly fewer participants thought action information was needed (77 percent).

In contrast to Vehicle D, Vehicle C was exiting the freeway and continuing on the cross street. Even so, most participants wanted an in-vehicle alert to notify the driver of the problem (65 percent) and its location (62 percent). Again, researchers believe participants were considering the possibility that the driver of Vehicle C might want to re-enter the freeway.

As indicated previously, only a few participants thought an in-vehicle alert should be sent to Vehicle H, which was on the cross street and leaving the impacted area. These few participants mainly wanted to know about the problem (15 percent).

Vehicle E and F were both located on the opposite side of the freeway from the wrong-way vehicle. Figure 20 shows that more participants felt they should be warned of the problem when the vehicle was located near the wrong-way driver (Vehicle E) and when there was not a physical barrier separating opposing travel lanes (i.e., grass median).

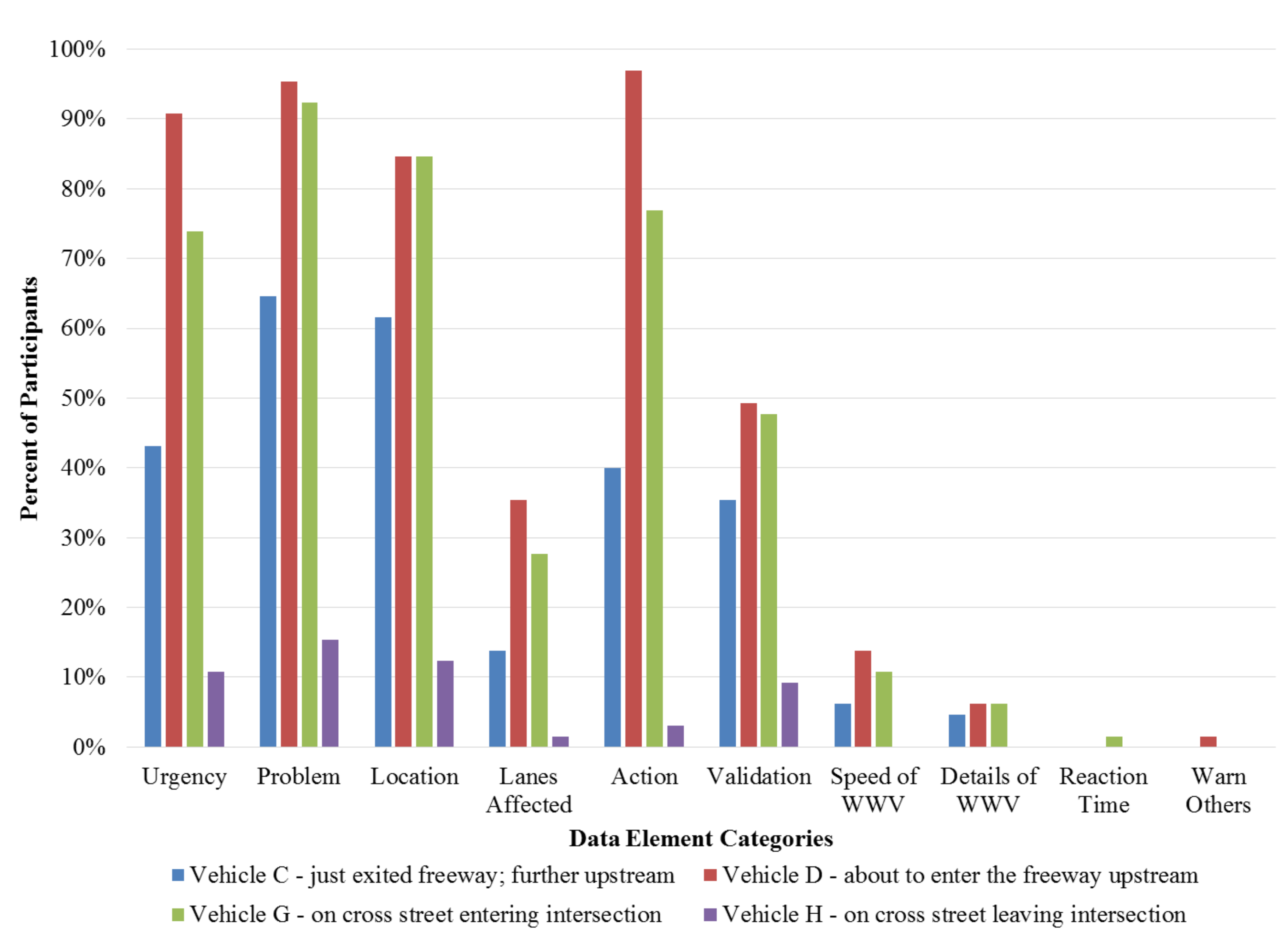


Figure 19. Information Wanted for Vehicles C, D, G, and H.

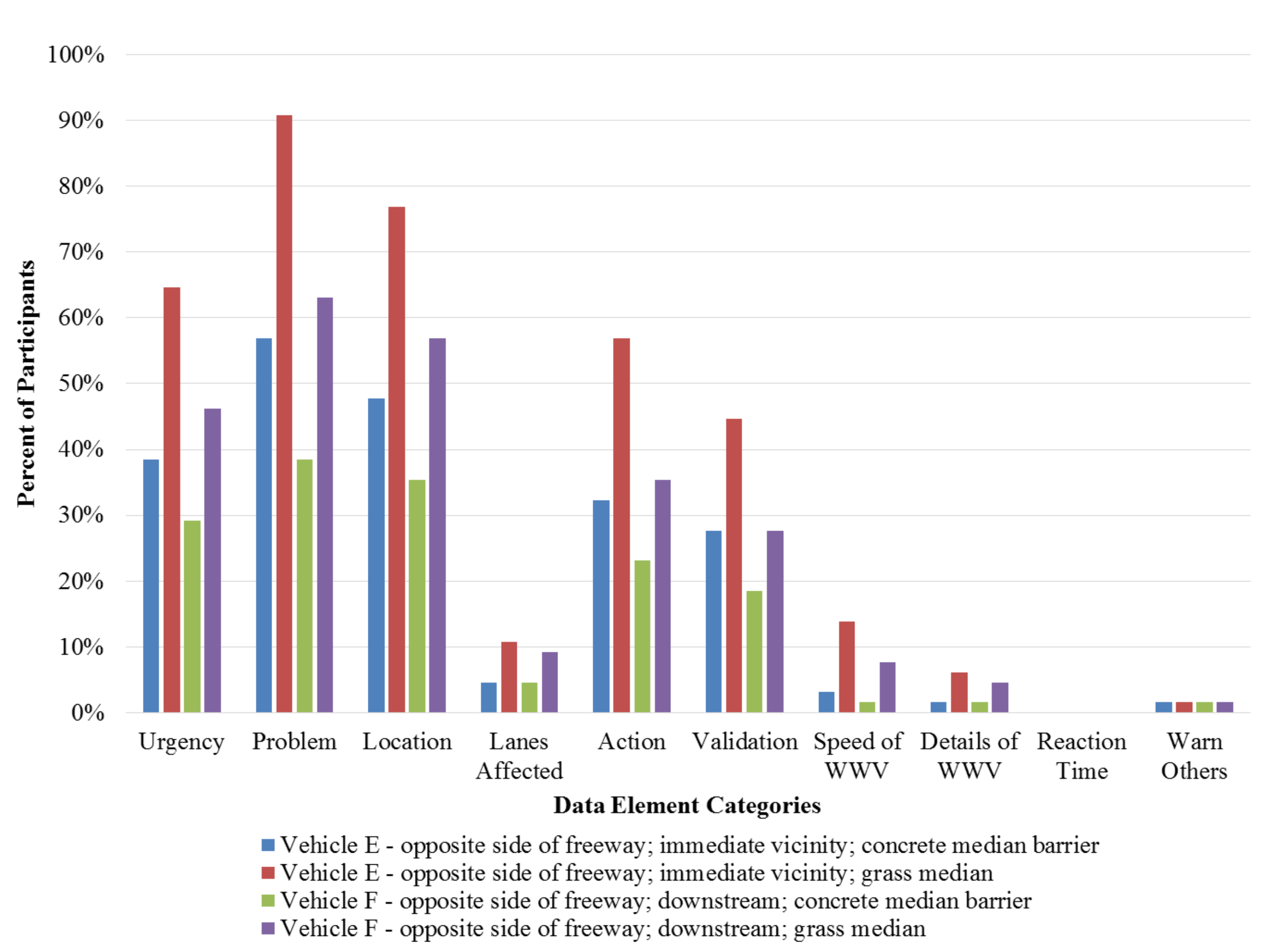


Figure 20. Information Wanted for Vehicles E and F.

Overall, participants felt that the urgency of the situation needed to be conveyed to the vehicles on the same side of the freeway and in the immediate vicinity of the wrong-way driver (Vehicles A, B, and D). More than 90 percent of participants thought the in-vehicle alert should contain information about the problem when a right-way driver was on the same side of the freeway approaching the wrong-way driver (Vehicle B) or could possibly enter the freeway and encounter the wrong-way driver (Vehicles D and G). In addition, participants thought these three vehicles would benefit from receiving information about the proper action, especially if exiting the freeway or not entering the freeway was an option, and about the location of the wrong-way vehicle. Since Vehicle A was on the same side of the road and could see the wrong-way driver, fewer participants thought the driver of Vehicle A needed these additional pieces of information.

For all of the right-way vehicle locations studied, less than half of the participants wanted information about the lanes affected or some element to validate the message. With respect to the lanes affected, participants commented that this could include the lane in which the wrong-way driver was traveling or the lane in which the right-way driver should travel. Participants noted that conveying information about specific lanes might be difficult (e.g., left, right, or middle) and that the wrong-way driver could change lanes.

