



Integration of Connected Vehicle and RWIS Technologies

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June 2024**

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| 16. Abstract <p>Connected vehicles (CVs) are equipped with advanced technologies that allow them to communicate with infrastructure, other vehicles, and external systems. Meanwhile, transportation agencies maintain networks of road weather information systems (RWIS) that monitor weather and pavement surface conditions and communicate these conditions to agency personnel in order to facilitate maintenance operations and decision-making. Integrating CV technology into RWIS infrastructure has the potential to significantly improve road safety by providing real-time weather information to drivers.</p> <p>This white paper presents the findings to date of the Integration of Connected Vehicle (CV) and Road Weather Information System (RWIS) Technologies project. The project reviewed the literature related to CV-RWIS integration, analyzed ongoing projects carried out by departments of transportation (DOTs) on CVs and RWIS, surveyed state and local transportation agencies regarding their investments in RWIS technologies to facilitate integration with CVs, conducted follow-up interviews with selected agencies, and prepared a summary of current challenges to CV-RWIS integration and recommendations for future research.</p> | | | | | |
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TABLE OF CONTENTS

| | |
|--|-----|
| ACKNOWLEDGMENTS | vii |
| ABBREVIATIONS | ix |
| INTRODUCTION | 1 |
| Connected Vehicles versus Connected and Autonomous Vehicles..... | 1 |
| LITERATURE REVIEW | 2 |
| Applications and Practical Feasibility of CAV-RWIS Integration..... | 3 |
| Practical Considerations for CAV-RWIS Integration..... | 7 |
| Methods of Communication | 10 |
| Current Practice | 14 |
| Overview of the Current Practices of DOTs..... | 15 |
| Challenges and Recommendations Identified from the Literature Review | 23 |
| SURVEY OF AGENCIES..... | 25 |
| Investment in RWIS Technologies to Support CAV Integration | 27 |
| Investments in IT and Data Communication and Management Technology | 34 |
| Maintenance Practices | 40 |
| Workforce Development..... | 42 |
| Development of Standards..... | 43 |
| TARGETED INTERVIEWS | 45 |
| Introduction..... | 45 |
| Ranking | 45 |
| Agency Selection and Findings | 46 |
| CHALLENGES AND RECOMMENDATIONS FOR FUTURE RESEARCH..... | 49 |
| Data Standards to Enhance Interoperability and Interpretability..... | 49 |
| Deployment Configurations, Adoption Rates, and Impacts | 49 |
| Investments in RWIS Technologies to Support CAV Integration..... | 49 |
| Investments in IT and Data Communication and Management Technology | 50 |
| Maintenance Practices | 50 |
| Workforce Development..... | 51 |
| REFERENCES | 53 |
| APPENDIX A. SURVEY..... | 59 |
| APPENDIX B1. TARGET INTERVIEW QUESTIONS BASED ON SURVEY RESPONSES | 71 |
| APPENDIX B2. SUMMARY OF TARGETED INTERVIEWS..... | 79 |

LIST OF FIGURES

| | |
|---|----|
| Figure 1. States participating in the survey..... | 25 |
| Figure 2. Type of organization..... | 27 |
| Figure 3. Type of RWIS technology investment made or planned..... | 28 |
| Figure 4. Communication method between sensor and RPU | 29 |
| Figure 5. Communication method between RPU and CPU..... | 29 |
| Figure 6. RWIS data storage..... | 30 |
| Figure 7. Other investments in RWIS technology to facilitate compatibility with CAVs | 31 |
| Figure 8. Investments planned in RWIS technology to facilitate compatibility with CAVs in the next three years | 31 |
| Figure 9. Investment in technology in relation to RWIS | 32 |
| Figure 10. Areas of investments | 35 |
| Figure 11. Reasons for investments in IT and data communication and management technology and RWIS technology | 35 |
| Figure 12. Plans to invest in IT and data management and communication technology specific to RWIS and applicable to CAV integration in the next three years..... | 38 |
| Figure 13. Interest in maintenance practices that will benefit from CAV integration into RWIS..... | 40 |
| Figure 14. Concern about other aspects of maintenance related to CAV integration..... | 42 |
| Figure 15. Updates to the agency’s workforce skills to handle the integration of CAVs..... | 43 |
| Figure 16. Agency involvement in the development of standards, new data formats, and protocols for exchanging RWIS data with CAVs within the next three years..... | 44 |
| Figure 17. Summary of all investments organizations plan to make in the next three years..... | 44 |

LIST OF TABLES

| | |
|---|----|
| Table 1. Summary of major differences between CVs and CAVs | 1 |
| Table 2. Operational connected vehicle deployments | 18 |
| Table 3. Planned connected vehicle deployments | 20 |
| Table 4. Motivation behind the investments in RWIS technology | 30 |
| Table 5. Example of a question with ranked responses | 45 |
| Table 6. Top 10 organizations that have already invested or plan to invest in technology for CAV integration | 46 |
| Table 7. Top 10 organizations that plan to invest in the technology in the next three years..... | 46 |

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ABBREVIATIONS

| | |
|----------|---|
| 4G | fourth generation |
| 5G | fifth generation |
| 5GTN | fifth generation test network |
| AI | artificial intelligence |
| API | application programming interface |
| ARC | Atlanta Regional Commission |
| ASOS | automated surface observing system |
| ATCMTD | Advanced Transportation and Congestion Management Technologies Deployment |
| ADS | automated deployment services |
| AV | autonomous vehicle |
| BUCL | Birmingham Urban Climate Laboratory |
| BUILD | Better Utilizing Investments to Leverage Development |
| Caltrans | California Department of Transportation |
| CAV | connected and autonomous vehicle |
| CAN | controller area network |
| CPU | central processing unit |
| CV | connected vehicle |
| C-V2X | cellular vehicle to everything |
| DNN | deep neural network |
| DOT | department of transportation |
| DSRC | dedicated short-range communication |
| ESS | environmental sensor station |
| FCC | Federal Communications Commission |
| FHWA | Federal Highway Administration |
| GDOT | Georgia Department of Transportation |
| GPRS | general packet radio service |
| GPS | global positioning system |
| GSM | global system for mobile communications |
| Het-Net | heterogeneous network |
| HMI | human-machine interface |
| I2V | infrastructure to vehicle |
| ICW | intersection collision warning |
| IEEE | Institute of Electrical and Electronics Engineers |
| ICM | integrated corridor management |
| IT | information technology |
| IoT | internet of things |
| LTE | long-term evolution |
| LTE-V2X | long-term evolution vehicle to everything |
| MDOT | Michigan Department of Transportation |
| MnDOT | Minnesota Department of Transportation |
| MPO | metropolitan planning organization |
| MTC | Metropolitan Transportation Commission |

| | |
|---------|--|
| NSTC | National Science and Technology Council |
| NYSDOT | New York State Department of Transportation |
| OBE | on-board equipment |
| OBD | on-board diagnostic |
| OBU | on-board unit |
| OEM | original equipment manufacturers |
| PATH | California Partners for Advanced Transportation Technology |
| PennDOT | Pennsylvania Department of Transportation |
| PTC | Pennsylvania Turnpike Commission |
| RPU | remote processing unit |
| RSC | road surface condition |
| RSE | road safety and efficiency |
| RSU | roadside unit |
| RWS | road weather station |
| RWIS | road weather information system |
| STEM | science, technology, engineering, and math |
| TIM | traffic incident management |
| TIGER | Transportation Investment Generating Economic Recovery |
| TNC | transportation network companies |
| V2I | vehicle to infrastructure |
| V2N | vehicle to network |
| V2P | vehicle to pedestrian |
| V2V | vehicle to vehicle |
| V2X | vehicle to everything |
| VDOT | Virginia Department of Transportation |
| VII | vehicle-infrastructure integration |
| VCC | Virginia Connected Corridors |
| VTI | Virginia Tech Transportation Institute |
| WAVE | wireless access for vehicular environments |

INTRODUCTION

This white paper presents the findings to date of the Integration of Connected Vehicle (CV) and Road Weather Information System (RWIS) Technologies project.

The document contains a brief introduction; a review of the relevant literature and an analysis of ongoing connected and autonomous vehicle (CAV) and RWIS projects carried out by department of transportation (DOT) entities; the results from a survey and targeted interviews conducted for this project; a summary of the challenges identified from the literature review, survey, and targeted interviews; and a list of recommendations for future research.

Connected Vehicles versus Connected and Autonomous Vehicles

Vehicles equipped with advanced technologies that allow them to interact with other vehicles, infrastructure, and external systems are known as CVs. These vehicles collect and transmit information about their position and performance. They facilitate communication between vehicles and infrastructure (vehicle to infrastructure [V2I], vehicle to vehicle [V2V], and infrastructure to vehicle [I2V]) through dedicated short-range communications (DSRC), line-of-site cellular technology, or commercial fifth generation (5G)/long-term evolution (LTE) V2I, which utilizes cellular network technologies. This connectivity can be used to improve traffic control and safety. Meanwhile, autonomous vehicles (AVs) employ a mix of sensors and machine learning algorithms to sense their surroundings and function with minimal or no human assistance. CAVs seamlessly fuse the two key features of CVs and AVs: connectivity and autonomy [1, 2].

Table 1 summarizes the major differences between CVs and CAVs.

Table 1. Summary of major differences between CVs and CAVs

| Aspect | CVs | CAVs |
|-------------------------------|---|---|
| Connectivity | Primarily focuses on internet connectivity and communication capabilities | Combine connectivity with autonomy for autonomous operations |
| Human Intervention | Human drivers responsible for driving and making decisions | Designed to operate with minimal or no human intervention |
| Levels of Automation | Do not have levels of automation | Categorized into five automation levels depending on their capability to handle driving tasks |
| Safety and Traffic Management | Contribute to safety and traffic management through V2I communication | Contribute to safety and traffic management but offer more advanced safety features |
| Use Cases | Often seen in newer vehicles, offering features that assist human drivers | Mainly still under development and testing |

The terms CV and CAV are used interchangeably in this white paper.

LITERATURE REVIEW

This literature review aimed to provide a comprehensive analysis of the integration of CAVs and RWIS across four themes:

Theme 1. Applications for and Practical Feasibility of CAV-RWIS Integration:

- Potential applications and practical feasibility of vehicle to everything (V2X) technology for road weather management, specifically the integration of RWIS into V2X technology
- Distinction between the direct use of mobile sensor information for decision-making or edge analysis and the use of data measured by mobile sensors
- Critical evaluation of the implications of two-way communication between vehicles and infrastructure (V2I and I2V) for transportation operations
- How RWIS stations (which have power supplies and communications equipment) can support the collection and timely communication of these enhanced data sources and, to this point, whether any modifications to RWIS equipment should be considered in the future

Theme 2. Practical Considerations for CAV-RWIS Integration:

- Potential applications and opportunities where both CV and RWIS data can be integrated to prepare for and manage the impacts of hazardous weather on motorists' safety and mobility
- Practical considerations of CV system applications and integration with RWIS
- CV-RWIS integration within the framework of the Federal Highway Administration's (FHWA's) intelligent transportation systems (ITS) architecture
- Conceptual needs and requirements to integrate CV and RWIS data in contrast to other less technical or less expensive options
- Feasibility of an open-source software solution for the integration of CV data with current weather systems and the maintenance of new data
- How to scale RWIS data management practices to take advantage of advanced CAV data management systems

Theme 3. Methods of Communication:

- Benefits of communication both to and from a vehicle beyond the value of using a vehicle as a mobile sensor
- Critical evaluation of CV methods of communication, specifically line-of-sight cellular or DSRC V2I/I2V/V2V and commercial 5G/LTE V2I, with an exploration of the benefits of each as well as the benefits of a combined architecture

Theme 4. Current Practice:

- Similar research and work being conducted

- Current practices and research studies related to CAV-RWIS integration at state DOTs and international transportation agencies, as well as in the private sector
- Environmental justice implications of CAV-RWIS integration

The following sections review studies on CAV applications for winter road weather management and CAV applications for multimodal travel based on the outlined themes. A summary is provided after the aspects of each theme are discussed in detail.

Applications and Practical Feasibility of CAV-RWIS Integration

Combining CAV technology and RWIS infrastructure has the potential to significantly improve road safety by providing real-time weather information to drivers. In a study conducted by Vaidya et al. [3], a cost-effective road weather system was developed using cloud and connected vehicle technology. The system incorporated a V2I hub, a roadside unit (RSU), environmental sensor stations (ESS), mobile ESS, CAVs, and a backend cloud server to provide real-time road conditions. V2I and V2V communications were achieved through DSRC and cellular V2X (C-V2X) technology. Data elements were wirelessly transmitted to the V2I hub when CAVs came within range of the RSU. Outputs were made available to data subscribers after processing to inform them of the road conditions. Edge cloud computing was used in this system to reduce the latency of data transfer between vehicles and the edge cloud server via RSUs.

In a study conducted to address the innovative use of connected vehicle technology for improving winter travel mobility, Shi et al. [4] proposed a connected vehicle application that enabled the collection of route-specific and not just point-specific road weather data in order to improve road safety at a network level. This proposed concept supplemented data from RWIS and included other equipment such as cameras, sensors, and roadside units to facilitate wireless communication with and data transmission to and from connected vehicles. The study predicted several benefits of implementing CV technology, including improvements to the accuracy and timeliness of road weather data compared to the traditional methods of collecting and distributing road weather data. According to the study, a foreseeable challenge will be to increase the density of roadside units and encourage more private cars to engage in the CV network in order to gather more data. Another identified challenge will be to increase server speeds and capabilities to manage the data processing demands. It was then recommended that appropriate algorithms be developed to turn unprocessed connected vehicle data, as well as other road weather and traffic data, into timely and useful information.

CAV technology can be helpful in improving traffic flow. Bento et al. [5] developed a microscopic open-source simulator that is highly customizable for different traffic scenarios. In this study, a module for V2V and V2I communications and precise positioning systems were integrated into the simulator, and this was used as an important tool to address the problem of traffic control at intersections. Roundabout and crossroad intersections were examined where there was a wireless exchange of information between vehicles and infrastructure. The results of the study showed an improvement in the traffic flow at the intersections using the developed simulator.

CAV technology can improve safety on roads in several ways. Outay et al. [6] proposed an alert system that uses a geo-broadcast transmission technique to warn vehicles in a network of potential weather-related hazardous situations through V2V communication, allowing the vehicles to take proper action to improve road safety. When a road hazard is detected by the RSU or a vehicle equipped with on-board equipment (OBE) sensors, the alert system transmits the warning messages to vehicles in the network via DSRC. The authors presented and validated the feasibility and efficiency of the system via a simulation framework using iTETRIS, an open-source simulation platform. The goal was to compare vehicle performance in two simulation scenarios: one with the proposed alert system and the other without it. To evaluate the performance of the system, the coverage efficiency, which is the ratio of the number of vehicles that receive the alert to the number of vehicles entering the hazardous zone, and the cumulative time to collision of all vehicles at every step of the simulation were determined. The simulation was run 30 times for each scenario, and the average was used to derive the results. The results of the study showed that the proposed V2V-based alert system leads to better road safety by having a coverage efficiency of over 85% and a low cumulative time to collision.

RWIS can act as additional RSUs in a CAV-RWIS system where data collected by CAVs and RWIS are combined and disseminated throughout the transportation network. Shi et al. [7] analyzed an intersection collision warning (ICW) application that was based on the exchange of messages between two vehicles using either DSRC or LTE communication devices. The results of the first part of the study, which involved direct V2V communication between the vehicles, showed that the application's effectiveness could not be guaranteed. The second part of the study, in which an RSU was used to help relay the messages between the two vehicles, was more successful. After the introduction of the RSU, the ICW was observed to function effectively at vehicle speeds of 0 to 110 km/h and provided a significant improvement in the package delivery rate but at double the latency.

Since the computational capability required of a given RSU may vary throughout the day based on the number of connected vehicles present, Hoque et al. [8] proposed a framework for drone-based roadside edge server deployment that uses drone-mounted edge computing devices to provide the appropriate number of RSUs to a location based on computational requirements. To evaluate the performance of the proposed framework, an experiment was conducted to analyze the mobility patterns of vehicles at intersections in an urban environment using a simulator. The framework proved to be successful, as virtual drones were booted to the locations where they were needed to help with computational requirements. The number of drones booted depended on the capability of the edge computing devices used and the number of vehicles at the intersection. The authors planned to evaluate the framework with other CAV applications in the future.

CAVs are made up of several sensors that each perform a distinct task. Varghese and Boone [9] evaluated the numerous sensors and systems that are included in CAV systems according to several criteria, including accuracy, resolution, sensitivity, dynamic range, etc. The sensors were divided into those used for internal vehicle systems and those used for external world sensing. Wheel speed sensors, yaw rate sensors, and steering inputs were some examples of sensors used for internal vehicle systems, whereas examples of sensors used for external world

sensing included global positioning system (GPS) modules, radar, lidar, cameras, and V2X communications.

In an effort to enhance road weather services, a study by Bogaerts et al. [10] focused on deploying a fleet of vehicles fitted with external sensors and controller area network (CAN) readers. The external sensors included GPS modules, cameras, gyroscopes, accelerometers, and temperature, humidity, and thermal image sensors. The GPS modules were set to generate a new position every three seconds, and sensor readings and CAN messages were recorded each time a new position was generated. The goal was to predict road weather conditions using the recorded measurements. Timestamps for rainfall events were identified from weather forecasts, and the recorded sensor measurements at those timestamps were examined. The sensor measurements revealed certain patterns that occur when rains start or stop. Future research can build deep learning methods to categorize road weather conditions using these patterns. The research results suggest a possible use for car sensors in relation to road weather conditions.

Using sensors and other smart devices connected to the internet, otherwise known as the internet of things (IoT), to collect road weather data is a possibility. Chapman et al. [11] developed a prototype to test the viability of employing internet-connected sensor data for applications related to winter maintenance. This study took advantage of the Birmingham Urban Climate Laboratory (BUCL), a dense sensor network situated in Birmingham, UK. Although the BUCL's primary objective is to measure urban climate, it is also operationally used to evaluate the condition of infrastructure, in this case conditions requiring winter road maintenance. Adding more temperature sensors to the BUCL by placing sensors on lampposts along a major arterial was the initial step in the study. In addition, front-facing cameras, air and surface temperature probes, and other devices were used to gather information about the state of the road surface. Through wireless communications (Global System for Mobile Communications [GSM]/General Packet Radio Service [GPRS] and Wi-Fi), the data gathered were added to an IoT hub. The trial brought to light a few drawbacks of the IoT strategy. Providing a sufficiently dense sensor network, which is necessary to obtain data representative of the entire region, was one issue. Powering the sensors was another. Although circumstances are rarely optimum, the battery-powered sensors employed were said to last around three years in optimum conditions. These restrictions can be overcome by the dense sensor network that connected vehicles offer.

Vehicle-based sensors were shown to be more accurate than smartphone (iPhone) sensors in a study by Ho et al. [12]. The study used vehicle-based sensors to locate and detect asphalt distresses caused by pavement temperature changes. The testing vehicle used in the study had five sensors installed: four sensors on the tires and one inside the vehicle including a sixth smartphone (iPhone) sensor in the vehicle. The sensors were installed with the intention of creating a low-cost sensing method for evaluating the condition of pavements and consisted of triple-axis accelerometers, computer boards, and a battery. The study involved converting the accelerometer data into identification of cracks on the pavement using GIS software in order to establish a relationship between pavement temperature and accelerometer data. The results showed that there was more noticeable pavement damage when pavement temperature increased and that the sensors installed on the car were more reliable than the iPhone sensors inside the vehicle. This showcases that the vehicle-based sensing approach is an efficient option for enhancing operations in highway pavement maintenance and safety.

The possible role of atmospheric and road condition data derived from vehicle-infrastructure integration (VII) in the analysis and forecasting of weather-related hazards was investigated in a study by Petty and Mahoney [13]. V2V and V2I communications would be made possible by VII. In the investigation, a vehicle equipped with sensors was used to gather data on wiper state, barometric pressure, and air temperature. Another set of data, comprising conventional weather data from the Automated Surface Observing System (ASOS) and radar data from the Detroit Weather Surveillance Radar 88 Doppler (WSR-88D) closest to the time of the vehicle data, were also obtained. The vehicle data and the conventional weather data had a good correlation when the two sets of data were compared, demonstrating the potential benefit of the mobile data.

A similar investigation was carried out in a study by Mercelis et al. [14], where local weather events were monitored using a vehicle fitted with inexpensive external sensors. Wheel speeds and other vehicle dynamics information from the vehicle's CAN bus were logged. The obtained vehicle data were then compared with reliable observations made at road weather stations and were found to be consistent with those observations. There were some anomalies that were assumed to be weather related in the vehicle dynamics data and that may be utilized to identify local weather occurrences. Additional data were supplied by the external sensors, upon which the assumptions were based.