Follow-Up Discussion

While most participants indicated they would like to receive in-vehicle alerts about a WWD event, there was not a clear consensus about when they would want to start receiving this information. Figure 21 illustrates the distribution of responses. Most participants found it hard to quantify when they would want to start receiving alerts, resulting in a variety of answers. Thus, researchers grouped the responses into three categories: 2 miles or less, 3 to 6 miles, and 10 miles or more. The majority of participants (65 percent) wanted to receive information within 2 miles or less of the wrong-way vehicle.

During the discussion about the in-vehicle alert needing a component that indicated the urgency of the situation, many participants noted the need for some type of audible sound (e.g., beep or tone) and/or visual alert (e.g., flashing light) to get the right-way driver’s attention. However, participants did indicate that the alert system itself should not startle the right-way driver in such a manner that it could lead to an erratic maneuver.

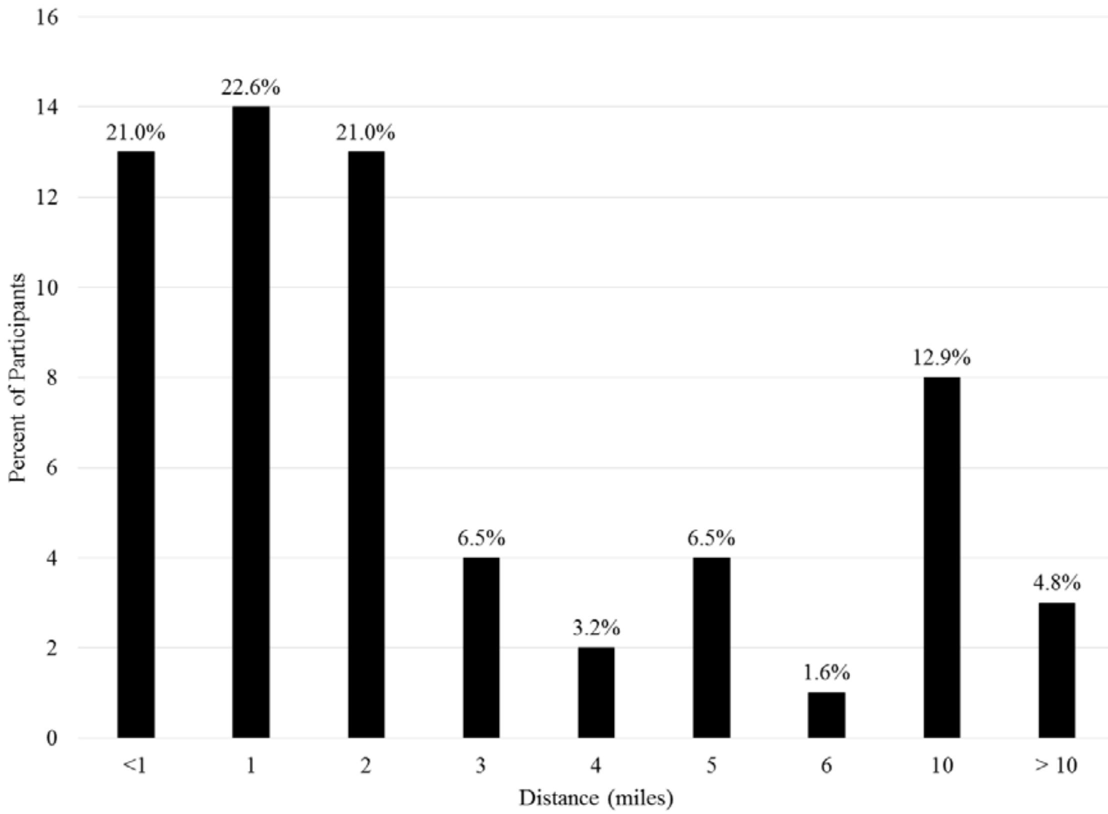


Figure 21. Distance at Which Participants Wanted to Start Receiving In-Vehicle Alerts (n=62).

Most participants (77 percent) felt that the in-vehicle alerts should become more frequent as they got closer to the wrong-way vehicle in order to get the right-way driver's attention and to inform them of the severity of the situation. One participant suggested color coding: red flashing would mean immediate danger, and yellow or orange would indicate hazard ahead or maybe to take an alternative route. Several participants mentioned that they would want the in-vehicle alerts to stop once they were no longer in the area impacted by the WWD event.

Of the participants that wanted the in-vehicle alert to contain information about the location of the wrong-way vehicle (n=57), 61 percent preferred the location be expressed as a distance (e.g., 2 miles ahead), and 25 percent preferred the location information be presented as a time (e.g., 5 minutes ahead). Both sides noted the difficulty with providing a distance or time since the speed of the wrong-way vehicle and the right-way vehicle could vary. The remaining responses included both time and distance, the specific location (e.g., cross street), and the specific lane the wrong-way vehicle was traveling in (e.g., left lane).

The majority of participants (77 percent) felt that the in-vehicle alert would be trusted as long as they knew it was from TxDOT or some other official agency. Other participants (11 percent) indicated that they would need to learn more about the system or have positive experiences with the system before they would completely trust it. A few participants (5 percent) wanted the time the wrong-way driver was reported to be shown or said as part of the in-vehicle alert. Eight percent of participants stated they would just trust the in-vehicle alert.

If the participants were to receive an in-vehicle wrong-way driver alert in their vehicle, 80 percent would assume that the police had been notified. However, 35 percent of these participants felt the police might not be responding yet. Similarly, the majority of the participants (88 percent) expected to receive an in-vehicle alert as soon as the WWD event was detected or reported by authorities.

Participants had a more difficult time trying to decide how long they would assume an in-vehicle alert was valid. Thirty-nine percent indicated they would assume the in-vehicle alert was valid until an all-clear message was received. Another 8 percent felt the message would be valid until they passed the wrong-way vehicle or drove out of the area affected by the WWD event (although how they would know that was not defined). Forty-eight percent of participants provided a time period for which the message would be valid. This time period ranged from 30 seconds to 1 hour, with 31 percent being 5 to 10 minutes.

When directly asked if an all-clear message should be broadcast, 89 percent of the participants responded yes. The remaining 11 percent did not want an all-clear message because they felt it was better to keep drivers overly cautious and it might cause a liability issue if an all-clear message was broadcast and the wrong-way driver was still in the area.

Most Critical Information Needs

Table 6 contains the percent of participants that ranked each type of information as number 1 (top choice), number 2 (second choice), or number 3 (third choice) and in total (one, two, and three rankings). The urgency and problem were ranked in the top three information needs by 82 percent of participants. Additionally, the location and action were ranked in the top three by 66 percent and 26 percent of participants, respectively. Participants did express liability concerns over the in-vehicle alert containing action information. These findings are similar to those found for wrong-way driver warning messages on DMSs (*1, 2*).

Table 6. Percent Responses for Most Importation Information Needs.

Ranking	Urgency	Problem	Location	Lanes Affected	Action	Validation	Speed of WWV	Details of WWV
1	52	25	5	0	5	9	0	2
2	20	40	23	2	8	5	0	2
3	9	17	38	15	14	2	2	0
Total	82	82	66	17	26	15	2	3

Note: WWV = wrong-way vehicle.

In-Vehicle Alerts versus DMS Messages

At the end of the discussion, researchers wanted to gauge motorists' trust or lack thereof with in-vehicle alert systems for the following situations:

- The driver received an in-vehicle alert about a WWD event, but the DMS was blank.
- The DMS displayed a WWD warning message, but the driver did not receive an in-vehicle alert.
- The driver personally witnessed a wrong-way driver but did not receive an in-vehicle alert.

Researchers also asked participants to identify advantages and disadvantages of in-vehicle alerts and warning messages posted on DMSs.

A majority of participants (94 percent) stated that they would trust and have confidence in the in-vehicle alert system even if there was no warning message posted on a DMS. One-quarter of these participants felt the DMS had not been programmed yet or was malfunctioning. When the scenario was reversed (i.e., warning message on the DMS but not an in-vehicle alert) only 38 percent stated that it would decrease their confidence in the in-vehicle alert system. In addition, 94 percent of participants indicated that they would trust the warning message on the DMS. In contrast, the percentage of participants whose confidence in the system would diminish almost doubled (68 percent) when they personally witnessed a wrong-way driver but did not receive an in-vehicle alert.

Overall, the majority of the participants (83 percent) stated that they had more confidence in the in-vehicle alert than a warning message posted on a DMS. Reasons included:

- Drivers might miss a message posted on a DMS.
- There may not be a DMS located in the affected area.

- DMSs are not reliable.
- Some people do not pay attention to DMSs.

Only 9 percent of participants had more confidence in the DMS. These participants were more skeptical of the in-vehicle technology. The remaining 8 percent of participants had equal confidence in both devices.

Table 7 contains the advantages and disadvantages identified by participants for in-vehicle systems used to convey WWD alerts. Advantages included that an in-vehicle system could:

- Get the driver's attention better.
- Was a faster way to warn right-way drivers.
- Could customize the message for each driver in the area.

The disadvantages consisted of:

- Device malfunction.
- The possibility of startling or frightening the driver.
- Annoying alerts (which could lead to drivers ignoring them).
- Drivers not hearing/recognizing the alert.

Table 7. Advantages and Disadvantages of an In-Vehicle System Used to Convey a WWD Alert.

Advantages	Percent	Disadvantages	Percent
Attention getter	31	None	28
Fast warning	28	Device malfunction	19
Could save a life	22	Startle or frighten driver	15
Individualized alerts	14	Annoying/distracting	15
Faster warning and attention	3	Do not hear/recognize alert	11
Everyone knows	1	Big brother	3
None	1	Too expensive	3
Total	100	Other	6
		Total	100

Table 8 contains the advantages and disadvantages identified by participants for DMSs used to convey warning messages about wrong-way drivers. Advantages included that:

- A DMS could offer extra warning.
- A DMS could warn all motorists.
- Drivers are familiar with DMSs.