CAV data have a better penetration rate, more widespread coverage, and better, almost lane-level positioning precision compared to other probe vehicle data. Deep learning methods can be applied to CAV data in order to make more accurate estimates in areas that have low to no CAV penetration rates. Khadka et al. [15] developed a framework based on CV data and a deep neural network (DNN) that can be used to estimate regional link volumes. Starting with over 1,000 sites where 100% counts of link volumes were gathered using roadside traffic detectors, the framework generated a training data set by matching CV counts at those sites. It was possible to create an efficient model to estimate counts on all road links using the CV counts due to the strong time-of-day consistency between the link traffic counts and CV counts. Using CV data from other locations, the trained DNN model estimated the corresponding link volumes for those locations. The DNN model was then compared with various estimating techniques such as random forest, polynomial, and linear regression models. The DNN model outperformed the other models by having the highest R^2 value and the lowest mean absolute error. The performance of the DNN model is anticipated to increase as additional infrastructure data are made accessible.

CAVs can have a full awareness of their driving surroundings with the help of resource sharing and collaboration with other CAVs. Innovative cooperative applications can be developed to increase road safety and efficiency (RSE). In order to create cooperative CAV technologies and applications, He et al. [16] proposed a research framework for studying CAV resource sharing methods. Four primary functional layers in a cooperative CAV system were identified, including cooperative sensing, cooperative RSE applications, cooperation among vehicles, and cooperation between vehicles and infrastructure, with all layers coming together to achieve a common purpose of improving RSE. The study also included preliminary research findings related to several identified CAV challenges. These challenges were classified as technical or nontechnical. Communication and sensing concerns were among the technical challenges. One key nontechnical challenge highlighted was a lack of interest from stakeholders, such as automobile manufacturers, CV communications firms, and policymakers, in cooperative CAV technologies.

Highlighting the limitations of conventional RWIS, Kwon [17] identified issues such as unreliable, slow, and nonstandardized communication. The author also noted that the central processing units (CPUs) of RWIS, provided by various suppliers, are unable to communicate with one another. Furthermore, RWIS lack a mechanism to verify the accuracy of the data delivered by sensors. To address these challenges, the author proposed a new generation of RWIS designed around interactive working modules. A comprehensive method was thoroughly outlined to facilitate the development and implementation of this improved system.

Understanding the feasibility of utilizing CAV data may require significant effort due to the diverse data formats and standards present among vehicle manufacturers, among different vehicle models produced by the same manufacturer, and among various sensor types and models [18].

The studies discussed above yielded considerable results, suggesting significant advancement in the integration of CAVs and RWIS. The benefits of integrating CAVs and RWIS can be observed not just in network-level improvements in road safety but also in general traffic flow improvements. Data interchange is more effective when RWIS operate as additional RSUs than when direct V2V interactions are used. CAVs can contribute to the collection and sharing of road weather data while also benefiting from these data in a timely manner. However, in order to handle data more quickly, RWIS/RSUs need to have adequate computational capabilities. Using edge computing can boost the data transfer process by reducing latency.

Practical Considerations for CAV-RWIS Integration

Integrating real-time CAV and RWIS data provides an opportunity to address existing information gaps and improve the overall picture of the conditions of the transportation network. Currently, there are several ways to capture vehicle data, including the use of mounted sensor devices like smartphones, tablets, or other retrofitted sensors; the on-board diagnostics (OBD) II interface; and direct access to CAN bus messages.

One method of determining road surface condition (RSC) is through the use of an automatic RSC monitoring system, where an application is installed on a smartphone device and mounted in a vehicle. The smartphone should have a clear view of the road ahead. The system captures GPS-tagged images of the road as the vehicle moves and sends the images to an online server for processing. After the images are processed, the RSCs are available online for public use. Linton and Fu [19] conducted a study to evaluate the performance of automatic RSC classification relative to manual classification of the recorded images. The study was conducted on a two-way, two-lane, asphalt-surfaced, approximately 70 km long section of a highway in Ontario, Canada, during the winter of 2013–2014. Data from four patrol vehicles, each equipped with a mobile automatic RSC monitoring system, were used in this study. As a spot-wise monitoring tool and based on the classification results of more than 16,000 images, the system was found to have an average classification accuracy of 73%.

In a study by Qian et al. [20], a method was proposed for classifying roads based on their conditions using still frames taken from uncalibrated dashboard cameras. The researchers

encountered challenges such as variability in camera positioning, road layout, and weather and lighting conditions. They utilized a dataset of 100 images taken under different weather conditions and at various times of the day. These images were then manually classified and randomly split into 50 training images and 50 test images. The classification system achieved an accuracy of 80% for two classes (bare versus snow/ice covered) and 68% for three classes (dry versus wet versus snow/ice-covered).

Building on previous smartphone-based road surface condition monitoring research, Linton and Fu [21] conducted a study to combine mobile imaging and RWIS data for improved reliability and accuracy. Although the study used images captured by smartphone cameras mounted in four patrol vehicles, front-facing vehicle cameras employed for lane changing assistance, active cruise control, and collision prevention on modern vehicles could also be utilized. The study focused on two highway sections in Ontario, Canada, and collected RWIS data from three stations on the study highway. A V2I connection between the smartphone-based system and the RWIS station allowed for real-time information exchange on road weather conditions. When RWIS data were incorporated into the image classification results from the cameras, an average improvement of 18% in classification results was observed.

Another method to consider is the use of other smartphone features besides the camera as sensors for identifying road surface conditions. Brunauer and Rehr [22] proposed a method that takes advantage of the smartphone's integrated accelerometer as an in-vehicle data source for tracking bituminous or concrete highway surface conditions. In this study, the vehicle-related vertical acceleration signal and the associated GPS coordinates were recorded and transmitted using an Android-based smartphone app called RoadSense. RoadSense displays the current position of the vehicle and the type of road surface condition on a map, and the data transmitted through the app are processed and stored in remote servers. Smartphones with the RoadSense app were mounted using cellphone holders on the bottom middle of the windshields of three maintenance staff members' vehicles during their daily routine drives. The study revealed that calibrating the readings obtained from the app with respect to the accelerometers used by different smartphones and the cushioning characteristics of different vehicles was challenging using this method. Overall, the findings of the study confirmed that the obtained road surface condition information may complement current maintenance data and serve as a valuable supplementary data source for road operators.

The results of a study by Raddaoui et al. [23] can be used to make informed decisions when designing CV applications and human-machine interfaces (HMI). HMIs are the in-vehicle displays in CVs that communicate information to the driver. The purpose of this research was to evaluate how exposure to CV weather and work zone warning notifications affected the behavior of professional truck drivers in a driving simulator environment. The participants, who were professional full-time truck drivers, drove two scenarios: a baseline scenario and a CV scenario. Each scenario had the same layout and the same driving and weather conditions while the participants navigated work zones on a simulated segment of I-80 in Wyoming. The baseline scenario had no HMI and no CV warnings, while the CV scenario had the HMI activated to display CV warnings. During the test, some notifications were sent to the drivers of the CV scenario. The first was an upcoming fog notification followed by a speed advisory for the impending fog. Four other distinct work zone advance warnings were also communicated to the

drivers downstream. According to the findings of the study, the baseline scenario drivers who did not have any knowledge about the upcoming weather conditions resorted to aggressive braking and deceleration as they moved from clear weather to foggy weather conditions, while drivers in the CV scenario gradually reduced their speeds in anticipation of the upcoming weather conditions. Also, warning drivers of an impending weather event did not cause them to significantly reduce their speed. The drivers' speeds did, however, drop more noticeably in response to the second signal, which suggested an advisory speed.

In order to demonstrate the important role of traffic and road weather services that use advanced communication technologies, Tahir et al. [24] conducted a study to analyze the performance of connected vehicles that exchanged traffic and road weather information over an LTE cellular network and the 5G Test Network (5GTN), a test network for 5G application development and testing, in V2V and V2I conditions. The test track, which was 1.7 km long, was equipped with one 5GTN base station, two RWIS, and various IoT sensors for traffic and weather data collection. For the V2I conditions, a vehicle passing on the test track interacted with the two RWIS, while for the V2V conditions two vehicles on the test track collected road service data such as collision warnings and temperature sensor data. The vehicles used in this study were equipped with dual-mode on-board units (OBUs) (5GTN and LTE interfaces). The results of the study revealed that the two networks performed satisfactorily, as they both fulfilled the minimum requirements to deliver safety messages in V2V and V2I conditions, therefore enhancing road weather data and contributing to road safety.

By developing an android app called ForecastRoad, Stepanova et al. [25] created a system that supplemented data from road weather stations (RWS). This system used cellular data and IEEE 802.11p to collect near-real-time road weather data. Many trucks equipped with ForecastRoad-enabled devices travelled on a 260 km route between two towns. Other meteorological instruments that measure road surface friction and temperature and devices to measure vehicle telematics were installed in the trucks. The trucks served as mobile data collectors, providing and relaying supplemental information to the RWS in addition to being system beneficiaries by receiving information from the RWS. According to an efficiency and cost analysis, one RWS and six trucks would cover 97.5% of the 260 km route with the same efficiency as 12 RWS. It was calculated that utilizing 12 RWS would cost nearly six times as much as using one RWS and six trucks.

To ascertain whether bad weather has an impact on vehicle-based sensors, Ma et al. [26] used an environmental simulation box to evaluate the functionality of key sensors, such as lidar, cameras, ultrasonic radar, millimeter wave (mmWave) radar, etc., under challenging weather conditions. The performance of sensors such as lidar was evaluated in different magnitudes of rain and fog conditions, and average attenuations were compared to those on a clear, sunny day. According to the study's findings, snow, fog, and rain had varying degrees of impact on practically all of the sensors. The accelerometers and gyroscopes, which are part of the inertial navigation equipment, were least impacted by weather conditions.

A study by Atmaca et al. [27] provided a thorough examination of the privacy challenges that arise when vehicles participate in ITS and CAV functions. The privacy issues associated with

each CAV function were found and categorized into three subclasses: data privacy, identity privacy, and location privacy. Recent privacy-preserving approaches based on anonymity, perturbation, and cryptography were identified and investigated. These approaches were used to address privacy concerns. The study did acknowledge, however, that using such approaches can reduce the efficacy of the CAV functions.

The studies discussed above demonstrated how integrating CAVs and RWIS improved the accuracy of current road surface monitoring and classification systems and how deployment of a suitable number of CAVs can lower the number of RWIS stations necessary without reducing system efficiency. Some privacy-preserving approaches were also described, which have the potential to mitigate privacy issues when integrating CAV data with RWIS.

Methods of Communication

DSRC, Wi-Fi, and cellular data connections are examples of low-latency communication solutions that are typically found in connected vehicles. CV communication systems provide anonymous, fast, standardized, and secure communication that enables V2V, V2I, vehicle-to-network (V2N), vehicle-to-pedestrian (V2P), or vehicle-to-device (V2X) applications. V2X incorporates V2V, V2I, V2N, and V2P [2].

DSRC or wireless access for vehicular environments (WAVE) uses IEEE 802.11p technology to support V2V and V2I with the aim of promoting road safety. DSRC makes use of RSUs and vehicles' OBUs. OBUs help vehicles within the coverage area directly communicate with each other (V2V), while the RSUs and OBUs engage in V2I when they communicate with each other [28].

In a study to explore ways of sending safety messages from one vehicle to another with high reliability and low delay, Xu et al. [29] proposed a protocol that is compatible with DSRC architecture. A DSRC simulator was developed based on SHIFT and NS-2, two other well-established traffic simulators. Simulations were carried out to test the sensitivity of the protocol's performance and the reliability of reception under various traffic conditions and vehicle traffic flows. The results showed that the proposed protocol is feasible for vehicle safety message dissemination using DSRC.

A study by Outay et al. [30] investigated the impact of communication among vehicles and between vehicles and infrastructure (V2V and V2I) on traffic safety and CO₂ emissions through simulation. An alert system was proposed that notifies moving vehicles as they approach hazardous zones, like areas with limited visibility, allowing them to slow down, maintain safer distances, and avoid collisions. The alert system involves roadside units or vehicles equipped with an OBE for V2I. V2V can be achieved by equipping vehicles with GPS receivers and DSRC/IEEE 802.11p wireless communication modules. After comprehensive simulation results, the proposed V2V/V2I alert systems were found to help lower the risks of collisions, indicating the effectiveness of the suggested strategy. Also, it was determined that CO₂ emissions were reduced due to smoother speed changes. A hybrid V2X alert system that combines V2V and V2I

communications is currently being investigated and will be used by the authors for further research.

Unfortunately, DSRC suffers from poor scalability. Its performance is relatively poor in non-line-of-sight circumstances and rapidly decreases when the number of vehicles is above a certain threshold [31]. Researchers generally acknowledge these flaws, and as a result several attempts have been made to enhance the performance of DSRC, with the medium access control (MAC) layer protocols receiving the majority of the attention. Most of these enhancements are theoretical, though, as a performance increase has only been demonstrated in simulation and very little real-world testing has been done [7].

Other short-range communications technologies exist but are not suitable for critical ITS applications due to security concerns. In an attempt to investigate the most suitable short-range communications technologies for noncritical ITS applications, Gheorghiu et al. [32] compared the applicability of Bluetooth and ZigBee in V2I communications. In an open space inside a building, two Bluetooth modules and two ZigBee modules (a transmitter and a receiver for both) were set up with a clear line of sight between the two pairs of communicating devices. Devices providing interference were placed between the transmitter and the receiver of the tested communication devices. The message exchange durations were compared for varying message lengths, communication distances, and levels of Wi-Fi interference between the two modules of each mode of communication. The findings indicated that longer messages required longer message transfer times for both types of communications, but ZigBee delivered messages without being overly influenced by interference and had significantly shorter average message delivery times than Bluetooth regardless of the environmental conditions. The majority of the time, Bluetooth exhibited numbers that are unsuitable for most vehicular applications.

An alternative to DSRC is to use cellular networks in what is called C-V2X. C-V2X uses the 5.9 GHz ITS spectrum and is a modification of the IEEE 802.11p standard for DSRC. Currently, long-term evolution vehicle to everything (LTE-V2X) technologies (PC5), which are based on LTE cellular technology, are used for C-V2X and are therefore able to operate in the ITS as well as cellular licensed bands. DSRC only operates in the ITS band [31].

The most crucial issue at this moment may be how superior C-V2X is to DSRC. To determine this, Nguyen et al. [33] modeled the two communication methods at both the link and system levels in a simulation environment. The first scenario of the simulation was done under freeway conditions with vehicles moving at higher speeds, while the second was done in an urban environment with vehicles moving at slower speeds. Even though an advanced DSRC receiver was used in this simulation rather than a more standard C-V2X receiver, the results of the evaluation showed that C-V2X provided significant improvements over DSRC in terms of communication range and either greatly outperformed DSRC or performed as well as DSRC in other respects.

In order to compare the effectiveness of DSRC and LTE, Bey and Tewolde [34] developed networking models using a simulator. The two communication modes were matched against each other in several simulated experiments with different traffic types, maximum allowed latency

times, congestion levels, and ranges. The packet delivery success rate for each mode was evaluated against every parameter in each scenario. When the maximum allowed latency was at its lowest, LTE outperformed DSRC, but as the maximum allowed latency rose, the performance of DSRC improved and approached that of LTE. Because speeds were higher in the highway experiment, DSRC functioned better in cities, but at distances of around 450 m, the packet delivery success rate began to rapidly decline, suggesting a limitation. The simulation results clearly showed that DSRC is functional as long as its specifications are followed. However, it might still be strengthened to make it more resilient against performance degradations under particular conditions. The use of fourth generation (4G)/LTE can bring about this improvement.

The emergence of 5G mobile networks introduces the possibility of faster speeds and even lower latency compared to LTE. This is evident in a study by Tahir et al. [24], which analyzed the performance of connected vehicles that exchanged traffic and road weather information over LTE and 5GTN cellular networks in V2V and V2I conditions. The results of the study revealed that the two networks performed satisfactorily. However, 5GTN, which supports ultra-low latency networking, performed better during the measurements. 5GTN had fewer packet losses, a higher network connectivity range, and a more stable and higher average throughput compared to LTE.

The performance and scalability issues with DSRC (IEEE 802.11p) and C-V2X (PC5) have been major areas of concern. This has led to the development of newer generation IEEE 802.11bd and C-V2X5G NR networks and discussions of a hybrid V2X that bridges the gap by using at least one iteration of DSRC and at least one iteration of C-V2X technology. However, Ansari [31] lists some potential problems of running a hybrid system, such as adjacent-channel interference, which can occur when the two technologies are in adjacent channels and their transmitters come in close proximity to each other, and harmful co-channel interference, which can occur if the two technologies are in the same channel without a mutual synchronization solution.

In a study by Dey et al. [35], the effectiveness of a heterogeneous network (Het-Net) composed of Wi-Fi, DSRC, and LTE technologies was evaluated for its ability to facilitate V2V and V2I communications in two case studies: (1) CAV traffic data collection and (2) CAV safety applications. In the first case study, Wi-Fi and LTE were found to extend the range of vehicle communication. Using a handoff method developed in the study, switching between Wi-Fi and LTE took approximately 25 seconds, while transitioning between DSRC and LTE took around 6 seconds. Despite the long handoff delays, the study demonstrated that Het-Net could effectively handle traffic data collection applications. In the second case study, vehicles within DSRC range could transmit safety messages with latencies lower than the required minimum of 200 milliseconds, while those outside of DSRC range could not receive safety warnings within the required minimum time via LTE. However, these vehicles were further upstream, so even if the safety messages were transmitted with greater latencies, there was still ample time for the vehicles to react to the event. Het-Net can be deployed as a complementary solution to provide advance warning for vehicles upstream and outside of DSRC range. To supplement and validate the field test results, simulation experiments with a larger number of connected vehicles were conducted. The simulated results and the outcomes of the field experiments showed a strong similarity.

Interworking between DSRC and cellular network technologies, which can be based on a flat or hierarchical DSRC-cellular hybrid architecture, is a viable way to serve V2X applications. Future V2X solutions should find a compromise between a number of factors, including installation costs, performance in actual vehicle environments, and compatibility with current V2X systems [36].

Another V2V communication technology based on mmWave has emerged as a potential technology for transmitting large amounts of sensor data. mmWave specifically refers to the radio spectrum between 10 GHz and 300 GHz. This high band is highly susceptible to obstructions and is best for short-range and high-performance applications.

Chen et al. [37] proposed a scheme for broadcasting vehicular sensor data using mmWave. According to simulation results, the proposed scheme has a greater delivery rate than the typical first-in-first-out scheme. Under various simulation scenarios, the suggested method has a maximum transmission latency that is approximately 30% lower than that of the conventional method, suggesting that the proposed scheme outperforms the traditional method in terms of broadcasting delay.

AASHTO [38] identified that state and local agencies face uncertainty due to the federal government's lack of guidance on communication protocols for V2V and V2I, including whether to use DSRC, 5G, or both. This ambiguity may be contributing to the delayed progress of CAV integration into fleets and facilities. As a result, the authors recommended that the U.S. DOT continue its efforts to establish a national standard for V2V safety communications, enabling the development and implementation of CAV applications more effectively.

The benefits of integrating CAVs and RWIS are reciprocal. As CAVs step in to close the information gap, offering a more thorough understanding of road conditions to enhance maintenance practices, reduce delays, and improve incidence response times, motorists will also be able to better plan their trips in light of road conditions through this integration [39].

The studies described above cover the various communication methods for CAVs and RWIS. Compared to Bluetooth, ZigBee was found to be more appropriate for noncritical ITS applications. DSRC has limited scalability, poor performance in non-line-of-sight situations, and only functions in ITS bands. In contrast, C-V2X operates in both ITS and cellular licensed bands, supports low-latency networking, and surpasses DSRC in terms of communication range. C-V2X can be based on LTE or 5G. Because of its fewer packet losses, greater network connectivity range, and more consistent and higher average throughput, 5G is superior to C-V2X. mmWave is another high-band communication technology that is well-suited for high-performance applications but has the disadvantage of being very vulnerable to obstructions. The lack of direction from the federal government regarding V2V and V2I communication protocols may be the reason for the slow pace of CAV integration into fleets and facilities.

Current Practice

RWIS is being used by DOTs to improve safety and mobility, especially in inclement weather. RWIS is used to reduce drivers' exposure to dangerous weather-related road conditions, boost the efficiency of winter maintenance, increase the quantity of interactive information provided to travelers, reduce traffic congestion and delays, and serve other needs [40–42].

The Minnesota Department of Transportation (MnDOT) currently maintains about 93 remote collecting stations that give near real-time surface and atmospheric information in order to provide the data needed to successfully operate and maintain the state transportation system. Although these data are primarily meant for internal use, they are posted online for public access [43].

To aid with winter weather operations, the Pennsylvania Department of Transportation (PennDOT) has so far placed over 50 RWIS sensors around the state. In addition to winter weather, other severe weather disasters, such as flooding and tornadoes, that result in unsafe road conditions and necessitate emergency transportation operations are detected [41].

Some DOTs have plans to integrate CAVs into their systems for detecting road surface conditions and forecasting road weather [44–47]. The short-, mid-, and long-term objectives of the Pennsylvania Turnpike Commission's CAV program roadmap include incorporation of CAVs into its road weather safety and traffic incident management targets [2]. The MnDOT RWIS integration and deployment document offers a sample test plan to allow testing and validation operations to guarantee that the system is developed, deployed, and operating in line with the system requirements. Among the system needs with regard to CAV infrastructure is the capacity to exchange warning messages and information about the state of the roads between CAVs and RWIS [48].

Integrating CAVs and RWIS will involve upgrading the skills of agency workforces. In a report by Fard et al. [49], recruiting and retaining tech-savvy employees for emerging technologies is discussed. The report provides recommendations for training materials for present and future staff as well as the ideal core skills required at the Michigan Department of Transportation (MDOT). Some of the suggested technical skills include cloud computing, data science, building information modeling, and IoT software development. Based on interviews with MDOT employees, Fard et al. [50] also suggest in a separate report that data management training be offered to enable the analysis and application of CAV data. According to the report, CAV databases are enormous, and workers will require the ability to identify problems, validate data, and use data to address transportation-related problems. The New York State Department of Transportation (NYSDOT) has recognized a gap in its approach to addressing mobility and reliability challenges in the state by identifying the need to upgrade its equipment and systems and the need for new workforce skills to cope with quickly changing technologies like CAVs [51].

Since local agencies generally do not have the resources to prepare for the widespread implementation of CAVs, Hallmark et al. [52] created a toolbox to summarize the information

they may need. The information provided in the report helps local agencies make use of existing programs and resources to prepare for CAVs in the short term. Local agencies can gradually integrate CAV technology into their road systems by addressing infrastructure needs such as pavement marking, signing, pavement maintenance, consistency and standardization, data capture and information sharing, and inventory and communication infrastructure.

In a report prepared for the National Capital Region Transportation Planning Board [53], the possible effects of CAVs on transportation planning are categorized into travel, social, and organizational impacts. Travel impacts include the direct effects of CAVs on public mobility, social impacts include the general societal issues of CAV integration, and organizational impacts include the effects that CAVs may have on the operations and duties of infrastructure owners and operators. The authors suggest that CAV integration be considered in both current projects and future travel modeling and analysis.

Although there are advantages to the integration of CAVs and RWIS or other corridor management systems, there are also difficulties. The benefits and challenges of CAV integration are examined in a primer by McGuckin et al. [39], which also contains a detailed discussion of the institutional, operational, and technological factors that influence effective integration. Stakeholders in institutional integration are those who provide the public with CAV services. These stakeholders are responsible for setting standards, ensuring data security and privacy, and formulating regulations that govern how CAV data should be used. Incompatible data standards and a lack of cross-network device-to-device connectivity are two examples of the technical difficulties that CAV integration efforts will face.

Overview of the Current Practices of DOTs

U.S. DOT

CAVs have the ability to greatly improve traffic operations and the maintenance of roadway infrastructure and to provide potential benefits for road users in terms of safety. Therefore, research on CAVs is of utmost importance. The FHWA takes the lead in CAV research as well as the secure development, evaluation, and implementation of autonomous vehicle technology by performing outreach activities, updating policies and guidance, and identifying research areas related to CAVs [54].

In order to identify areas of interest and incorporate automated vehicle considerations into FHWA programs and regulations, the FHWA has started a discourse with partners, stakeholders, and the general public with the creation of the National Dialogue on Highway Automation. Planning and policy, digital infrastructure and data, freight, operations, infrastructure design, and safety are the focus areas of the National Dialogue on Highway Automation. Original equipment manufacturers (OEMs), technology providers, transportation network companies (TNCs), state and local agencies, and public sector partners are just a few examples of stakeholders [55].

The FHWA's Policy and Strategy Analysis Team is actively involved in research on emerging technologies related to transportation. Some of this research includes incorporating CAVs into transportation planning processes and products. With the help of this research, state DOTs and metropolitan planning organizations (MPOs) will be able to properly prepare for the integration of CAV technologies into planning processes by examining the effects of CAVs on planning tools, methodologies, and data as well as by identifying the skills, knowledge, and training needed to accommodate CAV integration [56].

The federal government's involvement in research on transportation automation is mentioned in a recent U.S. DOT report [57]. The U.S. DOT seeks to remove needless impediments to innovation, particularly those resulting from current regulations, by identifying these impediments and devising strategies to do address them. Additionally, the U.S. DOT creates and validates projections of the effects of automation on safety, the state and performance of infrastructure, mobility, and the competitiveness of the US economy. The U.S. DOT encourages and supports the testing and development of automation technology across the nation with the fewest restrictions necessary for safety.

A report from the National Science and Technology Council (NSTC) and the U.S. DOT [58] outlines the federal government's efforts to support the growth of automated vehicle technology. The development of high-speed communications technology to facilitate V2V and V2X data sharing is one of the goals of the Federal Communications Commission (FCC). The NSTC has also outlined a plan for making high-quality science, technology, engineering, and math (STEM) education more widely available. Additionally, the American AI Initiative, introduced in 2019, directs federal organizations to pursue a multifaceted strategy to enhance artificial intelligence (AI) and offer educational and training opportunities to equip the American workforce for AI.

State DOTs

California Department of Transportation

The District 4 CAV Test Bed in California, the first public connected vehicle test bed in the United States, was established by the California Department of Transportation (Caltrans) in 2005 in collaboration with the Metropolitan Transportation Commission (MTC) and California Partners for Advanced Transportation Technology (PATH). In a subsequent collaboration with the U.S. DOT, Caltrans and PATH updated the test bed's equipment to bring it up to speed with the most recent connected vehicle implementation architecture and standards. The effective demonstration of CV-based traffic signal control and signal prioritization for transit, freight, and pedestrians was made possible by these advancements. As of 2019, there are 31 junctions in the test bed, up from the 11 initial intersections. The equipment used in the test bed consists of 16 DSRC and 15 C-V2X RSUs. This corridor for connected vehicles is anticipated to act as a prototype for similar deployments on routes in other urban areas of California. Caltrans is collaborating with PATH and ProspectSV to make sure that the test bed is accessible to all developers in order to evaluate the real-world performance of connected vehicle technologies [59].

Other Caltrans CAV projects include projects in Districts 11 and 12 [60]. These projects involve setting up RSUs at specific points in the area, for example, along road corridors and ramp meter locations. To evaluate V2I safety and mobility applications, CAV services such as queue warnings, upcoming work zone warnings, signal phase and timing (SPaT) messages, basic safety messages (BSMs), transit priority warnings, and wrong way driving warnings will be implemented. The information gathered from connected vehicles are expected to increase the situational awareness of the traffic management centers (TMCs) in these areas and give road users access to real-time traffic updates and safety alerts, with the goal of improving highway operations. The mobility of public and emergency vehicles is also expected to increase because to the connected vehicle infrastructure.

Virginia Department of Transportation

An extensive amount of prototyping and testing is required for agencies to fully grasp the difficulties and advantages of CV implementation. The Virginia Connected Corridors (VCC) project was developed through a collaboration between the Virginia Department of Transportation (VDOT) and the Virginia Tech Transportation Institute (VTTI) to aid in the understanding of CV deployment. CAV application development and evaluation are made possible by the VCC project, which is a CV environment with more than 60 RSUs. These RSUs are connected to a low-latency backhaul network using cellular and DSRC technologies. The VCC project works to create an open application development environment where third-party developers who are interested in developing and testing in a real-world CV environment can submit their applications. Depending on what is most suitable, developers may either construct applications that operate directly on the VCC cloud computing environment or access VCC data through a public application programming interface (API) [61].

Pennsylvania Department of Transportation

PennSTART, a cutting-edge training and testing center, is being developed in partnership with the Pennsylvania Turnpike Commission (PTC). The primary goal of PennSTART is to meet the state of Pennsylvania's and the Mid-Atlantic region's transportation demands regarding operations and safety. Emergency responders, transportation agencies, and research facilities will all benefit from the PennSTART test track facility. Examples of technologies that may be tested include traffic incident management (TIM) systems and new ITS equipment [62].

In addition, transportation agencies, research organizations, and universities in Pennsylvania, Ohio, and Michigan have formed the Smart Belt Coalition to concentrate on CAV programs. This coalition brings together experts on various technologies to advance research, testing, policy, financing efforts, and implementation. It also allows for data sharing and offers special possibilities for testers in the business sector [62].

Georgia Department of Transportation

The state of Georgia has made significant investments in CV and automated signal technology. While only 6 of the 654 licensed and deployed RSUs had C-V2X compatibility as of February 2021, there were still 330 DSRC RSUs to be deployed, and all upcoming deployments were expected to support both DSRC and C-V2X. Several CAV pilot applications were also underway as of February 2021, including emergency vehicle preemption, transit signal priority, incident responder interchange preemption, and freight-centered pilot applications in collaboration with Georgia Ports Authority. Some of the services offered by the pilot applications included the installation of RSUs, broadcasting of SPaT and MAP traveler information messages related to road conditions, and demonstration and implementation of freight signal priority applications. In order to regionally deploy CAV infrastructure that operates in the 5.9 GHz safety band, the Georgia Department of Transportation (GDOT) collaborated with the Atlanta Regional Commission (ARC) and local governments on the Regional Connected Vehicle Program [63].

Other State-Level Connected Vehicle Deployments

Table 2 shows the operational connected vehicle deployments by state according to the U.S. DOT [64].

Table 2. Operational connected vehicle deployments

| State | Deployment |
|------------|--|
| Alabama | <ul style="list-style-type: none"> • University of Alabama, ACTION Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) • University of Alabama, Center for Advanced Vehicle Technologies and Alabama DOT |
| Arizona | <ul style="list-style-type: none"> • Arizona Connected Vehicle Test Bed (Anthem) |
| California | <ul style="list-style-type: none"> • California Connected Vehicle Test Bed, Palo Alto • Prospect Silicon Valley Technology Demonstration Center ITS Lab • San Jose Connected Vehicle Pilot Study |
| Colorado | <ul style="list-style-type: none"> • Denver ATCMTD • US RoadX Connected Vehicle Project |
| Delaware | <ul style="list-style-type: none"> • Delaware DOT SPaT Challenge Deployment |
| Florida | <ul style="list-style-type: none"> • Gainesville SPaT Deployment • Osceola County Connected Vehicle Signal Project • Pinellas County SPaT • Seminole County SR434 CV Deployment • Smart Work Zones • Tallahassee US 90 SPaT Challenge Deployment • Tampa Hillsborough Expressway Authority Connected Vehicle Deployment |

| State | Deployment |
|----------------|---|
| Georgia | <ul style="list-style-type: none"> • City of Atlanta Smart Corridor Demonstration Project • GDOT Connected Vehicle ATCMTD • GDOT SPaT Project • Gwinnett County Connected Vehicle Project • I-85/“The Ray” Connected Vehicle Test Bed • Infrastructure Automotive Technology Laboratory • Marietta, Georgia, Emergency Vehicle Signal Preemption • North Fulton Community Improvement District |
| Hawaii | <ul style="list-style-type: none"> • Hawaii DOT DSRC Deployment |
| Idaho | <ul style="list-style-type: none"> • Ada County Highway District |
| Indiana | <ul style="list-style-type: none"> • Indiana Connected Vehicle Corridor Deployment Project |
| Maryland | <ul style="list-style-type: none"> • I-895 Baltimore Harbor Tunnel DSRC • I-95 Fort McHenry Tunnel DSRC • US 1 Innovative Technology Corridor |
| Massachusetts | <ul style="list-style-type: none"> • Hope TEST |
| Michigan | <ul style="list-style-type: none"> • American Center for Mobility (Willow Run) • Ann Arbor Connected Vehicle Test Environment • Detroit ATCMTD • I-75 Connected Work Zone (Oakland County) • Lansing DSRC Deployment • Macomb County Department of Roads (MCDR) DSRC Deployment (MCDR/Sterling Heights Fire Department) • MCDR DSRC Deployment (MDOT/General Motors SPaT Pilot) • MCDR DSRC Deployment (MDOT/SMART Pilot) • MCity Test Bed • MDOT Wayne County Project • MDOT I-94 Truck Parking Information and Management System • Road Commission for Oakland County DSRC • Safety Pilot Model Deployment • Smart Belt Coalition (Michigan) • Southeast Michigan Test Bed • U.S. Army Tank Automotive Research, Development and Engineering Center “Planet M Initiative” |
| Minnesota | <ul style="list-style-type: none"> • MnDOT DSRC • Roadway Safety Institute Connected Vehicle Test Bed |
| Nevada | <ul style="list-style-type: none"> • Las Vegas Freemont Street SPaT Corridor • I-580/Washoe County, Nevada |
| New Hampshire | <ul style="list-style-type: none"> • New Hampshire DOT SPaT, Dover |
| New Jersey | <ul style="list-style-type: none"> • City of New Brunswick Innovation Project • Integrated Connected Urban Corridor, Newark |
| New York | <ul style="list-style-type: none"> • New York City Connected Vehicle Project Deployment • NYSDOT Long Island Expressway INFORM I-495 Demonstration Test Bed • New York State Thruway Test Bed |
| North Carolina | <ul style="list-style-type: none"> • North Carolina DOT DSRC |

| State | Deployment |
|--------------|--|
| Ohio | <ul style="list-style-type: none"> • City of Columbus – Smart City Challenge • NW US33 Smart Mobility Corridor • Ohio Turnpike and Infrastructure Commission DSRC Project |
| Pennsylvania | <ul style="list-style-type: none"> • Pennsylvania Turnpike Harrisburg Connected Corridor • PennDOT Harrisburg Demonstration • PennDOT Ross Township Test Bed • PennDOT SPaT Deployments and Test Beds • Philadelphia SPaT • Smart Belt Coalition • SmartPGH |
| Tennessee | <ul style="list-style-type: none"> • Tennessee DOT SPaT Challenge Project (Knoxville) |
| Utah | <ul style="list-style-type: none"> • Provo Orem Bus Rapid Transit • Salt Lake Valley Snowplow Preemption • Utah Transit Authority DSRC Traffic Signal Pilot Project |
| Virginia | <ul style="list-style-type: none"> • Fairfax County Connected Vehicle Test Bed • Virginia Smart Roads |
| Washington | <ul style="list-style-type: none"> • Washington State Transit Insurance Pool Safety-Collision Warning Pilot Project |
| Wisconsin | <ul style="list-style-type: none"> • Connected Park Street Corridor |
| Wyoming | <ul style="list-style-type: none"> • Wyoming Connected Vehicle Project Deployment |

Source: [64]

Table 3 shows the planned connected vehicle deployments by state according to the U.S. DOT [64].

Table 3. Planned connected vehicle deployments

| State | Deployment |
|--------------|--|
| Alaska | <ul style="list-style-type: none"> • Alaska University Transportation Center |
| Arizona | <ul style="list-style-type: none"> • Loop 101 Mobility Project |
| California | <ul style="list-style-type: none"> • City of Fremont Safe and Smart Corridor • City of San Francisco ATCMTD • Contra Costa Automated Deployment Services (ADS) • Contra Costa ATCMTD • Freight Advanced Traveler Information System (FRATIS) • Los Angeles DOT Implementation of Advanced Technologies to Improve Safety and Mobility within the Promise Zone • San Diego 2020 ATCMTD |
| Colorado | <ul style="list-style-type: none"> • Colorado Better Utilizing Investments to Leverage Development (BUILD) • Colorado Transportation Investment Generating Economic Recovery (TIGER) • Colorado DOT Wolf Creek Pass ATCMTD |
| Delaware | <ul style="list-style-type: none"> • Delaware DOT ATCMTD |

| State | Deployment |
|---------------|---|
| Florida | <ul style="list-style-type: none"> • ATCMTD I-Frame • Automated and Connected Vehicle Technologies for Miami’s Perishable Freight Industry Pilot Demonstration Project • CAV Freight SR-710 • Central Florida AV Proving Ground • Connected Freight Priority System Deployment • Downtown Tampa AV Transit • I-75 Frame Ocala • Jacksonville BUILD • Lake Mary Boulevard CV Project • PedSafe Orlando • N-MISS • Pinellas City 2020 ATCMTD • SunTrax (Florida Turnpike) • University of Florida Pedestrian and Bicycle Safety • US 1 Keys Coast • US 98 Smart Bay |
| Georgia | <ul style="list-style-type: none"> • CV-1K+ Project |
| Hawaii | <ul style="list-style-type: none"> • Hawaii DOT C-V2X Project |
| Indiana | <ul style="list-style-type: none"> • Indiana DOT SPaT Deployment - Greenwood • Indiana DOT SPaT Deployment - Merrillville |
| Iowa | <ul style="list-style-type: none"> • Iowa City ADS |
| Kentucky | <ul style="list-style-type: none"> • Louisville TIGER |
| Maine | <ul style="list-style-type: none"> • Maine BUILD • Maine DOT 2020 ATCMTD |
| Massachusetts | <ul style="list-style-type: none"> • Mass DOT DSRC Route 9 DSRC Corridor |
| Michigan | <ul style="list-style-type: none"> • Michigan ADS • Michigan BUILD • Michigan TIGER • MDOT Intelligent Woodward Corridor Project • University of Michigan 2020 ATCMTD |
| Missouri | <ul style="list-style-type: none"> • Kansas City US 69 Corridor SPaT Challenge • Springfield, Missouri, SPaT Project • St. Louis SPaT Deployment Project |
| Nebraska | <ul style="list-style-type: none"> • Nebraska Integrated Corridor Management (ICM) • Nebraska TIGER |
| Nevada | <ul style="list-style-type: none"> • Las Vegas BUILD • RTC 2020 ATCMTD |

| State | Deployment |
|----------------|--|
| New Jersey | <ul style="list-style-type: none"> • Route US 322 and US 40/322 Adaptive Traffic Signal (ATS) Project, Pleasantville, New Jersey • Route 23, Route 80 to CR 694 (Paterson Hamburg Turnpike), ATS C#1 • Route 29, Route 295 to Sullivan Way, ATS C#1, Hamilton Township and Trenton • Route 38, Route 70 to Union Mill Road, ATS C#1, Camden County • Route 40, CR 606 to Atlantic Ave Intxn, Rt 50, Rt 40 to Cedar St ATS C#1, Atlantic City • Route 46, Main St/Woodstone Rd (CR 644) to Rt 287, ITS, Parsippany-Troy Hills • Route 46, Route 23 (Pompton Ave.) to Rt 20, ITS, Clifton Township • Route 46, Route 287 to Route 23 (Pompton Ave), ITS, Fairfield • Route 73, Haddonfield Road to Delaware River, ATS C#2, Pennsauken Township Camden County • Route 1T and Route 440 by Communipaw Ave, Jersey City, ATS C#1, Jersey City • Route 18, Paulus Blvd to Route 287 SB Ramp, ATS C#2, Piscataway |
| New York | <ul style="list-style-type: none"> • Connected Region: Moving Technological Innovations Forward in the Niagara International Transportation Technology Coalition (NITTEC) Region |
| North Carolina | <ul style="list-style-type: none"> • North Carolina DOT Multimodal CV Pilot |
| Ohio | <ul style="list-style-type: none"> • Ohio ADS • Smart Belt Coalition (Ohio) |
| Oregon | <ul style="list-style-type: none"> • Oregon ATCMTD |
| Pennsylvania | <ul style="list-style-type: none"> • Pennsylvania ADS • PennDOT I-76 Multimodal Corridor Management Project |
| South Carolina | <ul style="list-style-type: none"> • South Carolina Connected Vehicle Test Bed |
| Tennessee | <ul style="list-style-type: none"> • Chattanooga Smart City Corridor Test Bed • Metro Nashville 2020 ATCMTD • Tennessee DOT I-24 Corridor Nashville |
| Texas | <ul style="list-style-type: none"> • Arlington Cooper St. CV2X Project • Automated and Connected Vehicle Test Bed to Improve Transit, Bicycle and Pedestrian Safety • ConnectSmart - Houston • Dallas 2020 ATCMTD • Houston TIGER • Texas Connected Freight ATCMTD • Texas ADS • Texas I-10 ATCMTD |
| Utah | <ul style="list-style-type: none"> • Utah DOT Connected Utah ATCMTD • Utah 2020 ATCMTD • Utah DOT CV Data Eco-system Project |
| Virginia | <ul style="list-style-type: none"> • Virginia ADS • Virginia Port 2020 ATCMTD • Virginia Truck |

| State | Deployment |
|------------|--|
| Washington | <ul style="list-style-type: none"> • Washington State DOT SPaT Challenge (Poulsbo) • WSDOT SPaT Challenge Project (Spokane) • WSDOT SPaT Challenge Project (Vancouver) • WSDOT SPaT Projects in Lake Forest Park/Kenmore |
| Wyoming | <ul style="list-style-type: none"> • Wyoming BUILD |

Source: [64]

Challenges and Recommendations Identified from the Literature Review

Developing a CV network comes with several challenges that must be addressed to ensure scalable, robust, low-latency, and high-throughput technologies for safety applications. While CVs offer significant advantages in terms of safety, economy, road efficiency, and mobility, there are inherent shortcomings and technological obstacles to consider.