Disadvantages included that:

- Drivers do not or cannot read messages on DMSs.
- DMSs are not located on all roadways (i.e., cover a limited area).

Table 8. Advantages and Disadvantages of a DMS Used to Convey a WWD Alert.

Advantages	Percent	Disadvantages	Percent
An extra warning	42	Do not or cannot read sign	55
Warns everyone	15	No DMS in area	14
Familiar with them	11	None	11
Easier to read	9	Signs obsolete	9
Better for deaf/motorcycles	6	Malfunction	6
None	6	Other	5
Validation	5	Total	100
Other	6		
Total	100		

Summary, Conclusions, and Implications for Survey

Researchers conducted individual structured interviews with 65 drivers from the Dallas/Fort Worth, Houston, and San Antonio areas to examine the timing and information content of WWD alerts received in the vehicle through a CV system. The questions in these interviews used illustrations of vehicles in various positions relative to a wrong-way vehicle.

The majority of participants wanted to receive in-vehicle WWD event alerts if they were:

- On the same side of the freeway and upstream of the wrong-way driver.
- On a ramp or frontage road on the same side of the freeway as the wrong-way driver.
- On a cross street approaching the area impacted by the wrong-way driver.
- On the opposite side of the freeway from the wrong-way driver and there was not a physical barrier between the opposing travel directions.

More than 80 percent of participants wanted the in-vehicle alert to contain information about the problem and its urgency. With respect to urgency, participants noted the need for an audible sound or visual alert to get the right-way driver's attention. Participants also wanted the frequency of the alert to increase as they got closer to the wrong-way vehicle. About two-thirds of the participants wanted information about the location of the wrong-way vehicle. However, there was not a clear response about the participants' preference of distance (e.g., 2 miles ahead) or time (e.g., 5 minutes ahead). Only one-quarter of the participants indicated the need for action information (e.g., exit the freeway). Very few participants wanted to receive information about the lanes affected, validation, or details about the wrong-way vehicle (e.g., description and speed). Participants noted that the lanes affected could include the lane in which the wrong-way driver was traveling or the lane in which the right-way driver should travel. In addition, participants noted that conveying information about specific lanes might be difficult (e.g., left, right, or middle).

The majority of the participants expected to receive an in-vehicle alert as soon as the WWD event was detected or reported by authorities. However, there was not consensus about the distance away from the wrong-way driver they would want to start receiving in-vehicle alerts. Once the WWD event is over, the majority of participants agreed that an all-clear message should be broadcast. Otherwise, the participants were unsure how long the in-vehicle alert would be valid.

Most participants stated that they would trust the in-vehicle alert if they knew it was coming from TxDOT or some other official agency. However, it was uncertain how the use of a time stamp might impact trust in the accuracy of the message. Interestingly, participants indicated that their confidence in the in-vehicle system would not be impacted if a WWD alert was posted on a DMS but not received in their vehicle. In contrast, confidence in the in-vehicle system would be decreased if the participants personally witnessed a wrong-way driver but did not receive an in-vehicle alert.

Based on the structured interview findings, researchers identified the following areas that needed additional investigation:

- Preference of time or distance units of measure for wrong-way vehicle location.
- Whether or not a time stamp would increase trust in the accuracy of the message.
- Understanding of lane references with respect to a recommended action versus location of the wrong-way vehicle.

- The impact the median type (barrier versus grass) has on information needs.
- Whether or not an all-clear message should be broadcast.

TABLET-BASED SURVEY

Researchers designed the survey based on the structured interview results and the desire to evaluate motorist comprehension of potential wording that could be used to generate in-vehicle alerts about approaching wrong-way vehicles. Researchers wanted to limit the content of the in-vehicle messages to wording that could be supported by the industry standards for CV RSA messages. The CV RSA message set is described in the Phase I report (*1*). A section of that report is repeated here to provide context for the messages evaluated in the survey.

Roadside Alert Messages

RSA messages are used to send alerts about nearby hazards to travelers. Typically, these messages are used to provide simple alerts to travelers, through both in-vehicle display devices and portable devices. Generally, these messages are intended to provide warning and alert information about roadway hazards that might affect travel, and not vehicle-to-vehicle (V2V) communications, mayday, or other safety applications. Typical example messages would be BRIDGE ICING AHEAD, TRAIN COMING, or AMBULANCE OPERATING IN THE AREA. A full range of typical phrases is supported, but messages dealing with mobile hazards, construction zones, and roadside events are the ones that are most frequently expected to be found in use.

Generally, RSA messages are generated by a traffic management entity either at a TMC or by a roadside infrastructure device. In generating an RSA, it is presumed that each receiving device can determine its own position and heading and can determine whether or not the message is applicable to itself, but this is not a requirement to receive or understand these messages. It is also not a requirement of the vehicle (or device) to have any knowledge of the roadway itself to understand and use the message. The typical RSA message contains the following types of information:

- Event type—an integer code that is equal to a specific type of alert, danger, or hazard identified. This data element is a mandatory component of an RSA message.

- Description—a sequence of up to eight additional ITS codes that can be used to further describe the event, give advice to drivers, or recommend a course of action to drivers in response to the event. This data element is a mandatory component of an RSA message.
- Priority—an optional field in the RSA message that is used to describe the urgency of the message, in relative degree of merit compared to other similar messages of this type.
- Heading—an optional field in the RSA message that is intended to provide the heading and direction of travel for which the message is applicable.
- Extent—an optional field in the RSA message that is intended to provide the spatial distance over which the message application should be presented to the driver.
- Position—an optional field in the RSA message that is intended to provide information about the position, heading, rate of speed, etc., of the event in question. This field can also be used to describe the position information for stationary and wide-area events.

RSA messages have a rigid content, and the standard does not allow free-form text to be used. The RSA messages draw from existing automotive standards for message wording for navigation systems called the International Traveler Information Systems (ITIS) SAE Standard J2540.2 (*8*). The basic message types themselves are represented by a standard code sent only in their integer representation formats, and each integer has as specific message (e.g., ITIS Code 513 is ACCIDENT, and ITIS Code 8452 is FOLLOW DETOUR SIGNS). SAE J2540.2 contains a complete list of codes that are currently being used to generate an RSA. To promote inoperability, this list of codes is national in scope and does not allow local additions.

Table 9 shows the ITIS phrases that researchers used to generate in-vehicle messages for the survey. Previous research about wrong-way driver warning messages for DMSs (*1*, *2*) recommended the message shown in Figure 3 based on focus group and motorist survey findings. Therefore, researchers wanted to use WRONG WAY DRIVER in the in-vehicle messages. While WRONG WAY and VEHICLE TRAVELING WRONG WAY are found in SAE J2540.2, DRIVER is not. Researchers believe that the WRONG WAY and VEHICLE TRAVELING WRONG WAY messages are to warn a driver that he or she is going the wrong way. However, there is also a need to warn right-way drivers about a wrong-way driver via in-vehicle alerts. Thus, researchers decided to study the wording WRONG WAY DRIVER even though DRIVER is not currently in SAE J2540.2.

Table 9. ITIS Phrases That Can Be Used to Generate RSA Messages about a WWD Event.

Message Element	Information Content	ITIS Phrase Code
Problem	VEHICLE TRAVELING WRONG WAY WRONG WAY	1793 12310
Location	[n] MINUTES AHEAD [n] MILE[S] AHEAD EXIT [n]	[12545–12644], 8728, 13569 [12545–12644], 8711[8712], 13569 11794, [12545–12644]
Lanes affected	IN LEFT LANE	7683, 8195
Action	DRIVE WITH EXTREME CAUTION DO NOT ENTER FREEWAY USE RIGHT LANE USE NEXT EXIT	7170 12314, 11778 7427 7716, 13582, 11794
Validation	REPORTED REPORTED AT 1:38 PM	7711 7711, 7687, 7735, <time>, 8724

Survey Elements

Researchers created two versions of the survey in order to evaluate different messages for similar situations. Each survey contained the same eight questions and answer choices. However, the messages shown for Questions 1, 5, and 7 differed between the two surveys. The following eight topics were covered in both surveys:

1. *Comprehension of wording that can be used to indicate there is a wrong-way driver in the area.* Survey 1 used the wording VEHICLE TRAVELING WRONG WAY/USE NEXT EXIT, and Survey 2 used WRONG WAY DRIVER/USE NEXT EXIT. The question and answers allowed researchers to determine whether the participant thought he or she was driving the wrong way or another vehicle was driving the wrong way.
2. *Preference between the use of time or distance as an indication of the wrong-way vehicle's location.* The participant was shown two alerts simultaneously, one stating WRONG WAY DRIVER/3 MINUTES AHEAD and the other stating WRONG WAY DRIVER/3 MILES AHEAD. The question asked which wording best warned that there was a wrong-way driver in the area (i.e., minutes or miles).

3. *Comprehension of the use of exit numbers as an indication of the wrong-way vehicle's location.* The in-vehicle alert contained the following message: WRONG WAY DRIVER/EXIT 368/DRIVE WITH EXTREME CAUTION. The question and answers allowed researchers to determine whether the participant thought the wrong-way driver was near that exit or whether he or she, the right-way driver, was supposed to use that exit to avoid the wrong-way driver.
4. *Impact on the trust in the accuracy of the message if a time stamp and/or the word REPORTED is used.* The in-vehicle alert contained the following message: WRONG WAY DRIVER/3 MILES AHEAD/REPORTED AT 1:38 PM. The participant was told that he or she received this message at 1:42 p.m. The question and answers permitted researchers to determine how the following aspects of the message impacted the participant's level of trust in the message: the use of a specific time, the use of the word REPORTED, and the time difference between when the event was reported and received. For this question only, the participant could choose multiple answers.
5. *Comprehension of wording that can be used to indicate the lane the wrong-way driver is traveling in versus the lane the right-way driver should travel in to avoid the wrong-way driver.* This question examined the difference in wording between a recommended action (USE RIGHT LANE) (Survey 2) and a statement describing the wrong-way vehicle location (IN LEFT LANE) (Survey 1).
6. *Comprehension of wording that can be used to tell a driver on the frontage road not to enter the freeway*. The image associated with the question showed a driver's viewpoint of a freeway entrance ramp from a frontage road along with an in-vehicle message stating WRONG WAY DRIVER/REPORTED/DO NOT ENTER FREEWAY. The question asked whether or not the participant would enter the freeway.
7. *Need for an in-vehicle alert on a divided freeway with a grass median versus a concrete median barrier when the right-way driver is traveling on the opposite side of the freeway.* Two image versions were associated with this question. Survey 1 showed a divided freeway with a grass median, and Survey 2 showed a divided freeway with a concrete median barrier. The question asked whether the in-vehicle

system should send a warning about a wrong-way driver on the other side of the freeway.

8. *Need for an all-clear in-vehicle message once the WWD event has been canceled or resolved.* This question asked whether the participant wanted to know that the WWD event was resolved after having received in-vehicle messages concerning the event for the previous 10 minutes.

Study Methods

Locations

Researchers conducted a pilot of the survey in the Bryan/College Station Department of Public Safety (DPS) office with 10 participants. This pilot effort allowed researchers to test the survey procedures, software, and questions. Researchers then conducted the surveys at DPS offices in Garland (Dallas/Fort Worth area), Spring (Houston area), and San Antonio.

Participants

Researchers recruited 361 individuals (approximately 120 in each area) that were over 18 years of age, had a valid driver's license, and could read and speak English. A total of 179 individuals completed Survey 1, and 182 completed Survey 2. Table 10 shows the demographics for the sample survey and for Texas licensed drivers. Researchers believe the survey sample represents Texas drivers reasonably well.

Table 10. Demographics of Study Sample and of Texas Drivers.

Sample	Male (50%)			Female (50%)			Total
	18–39	40–54	55+	18–39	40–54	55+	
Study sample (n=361)	17%	17%	16%	17%	17%	16%	100%
Texas data (*7*)	19%	14%	15%	20%	14%	16%	98%[a]

[a] 2 percent were licensed drivers under the age of 18.

Study Procedure

This activity was considered human subjects research by the Texas A&M Office of Human Subject Protection. For this reason, all participant recruiting materials and survey questions were reviewed and approved by the Texas A&M IRB before conducting the surveys. This review included assurances that participants and their responses would be anonymous.

Researchers approached individuals and ask them if they would like to participate in a short survey. Researchers explained that participation was on a volunteer basis only. If an individual was willing to complete the survey, researchers first ensured they met the participation criteria. A researcher then told the participants that the survey questions dealt with future technology that might appear in their vehicle to warn them of roadway hazards. Researchers asked participants to assume that these systems would speak the warning to them, as well as show it as a written message on a screen on their dashboard. A researcher then showed the participants the tablet they would be using during the survey (Figure 22) and an example of the message on a dashboard screen (Figure 23). The researcher explained that the speaker icon shown on the dashboard was to reinforce the idea that the message could also be coming through the vehicle's speakers as an audio message.

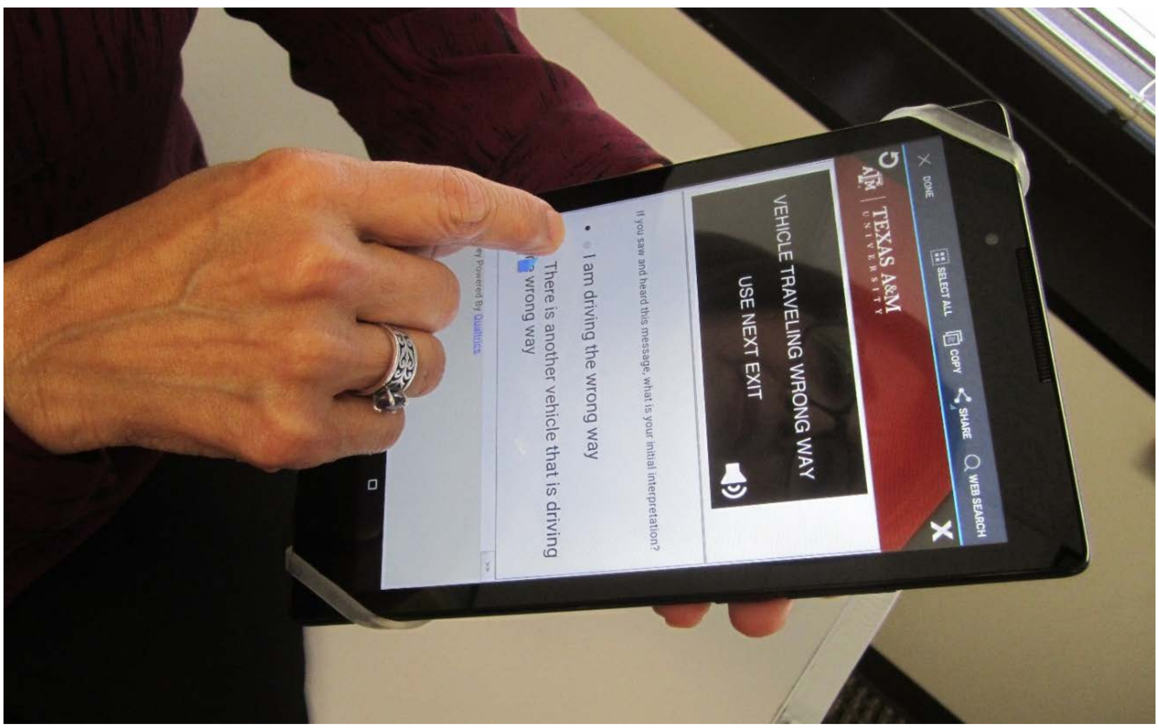


Figure 22. Tablet Used for the Survey.

Figure 23. Illustration Shown to Survey Participants to Describe the In-Vehicle Message.

It was not necessary for someone to know how to use a tablet to participate in this survey. To answer a question, the participant had to touch the button next to the answer. To advance to the next screen, the participant had to press NEXT QUESTION, which was located on the bottom right of the screen. Before starting the survey, participants were allowed to ask questions. A researcher stood close by the participant to monitor progress and answer any questions that arose during the survey. Each survey took between 5 and 10 minutes to complete.

Results

A message was considered acceptable for use when 85 percent of the total survey participants correctly interpreted the meaning (*9*). When the comprehension level was less than 85 percent, researchers used a confidence interval test with a 5 percent significance level (alpha=0.05) to determine if the comprehension percentage was statistically different from the 85 percent criterion. If 0.85 fell within the boundaries of the confidence interval, then the level of comprehension for the tested message was not statistically different from 85 percent.

Comprehension of Wording Used to Indicate a Wrong-Way Driver

The first survey question addressed motorist comprehension of two possible wordings that could be used to convey the problem (i.e., VEHICLE TRAVELING WRONG WAY and WRONG WAY DRIVER). Researchers wanted to determine if participants understood that the alert was about a wrong-way driver in the area and not that they themselves were driving in the wrong direction. For this question, half of the participants saw the message in Survey 1, and the other half saw the message in Survey 2 (Figure 24). The survey stated, "If you saw and heard this message, what is your initial interpretation?" The participants could select either "I am driving the wrong way" or "there is another vehicle that is driving the wrong way."

a) Survey 1 Message. **b) Survey 2 Message.**

Figure 24. Two Messages Shown for Question 1.

For Survey 1, only 56 percent of the participants felt that VEHICLE TRAVELING WRONG WAY indicated that another vehicle was traveling the wrong way. Similarly, only 54 percent understood that WRONG WAY DRIVER was about another vehicle. Researchers think this response could be a result of drivers believing that messages received in their vehicle, versus on a DMS, are directed at their behavior. Perhaps adding the word AHEAD or REPORTED to these messages would convey that the message is talking about some other vehicle. Further research is needed to identify wording that can be used by in-vehicle systems to convey that a wrong-way driver is in the vicinity.

Preference between Time and Distance References for Wrong-Way Vehicle Location

Researchers asked the next question to determine motorists' preference for using time (minutes) or distance (miles) to convey how far away the wrong-way driver was from the right-way driver. Figure 25 shows the two messages that were shown simultaneously on the screen in both surveys. While viewing these messages, participants were asked, "Which of these messages best warns you that there is a wrong-way driver in the area?" As with the structured interview findings, there was no clear consensus on preference. Nearly half of the participants (48 percent) preferred 3 MINUTES AHEAD, and slightly more than half of the participants (52 percent) favored 3 MILES AHEAD. While it would be possible in a CV system to calculate the time between the right-way and wrong-way vehicle, it may be preferable to use mileage since it corresponds with other directives, such as exit numbers and the distance to destinations and construction activities.

Figure 25. Simultaneous Messages Shown for Question 2.