Dependency on High Penetration Rates of CVs and Large Numbers of RSUs

CAV technology relies on message exchange to create mutual awareness, which requires a high CAV penetration rate. Increasing the density of roadside units and encouraging more private cars to participate in the CV network are essential for gathering more data [4, 16].

Data Size/Computing Requirements

CAVs produce enormous amounts of data, which makes CAV data more difficult to process and store than standard traffic data. There is a need to increase server speeds and capacities to handle the demands for data processing and a need to develop innovative ways to store the data [4, 15, 16]. Since computation, communication, and storage resources are major constraints for CAVs, mobile edge computing offers a practical way to serve safety applications at the network edge. Also, appropriate algorithms must be created to transform raw data from connected vehicles in a timely manner into information that will be useful [16].

Privacy

CAV data are used for many different functions and are shared with other applications. These data contain sensitive personal, commercial, or research-related information. The need to protect CAV users' privacy in terms of identity and location arises from the ways CAV data are used [65].

Communication Range, Sensing Range, and Latency

Communication range and latency are of utmost importance for CAV applications. For example, CAVs require a communication latency lower than 200 ms to be able to support safety applications. A challenge identified in the literature is to find a communication method that

provides an adequate range and the minimum (or lower) latency required to support safety and other CAV applications [16, 35, 36]. Since mmWave technology produces lower latencies than other technologies, extensive research should be conducted on improving the range and line of sight qualities of this technology [16].

Communication Standards

The lack of standards for V2V safety communications may be a cause of the delays in CAV integration. Developing and implementing national standards for CAV applications will provide guidance on V2X communication protocols and promote effective communication between different CAV system components made by different manufacturers [17, 38].

SURVEY OF AGENCIES

State and local transportation agencies were surveyed to investigate their investments in RWIS technologies, including traditional, portable, mini, modular, and mobile RWIS, to support CAV integration and the impact of these investments on leveraging the rapidly expanding CAV space. The survey was developed using Qualtrics (Appendix A), and a link to the survey was emailed to various state and national committees. The survey received a total of 54 responses from 46 state DOTs, local government agencies, and consultants or toll authorities.

The survey was grouped into six sections. Section 0 collected the respondent's information. In Section I, organizations were asked about their investments in RWIS technologies to leverage and accommodate CAVs. Section II concentrated on investments in information technology (IT) and data management technologies to enable data exchange between RWIS and CAVs. Section III investigated maintenance practices that would benefit from CAV-RWIS integration and changes in maintenance practices that would be required to facilitate seamless leveraging of CAV infrastructure for RWIS applications. Section IV explored agencies' investments in workforce development and collaborations with various stakeholders to adapt or leverage the CAV industry for RWIS applications, and Section V examined agencies' investments in the development of standards and protocols to accommodate CAVs. Figure 1 shows the states participating in the survey.

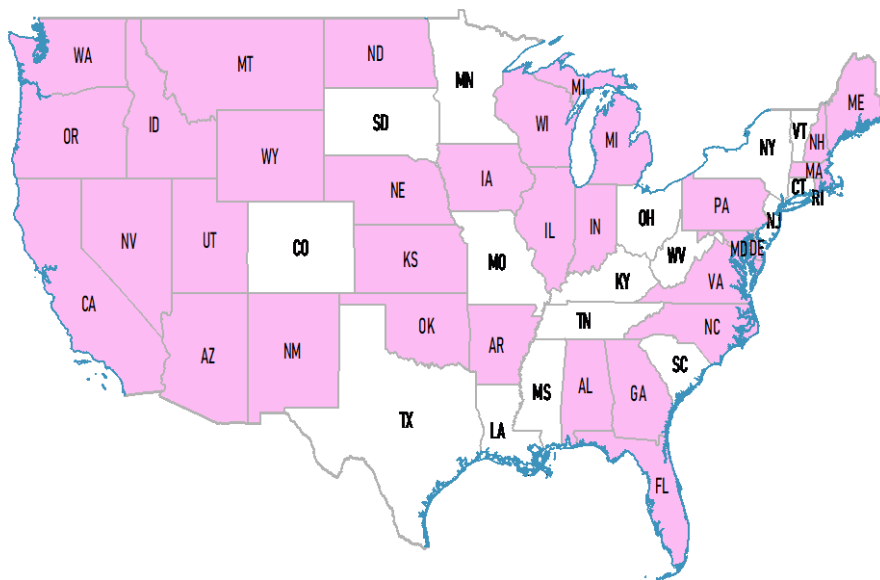


Figure 1. States participating in the survey

The survey was structured in such a way as to differentiate between the investments currently in place and investments planned for the near future (within the next three years). Each section included key questions that, based on the response, asked a set of follow-up questions to obtain more detail about the response to the question. The questions in each section were as follows:

Investment in RWIS Technologies to Support CAV Integration:

- Have there been any investments in the following technologies in relation to RWIS? i. Sensor technology (addition, replacement, upgrading) ii. RPU [remote processing unit] (addition, replacement, upgrading) iii. CPU (addition, replacement, upgrading) iv. Storage and data integration (addition, replacement, upgrading)
- What was the motivation behind the investments?
- Have there been any other investments in RWIS technology to be compatible with CAVs, such as a proof-of-concept demonstration, testing, or a market survey of available options?
- Do you plan to make any investments in RWIS technology to be compatible with CAVs in the next three years?

Investments in IT and Data Communication and Management Technology:

- Have there been any recent investments in IT and data communication and management technology?
- What was the reason for the recent investments in IT and data communication and management technology?
- Do you plan to make investments in IT and data management and communication technology specific to RWIS toward CAV integration in the next three years?

Maintenance Practices:

- What maintenance practices is your agency interested in that will benefit from CAV integration into RWIS?
- Are there any partnerships or collaborations with other stakeholders (e.g., other agencies, private companies, research institutions) in the development or implementation of maintenance practices for CAV-RWIS integration?
- Are there any lessons learned or best practices your organization has identified from its maintenance requirements and practices to support CAV-RWIS integration?

Workforce Development:

- Have there been any updates to the agency's workforce skills to handle the integration of CAVs?
- Has your agency been involved in any collaboration between RWIS and CAV stakeholders including other DOTs, OEMs, private companies, and academia?

Development of Standards:

- Is your agency involved in the development of standards and protocols for RWIS communication and data exchange to accommodate CAV integration?

- Will your agency be involved in the development of standards, new data formats, and protocols for exchanging RWIS data with CAVs within the next three years?

In cases where multiple participants within an agency responded to the survey, their responses were combined using a ranking system (described in the following chapter). For instance, if one participant indicated that the agency had invested in upgraded technology and another indicated that the agency had yet to integrate CAVs, the response with the highest rank was included in the aggregated response for the state.

A summary of survey responses is provided in the following sections.

Section 0 asked respondents for their information. The responses revealed that 72% of participating organizations were state DOTs, 22% were local governments, and 5% were consultants or toll authorities (Figure 2).

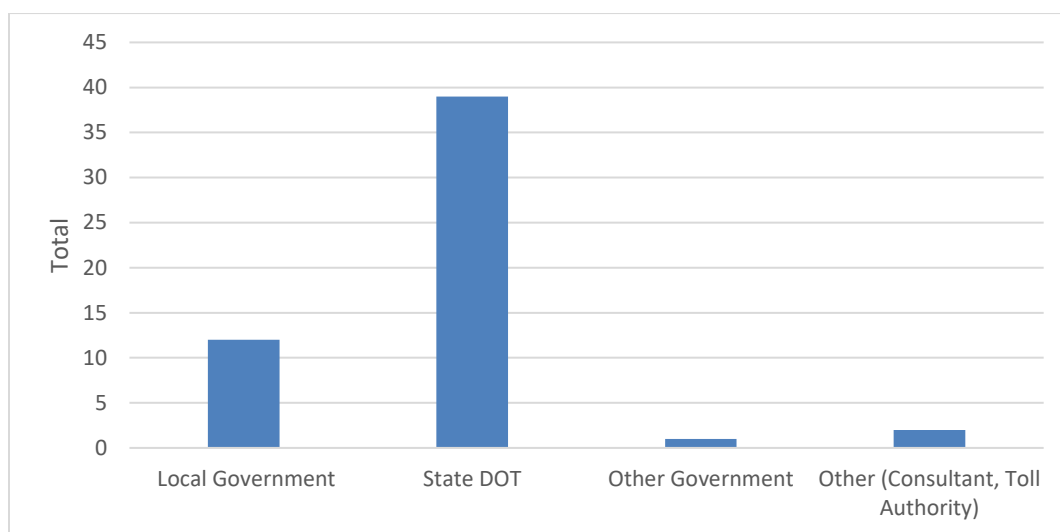


Figure 2. Type of organization

Investment in RWIS Technologies to Support CAV Integration

Question 1.1 Which RWIS technologies has your organization invested in or plan to invest in to support CAV integration?

Less than half (27 out of 58, or about 47%) of the responding organizations have invested in or plan to invest in traditional RWIS technology (Figure 3). Of those, 64% are state DOTs and 8.3% are local government organizations. Other types of investments made or planned included mobile, mini, portable, and modular RWIS, and eight agencies responded with “other.” While three of these eight agencies responded with “none” or “no decision,” five of the “other” responses included the following:

- Evaluating virtual services
- Mobile (MARWIS), RPU to CPU link includes fiber and cellular, investment in next three years is possible not confirmed
- RWIS hardware and applications are used to monitor road weather conditions to support our snow and ice program.
- We have traditional, are in the process of trying a few mini sites, and have a current research project underway to evaluate the future potential of mobile. None of our current RWIS network has been directed for CAV integration.
- Not specifically for CAV integration

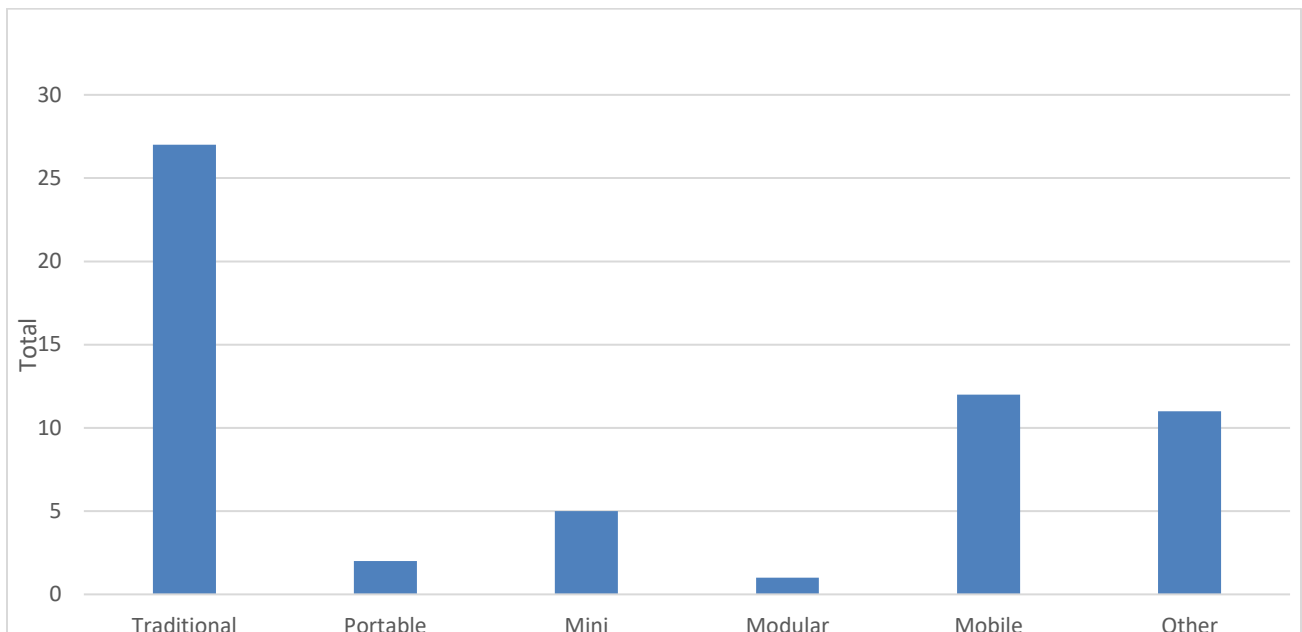


Figure 3. Type of RWIS technology investment made or planned

Question 1.2: What is the communication method between: i. Sensor and RPU ii. RPU and CPU?

The most commonly used method of communication between sensor and RPU is cable (15 out of 37, or 40.5%), while cellular (17 out of 35, or 48.6%) is the most commonly used method of communication between RPU and CPU. Summaries of the responses are provided in Figure 4 and Figure 5, respectively.

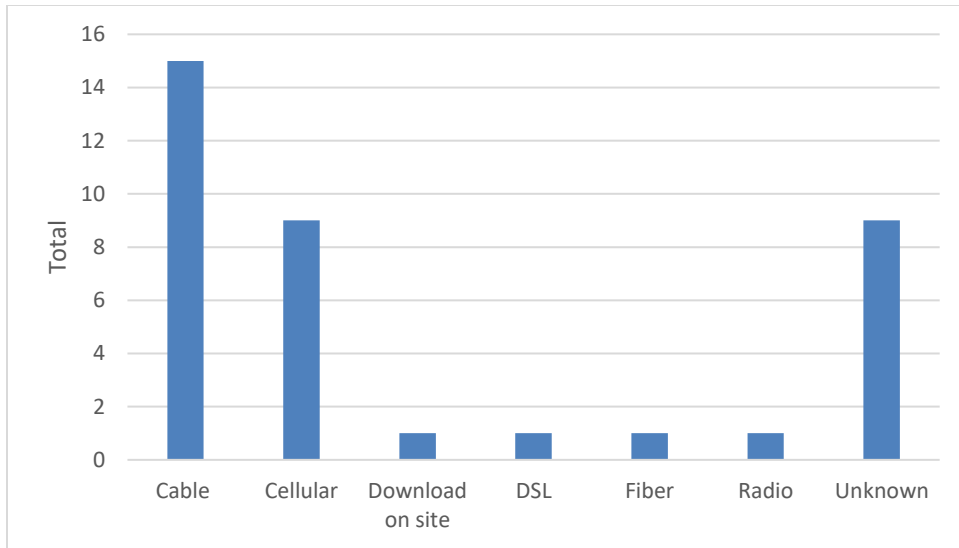


Figure 4. Communication method between sensor and RPU

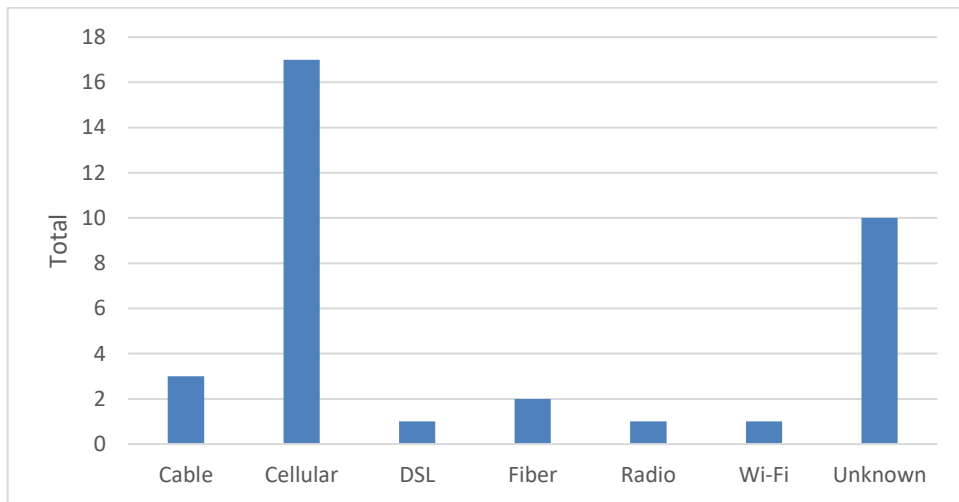


Figure 5. Communication method between RPU and CPU

Question I.3: How do you currently store RWIS data?

Out of all responding organizations, only 9 (20%) indicated using cloud storage, 12 (27%) store RWIS data in-house, and about 20 (45%) store RWIS data using vendors. Figure 6 provides a summary of how organizations currently store RWIS data.

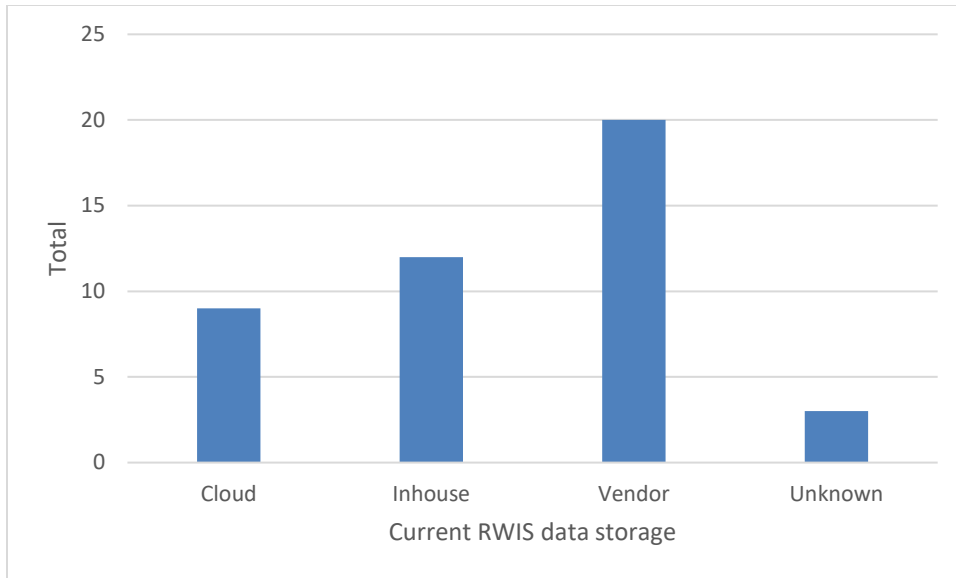


Figure 6. RWIS data storage

Question I.5: What was the motivation behind the investments?

The major motivation behind the investments in RWIS technology for more than half of the responding agencies (56%) was to upgrade to newer or more advanced technology. About 36% invested in RWIS to replace existing technology, and only about 8% invested in RWIS to accommodate CAVs. Table 4 summarizes the motivations behind the investments in RWIS technology. In addition, a few agencies (about 8%) had made other investments in RWIS technology that were compatible with CAVs, such as a proof-of-concept demonstration, testing, or a market survey of available options (Figure 7), and only about 29% out of 38 respondents indicated that their plan was to make investments in RWIS technology to facilitate compatibility with CAVs in the next three years (Figure 8).

Table 4. Motivation behind the investments in RWIS technology

| What was the motivation behind the investments? | Total |
|---|-------|
| To specifically accommodate CAVs | 3 |
| To upgrade to a newer or more advanced technology | 22 |
| To replace existing technology | 14 |

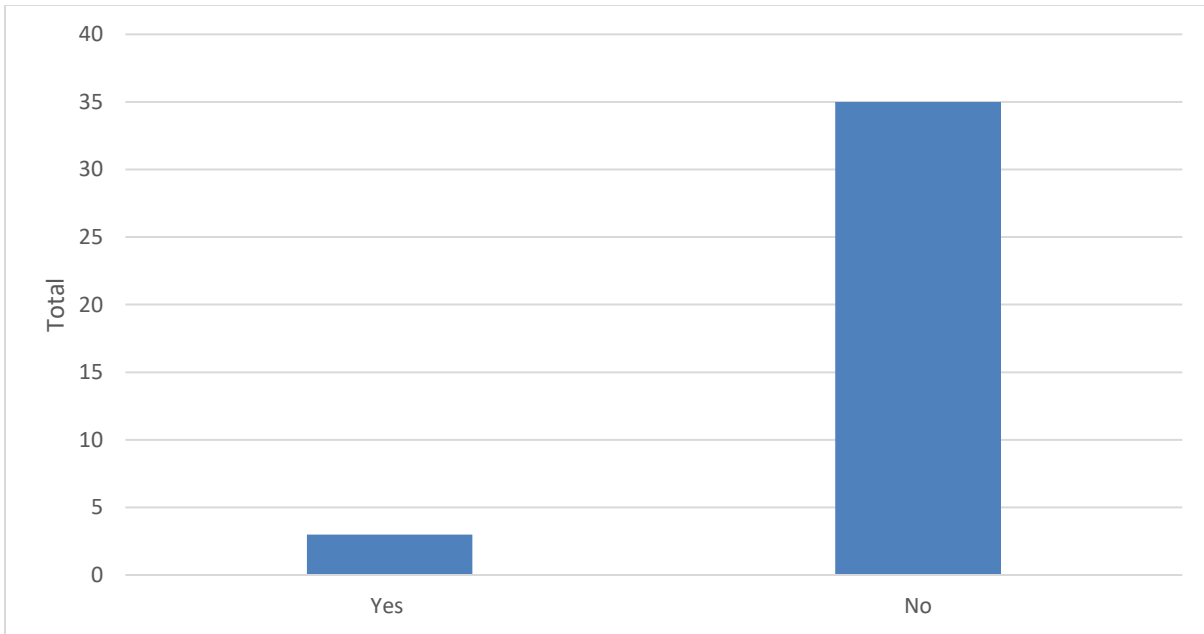


Figure 7. Other investments in RWIS technology to facilitate compatibility with CAVs

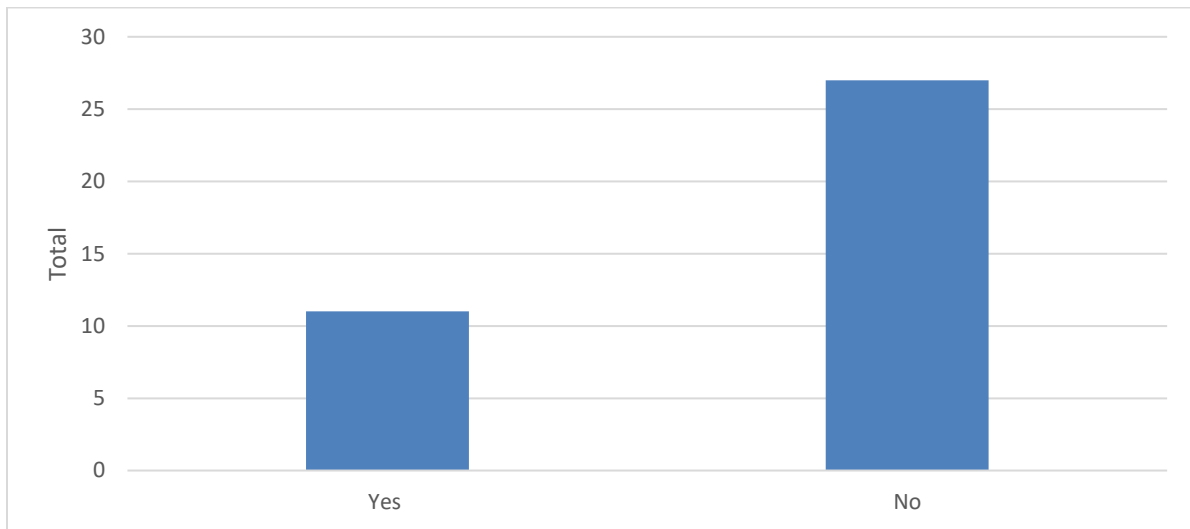


Figure 8. Investments planned in RWIS technology to facilitate compatibility with CAVs in the next three years

Question I.6: Have there been any investments in the following technologies in relation to RWIS? i. Sensor technology (addition, replacement, upgrading) ii. RPU (addition, replacement, upgrading) iii. CPU (addition, replacement, upgrading) iv. Storage and data integration (addition, replacement, upgrading)

Twenty-five (65%) of the participating agencies indicated investment in sensor technology, 21 (58%) have invested in RPU technology, 13 (36%) have invested in CPU technology, and 20

(55%) have invested in storage and data integration. Figure 9 summarizes the investments in these technologies.

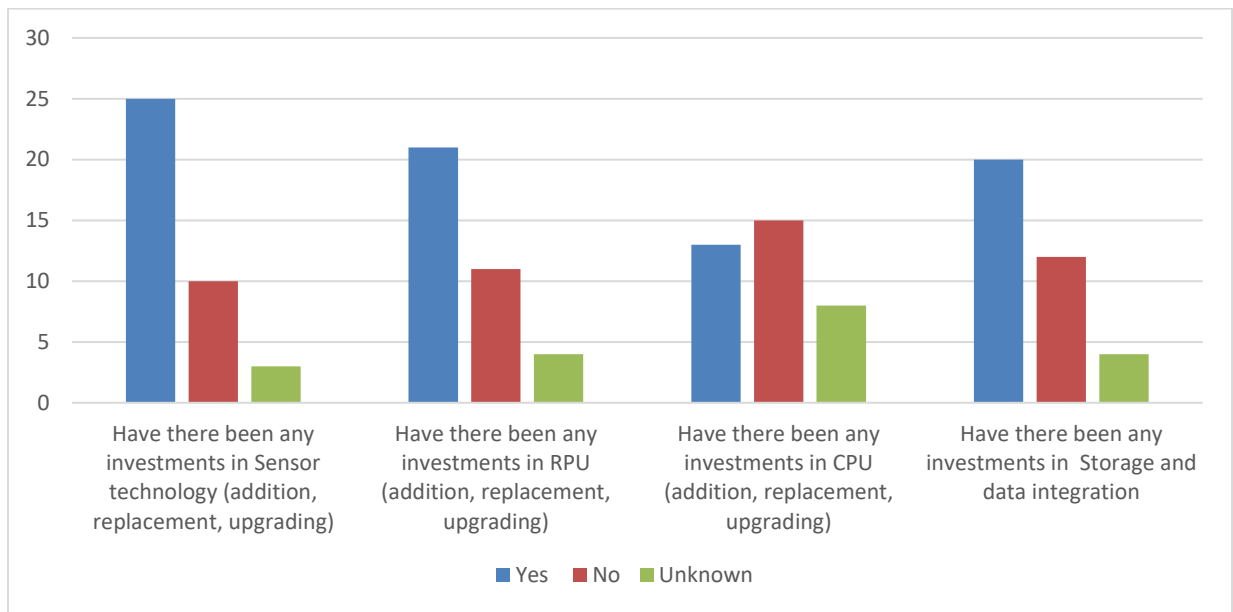


Figure 9. Investment in technology in relation to RWIS

Question I.8: How does your organization prioritize investments in RWIS technologies to support CAV integration?

Following Saldaña [66], an inductive coding methodology was used to summarize the primary topic of each response to this question and generate four response categories. Categories included the following:

- Road safety management/improvements
- System upgrade/maintenance
- Exploring CAV and RWIS technology
- Projects with benefits

Below are the actual responses:

- At this time, we are not focusing on CAV. When industry gets a standard we can work from, we will focus on deployment of those devices at that time.
- Based on the potential to improve safety and mobility options for road users.
- Currently we are building a roadmap to prepare for the future technologies. That process will determine the prioritization of all of our investments.
- Priorities are based on operational needs. Focus is on system maintenance. The existing system triggers for highway messages and warnings could also be utilized to provide weather

related basic safety messages (BSM). Recent RWIS enhancements include visibility sensors to implement fog warnings for land and water-based traffic.

- Priority is given to upgrading current tech to be ready for CAV deployment (CPUs, Controllers, etc.).
- Projects with tangible benefits, including RWIS in existing infrastructure that already uses CAV (traffic signals).
- Right now, we are investigating the opportunities with utilizing CAV and RWIS technologies. We have not done anything with this, but we are interested in the capabilities.
- We are investing into Panasonic to build V2X infrastructure utilizing existing RWIS technology.
- We are just starting to explore the option to add this tech.
- We invest in RWIS to support our weather prediction and road management systems. We generally don't invest in RWIS solely to support CV. We have experimented with infrared cameras to improve road ice prediction and to support our CV road weather information messages.

Question I.10: What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?

Similarly to Question I.8, an inductive coding methodology was used to summarize the primary topic of each response to this question and generate response categories [66]. Responses involving “none/no plan/decision to implement technology” were excluded from the analysis. Seven major categories were generated from participants’ responses: financial support, implementation uncertainty/better future technology, reliable data, organizational culture, organizational location, technical support/time consumption, and project worth. The actual responses, excluding information identifying an organization, are listed below:

- Maintenance resources
- Funding and servicing
- RWIS is site specific. Our CV application focuses on road ice and wind, but is intended to apply more broadly than the specific location of the RWIS. We struggle to get reliable data at the RWIS site (without false positives) and more broadly. We also are still working on success metrics.
- Impact will largely be driven by what upgrades are needed. Any hardware upgrades will take time and funding. Depending on how the CAV data is shared, it could also be an increase in cost. Funding is limited and certain equipment delivery can be very slow.
- The unknown of the implementation and how it would work overall. Possibly the cost and ensuring we have the supporting capabilities
- None. The data is available for CAV integration.
- No plans to implement RWIS technologies for CAV integration, but the situation will likely receive interest and possible investment.
- No decision as of yet
- The CAV standards are not yet mature enough to consider making significant investments
- Proof of need (customer base, volume of vehicles with active CAV systems)

- Depends on the size and scale of the project. Generally, we did well.
- Funding, technical support, uncertainty of CAV technology developments
- Lack of leadership promotion of CAV
- Small rural state and CAV has limited penetration.
- We do not foresee hardware compatibility issues with existing RWIS and CAV. CAV-RWIS data integration is the primary challenge.
- This is not an issue that the city council has addressed.
- There aren't a lot of known applications, so all things will be new. Integration of technologies will be most difficult.
- We currently have a moratorium on new deployments.
- Part of the anticipations is implementation and then new, better technology is developed. So, by the time the state collects data, gets a project going, implements.... it is already out of date.
- The need to collect data in our disconnected rural areas
- Funding, guidance, technology selection, implementation, value versus cost
- Communication to the vehicles is the largest hurdle. We are in the process of developing a connected vehicle ecosystem with the intention of it using our existing RWIS public data feed and providing alerts to the public via OEM installed cellular telematics.
- Challenges include: limited resources to deploy assets in the field, delays in obtaining and certifying new tech to allow CAV integration.
- We are not certain what the standard will be. We don't want to install something that won't be utilized.
- Unsure how the CAV field will develop with the OEMs and what things will be important and what won't be. It's still so new we're not sure what direction it'll go.

Investments in IT and Data Communication and Management Technology

The second section asked organizations about their investments or plans to invest in IT and data communication and management technology.

Question II.1 Have there been any recent investments in IT and data communication and management technology?

Only 47% of 38 organizations have recently invested in IT and data communication and management technology. This investment was mostly toward cloud and in-house data storage capabilities, as shown in Figure 10. The primary reasons cited for the investments were to accommodate CAVs and equally to upgrade to a newer or more advanced technology; in contrast, the majority of the organizations that recently invested in RWIS technology cited upgrading to newer or more advanced technology as the reason. Other investment reasons included system updates, hardware replacement, storage expansion, and improvements to communication speeds. A summary of the reasons for the investments in IT and data communication and management technology and in RWIS technology is presented in Figure 11.

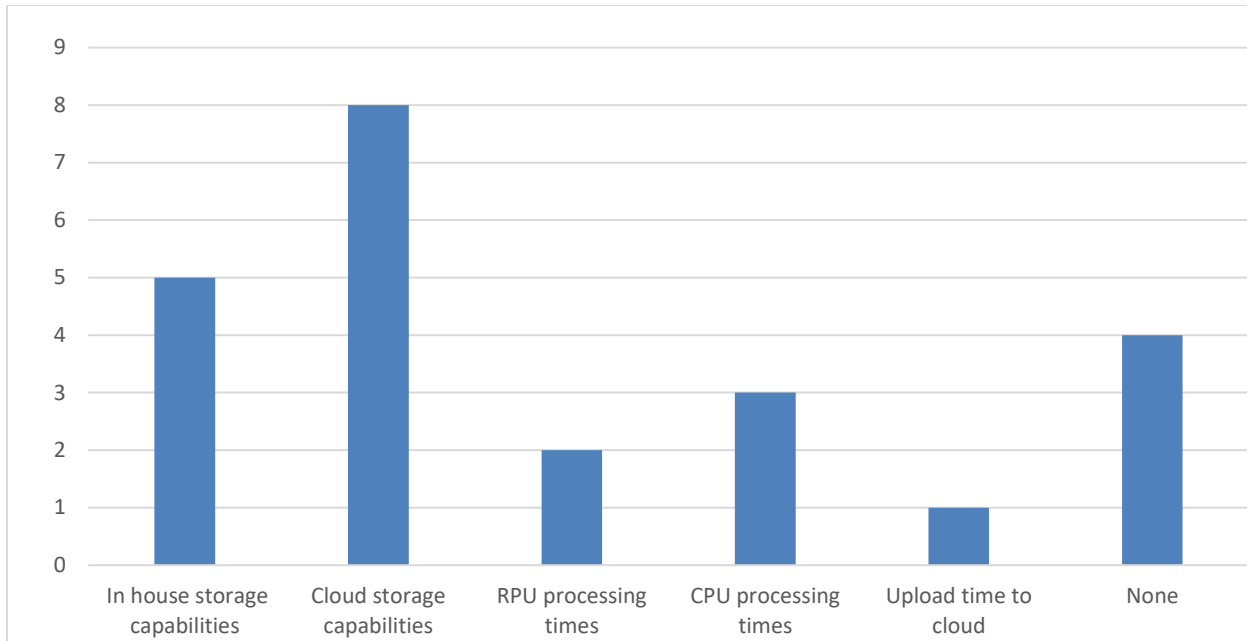


Figure 10. Areas of investments

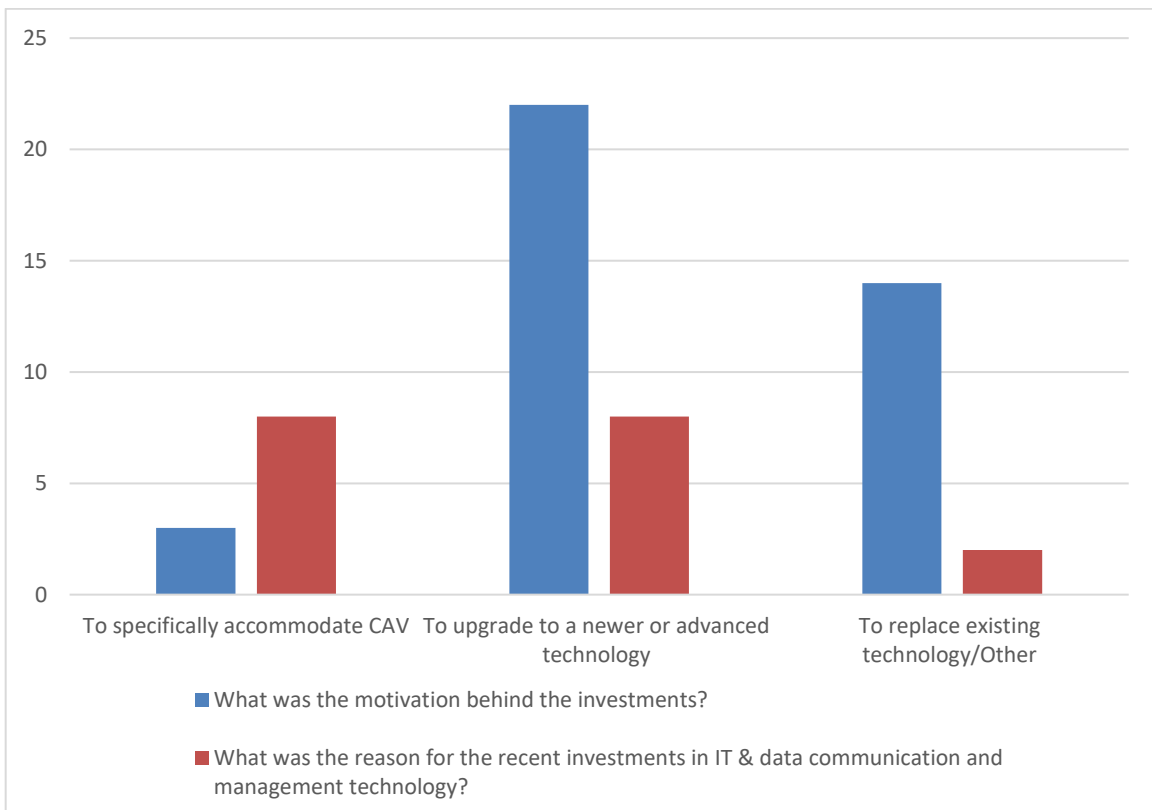


Figure 11. Reasons for investments in IT and data communication and management technology and RWIS technology

Question II. 3: What IT and data management systems has your organization implemented or plans to implement to facilitate data exchange between RWIS and CAVs?

Implementing a V2X data exchange platform was the only common theme/category that emerged from the responses. The following are the actual participant responses, with all identifying information removed and minor typographical errors corrected:

- Our CV ecosystem had developed cloud-based storage and analytics capabilities. It is still evolving. From a weather standpoint, that is where we merge RWIS and other weather data to create a TIM message for broadcast.
- None, pure vendor cloud based
- We're at the beginning stages of implementing a V2X data exchange as part of our ATMS upgrade.
- GWORKS
- Data loggers in state vehicles, MARWIS in vehicles
- IT system upgrade is being managed separately.
- V2X data exchange platform—under development
- security upgrades
- IRIS
- Panasonic has developed a method to integrate RWIS data into their V2X infrastructure.
- We are investing in a central software program to manage this data.
- We are in the process of developing a cloud based connected vehicle ecosystem that will provide RWIS and basic safety message alerts to the public.
- New storage and servers at some traffic management centers
- Just keeping our existing open data portal working well and modernized

Question II.5: How has your organization prioritized its investments in IT and data management technologies to support RWIS-CAV integration?

Four major categories were developed after participant responses were coded using the inductive coding methodology [66]. These categories included V2X technology, technology upgrade, traffic management, and data management. The following are the actual participant responses, with all identifying information removed and minor typographical errors corrected:

- We support upload to cloud information providers, e.g., Waze. We support upload to US Weather Service. We populate data on our 511 site and apps. I'm not sure what you mean by CAV. Is it the use of RSU's to collect and disseminate data, or is it more broadly the use of any technology that provides information from the RWIS to the "driver"?
- We focus on needs for specific applications but the cloud-based system is built to manage all our CV data. We are also implementing a new ATMS system in our traffic control center and will be integrating that with our CV system.
- None at this time. We share data from vendor's platform at needed. This may include some future CAV activity.

- We're creating a data exchange that can integrate all of the department's data through V2X technologies, so it wasn't prioritized just to support RWIS. One of the ways that we prioritize our CAV related upgrades is through projects where we can get day-one benefits when the project is deployed. Through the V2X data exchange, we can begin integrating the data that we have through 4G/5G V2X (i.e., services like Haas Alert), then later use the data for C-V2X once that's deployed.
- It hasn't (at this time).
- We have not as of yet
- Our ITMS programs address RWIS and CAV
- IT system upgrade is being managed separately.
- RWIS will be one of the use cases as we plan to roll out the V2X data exchange platform
- Unprioritized
- It's a non-priority
- Have not at this point
- It has not.
- We have a project in our STIP that is a feasibility/scoping study for CV, RWIS, Plows, etc. This will likely be rescoped to focus more on RWIS versus CV-RWIS integration.
- Separately, we have a safety project to put noninvasive pavement sensors at a traffic signal on a grade that can be too steep for trucks during winter weather conditions. It's undecided if we will integrate that with our standard intersection CV system.
- IT is currently working on data management solutions but there has been no decision nor am I privy to the discussions
- recognized the need to have a central hub to coordinate and collect the data
- At this time, we are in the planning stage working with our vendor to develop data acquisition, operations, security, commercialization, and partnerships to encompass all of our needs into the system.
- Priority is given to upgrading current tech to prepare for increased speed and data demands.
- Most investments are prioritized for other things, but CAV could be an additional use

Question II.6: Do you plan to make investments in IT and data management and communication technology specific to RWIS toward CAV integration in the next three years?

Only a few (34.3%) of the 32 responding organizations indicated that they plan to invest in IT and data communication and management technology specific to RWIS and applicable to CAV integration in the next three years (Figure 12).