Comprehension of Exit Numbers as Reference for Wrong-Way Vehicle Location

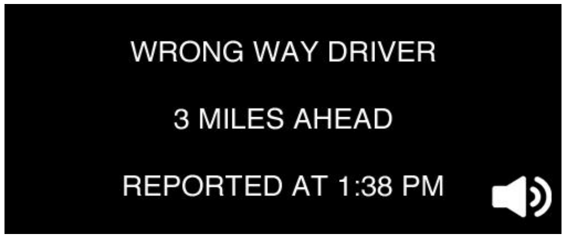
The purpose of the third question and associated image (Figure 26) in both surveys was to determine if motorists understood the use of an exit number by itself as the last reported location of the wrong-way vehicle. The survey asked, "If you saw and heard this message, what is your interpretation?" The participants could select either "I should exit the freeway at Exit Number 368" or "the wrong-way driver was last reported to be near Exit Number 368." Just over half of the participants (52 percent) indicated that the exit number was the last reported location of the wrong-way vehicle. The remaining participants (48 percent) thought they should exit the freeway at Exit Number 368. Prompt words, such as AT, NEAR, or USE, may help motorists distinguish between the location of the wrong-way vehicle and a suggested driving action. However, further studies would be needed to verify this hypothesis.

Figure 26. Message Shown for Question 3.

Time Stamp and REPORTED Impact on Trust in the Accuracy of the Message

Previous research on the design of wrong-way driver warning messages for DMSs (*2*) found that motorists placed a low priority on validation information, such as a time stamp. While participants thought a time stamp could be beneficial, they also acknowledged that a difference between the warning time (e.g., 2:00 a.m.) and the current time (e.g., 2:15 a.m.) could cause some drivers to be less cautious, thinking that the wrong-way driver was gone and there was no longer any danger. Instead of a time stamp, researchers recommended that REPORTED be used to convey that the DMS message regarded an active event, not just a general traffic safety message.

During the structured interviews, 77 percent of participants felt that the in-vehicle alert could be trusted as long as they knew the information was from TxDOT or some other official agency. However, a small percentage of participants wanted the time the wrong-way driver was reported to be included in the in-vehicle alert. To further investigate the need for a time stamp and/or the word REPORTED for in-vehicle alerts, researchers showed participants the image, scenario, and question in Figure 27 in both surveys.



"Imagine you received this message on your vehicle's screen at 1:42 p.m. The message includes information about the time the wrong way driver was reported. How does this information about the time affect your trust in the accuracy of the message? (choose all that apply)

a. Increases my trust because it is a specific time.
b. Increases my trust because it says "reported."
c. Decreases my trust because it is 4 minutes old.
d. Doesn't affect my trust one way or the other.

Figure 27. Message Shown for Question 4.

Table 11 shows that about one-third of the participants felt that their trust in the message was increased because it contained a specific time. However, 27 percent of participants thought the time discrepancy (4 minutes) between the alert (1:38 p.m.) and current time (1:42 p.m.) would decrease their trust in the accuracy of the message. This finding supports the comments made by focus group participants in previous research (*2*). Eighteen percent of participants felt that the word REPORTED increased their trust in the message. An additional 9 percent of participants indicated that their trust was increased because the message contained both a specific time and the word REPORTED. Overall, including a specific time and/or the word REPORTED within the in-vehicle alert had very little effect on the survey participants' trust in the message. The findings also show the importance of keeping in-vehicle messages timely.

Comprehension of Lanes Affected Wording

Researchers asked this question to determine motorist understanding of a statement describing the wrong-way vehicle location (IN LEFT LANE) and a recommended driving action (USE RIGHT LANE). Figure 28 shows the two different messages and associated images shown in the two surveys. In both surveys, the question asked, "If you saw and heard the following message in your car while traveling in the middle lane, which lane you would travel in?" The participants could select either orange, green, or blue as shown in Figure 28. These colors represented the left, middle, and right lanes, respectively.

Table 11. Results for Question 4.

Response	Percent of Participants (n=361)[a]
Increases my trust because it is a specific time	33
Increases my trust because it says "reported"	18
Increases my trust because it is a specific time and says "reported"	9
Decreases my trust because it is 4 minutes old	27
Doesn't affect my trust one way or the other	18

[a] Total percent equals more than 100 since participants could choose multiple answers.

a) Survey 1 Message and Image. **b) Survey 2 Message and Image.**

Figure 28. Images Shown for Question 5.

For the message indicating that the wrong-way vehicle was in the left (orange) lane (Survey 1), 74 percent of participants stated that they would travel in the right (blue) lane. An additional 13 percent indicated they would continue to travel in the middle (green) lane. Overall, 87 percent of the participants understood that the wrong-way driver was in the left (orange) lane.

For the message that recommended the right-way driver travel in the right (blue) lane (Survey 2), 84 percent indicated they would use this lane. Researchers verified that this percentage was not statistically different from the 85 percent criterion established as the threshold for comprehension. Another 5 percent reported that they would continue to travel in the middle (green) lane.

For both messages, 11 to 13 percent of the participants indicated they would drive in the incorrect lane (i.e., left or orange). This suggests that some motorists may be confused by the use of LEFT and RIGHT, as theorized by some of the structured interview participants. Previous research (*2*) and the structured interviews found that motorists understand the dynamic nature of WWD events and thus the difficulty with providing lanes affected or specific action statements. Even though CVs will be capable of determining both the right-way and wrong-way vehicles' position and motion, caution should be used when providing information about the lanes affected and specific driving lane actions until the CV systems have been vetted and more research on in-vehicle messages has been conducted.

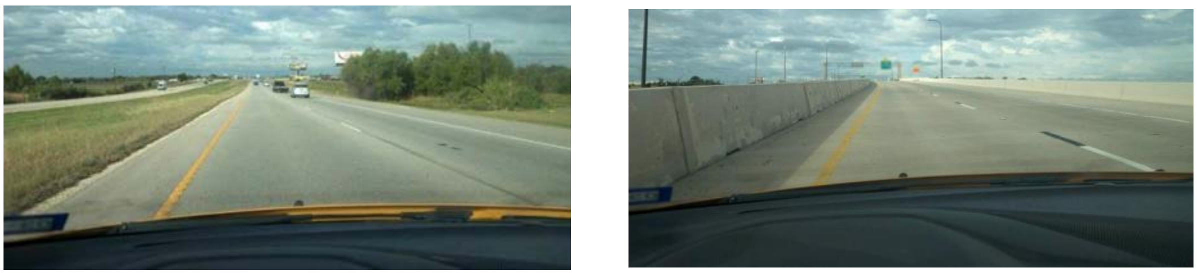
Comprehension of Wording Used to Indicate Do Not Enter Freeway

The sixth question examined motorist understanding of wording that could be used to direct right-way drivers not to enter the freeway. Figure 29 contains the image and message shown to participants in both surveys. Participants were told, "You are driving on a frontage road intending to get on the freeway, and you receive this message through your vehicle. Would you enter the freeway?" Participants could answer yes or no. Ninety-four percent of the participants stated that they would not enter the freeway. This result indicates motorist understanding of this message, as well as a propensity to follow the prescribed action.

Figure 29. Image and Message Shown for Question 6.

Need for In-Vehicle Alert Dependent upon Median Type

During the structured interviews, researchers discovered that participants' need for in-vehicle information about drivers on the opposite side of the road from the wrong-way driver was dependent upon whether or not the freeway was divided by a concrete median barrier or grass. Most participants thought the median barrier provided a physical obstacle between the wrong-way driver and them. In contrast, when there was a grass median, the wrong-way driver could possibly cross onto their side of the freeway. Based on these findings, researchers decided to show one survey group an image of a freeway with a grass median (Survey 1) and the other group an image of a freeway divided by concrete median barrier (Survey 2). Figure 30 contains both images. Both groups were asked, "Do you think it is necessary that the system send you a warning about a wrong-way driver traveling on the other side of the freeway?"



a) Survey 1 Image. **b) Survey 2 Image.**

Figure 30. Images for Question 7.

With a grass median, 78 percent of participants wanted an in-vehicle alert about a wrong-way driver traveling on the opposite side of the freeway. With the concrete barrier, 62 percent of participants desired in-vehicle alerts. The difference between these two groups (16 percent) was less than that found in the structured interviews (34 percent). Overall, there was still no clear consensus. Even so, these findings show the desire for in-vehicle WWD alerts for those traveling on the opposite side of the freeway. If CV systems display WWD alerts in all vehicles within a certain area, then the type of median is inconsequential. However, if it is envisioned that CV systems would only display WWD alerts in certain vehicles, then these systems would need to have roadway information stored in their mapping systems that indicates median type and then deliver a message only when there was a traversable median.

Need for All-Clear Message

Researchers used the last question in both surveys to collect more data about the need for an all-clear message once the WWD event has been canceled or resolved. All participants were told the following, "Imagine you've been receiving messages about a wrong-way driver in the area for the last 10 minutes." Participants were then asked, "Do you think it is necessary that the system send you a notification that the wrong-way driver has been stopped and it is safe to proceed?" Ninety-four percent of the participants indicated that they thought the in-vehicle system should broadcast this type of an all-clear message. This finding was similar to that found in the structured interviews (89 percent). In order to maintain the credibility of an in-vehicle wrong-way driver alert, motorists should be notified in some manner that the wrong-way driver alert is no longer valid. Researchers did not investigate how motorists would respond if the alert simply stopped.

SUMMARY AND CONCLUSIONS

Researchers conducted a formal task analysis to identify critical stages where right-way drivers could make a better decision if information was provided to them through CV technology. Researchers then used structured interviews and surveys to identify the information needs of right-way drivers and evaluate comprehension and preference of message wording and timing.

The majority of the structured interview participants wanted to receive in-vehicle WWD event alerts if they were:

- On the same side of the freeway and upstream of the wrong-way driver.
- On a ramp or frontage road on the same side of the freeway as the wrong-way driver.
- On a cross street approaching the area impacted by the wrong-way driver.
- On the opposite side of the freeway from the wrong-way driver and there was not a physical barrier between the opposing travel directions.