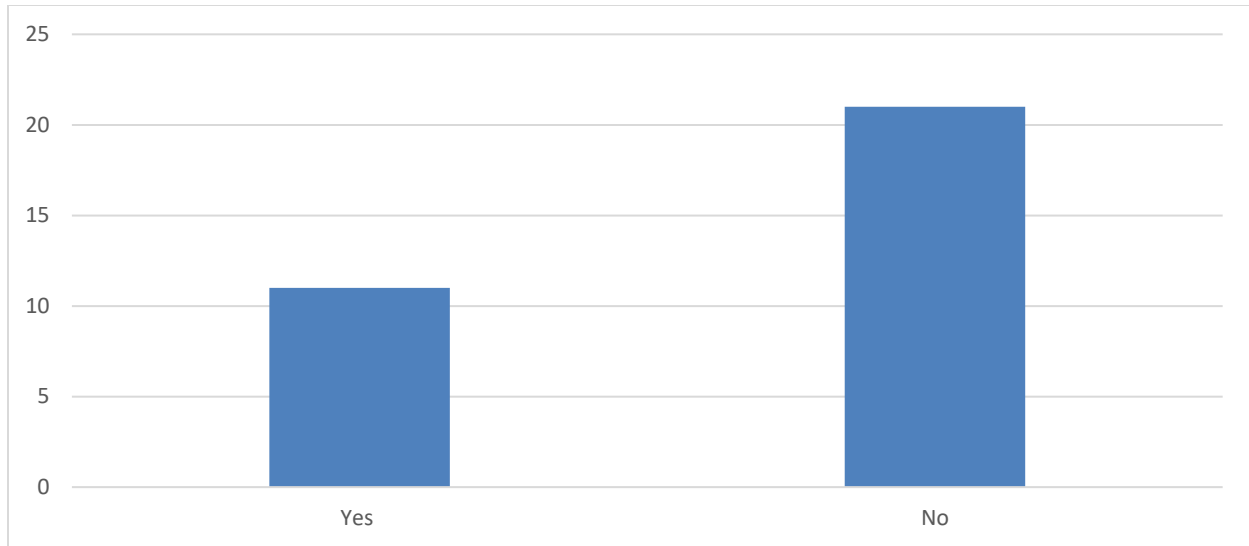


Figure 12. Plans to invest in IT and data management and communication technology specific to RWIS and applicable to CAV integration in the next three years

Question II.7: How does your organization ensure the security and privacy of data exchanged between RWIS and CAVs?

Use of a third-party contract was the only common theme/category that emerged from the responses. The following are the actual participant responses, with all identifying information removed and minor typographical errors corrected:

- We upload on a “best efforts” basis to the cloud using the vendors/distributors security algorithms, if any.
- Our fiber network is a closed network with the usual security protocols.
- Cellular private APN
- This is currently through a vendor
- I believe our V2X data exchange will have built in privacy protection protocols.
- Industry standard IT security
- IT protocols for network management affect system unless ITS equipment is kept off the network.
- Cybersecurity is an important layer of the CAV ecosystem.
- SCMS
- Currently, our RWIS data is public. We do not have any CAV data yet.
- Our standard IT operating procedures and security requirements are followed on our separate traffic operations network that is maintained by traffic operations division.
- We are not doing this at this time.
- We don’t communicate directly from RWIS to CAVs. We put our data out for companies to gather but we’d rely on them to push anything direct to a CAV.

Question II.8: How does your organization handle data standardization and interoperability between different RWIS and CAV systems?

No common theme/category emerged from the responses. The following are the actual participant responses, with all identifying information removed and minor typographical errors corrected:

- We follow the CV standards developed in SAE J2735, J2945, CTI 4501, and associated NTCIP and IEEE standards.
- GWORKS
- Industry standards, avoid proprietary systems
- Work in progress. This is a part of the discussion with the V2X data exchange platform.
- Our projects use statewide standard specifications to ensure interoperability.
- We are not doing this at this time.
- Our RWIS data comes to the data portal in a consistent manner regardless of RWIS manufacturer. But we don't push to CAV directly.

Question II.9: What challenges has your organization faced or anticipates facing in implementing IT and data management systems for RWIS-CAV data exchange?

Seven major categories emerged after the responses were coded using the inductive coding methodology [66]. Three challenges were identified that were common to both implementing IT and data management systems and implementing RWIS technologies to support CAV integration: financial support, organizational location, and technical support. Other challenges that emerged included uncertainty about technology, data incompatibility, standardization, and training/workforce development. The following are the actual participant responses, with all identifying information and unknown responses removed and minor typographical errors corrected:

- Resources for maintenance
- Haven't yet created data management policies for data storage. We are sharing some but not all of this data and are still working on those processes and limits.
- Already doing, don't see issues
- Variability, lack of standardization, incompatible data formats, etc.
- Funding and technical support, uncertainty about technology and opportunities available
- Feed integrations.
- The challenge again will be getting data back from the disconnected rural areas
- Communication to the public is the largest challenge. Agreements will have to be made with OEMs to get messages to vehicles, and to get vehicle that indicates weather conditions into the system that can provide alerts for hazardous weather.
- Will require training for staff on new tech and procedures. Funds to bring all districts up to new standards and enough staff to do this.
- Standardization

Maintenance Practices

The third section asked organizations about their maintenance practices.

Question III.1: What maintenance practices is your agency interested in that will benefit from CAV integration into RWIS?

Organizations expressed the most interest in winter maintenance, information dissemination, and traffic data collection (62%), with the highest level of interest in winter maintenance (Figure 13).

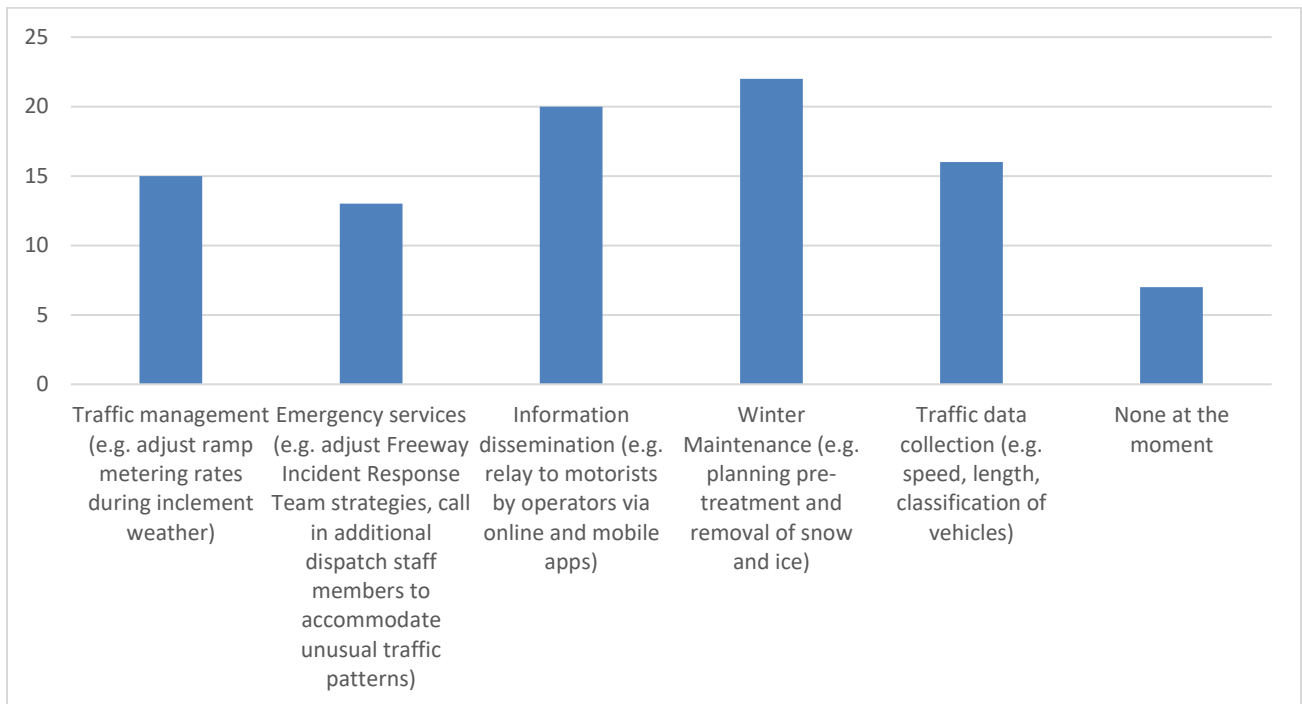


Figure 13. Interest in maintenance practices that will benefit from CAV integration into RWIS

Question III.2: How has your organization adopted its maintenance practices to accommodate RWIS with CAV infrastructure?

No common theme/category emerged from the responses. The actual participant responses are listed below, with all identifying information removed and minor typographical errors corrected:

- None yet
- None foreseeable at this time
- None yet
- none
- No direct integration of CAV with RWIS at this time

- We are still in the planning phases and do not have a defined integration yet.
- Will have to provide training to maintenance staff.

Question III.4: How does your organization prioritize maintenance activities and investments to support the integration of RWIS into the CAV infrastructure?

Similarly to Question III.2, no common theme/category emerged from the responses. The actual participant responses are listed below, with all identifying information removed and minor typographical errors corrected:

- Not on our priority list
- Low priority
- Our weather team manages the RWIS network very proactively—using summer months to repair and expand the network. They have a priority list of expansion sites. CV systems are currently maintained by consultants working with our CV group.
- We have not done this yet, but it would likely be based off of the priority routes, communications, and incidents.
- Prioritized the transportation management system, which includes RWIS and CAVs
- Priorities are based on operational needs. Focus is on system maintenance.
- No response
- Currently the prioritization of CAV-RWIS integration is low compared to other maintenance activities and funding needs.
- CAV related RWIS sites have a higher prioritization.
- None so far
- We are still in the planning phases and do not have a defined integration yet.
- Prioritize upgrading RWIS locations to be ready to integrate into CAV and training for maintenance staff for local hardware repairs
- Maintaining station and sensor uptime and reliability. Core need is to make sure the data is reliable, accessible, and accurate.

Question III.7: Please list the lessons learned or best practices your organization has identified from its maintenance requirements and practices to support RWIS-CAV integration.

This question received only one response:

- It is hard to get rapid service at a reasonable price for maintenance and new installations in remote (most) areas.

Question III.9: What are the other aspects of maintenance related to the integration of CAVs that you are concerned about?

About 35% of the 28 total responses expressed concern about other aspects of maintenance related to the integration of CAVs, as summarized in Figure 14.

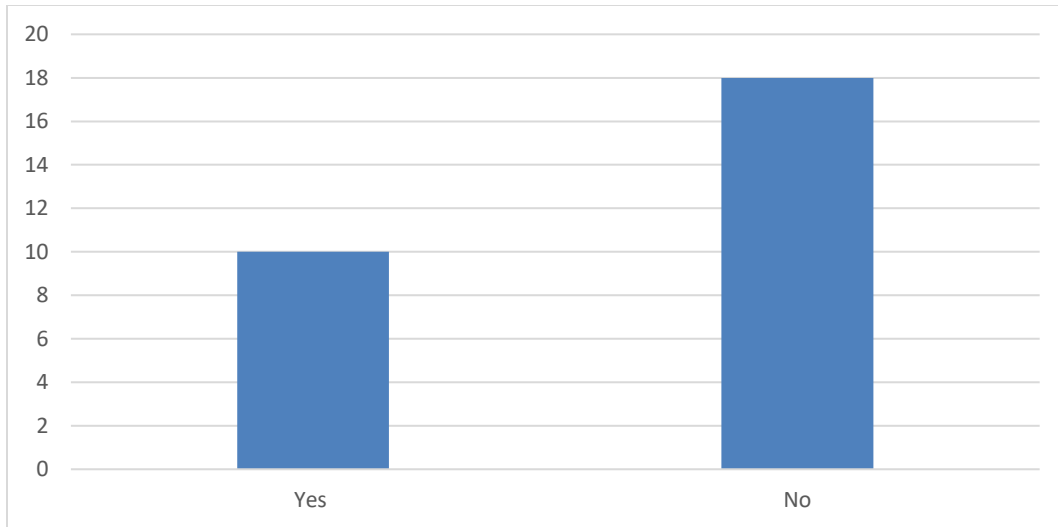


Figure 14. Concern about other aspects of maintenance related to CAV integration

The categories generated using the inductive coding methodology [66] were similar to some of the categories generated for the challenges in implementing RWIS technologies and in implementing IT and data management systems. The categories included training and workforce, data reliability, financial support, uncertainty about technology, technical support/time consumption, and public safety communication. The actual responses, excluding information identifying an organization, are listed below:

- Availability of staff resources and third-party services
- Reliability
- As our CV system expands, we need to integrate the management and maintenance of this system, including our asset management, with our other ITS systems. That transition will require resources and training.
- Data overload—how to successfully implement actions based on big data
- The training, reliability, cost and if we would need to add personnel. Currently, a lot of unknowns, but we are very interested.
- More to do utilizing the same budget and resources (personnel, equipment, etc.). Multi-jurisdictional collaboration for cross-border operational activities. Data accuracy relayed to/from CAVs. Cybersecurity. Authentication and timeliness of messaging.
- Funding, technical support, PM schedules to maintain system, replacement cycles, new unknown technologies, and uncertainty related to data availability.
- Cost
- Uptime of all devices and feeds. Reliability of data.
- In addition to RWIS data, basic safety messages like road closures, detours, work zones, etc. need to be included in the system to communicate with the public for safety enhancements.

Workforce Development

The fourth section asked organizations about their workforce development plans.

Question IV.1: Have there been any updates to the agency’s workforce skills to handle the integration of CAVs?

About 18% of the 27 total responses indicated that workforce skills have been updated to handle the integration of CAVs, as summarized in Figure 15 below.

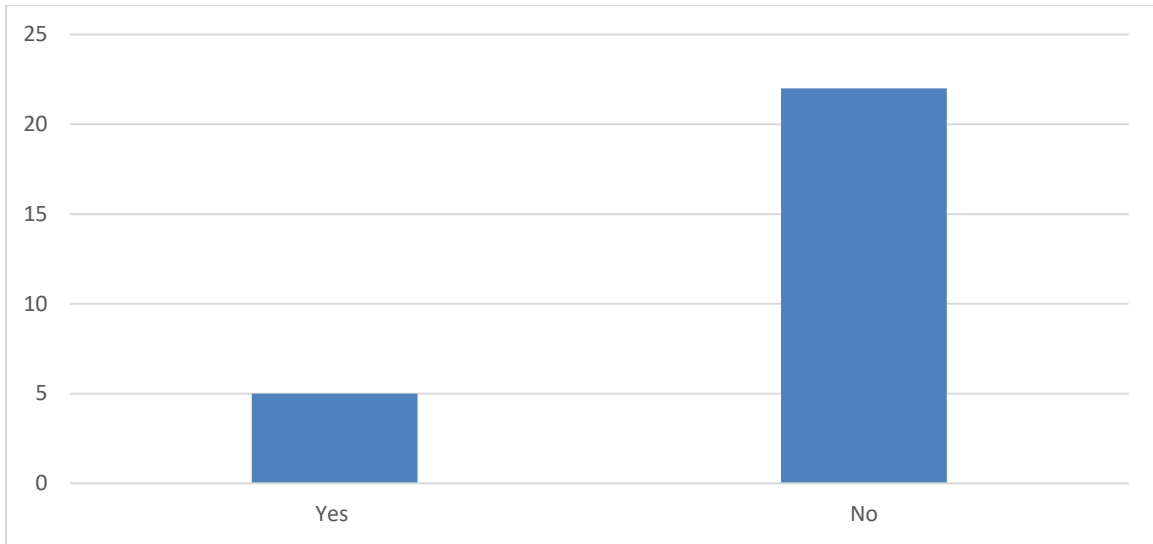


Figure 15. Updates to the agency’s workforce skills to handle the integration of CAVs

Development of Standards

The final set of questions focused on standards developed by agencies regarding RWIS/CAV data and other items.

Question V.1: Will your agency be involved in the development of standards, new data formats, and protocols for exchanging RWIS data with CAVs within the next three years?

About 15% of the 26 responses indicated that the organization will be involved in developing standards, new data formats, and protocols for exchanging RWIS data with CAVs within the next three years, as summarized in Figure 16.

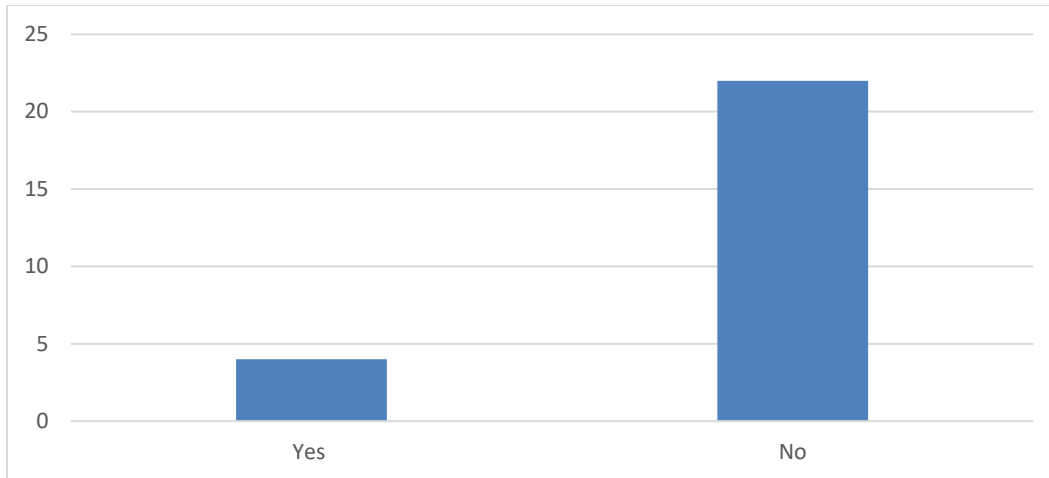


Figure 16. Agency involvement in the development of standards, new data formats, and protocols for exchanging RWIS data with CAVs within the next three years

Question V.2: What investments has your organization made or plans to make in developing standards and protocols for CAV integration with RWIS technologies?

Figure 17 shows a summary of all investments organizations plan to make in the next three years.

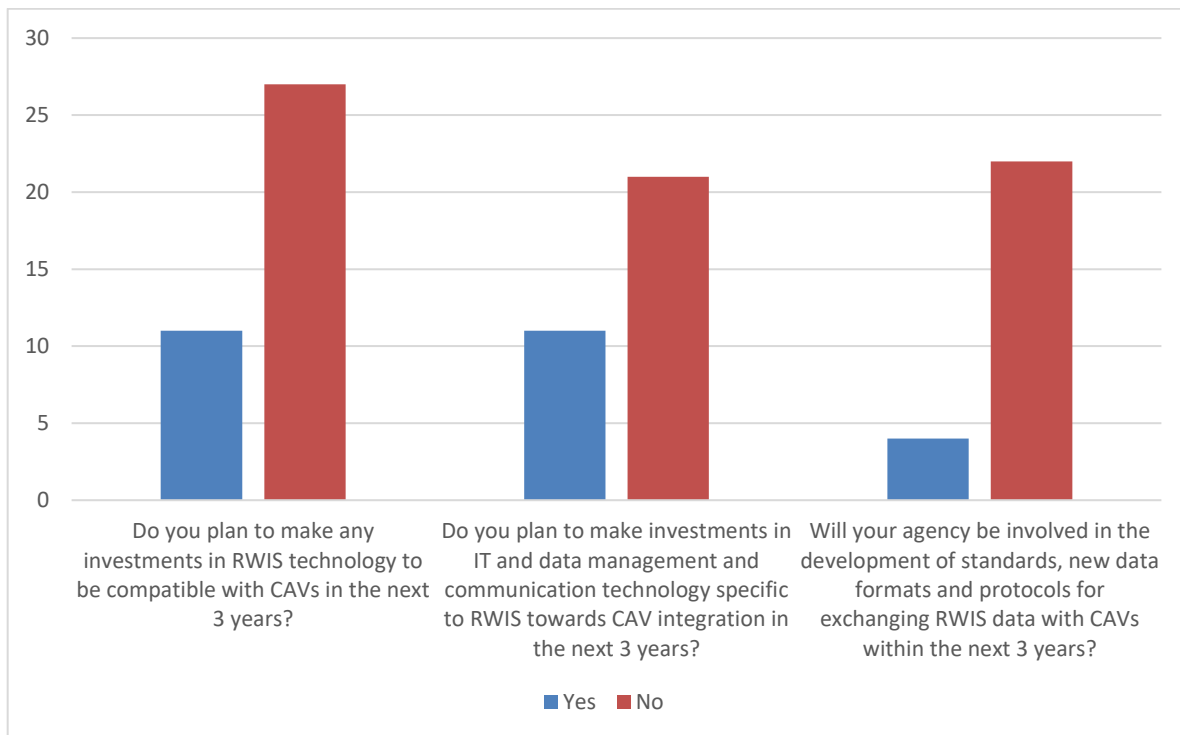


Figure 17. Summary of all investments organizations plan to make in the next three years

TARGETED INTERVIEWS

Introduction

To augment the survey described in the previous chapter, the research team conducted follow-up interviews based on the survey responses. Agencies that participated in the survey and appeared to be the most mature in their accommodation of CAV technology were ranked using the system described below, and the top five were selected for targeted interviews. The interviews were specific to each agency based on the agency’s proposed frameworks, investments, and technology deployments.

Ranking

In cases where multiple participants within an agency responded to the survey, their responses were combined using a ranking system. For instance, if one participant indicated that the agency had invested in upgraded technology and another indicated that the agency had yet to integrate CAVs, the response with the highest rank was included in the aggregated response for the state.

A practical example of a question with ranked responses was “What was the motivation behind the investments?” Options were as follows: “To specifically accommodate CAVs,” “To upgrade to a newer or more advanced technology,” “To replace existing technology,” and “None of the above,” which were ranked 3, 2, 1, and 0, respectively. Table 5 shows the ranking matrix for this question with all identifying information removed. Questions with yes/no or zero/nonzero responses were ranked 1 for Yes and 0 for No.

Table 5. Example of a question with ranked responses

| Question | Ranking | | | |
|--|----------------------------------|---|--------------------------------|-------------------|
| | To specifically accommodate CAVs | To upgrade to a newer or more advanced technology | To replace existing technology | None of the above |
| | 3 | 2 | 1 | 0 |
| What was the motivation behind the investment? | | | | |

Based on the ranking results, Table 6 show the top 10 organizations that have already invested or plan to invest in technology for CAV integration, while Table 7 shows the top 10 organizations that plan to invest in the technology in the next three years.

Table 6. Top 10 organizations that have already invested or plan to invest in technology for CAV integration

| Agency | Total |
|-----------------------------------|--------------|
| Caltrans | 21 |
| Utah DOT | 19 |
| Delaware DOT | 12 |
| Florida DOT | 12 |
| PennDOT | 11 |
| Maryland Transportation Authority | 10 |
| Georgia DOT | 10 |
| Oregon DOT | 9 |
| Arizona DOT | 9 |
| Maine DOT | 7 |

Table 7. Top 10 organizations that plan to invest in the technology in the next three years

| Agency | Total |
|-----------------------------------|--------------|
| Utah DOT | 3 |
| Arizona DOT | 2 |
| Georgia DOT | 2 |
| Maryland Transportation Authority | 2 |
| Florida DOT | 2 |
| Maine DOT | 2 |
| Nevada DOT | 2 |
| City of Bondurant, Iowa | 2 |
| Caltrans | 2 |
| North Dakota DOT | 2 |

Agency Selection and Findings

Of the top six organizations listed in Table 6, the Delaware DOT had no plans for significant investments in CAV-RWIS integration in the near future. In addition, the Maryland Transportation Authority declined to participate in a targeted interview. For each of the four remaining organizations, the questions posed were derived from their initial survey responses. The specific questions and detailed responses can be found in Appendices B1 and B2, and the key findings are summarized as follows:

1. Investments in CAV-RWIS Integration, IT, and Data Management

When addressing the issues associated with the integration of RWIS and CAVs, agencies continually emphasized resource constraints as a common challenge. Given this limitation, investment decisions for CAV-RWIS integration were prioritized based on certain conditions. Caltrans, for example, underlined the importance of upgrading existing RWIS technology to ensure readiness for CAV deployment. Similarly, the Florida DOT prioritized improvements

based on the potential to improve safety and mobility options for road users. Collaboration strategies have also emerged as critical components, with the Utah DOT collaborating with an OEM for data exchange and integration systems and Caltrans engaging a contractor to develop a comprehensive CAV master plan that includes RWIS integration.

In terms of investments in IT and data management, agencies tailored their priorities to accommodate the evolving technological landscape. Recognizing the need for enhanced capabilities in the face of a growing demand for faster data transfer speeds and higher volumes of data, Caltrans prioritized upgrades to current systems. The Florida DOT and PennDOT were both heavily involved in the development of V2X data exchange platforms, with the Utah DOT already having a V2X infrastructure in place to manage RWIS data. The Utah DOT also intended to integrate RWIS data with other weather-related information into an established CV ecosystem, which would include cloud-based storage and analytic capabilities.

2. Maintenance Practices

Acknowledging the potential benefits of CAV-RWIS integration in maintenance practices, agencies unanimously identified traffic management, information dissemination, and traffic data collection as advantageous outcomes. Winter maintenance, which includes pre-treatment of roads and removal of snow and ice, was also identified as an area that could benefit from integration. However, the size and scale of the maintenance operations in question were identified as crucial factors influencing the selection of technologies and determining the necessary maintenance practices. Maintenance staff training emerged as a critical issue, with agencies emphasizing the importance of comprehensive training programs to guarantee effective coordination of maintenance operations. The questions in this section were intended to address winter road maintenance practices; however, based on the survey responses and information gathered during the targeted interviews, some participants interpreted the questions as referring to maintenance of equipment.

3. Workforce Development

All agencies identified workforce development as an issue, emphasizing the importance of training both internal and maintenance workers on new technologies, policies, and procedures. Caltrans had difficulties in certifying new technicians and experienced staffing constraints across all districts during its CAV-RWIS integration efforts. Plans were in the works to develop a CAV academy to fully train Caltrans workers on CAV technology and deployment. PennDOT highlighted an in-house division dedicated to emerging technologies that provided personnel with access to training, which is helpful for CAV-RWIS integration. Specific skills in areas such as networking, communications, and equipment troubleshooting were identified as important for enabling staff to effectively support CAV-RWIS integration, with a foundational competency in RWIS and road weather being deemed essential.

4. Development of Standards

A shared concern across all agencies was the absence of standards to facilitate CAV-RWIS integration. Caltrans expressed a commitment to actively participate in the development of standards, formats, and protocols. All agencies were working on establishing processes, policies, and data sharing platforms to integrate various systems. Caltrans emphasized the need to guarantee interoperability and compatibility for all projects by utilizing statewide Special Provision Specifications. While recognizing the need to create policies for managing and storing data, the Utah DOT acknowledged potential limitations that might be encountered.

CHALLENGES AND RECOMMENDATIONS FOR FUTURE RESEARCH

Efforts to integrate CAVs and RWIS face significant challenges, as identified from the literature review, the survey, and the targeted interviews. The following is a list of identified challenges along with some recommendations from the literature and the survey of agencies.

Data Standards to Enhance Interoperability and Interpretability

The integration of CAVs and RWIS necessitates adherence to robust data standards. As highlighted in the literature review, survey, and targeted interviews, diverse data characteristics, including differences in format, transmission frequency, and reliability, is an ongoing challenge that hinders data interoperability and poses integration challenges. Furthermore, the lack of standard protocols for data exchange and processing between CAVs and RWIS reduces the usability of the available data by relevant stakeholders. Therefore, it is important to develop and implement standardized data formats and communication protocols for seamless integration between CAVs and RWIS. Establishing guidelines for data quality assurance and verification to ensure reliability and accuracy is also a useful step in this regard to facilitate implementation of standards by agencies and collaboration between industry stakeholders, standardization bodies, and regulatory authorities.

Deployment Configurations, Adoption Rates, and Impacts

Research is needed to understand the suitable hardware and software configurations and the adoption rate of relevant technologies, such as DSRC and cellular onboard units, and to assess the impacts of CAV-RWIS integration on various facets of transportation systems. Agencies need to establish a technology baseline for the front-end and back-end systems that support CAV-RWIS integration. This calls for the construction of testbeds to evaluate different technologies and determine best practices. Testbeds enable assessment of the adoption rate of the relevant technologies and evaluation of the impacts of CAV-RWIS integration, hence providing insights about a broad spectrum of considerations such as technological readiness, regulatory frameworks, public acceptance, traffic flow optimization, safety enhancements, environmental sustainability, and economic implications. The first line of research in this regard must address the technology standards, minimum system requirements, and hardware or software configurations that best support the deployment of technologies that enable CAV-RWIS integration. The outcomes of such research efforts should provide agencies with detailed information about the array of technical options available and the factors involved in selecting, deploying, and operating them. This information should be both comprehensive and descriptive, facilitating well-informed decisions about deploying technologies for effective integration of RWIS and CAV.

Investments in RWIS Technologies to Support CAV Integration

Efficient data handling by RWIS and RSUs requires robust computational capabilities for swift processing and exchange, and determining the optimal number of CAVs and RWIS stations for

efficient integration poses a challenge, as highlighted in the literature review [4, 16]. The survey results emphasized seven major challenges, including financial support, uncertainty regarding implementation and future technology, data reliability, organizational culture, location, technical support, and project worth. The targeted interviews revealed a common issue where limited resources hindered integration efforts, with agencies facing challenges in deploying both equipment and personnel in the field.

Edge computing, a concept that brings computation closer to the point of need, provides a solution for faster data processing and exchange [16]. Edge computing can be deployed in RWIS/RSU environments to optimize data processing and exchange. However, its implementation can also present some difficulties, such as increased costs and issues regarding integration with existing systems. Research efforts can focus on developing efficient and compatible edge computing equipment and on determining the optimal number of CAVs and RWIS stations for cost-effective integration.

Investments in IT and Data Communication and Management Technology

The literature review indicated that CAVs generate extensive amounts of data, posing greater challenges in the processing and storage of these data compared to traditional traffic data and leading to challenges in providing sufficient computation, communication, and storage resources [4, 15, 16]. Finding a communication method with sufficient range and sufficiently low latencies to support safety and other CAV applications was another identified challenge. CAV-RWIS integration also raises privacy concerns, necessitating a balance between data interchange and user privacy preservation [65]. The survey identified common challenges in implementing IT and data management systems for CAV integration, including challenges related to financial and technical support and organizational location. Additional challenges encompassed uncertainty about technology, data incompatibility, standardization, and training/workforce development. The findings from the targeted interviews highlighted the recurring theme among agencies of insufficient resources.

Addressing communication issues related to the integration of CAVs and RWIS necessitates the development of a strong communication infrastructure [16, 35, 36]. Investments in high-speed networks, particularly the deployment of technologies such as 5G, are critical for enabling real-time data transmission between CAVs and RWIS and thus improving the overall efficiency of the system. Concurrently, data security is critical, necessitating the use of strong cybersecurity techniques such as encryption, secure authentication, and continuous monitoring. To identify and address vulnerabilities, a comprehensive strategy should include regular updates, patches, security audits, and collaboration with cybersecurity experts. This method protects the integrity and confidentiality of data exchanged between CAVs and RWIS, resulting in a more secure and efficient integration system.

Maintenance Practices

Organizations expressed concerns about maintenance practices in the survey, with key concerns identified as training the workforce, ensuring the reliability of data, securing financial and

technical support, and addressing uncertainties about technology. These concerns highlight the challenges that organizations anticipate facing in effectively maintaining an integrated CAV-RWIS system.

Ensuring the quality and accuracy of data can significantly improve road maintenance programs because reliable data are required for effective planning, decision-making, and resource allocation [26, 39]. To ensure the reliability of data, the sensors in both CAVs and RWIS need to be able to perform effectively even in adverse weather conditions. It is recommended to develop algorithms capable of detecting and minimizing the impact of erroneous or inaccurate sensor data. In addition, frequent maintenance and calibration programs are required to maintain the dependability of sensor data over time. This approach to sensor data quality assurance is critical for maintaining the integrity of the integrated CAV-RWIS system, which contributes to its overall efficacy and performance.

Additionally, performance data are needed to develop standards or performance metrics so that maintenance can be planned for and programmed. While RWIS technology is mature, many of the sensors and components that need to be integrated to accommodate CAVs are not. For instance, RSUs have not been utilized for a long enough period to assess their maintenance needs, failure rates, and life cycles. As technologies such as RSUs become more mature, performance standards can be developed that will help agencies better scope costs and other resources required for maintenance.

Another challenge is that technologies are changing rapidly, which can frequently render an existing technology obsolete. This makes it difficult for agencies to make investment decisions and assess maintenance needs.

Workforce Development

The integration of CAVs and RWIS requires agencies to upgrade the skills of their workforce, as indicated in the literature review [49]. This involves recruiting and retaining tech-savvy staff. The survey revealed that organizations recognize the importance of computing, networking, electronics, and software skills for supporting integration. Most organizations are already supporting workforce development efforts and encouraging staff to enroll in training opportunities such as conferences and webinars to develop these necessary skills. In the targeted interviews, all agencies identified the need to train internal and maintenance staff on new technologies, policies, and procedures. Some agencies also face shortages in the staffing required to manage CAV-RWIS integration across all districts.

A comprehensive approach is recommended to address this challenge. This includes budgeting for customized training programs for internal employees, maintenance personnel, and new technicians. Working with outside experts and investing in training infrastructure ensures that training is current and effective. Collaborating with educational institutions and providing financial incentives for training can help agencies overcome resource constraints. Additionally, partnerships with educational institutions can be used to develop apprenticeship programs to close the skills gaps. Another recommendation is to develop nationally consistent credentials and

training programs for the various skills needed to maintain equipment such as RWIS and sensors. Such programs are necessary to ensure that agencies can depend on the skills gained in a given training program and that different training programs have a consistent level of quality.

Funding sources must be identified to support training initiatives and help create a culture of continuous learning and mentorship programs that will promote ongoing skill development. Finally, putting in place performance monitoring and evaluation mechanisms ensures the effectiveness of training programs and allows for continuous improvement throughout the CAV integration process.

Another challenge is retention of qualified staff. A survey of state agencies by Hallmark et al. [67] indicated that agencies often spent time and resources training existing staff in the needed technical skills only to have them recruited away by private sector employers that were able to pay higher salaries. This is primarily due to the insufficiency of existing position classifications and pay ranges for recruiting and retaining new talent.

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APPENDIX A. SURVEY

Introduction

Integration of Connected Vehicle and RWIS Technologies

Background

Aurora Pooled Fund: Integration of Connected Vehicle and RWIS Technologies (White Paper) is being conducted by a team led by the Institute of Transportation at Iowa State University.

The objective of this survey is to investigate transportation agencies' investments in RWIS technologies, including traditional, portable, mini, modular, and mobile RWIS, for the purpose of supporting connected and automated vehicle (CAV) integration and their impact on leveraging the rapidly expanding CAV space. This survey consists of five main sections. The results of this survey will guide the team in creating a framework and approach to address implementation challenges and lessons learned.

If you are not the correct person to answer this survey, kindly forward it to others who may be able to answer the questions.

If you have questions you may contact Inya Nlenanya, inya@iastate.edu.

1. Your Name:

2. Your Email Address:

3. Your Title:

4. Location (City, State):

5. Organization Name:

6. Organization Type:

- State DOT
- MPO or RPO
- Transit Agency
- Local Government
- Other Government
- Other (please specify)

7. Which of the following best describes the area which your organization serves?

- Predominantly Rural
- Predominantly Urban
- Rural and Urban
- Tribal

Section I seeks to classify your organization based on investments in RWIS technologies to leverage and accommodate CAVs.

1. Which RWIS technologies has your organization invested in or plans to invest in to support CAV integration?

- Traditional
- Portable
- Mini
- Modular
- Mobile
- Other

Remote Processing Units (RPU)s are roadside stations that relay information collected by sensors to **Central Processing Units (CPU)s**, which is the database or server that processes the data from the RPU.

2. What is the communication method between:

i. Sensor and RPU?

- Fiber
- Cable
- DSL
- Cellular
- Wi-Fi
- ZigBee
- WiMAX
- Radio
- Download on site
- Unknown

2. What is the communication method between:

ii. RPU and CPU?

- Fiber
- Cable
- DSL
- Cellular
- Wi-Fi
- ZigBee
- WiMAX
- Radio
- Download on site
- Unknown

3. How do you currently store RWIS data?

Cloud

Inhouse

Vendor

4. Have there been any investments in the following technologies in relation to RWIS?

i. Sensor technology (addition, replacement, upgrading)

Yes

No

Unknown

ii. RPU (addition, replacement, upgrading)

Yes

No

Unknown

iii. CPU (addition, replacement, upgrading)

Yes

No

Unknown

iv. Storage and data integration (addition, replacement, upgrading)

Yes

No

Unknown

5. What was the motivation behind the investments?

- To specifically accommodate CAV
- To upgrade to a newer or advanced technology
- To replace existing technology
- None of the above

6. Has there been any other investments in RWIS technology to be compatible with CAV, such as a proof-of-concept demonstration, testing or market survey of available options?

- Yes
- No

7. Do you plan to make any investments in RWIS technology to be compatible with CAVs in the next 3 years?

- Yes
- No

10. What challenges have your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?

Section II:

Section II concentrates on investments in Information Technology (IT) and data management technologies to enable data exchange between RWIS and CAVs.

1. Have there been any recent investments in IT & data communication and management technology?

- Yes
- No

3. What IT and data management systems has your organization implemented or plans to implement to facilitate data exchange between RWIS and CAVs?

5. How has your organization prioritized its investments in IT and data management technologies to support RWIS-CAV integration?

6. Do you plan to make investments in IT and data management and communication technology specific to RWIS towards CAV integration in the next 3 years?

Yes

No

3. What IT and data management systems has your organization implemented or plans to implement to facilitate data exchange between RWIS and CAVs?

5. How has your organization prioritized its investments in IT and data management technologies to support RWIS-CAV integration?

6. Do you plan to make investments in IT and data management and communication technology specific to RWIS towards CAV integration in the next 3 years?

Yes

No

7. How does your organization ensure the security and privacy of data exchanged between RWIS and CAVs?

8. How does your organization handle data standardization and interoperability between different RWIS and CAV systems?

9. What challenges has your organization faced or anticipates facing in implementing IT and data management systems for RWIS-CAV data exchange?

Section III investigates changes in maintenance practices and needs to facilitate seamless leverage of the CAV infrastructure specific to RWIS.

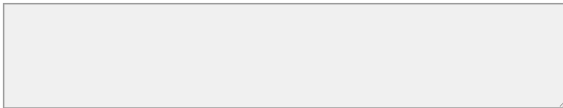
1. What maintenance practices is your agency interested in that will benefit from the CAV integration into RWIS?

- Traffic management (e.g. adjust ramp metering rates during inclement weather)
- Emergency services (e.g. adjust Freeway Incident Response Team strategies, call in additional dispatch staff members to accommodate unusual traffic patterns)
- Information dissemination (e.g. relay to motorists by operators via online and mobile apps)
- Winter Maintenance (e.g. planning pre-treatment and removal of snow and ice)
- Traffic data collection (e.g. speed, length, classification of vehicles)
- None at the moment

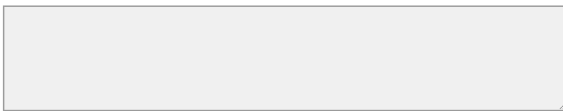
2. How has your organization adapted its maintenance practices to accommodate RWIS integration with CAV infrastructure?



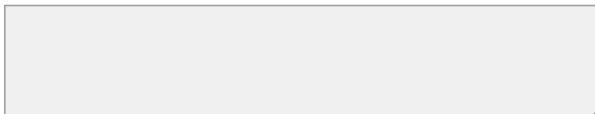
3. What specific maintenance requirements or challenges have emerged due to RWIS-CAV integration?




4. How does your organization prioritize maintenance activities and investments to support the integration of RWIS into the CAV infrastructure?



2. How has your organization adapted its maintenance practices to accommodate RWIS integration with CAV infrastructure?



3. What specific maintenance requirements or challenges have emerged due to RWIS-CAV integration?



4. How does your organization prioritize maintenance activities and investments to support the integration of RWIS into the CAV infrastructure?

5. Are there any partnerships or collaborations with other stakeholders (e.g., other agencies, private companies, research institutions) in the development or implementation of maintenance practices for RWIS-CAV integration?

Yes

No

7. Are there any lessons learned or best practices your organization has identified from its maintenance requirements and practices to support RWIS-CAV integration?

Yes

No

9. Are you concerned about other aspects of maintenance related to the integration of CAVs?

Yes

No

Section IV explores how agencies are investing in workforce development and collaboration with various stakeholders to adapt or leverage the CAV industry.

1. Have there been any updates to the agency's workforce skills to handle the integration of CAVs?

Yes

No

2. What workforce development initiatives has your organization implemented or plans to implement to adapt to the CAV industry?

3. How has your organization prioritized its investments in workforce development related to CAV integration and RWIS technologies?

4. What specific skills or competencies does your organization deem necessary for employees to effectively support RWIS-CAV integration?

5. Are there any partnerships or collaborations with other stakeholders (e.g., other agencies, private companies, research institutions) in the development or implementation of workforce development initiatives for CAV integration?

6. How does your organization address the need for continuous learning and skill development to keep up with the evolving CAV landscape?

7. Has your agency being involved in any collaboration between RWIS and CAV stakeholders including other DOTs, OEMs, private companies, and academia?

Yes

No

Section V examines agencies' investments in developing standards and protocols to accommodate CAVs.

1. Is your agency involved in the development of standards and protocols for RWIS communication and data exchange to accommodate CAV integration?