These findings show the desire for in-vehicle WWD alerts for multiple right-way vehicle locations. If CV systems display WWD alerts in all vehicles within a certain area, then the location and type of median are inconsequential. However, if it is envisioned that CV systems would only display WWD alerts in certain vehicles, then these systems would need to have roadway information (whether or not traversable median, cross streets, etc.) stored in their mapping systems and then deliver a message only to applicable vehicles.

More than 80 percent of structured interview participants wanted the in-vehicle alert to contain information about the urgency and problem. Participants indicated that the alert needed to catch the right-way driver's attention and should increase in frequency as they got closer to the wrong-way driver. With respect to the problem, researchers investigated two potential messages:

VEHICLE TRAVELING WRONG WAY and WRONG WAY DRIVER. When these phrases were shown as in-vehicle alerts in the survey, less than 60 percent of the participants interpreted them correctly. Perhaps adding the word AHEAD or REPORTED would convey that the message is talking about some other vehicle. These terms, along with other alternative wordings, need to be further investigated.

About two-thirds of the structured interview participants wanted information about the location of the wrong-way vehicle. Based on the structured interview and survey findings, there was no clear preference for indicating the location of the wrong-way driver using distance (e.g., 2 miles ahead) or time (e.g., 5 minutes ahead). While it would be possible in a CV system to calculate the time between the right-way and wrong-way vehicles, it may be preferable to use mileage since it corresponds with other directives, such as exit numbers and the distance to destinations and construction activities.

Researchers also investigated motorist comprehension of the use of an exit number by itself to indicate the last reported location of the wrong-way driver. Approximately half of the survey respondents thought that the exit number indicated where they should exit rather than signifying the last reported location of the WWD. This survey finding revealed that wording used on roadside signs cannot simply be put directly into in-vehicle messages because drivers' point of reference is different when considering in-vehicle devices.

Only one-quarter of the structured interview participants indicated the need for action information (e.g., exit freeway). In addition, very few participants wanted to receive information about the lanes affected and validation. Even so, researchers investigated the wording USE RIGHT LANE as a possible action message and IN LEFT LANE to describe the lanes affected. While these phrases were understood by most survey participants, there was an indication that some motorists might get confused with RIGHT versus LEFT terminology. Even though CVs will be capable of determining both the right-way and wrong-way vehicles' position and motion, caution should be used when providing information about the lanes affected and specific driving lane actions until the CV systems have been vetted and more research on in-vehicle messages has been conducted.

Researchers also evaluated motorist understanding of wording that could be used to direct right-way drivers not to enter the freeway. Researchers found that 94 percent of the survey respondents understood the DO NOT ENTER FREEWAY wording in the context of the message shown. In addition, the survey findings revealed the tendency of the participants to follow the recommended action.

The majority of the structured interview participants expected to receive an in-vehicle alert as soon as the WWD event was detected or reported by authorities. However, there was not consensus regarding the distance away from the wrong-way driver they would want to start receiving in-vehicle alerts. Once the WWD event is over, the majority of the structured interview and survey participants agreed that an all-clear message should be broadcast. Otherwise, motorists would be unsure how long the in-vehicle alert would be valid. Researchers did not investigate how motorists would respond if the alert simply stopped.

Most structured interview participants stated that they would trust the in-vehicle alert if they knew it was coming from TxDOT or some other official agency. Interestingly, structured interview participants indicated that their confidence in the in-vehicle system would not be impacted if a WWD alert was posted on a DMS but not received in their vehicle. In contrast, confidence in the in-vehicle system would be decreased if the structured interview participants personally witnessed a wrong-way driver but did not receive an in-vehicle alert.

Including a specific time and/or the word REPORTED within the in-vehicle alert had very little effect on the survey participants' trust in the message. However, as the difference between the in-vehicle alert and current time increases, motorists' trust in the relevance of the in-vehicle alert may decrease. This finding confirms the importance of keeping in-vehicle messages timely.

CHAPTER 4: NEXT STEPS

At the end of Phase II of the project, the research team identified challenges with deploying CV technology, determined additional research efforts, and considered potential locations for a Phase III model field deployment.

PHASE III CHALLENGES

The original Phase III proposal included a model field deployment of the CV WWD detection and management system in at least one TxDOT district. While potential corridors for the model field deployment were identified in Phase I of this project, there are several challenges regarding implementation in a major urban area that are worth noting.

While CVs are now in production (Table 12), the market penetration over the next several years will be driven by the NHTSA proposed rulemaking (*10*). Through the proposed rule, phase-in requirements for production volumes would occur over a 3-year span, with 50 percent for the first year, increasing 25 percent each following year and culminating in 100 percent by the third year and beyond. Assuming production volumes are consistent with current statistics (*11*), this would result in 8.75 million new CVs in the first year of the phase-in and 17.5 million new vehicles each year by the third year. Original expectations anticipated 100 percent of new production vehicles would be V2V capable by 2023, although this date is dependent upon a final rulemaking in 2019.

Table 12. U.S. Production Volumes for Connected Vehicles (as of July 2017).

Cars in Production with DSRC	Total U.S. Sales Figure
Mercedes Benz 2017 E-Class	27,430
Cadillac 2017 CTS Sedan	5,845

Source: (*12, 13*)

The limited number of CVs in general use expected in Texas over the next 2 years limits the ability of the CV WWD system to detect and warn wrong-way drivers and alert right-way drivers. In addition, the dynamic environment surrounding CVs is leading to rapid technological advances, which instigate changes to standards and impact the service life of equipment. While these challenges may preclude a model field deployment in a major urban area where motorists are requesting countermeasures and detection systems that will effectively mitigate WWD today, there is still the need to further develop the CV WWD system in a real-world environment to prepare TxDOT for the approaching CV environment.

POTENTIAL PHASE III TASKS

As part of the Safety through Disruption University Transportation Center (UTC), TTI is working toward creating a smart connected corridor along SH 47 between the Texas A&M main campus and RELLIS campus. This corridor contains a multi-lane, divided facility that includes a limited-access section with entrance and exit ramps, as well as a divided-highway portion with at-grade intersections.

Currently, TTI is working with other university groups, TxDOT, and other governmental agencies to define the requirements for a connected/automated vehicle test bed. In addition, TTI is conducting an inventory of existing traffic control devices, power and communication locations, and roadway design elements along the corridor. In fiscal year 2018, TTI plans to develop a preliminary system architecture, conduct testing of deployment technologies, develop a detailed system design, and install initial equipment.

In Phase III of this research effort, the research team could design and deploy a model field deployment of the CV WWD detection and management system in conjunction with the ongoing smart connected corridor development. This would allow researchers to further develop the CV WWD system for real-world environments and be better prepared when the CV market penetration makes the deployment of such a system in a major urban area more feasible. This approach could leverage federal money from the UTC that is being directed toward instrumenting this corridor. The UTC-funded instrumentation will include cameras and other monitoring systems that could be used for ground-truth verification for testing a CV WWD system on a real roadway.

The following efforts could be undertaken in Phase III of the project as part of the model field deployment:

- Real-world design and deployment of CV WWD system roadside equipment.
- Real-world deployment of CV WWD system onboard equipment.
- Dynamic versus static mapping.
- Roadway interactions (i.e., main lanes, frontage roads, and intersections).

- Complexity of increased wrong-way protection areas and more incoming data elements.
- Robustness of roadside equipment.
- Integration of the stand-alone CV WWD system.

Roadside Equipment

Roadside equipment (e.g., trailers, field computers, and DSRC) purchased in Phase II of this project could be leveraged with the ongoing development of the SH 47 smart connected corridor. In addition, Phase III of this project could provide additional equipment that would be needed to ensure adequate DSRC coverage at the selected locations for the CV WWD model field deployment.

Through the model field deployment, the research team could identify challenges and solutions about the design and installation of roadside equipment on a real roadway. Documenting these efforts will be beneficial to future real-world deployments. For example, due to the straight wide-open alignment used for the prototype system on the closed course, only one RSU was needed. However, the topographical layout of a real roadway will impact the location and number of RSUs needed for a CV WWD system deployment.

A model deployment would allow for real-world interoperability testing of upcoming commercial off-the-shelf (COTS) DSRC equipment. Each vendor's equipment could be operated within the smart connected corridor as the device in test, and performance metrics could be gathered about the device in test. Much of the ongoing interoperability testing is performed in laboratories and very carefully controlled environments. The model field deployment could serve to validate or expose real-world issues with interoperability. Properly performing devices would have similar performance to that of the vendors integrated into the prototype system (i.e., Cohda OBU and RSU, and Savari™ OBU).

Connected Vehicles

As mentioned previously, one hindrance to deployment of the CV WWD system is the small number of CV-enabled vehicles on the road today. Trips to the Texas A&M RELLIS campus from the main Texas A&M campus are expected to increase as the RELLIS campus grows. In addition, by 2019 TTI will be located on the RELLIS campus. As part of Phase III of this project, TTI could outfit 10 to 15 of its vehicles with DSRC and associated components to make them CV enabled. In addition, the Texas A&M Department of Mechanical Engineering is envisioning using the SH 47 smart connected corridor to showcase its connected/automated vehicles by driving visitors from the Easterwood Airport to the RELLIS campus. DSRC and traditional ITS equipment installed along the corridor would enable monitoring and performance measurements on these vehicles. A portion of these vehicles could also be outfitted with in-vehicle displays that would present wrong-way driver warnings.