Yes

No

2. What investments has your organization made or plans to make in developing standards and protocols for CAV integration with RWIS technologies?

3. How does your organization ensure interoperability and compatibility between different CAV and RWIS systems through the use of these standards and protocols?

4. Is your agency involved in the development of new data formats for exchanging RWIS data with CAVs, or the development of new methods for integrating RWIS data into CAV systems?

Yes

No

5. How does your organization address the need for continuous updates and revisions to standards and protocols as CAV and RWIS technologies evolve?

6. What challenges has your organization faced or anticipates facing in developing or adopting standards and protocols for CAV integration with RWIS technologies?

7. How does your organization plan to address future standardization and protocol needs as the CAV industry continues to evolve and expand?

8. Will your agency be involved in the development of standards, new data formats and protocols for exchanging RWIS data with CAVs within the next 3 years?

Yes

No

If we need any clarification, may we contact you for a follow up interview?

Yes

No

APPENDIX B1. TARGET INTERVIEW QUESTIONS BASED ON SURVEY RESPONSES

Caltrans

Number of Respondents: 1

Name: Mohammad Iraki, mohammad.iraki@dot.ca.gov

Title: Branch Chief, Office of Connectivity and Broadband

Organization: Caltrans

Section 1

General Questions.

6. Have there been any other investments in RWIS technology to be compatible with CAVs, such as a proof-of-concept demonstration, testing, or a market survey of available options?

Response: Yes

Follow up: What was the investment? What were the results? How will it address the integration of CAV?

10. What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?

Response: Challenges include: limited resources to deploy assets in the field, delays in obtaining and certifying new tech to allow CAV integration.

Follow up: What kind of assets, give examples? Is there a plan in place to overcome the challenges? If yes, what is the plan?

Section 2

General Questions.

9. What challenges has your organization faced or anticipates facing in implementing IT and data management systems for RWIS-CAV data exchange?

Response: Will require training for staff on new tech and procedures. Funds to bring all districts up to new standards and enough staff to do this.

Follow up: Do you have a training manual that you can share? Or do you know what topics you will cover in this training? Will this training be conducted in-house or will you bring in a 3rd party/consultant to do it?

Section 3

General Questions.

3. What specific maintenance requirements or challenges have emerged due to RWIS-CAV integration?

Response: Will have to provide training to maintenance staff.

Follow up: Give examples of these specific maintenance requirements? Can you share the training outline? Do you have a list of maintenance practices you want to invest in if RWIS_CAV integration were in place?

6. Please list the partnerships or collaborations with other stakeholders (e.g., other agencies, private companies, research institutions) in the development or implementation of maintenance practices for RWIS-CAV integration.

Response: Contractor for development of CAV master plan, including RWIS integration.

Follow up: How far are you into the development of the master plan? Early, middle, final stages? How will it address the integration of RWIS/CAV? Have there been any challenges encountered during the development of this master plan? If so, can you share with us?

Section 4

General Questions.

Section 5

General Questions.

Agreed to a follow up interview - YES

Utah DOT

Number of Respondents: 2

Respondent 1

Name: Jeff Williams, JeffWilliams@utah.gov

Title: Weather Program Manager

Organization: Utah DOT

Section 1

General Questions.

6. Have there been any other investments in RWIS technology to be compatible with CAVs, such as a proof-of-concept demonstration, testing, or a market survey of available options?

Response: Yes

Follow up: Can you provide more information on the nature of this investment? What is the proposed method for integration? How do you define compatibility? What were the results?

10. What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?

Response: We do not foresee hardware compatibility issues with existing RWIS and CAV. CAV-RWIS data integration is the primary challenge

Follow up: Do you already have the systems working in sync without issue? What are the issues that you are seeing with the CAV-RWIS integration that are challenging? How do you intend to overcome the data integration challenge?

Section 2

General Questions.

3. What IT and data management systems has your organization implemented or plans to implement to facilitate data exchange between RWIS and CAVs?

Response: Panasonic has developed a method to integrate RWIS data into their V2X infrastructure.

Follow up: Are you currently using this method? If yes, have there been any challenges? Can you share the data exchange framework or is it proprietary?

Section 3

General Questions.

Section 4

General Questions.

Section 5

General Questions.

8. Will your agency be involved in the development of standards, new data formats, and protocols for exchanging RWIS data with CAVs within the next three years?

Response: Yes

Follow up: What is your agency's anticipated involvement?

Agreed to a follow up interview - YES

Respondent 2 (Best Person to Call)

Name: Blaine D Leonard, bleonard@utah.gov

Title: Transportation Technology Engineer

Organization: Utah DOT

Section 1

General Questions.

6. Have there been any other investments in RWIS technology to be compatible with CAVs, such as a proof-of-concept demonstration, testing, or a market survey of available options?

Response: Yes

Follow up: What was the investment? What were the results? How will it address the integration of CAV?

10. What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?

Response: RWIS is site specific. Our CV application focuses on road ice and wind, but is intended to apply more broadly than the specific location of the RWIS. We struggle to get reliable data at the RWIS site (without false positives) and more broadly. We also are still working on success metrics.

Follow up: What is the current spatial coverage of your CV application focus? Can you provide more detail on the CV application focus- framework, implementation, data collection, how does it communicate with the RWIS or it is just a standalone application? Regarding success metrics, are you focused on RWIS/CAV integration or the success metrics of your CV applications? How do you intend to overcome the challenges listed?

Section 2

General Questions.

9. What challenges has your organization faced or anticipates facing in implementing IT and data management systems for RWIS-CAV data exchange?

Response: Haven't yet created data management policies for data storage. We are sharing some but not all of this data and are still working on those processes and limits.

Follow up: Which data is currently been shared and how is the data currently shared? Any timeline on the others and what are the others?

Section 3

General Questions.

6. Please list the partnerships or collaborations with other stakeholders (e.g., other agencies, private companies, research institutions) in the development or implementation of maintenance practices for RWIS-CAV integration.

Response: We have contracts with Panasonic to develop applications, build and maintain the cloud data integration system, deploy CV systems, and maintain all this. We have contracts with Narwhal for other CV maintenance.

Follow up: What applications are been developed? Are you currently using, or have you tested any of the developed applications or systems and have you encountered any challenges so far?

Have you or Narwhal encountered any challenges so far in maintaining the CV systems?

Section 4

General Questions.

Section 5

General Questions.

Agreed to a follow up interview - YES

Florida DOT

Number of Respondents: 1

Name: Raj Ponnaluri, raj.ponnaluri@dot.state.fl.us

Title: Manager, Emerging Technologies

Organization: Florida DOT

Section 1

General Questions.

10. What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?

Response: Depends on the size and scale of the project. Generally, we did well

Follow up: Can you provide more details or documentation on what was done for the RWIS-CAV integration?

What were the specific challenges? How did you overcome the challenges you faced?

Section 2

General Questions.

3. What IT and data management systems has your organization implemented or plans to implement to facilitate data exchange between RWIS and CAVs?

Response: V2X data exchange platform—under development.

(RWIS will be one of the use cases as we plan to roll out the V2X data exchange platform)

Follow up: How far are you into the development of the V2X data exchange platform? Early, middle, final stages?

What is the architecture, framework or outline of the platform?

Section 3

General Questions.

Section 4

General Questions.

Section 5

General Questions.

Agreed to a follow up interview - YES

PennDOT

Number of Respondents: 1

Name: Gunnar Rhone, grhone@pa.gov

Title: Engineering Specialist

Organization: PennDOT

Section 1

6. Have there been any other investments in RWIS technology to be compatible with CAVs, such as a proof-of-concept demonstration, testing, or a market survey of available option?

Response: No

7. Do you plan to make any investments in RWIS technology to be compatible with CAVs in the next three years?

Response: No

10. What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?

Response: None. The data is available for CAV integration.

Follow up: Can you clarify what you mean by the data is available for CAV integration? Is it already integrated with RWIS? Or is it separate but can be integrated, if so, what technology or platform are you using for this?

Section 2

3. What IT and data management systems has your organization implemented or plans to implement to facilitate data exchange between RWIS and CAVs?

Response: We're at the beginning stages of implementing a V2X data exchange as part of our ATMS upgrade.

5. How has your organization prioritized its investments in IT and data management technologies to support RWIS-CAV integration?

Response: We're creating a data exchange that can integrate all of the department's data through V2X technologies, so it wasn't prioritized just to support RWIS. One of the ways that we prioritize our CAV related upgrades is through projects where we can get day-one benefits when the project is deployed. Through the V2X data exchange, we can begin integrating the data that we have through 4G/5G V2X (ie, services like Haas Alert), then later use the data for C-V2X once that's deployed.

Follow up: How far are you into the development of the V2X data exchange platform? Early, middle, final stages? What is the architecture, framework or outline of the platform?

Does the V2X data exchange involve communication with RWIS?

Section 3

General Questions.

Section 4

General Questions.

Section 5

General Questions.

Agreed to a follow up interview - YES

Oregon DOT

Number of Respondents: 1

Name: Blaine Van Dyke, blaine.vandyke@odot.oregon.gov

Title: ITS Engineer

Organization: Oregon DOT

Section 1

General Questions.

7. Do you plan to make investments in RWIS technology to be compatible with CAVs in the next three years?

Response: No

10. What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?

Response: Communication to the vehicles is the largest hurdle. We are in the process of developing a Connected Vehicle Ecosystem with the intention of it using our existing RWIS public data feed and providing alerts to the public via OEM installed cellular telematics.

Follow up: How does your agency intend to address the communication challenge? How far are you into the development of the ecosystem? Early, middle, final stages? What is the architecture, framework or outline of the ecosystem?

Section 2

General Questions.

1. What IT and data management systems has your organization implemented or plans to implement to facilitate data exchange between RWIS and CAVs?

Response: We are in the process of developing a cloud based Connected Vehicle Ecosystem that will provide RWIS and basic safety message alerts to the public.

Follow up: Have there been any challenges encountered during the development? If so, can you share with us? What is the planned/proposed architecture, framework or outline of the ecosystem?

6. Do you plan to make investments in IT and data management and communication technology specific to RWIS toward CAVs in the next three years?

Response: Yes

Follow up: What type of investments do you plan to make? Does it involve buying new RWIS equipment, upgrading existing equipment, or conducting research/studies? How will this investment address RWIS and CAV integration?

9. What challenges has your organization faced or anticipates facing in implementing IT and data management systems for RWIS-CAV data exchange?

Response: Communication to the public is the largest challenge. Agreements will have to be made with OEMs to get messages to vehicles, and to get vehicle that indicates weather conditions into the system that can provide alerts for hazardous weather.

Follow up: Is your agency in talks with OEMs to reach this agreement? Are the OEMs hesitant or eager to allow exchange of information? Are they proposing conditions for this to happen and what are those conditions?

Section 3

General Questions.

2. How has your organization adapted its maintenance practices to accommodate RWIS integration with CAV infrastructure?

3. What specific maintenance requirements or challenges have emerged due to RWIS-CAV integration?

4. How does your organization prioritize maintenance activities and investments to support the integration of RWIS into the CAV infrastructure?

Response to above questions: We are still in the planning phases and do not have a defined integration yet.

Follow up: How far are you in the planning phase? Early, middle, final stages?

5. Are there any partnerships or collaborations with other stakeholders (e.g., other agencies, private companies, research institutions) in the development or implementation of maintenance practices for RWIS-CAV integration?

Response: Yes

Follow up: What or who are these partners, OEMs, research institutes, etc? How will these partnerships address the integration of RWIS/CAV? Have there been any challenges encountered so far? If so, can you share with us?

6. Please list the partnerships or collaborations with other stakeholders (e.g., other agencies, private companies, research institutions) in the development or implementation of maintenance practices for RWIS-CAV integration.

Response: Local transportation agencies around the state will need to be involved in the RWIS-CAV integration effort.

Follow up: How will these partnerships improve the integration of RWIS/CAV? Have there been any challenges so far in trying to seek the involvement of the local transportation agencies?

9. Are you concerned about other aspects of maintenance related to the integration of CAVs?

Response: Yes

10. What are the other aspects of maintenance related to the integration of CAVs that you are concerned about?

Response: In addition to RWIS data, basic safety messages like road closures, detours, work zones, etc. need to be included in the system to communicate with the public for safety enhancements.

Follow up: Can you explain how this is a maintenance issue? How do you intend to address this issue?

Section 4

General Questions.

2. What workforce development initiatives has your organization implemented or plans to implement to adapt to the CAV industry?

Response: We have a price agreement with a contractor to work with agencies and OEMs for data integration and communication.

Follow up: Does this agreement involve developing your agency's workforce to adapt to the CAV industry? If yes, can you explain further?

Section 5

General Questions.

3. How does your organization ensure interoperability and compatibility between different CAV and RWIS systems through the use of these standards and protocols?

Response: We are still in the planning phase at this time and have not incorporated any standards into our data management.

6. What challenges has your organization faced or anticipates facing in developing or adopting standards and protocols for CAV integration with RWIS technologies?

Response: As the previous question suggests the standards are new and will be under continuous updates. Conforming to the latest version of those updates will be a challenge depending on how often standards change.

Agreed to a follow up interview – YES

APPENDIX B2. SUMMARY OF TARGETED INTERVIEWS

California Department of Transportation

Mohammad Iraki, Office of Connectivity and Broadband. Mohammad.iraki@dot.ca.gov

Overall key findings during interview summarized as follows:

- Challenges include limited resources to deploy assets in the field. Assets include equipment and personnel
- We have experienced delays in obtaining and certifying new technicians. Certification is necessary to allow CAV integration. The challenge is we do not have the resources needed for this at this time or at least funds will need to be re-allocated to this program
- Efforts will require training for internal staff on new technologies, policies and procedures
- Challenged to bring funding to all districts and meet new standards and need enough staff to do this
- Will have to provide training to maintenance staff also so they coordinate efforts
- Contractor for development of CAV master plan, including RWIS integration
- Costs are difficult to quantify; many technologies are new so costs are higher than they may ultimately be and technologies are changing

For details of what specific survey questions were directly answered and how, please see below:

Question: *Have there been any other investments in RWIS technology to be compatible with CAVs, such as a proof-of-concept demonstration, testing, or a market survey of available options?*

Response: *Yes*

Question: *What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?*

Response: *Challenges include: limited resources to deploy assets in the field, delays in obtaining and certifying new tech to allow CAV integration.*

Question: *What challenges has your organization faced or anticipates facing in implementing IT and data management systems for RWIS-CAV data exchange?*

Response: *Will require training for staff on new tech and procedures. Funds to bring all districts up to new standards and enough staff to do this.*

Question: *What specific maintenance requirements or challenges have emerged due to RWIS-CAV integration?*

Response: *Will have to provide training to maintenance staff.*

Question: *Please list the partnerships or collaborations with other stakeholders (e.g., other agencies, private companies, research institutions) in the development or implementation of maintenance practices for RWIS-CAV integration.*

Response: *Contractor for development of CAV master plan, including RWIS integration.*

Utah Department of Transportation

Jeff Williams, Weather Program Manager (National SME). JeffWilliams@utah.gov

Overall key findings during interview summarized as follows:

- Challenges include CAV and RWIS integration
- We have started using Panasonic to integrate data infrastructure
- Agency plans on participating in the development of standards, formats and protocols

For details of what specific survey questions were directly answered and how, please see below:

Question: *Have there been any other investments in RWIS technology to be compatible with CAVs, such as a proof-of-concept demonstration, testing, or a market survey of available options?*

Response: *Yes*

Question: *What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?*

Response: *We do not foresee hardware compatibility issues with existing RWIS and CAV. CAV-RWIS data integration is the primary challenge*

Question: *What IT and data management systems has your organization implemented or plans to implement to facilitate data exchange between RWIS and CAVs?*

Response: *Panasonic has developed a method to integrate RWIS data into their V2X infrastructure*

Question: *Will your agency be involved in the development of standards, new data formats, and protocols for exchanging RWIS data with CAVs within the next three years?*

Response: *Yes*

Utah Department of Transportation.

Blaine, Transportation Technology Engineer. bleonard@utah.gov

Overall key findings during interview summarized as follows:

- Challenges include site specific limitations with inability to be flexible with RWIS having a fixed location
- Policies need to be created to be able to manage and store data, this could have limitations
- Working with Panasonic technologies

For details of what specific survey questions were directly answered and how, please see below:

Question: *Have there been any other investments in RWIS technology to be compatible with CAVs, such as a proof-of-concept demonstration, testing, or a market survey of available options?*

Response: *Yes*

Question: *What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?*

Response: *RWIS is site specific. Our CV application focuses on road ice and wind, but is intended to apply more broadly than the specific location of the RWIS. We struggle to get reliable data at the RWIS site (without false positives) and more broadly. We also are still working on success metrics*

Question: *What challenges has your organization faced or anticipates facing in implementing IT and data management systems for RWIS-CAV data exchange?*

Response: *Haven't yet created data management policies for data storage. We are sharing some but not all of this data and are still working on those processes and limits*

Question: *Please list the partnerships or collaborations with other stakeholders (e.g., other agencies, private companies, research institutions) in the development or implementation of maintenance practices for RWIS-CAV integration.*

Response: *We have contracts with Panasonic to develop applications, build and maintain the cloud data integration system, deploy CV systems, and maintain all this. We have contracts with Narwhal for other CV maintenance.*

Florida Department of Transportation

Raj Ponnaluri, Emerging Technologies Manager. Raj.ponnaluri@dot.state.fl.us

Overall key findings during interview summarized as follows:

- Size and scale of project determines what technologies we implement
- Processes, policies and data exchange platforms are currently under development

For details of what specific survey questions were directly answered and how, please see below:

Question: *What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?*

Response: *Depends on the size and scale of the project. Generally, we did well*

Question: *What IT and data management systems has your organization implemented or plans to implement to facilitate data exchange between RWIS and CAVs?*

Response: *V2X data exchange platform—under development. (RWIS will be one of the use cases as we plan to roll out the V2X data exchange platform)*

Pennsylvania Department of Transportation.

Gunnar Rhone – Engineering Specialist. grhone@pa.gov

Overall key findings during interview are summarized as follows:

- Data is freely available for CAV integration
- In development phase of data exchange and integration to benefit program
- Working on streamlining various data formats from different departments to integrate into system
- Looking at how to integrate other systems they are using
- This may not be a top priority so an implementation date is not available at this time

For details of what specific survey questions were directly answered and how, please see below:

Question: *What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?*

Response: *None. The data is available for CAV integration.*

Question: *How has your organization prioritized its investments in IT and data management technologies to support RWIS-CAV integration?*

Response: *We're creating a data exchange that can integrate all of the department's data through V2X technologies, so it wasn't prioritized just to support RWIS. One of the ways that we prioritize our CAV related upgrades is through projects where we can get day-one benefits when the project is deployed. Through the V2X data exchange, we can begin integrating the data that we have through 4G/5G V2X (i.e., services like Haas Alert), then later use the data for C-V2X once that's deployed.*

Question: *What challenges has your organization faced or anticipates facing in implementing RWIS technologies to support CAV integration?*

Response: *None. The data is available for CAV integration.*

Question: *Can you clarify what you mean by the data is available for CAV integration?*

Response: *This answer came from our RWIS people, and I believe they meant that the APIs are available to be integrated.*

Question: *Is it already integrated with RWIS?*

Response: *No*

Question: *Or is it separate but can be integrated, if so, what technology or platform are you using for this?*

Response: *Vaisala hosts our data and we access it through a website that they provide. Our data is also available through an API which we share with some of our partners like NWS, AccuWeather and 511PA. PennDOT also ingests the data so it can be used in Maintenance IQ and any other applications we would want to use it in.*

Question: *How has your organization prioritized its investments in IT and data management technologies to support RWIS-CAV integration?*

Response: *We're creating a data exchange that can integrate all of the department's data through V2X technologies, so it wasn't prioritized just to support RWIS. One of the ways that we prioritize our CAV related upgrades is through projects where we can get day-one benefits when the project is deployed. Through the V2X data exchange, we can begin integrating the data that we have through 4G/5G V2X (IE, services like Haas Alert), then later use the data for C-V2X once that's deployed.*

Question: *How far are you into the development of the V2X data exchange platform?*

Response: *Release 1 is scheduled for end of this year, with Release 2 (and maybe 3) in 2024. I don't believe RWIS is in the first release, but integrating weather data is somewhere on the roadmap.*

Question *Early, middle, final stages?*

Response: *Unsure where the integration is on the priorities.*

Question: *What is the architecture, framework or outline of the platform?*

Response: *The V2X data exchange is basically a module in our new ATMS. It allows us to have a location where we can publish a data stream that other 3rd party data users can ingest, and also allow authorized third parties to publish to (like OEM data) that we can use in operations.*

Question: *Does the V2X data exchange involve communication with RWIS?*

Response: *We plan on integrating the RWIS API with the V2X data exchange in future releases.*

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