As part of the TxDOT I-35 Connected Work Zone Project, TTI has purchased two SmartMicro 3DHD detectors. These radar detectors use a wider field of view and longer range to track oncoming vehicles' location and speed. This detector also automatically detects the correct travel direction. These data elements can be used to calculate a vehicle's latitude, longitude, and heading; essentially creating a BSM for the detected vehicles. To date, this is the only COTS equipment available that can provide the data elements necessary to calculate the inputs needed to generate BSMs for non-equipped vehicles. TTI began testing these detectors in September 2017. In Phase III, the potential to use these detectors to generate BSMs for non-equipped vehicles could be further explored and applied to the CV WWD system. This radar technology has the potential of providing CV information (i.e., BSMs) for non-equipped vehicles detected within the range of the radar (1000 to 1500 ft) upstream of the location where the radar is installed on the roadside. This would increase the number of vehicles providing information to the system and thus increase the chances of detecting an actual (not staged) WWD.

A WWD event could also be staged with one of the CV-enabled TTI vehicles. Instead of shutting down a section of roadway for the vehicle to travel in the wrong direction, the research team could rely on a virtual software modification. By changing the correct heading in the software, a CV-enabled vehicle could be driven in the proper direction but would be detected by the software as a WWD event. This would test the model field deployment system without requiring physical manipulation of traffic and roadway availability.

Dynamic Mapping

The prototype system uses static maps for detection zones along the test bed roadway (e.g., referenced as SH 47) (Figure 11). The zones for the static map were defined as polygons with a specific direction indicating the correct travel heading (i.e., green arrows). These static maps were created through a manually intensive process, which was sufficient for the limited area that was instrumented in Phase II.

Alternatively, through Phase III efforts, data could be gathered from CV-enabled vehicles dynamically and be used to generate dynamic maps (Figure 31). The dynamic mapping solution that has been piloted by SwRI uses a neural network to analyze the reported positions of each CV-enabled vehicle. The output of the algorithm is a road network with lane-level mapping of latitude and longitude coordinates to a road network. Using and honing this technique through a limited model deployment project will save vast amounts of time that would otherwise be spent creating (or purchasing) static maps.

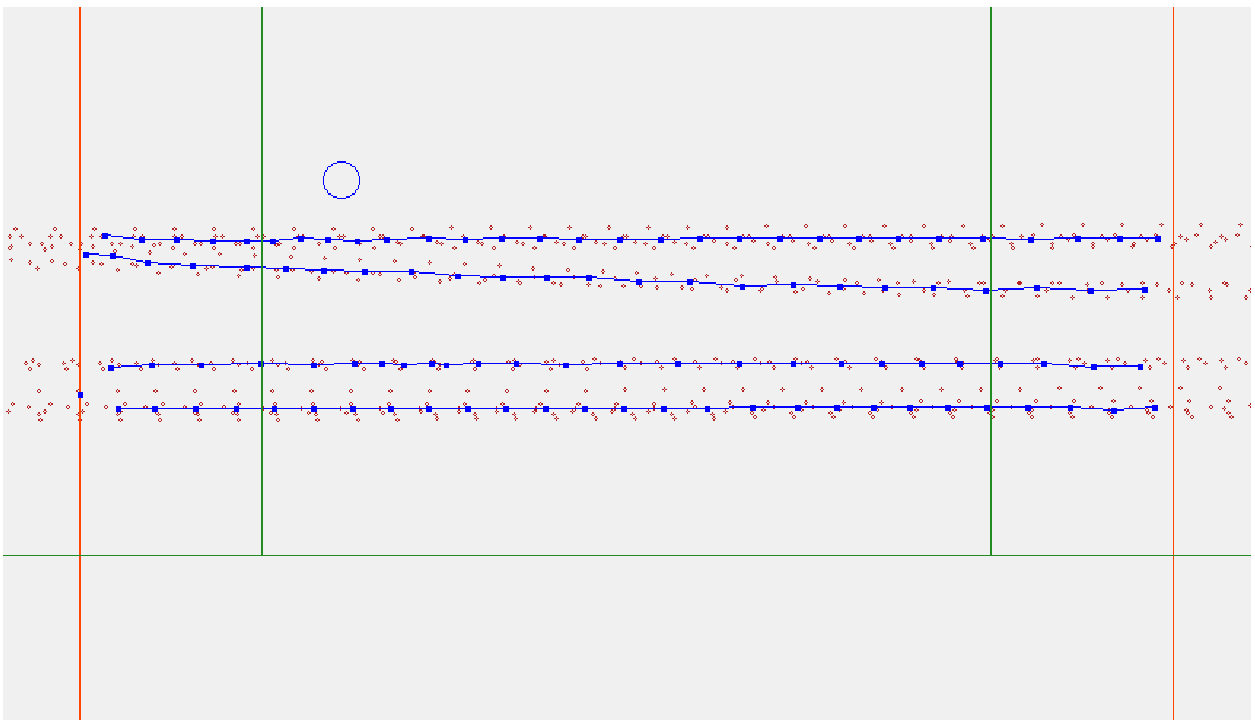


Figure 31. Example of a Neural Network Automatically Generating a Road Network from Basic Safety Messages.

Roadway Interactions

Currently, only one side (northbound) of a multi-lane freeway is included in the test bed design. Phase III would help to identify and address issues with interactions between the main lanes, frontage roads, and intersections. These interactions would be crucial to driver trust in the system. Adding these additional real-world roadway components will also allow the research team to test out the different scenarios identified during interviews (i.e., which vehicles should get an alert and which vehicles should not) (Figure 17).

Complexity of Increased Wrong-Way Protection Areas and More Incoming Data Elements

As the size and complexity of real-world deployment increase, the computing complexity of comparing each incoming BSM (at 10 times per second per vehicle) against every wrong-way protected area will be substantial. Initial estimations quantify this at 18 zones (or dynamic paths) per RSU along SH 47. Once all the roadside equipment is in place and all of the test vehicles are equipped with CV technology, comparisons of BSMs to zones could result in several thousand comparisons per second. This could dramatically increase if the SmartMicro 3DHD detectors can be successfully used to provide CV information (i.e., BSMs) for non-equipped vehicles. There are a number of possibilities that have been proposed to address this issue, from hierarchical structure of wrong-way zones (or dynamic paths) to historical buffering of the previous zone. Investigating and possibly testing some of these possibilities in the smart connected corridor will be beneficial to ensuring the success of future projects using a roadway map.

Robustness

Through previous TxDOT project efforts, three RSUs have been deployed and connected to the TxDOT backhaul in San Antonio. The robustness of those devices was concerning to the research team (Table 13). Factors that contributed to this lack of robustness included networking issues, power issues, software bugs, and environmental factors. Phase III could help to address some of those situations by providing additional data points for the investigation of robustness issues prior to full-scale deployment. One modification that has been tested in the laboratory is the introduction of a WebRelay device, which automatically monitors the RSUs for responsiveness (through an internet protocol ping) and will power-cycle the device if it is not responsive (Figure 32). This addresses many of the issues. Additionally, alerts can be generated if resets are occurring more frequently than desired and the root cause can be investigated. This root cause analysis would be a valuable output from Phase III efforts.

Table 13. Rough Uptime for Each RSU from Summer 2014 to Summer 2015.

RSU Location	Total Days	Number of Operational Days
I-410 and US 281	342	200
I-410 and Ingram	347	199
I-410 and I-10	419	157

Figure 32. WebRelay Hardware Device.

Integration of the Stand-Alone CV WWD System

The FHWA V2I Hub is being updated to incorporate the modified message formats in the latest SAE J2735 2016 standard. The stand-alone (non-Lonestar®) roadside CV WWD system can be updated to comply with the latest V2I Hub version in Phase III. This stand-alone system can also be tested in the smart connected corridor.

SUMMARY AND RECOMMENDATION

In Phase II of this research project, the research team developed and tested the CV WWD detection and management system in a closed-course test bed environment. While there are challenges to deploying this system in a major urban area, the research team recommends the installation of a model field deployment on SH 47 (in conjunction with the ongoing development of a smart connected corridor). This real-world application will allow researchers and TxDOT to further prepare for the approaching CV environment and its ability to improve wrong-way detection, more quickly notify public agencies and law enforcement, and alert right-way drivers.

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APPENDIX:
LONESTAR® SYSTEM VALIDATION TESTING

Table A1. Test Case 1: Connected Vehicle Entering the Freeway the Wrong Way from the Ramp.

	Tests	Expected		Observed	
		Yes	No	Yes	No
Test outcomes	Did the CV-enabled vehicles transmit BSMs (Req. 1.2.1)?	☒	☐	☒	☐
	Did the RSU receive BSMs from the wrong-way CV-enabled vehicle (Req. 1.2.2)?	☒	☐	☒	☐
	Did the RSU properly detect that the CV-enabled vehicle was traveling in the wrong direction (Req. 1.2.4)?	☒	☐	☒	☐
	Did the RSU transmit a “notification” message to the TMC indicating the time and location where the wrong-way vehicle was detected (Req. 1.2.10 and 1.2.9)?	☒	☐	☒	☐
	Did the TMC receive the “notification” message from the RSU (Req. 1.2.11)?	☒	☐	☒	☐
	Did the TMC system provide the capability of displaying WWD event information to an operator (Req. 1.2.12, 1.2.13, 1.2.14, and 1.2.15)?	☒	☐	☒	☐
	Did the RSU transmit an “alert” message that a wrong-way vehicle was detected to the right-way CV-enabled vehicle (Req. 1.2.5 and 4.2.3)?	☒	☐	☒	☐
	Did the RSU transmit an “alert” message that a wrong-way vehicle was detected to the CV-enabled law enforcement vehicle (Req. 4.3.3)?	☒	☐	☒	☐
	Did the OBU receive and display an “alert” message to the right-way CV-enabled vehicle (Req. 1.2.6, 1.2.7, 4.2.4, and 4.2.5)?	☒	☐	☒	☐
	Did the OBU receive and display an “alert” message to the CV-enabled law enforcement vehicle (Req. 4.3.4 and 4.3.5)?	☒	☐	☒	☐
	Did the RSU continue to broadcast the “alert” message?	☒	☐	☒	☐
	Did the RSU stop broadcasting when the WWD event was terminated (Req. 5.4.3)?	☒	☐	☒	☐
Notes and observations	Requirements are located in the appendix of the Phase I report.				

Table A2. Test Case 2: Wrong-Way Connected Vehicle Traveling on the Main Lane.

	Tests	Expected		Observed	
		Yes	No	Yes	No
Test outcomes	Did the CV-enabled vehicles transmit BSMs (Req. 1.2.1)?	☒	☐	☒	☐
	Did the RSU receive BSMs from the wrong-way CV-enabled vehicle (Req. 1.2.2)?	☒	☐	☒	☐
	Did the RSU properly detect that the CV-enabled vehicle was traveling in the wrong direction (Req. 1.2.4)?	☒	☐	☒	☐
	Did the RSU transmit a "notification" message to the TMC indicating the time and location where the wrong-way vehicle was detected (Req. 1.2.10 and 1.2.9)?	☒	☐	☒	☐
	Did the TMC receive the "notification" message from the RSU (Req. 1.2.11)?	☒	☐	☒	☐
	Did the TMC system provide the capability of displaying WWD event information to an operator (Req. 1.2.12, 1.2.13, 1.2.14, and 1.2.15)?	☒	☐	☒	☐
	Did the RSU transmit an "alert" message that a wrong-way vehicle was detected to the right-way CV-enabled vehicle (Req. 1.2.5 and 4.2.3)?	☒	☐	☒	☐
	Did the RSU transmit an "alert" message that a wrong-way vehicle was detected to the CV-enabled law enforcement vehicle (Req. 4.3.3)?	☒	☐	☒	☐
	Did the OBU receive and display an "alert" message to the right-way CV-enabled vehicle (Req. 1.2.6, 1.2.7, 4.2.4, and 4.2.5)?	☒	☐	☒	☐
	Did the OBU receive and display an "alert" message to the CV-enabled law enforcement vehicle (Req. 4.3.4 and 4.3.5)?	☒	☐	☒	☐
	Did the RSU continue to broadcast the "alert" message?	☒	☐	☒	☐
	Did the RSU stop broadcasting when the WWD event was terminated (Req. 5.4.3)?	☒	☐	☒	☐
Notes and observations	Requirements are located in the appendix of the Phase I report.				

Table A3. Test Case 3: Right-Way Connected Vehicle Traveling on the Freeway Main Lanes.

	Tests	Expected		Observed	
		Yes	**No**	**Yes**	**No**
Test outcomes	Did the RSU receive BSMs from the CV-enabled vehicle (Req. 1.2.2)?	☒	☐	☒	☐
	Did the RSU properly determine that the CV-enabled vehicle was traveling in the right direction (Req. 1.2.4)?	☒	☐	☒	☐
Notes and observations	Requirements are located in the appendix of the Phase I report.				

Table A4. Test Case 4: Non-connected Vehicle Entering the Freeway the Wrong Way from the Ramp.

	Tests	Expected		Observed	
		Yes	No	Yes	No
Test outcomes	Did the infrastructure-based sensors detect the non-CV vehicle entering the freeway the wrong way (Req. 1.1.1)?	☒	☐	☒	☐
	Did the infrastructure-based system activate the “WRONG WAY” LED sign?	☒	☐	☒	☐
	Did the infrastructure-based system transmit a “notification” message to the TMC indicating the time and location where the wrong-way vehicle was detected (Req. 1.1.2, 1.1.3, 1.1.4, and 1.1.5)?	☒	☐	☒	☐
	Did the TMC receive the “notification” message from the infrastructure-based sensors (Req. 1.1.13)?	☒	☐	☒	☐
	Did the TMC system provide the capability of displaying WWD event information to an operator (Req. 1.1.14, 1.1.15, 1.1.16, and 1.1.17)?	☒	☐	☒	☐
	Did the RSU transmit an “alert” message that a wrong-way vehicle was detected to the right-way CV-enabled vehicle (Req. 1.1.7 and 4.2.3)?	☒	☐	☒	☐
	Did the RSU transmit an “alert” message that a wrong-way vehicle was detected to the CV-enabled law enforcement vehicle (Req. 4.3.3)?	☒	☐	☒	☐
	Did the OBU receive and display an “alert” message to the right-way CV-enabled vehicle (Req. 1.1.8, 1.1.9, 4.2.4, and 4.2.5)?	☒	☐	☒	☐
	Did the OBU receive and display an “alert” message to the CV-enabled law enforcement vehicle (Req. 4.3.4 and 4.3.5)?	☒	☐	☒	☐
	Did the RSU continue to broadcast the “alert” message?	☒	☐	☒	☐
	Did the RSU stop broadcasting when the WWD event was terminated (Req. 5.4.3)?	☒	☐	☒	☐
Notes and observations	Infrastructure-based system triggered alerts were integrated with the CV system through the Lonestar® software subsystems. Requirements are located in the appendix of the Phase I report.				

Table A5. Test Case 5: System Provides Continuous Detection and Notification of a Wrong-Way Event.

	Tests	Expected		Observed	
		Yes	No	Yes	No
Test outcomes	Did the CV-enabled vehicles transmit BSMs (Req. 1.2.1)?	☒	☐	☒	☐
	Did the RSU receive BSMs from the wrong-way CV-enabled vehicle (Req. 1.2.2)?	☒	☐	☒	☐
	Did the RSU properly detect that the CV-enabled vehicle was traveling in the wrong direction (Req. 1.2.4)?	☒	☐	☒	☐
	Did the RSU transmit a “notification” message to the TMC indicating the time and location where the wrong-way vehicle was detected (Req. 1.2.10 and 1.2.9)?	☒	☐	☒	☐
	Did the infrastructure-based sensors detect the non-CV vehicle entering the freeway the wrong way (Req. 1.1.1)?	☒	☐	☒	☐
	Did the infrastructure-based system activate the “WRONG WAY” LED sign?	☒	☐	☒	☐
	Did the infrastructure-based system transmit a “notification” message to the TMC indicating the time and location where the wrong-way vehicle was detected (Req. 1.1.2, 1.1.3, 1.1.4, and 1.1.5)?	☒	☐	☒	☐
	Did the TMC receive the “notification” message from the RSU (Req. 1.2.11)?	☒	☐	☒	☐
	Did the TMC receive the “notification” message from the infrastructure-based sensors (Req. 1.1.13)?	☒	☐	☒	☐
	Did the TMC system provide the capability of displaying WWD event information to an operator (Req. 1.1.14, 1.1.15, 1.1.16, 1.1.17, 1.2.12, 1.2.13, 1.2.14, and 1.2.15)?	☒	☐	☒	☐
	Did the CV WWD system update the position of the wrong-way vehicle as it traveled?	☒	☐	☒	☐
	Did the RSU transmit an “alert” message that a wrong-way vehicle was detected to the right-way CV-enabled vehicles (Req. 1.2.5 and 4.2.3)?	☒	☐	☒	☐
	Did the RSU transmit an “alert” message that a wrong-way vehicle was detected to the CV-enabled law enforcement vehicle (Req. 4.3.3)?	☒	☐	☒	☐
	Did the OBU receive and display an “alert” message to right-way CV-enabled vehicles (Req. 1.2.6, 1.2.7, 4.2.4, and 4.2.5)?	☒	☐	☒	☐

Table A5. Test Case 5: System Provides Continuous Detection and Notification of a Wrong-Way Event (Continued).

	Tests	Expected		Observed	
		Yes	No	Yes	No
Test outcomes	Did the OBU receive and display an "alert" message to the CV-enabled law enforcement vehicle (Req. 4.3.4 and 4.3.5)?	☒	☐	☒	☐
	Did the CV WWD system activate the PCMS when a wrong-way vehicle was detected (Req. 4.1.1)?	☒	☐	☒	☐
	Did the RSU continue to broadcast the "alert" message?	☒	☐	☒	☐
	Did the RSU stop broadcasting when the WWD event was terminated (Req. 5.4.3)?	☒	☐	☒	☐
	Did the PCMS message clear once the WWD event was terminated (Req. 5.3.1 and 5.3.2)?	☒	☐	☒	☐
Notes and observations	Infrastructure-based system triggered alerts were integrated with the CV system through the Lonestar® software subsystems. Requirements are located in the appendix of the Phase I report.				

Table A6. Test Case 6: Wrong-Way Roadside Alert Message Propagated Upstream by Connected Vehicles.

	Tests	Expected		Observed	
		Yes	No	Yes	No
Test outcomes	Did the RSU transmit an “alert” message that a wrong-way vehicle was detected to the first right-way CV-enabled vehicle (Req. 1.2.5 and 4.2.3)?	☒	☐	☒	☐
	Did the OBU receive and display an “alert” message to the first right-way CV-enabled vehicle (Req. 1.2.6, 1.2.7, 4.2.4, and 4.2.5)?	☒	☐	☒	☐
	Did the OBU in the first right-way CV-enabled vehicle rebroadcast the “alert” message (Req. 1.2.8)?	☒	☐	☒	☐
	Did the OBU in the second right-way CV-enabled vehicle receive and display the “alert” message from the first right-way CV-enabled vehicle (Req. 1.2.6, 1.2.7, 4.2.4, and 4.2.5)?	☒	☐	☒	☐
	Did the OBU in the third right-way CV-enabled vehicle receive and display an “alert” message from the second right-way CV-enabled vehicle (Req. 1.2.6, 1.2.7, 4.2.4, and 4.2.5)?	☒	☐	☐	☒
Notes and observations	Propagation verification was limited to a single vehicle in order to reduce the logistical complexity of the validation test. Requirements are located in the appendix of the Phase I report.				