Scientific Research Publishing

Journal of Transportation Technologies, 2025, 15(3), 374-412
https://www.scirp.org/journal/jtts
ISSN Online: 2160-0481
ISSN Print: 2160-0473

Leveraging the Integration of Connected Vehicle and RWIS Technologies

Adnan Inusah[1], **Inya Nlenanya**[2], **Shauna Hallmark**[1*]

[1]Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, USA
[2]Institute for Transportation (InTrans), Iowa State University, Ames, IA, USA
Email: inusah@iastate.edu, inya@iastate.edu, *shallmar@iastate.edu

How to cite this paper: Inusah, A., Nlenanya, I. and Hallmark, S. (2025) Leveraging the Integration of Connected Vehicle and RWIS Technologies. *Journal of Transportation Technologies*, **15**, 374-412.
https://doi.org/10.4236/jtts.2025.153017

Received: March 22, 2025
Accepted: July 7, 2025
Published: July 10, 2025

Abstract

Transportation agencies across the US rely on Road Weather Information Systems (RWIS) to help predict and manage the impacts of weather on transportation safety and mobility. RWIS monitors temperature, precipitation, and road surface condition from roadside stations. However, these conditions can change rapidly and often vary across a road corridor, to an extent that fixed RWIS stations cannot fully capture, creating a gap in the data collected. Integrating Connected Vehicle (CV) technologies and RWIS can help provide substantially more granular real-time data of the road weather conditions to help fill the gap. This study explores the practical feasibility and emerging technologies necessary for this integration by conducting an extensive literature review and conducting surveys and interviews with transportation agencies. Survey and interview findings reveal resource constraints as a significant barrier to CV-RWIS integration, emphasizing the need for targeted IT, data management, and workforce development investments. Agencies also highlighted the importance of developing standards and protocols to ensure interoperability and compatibility. Recommendations for future research include establishing robust data standards, evaluating hardware and software configurations, and understanding the impacts of CV-RWIS integration on transportation systems. Investments in edge computing, high-speed networks, and cybersecurity are crucial. Workforce development through customized training programs and partnerships with educational institutions is essential to address skill gaps and retain qualified staff. Overall, while the integration of CV and RWIS technologies presents challenges, it holds promise for enhanced road safety and traffic management.

Keywords

RWIS, Connected Vehicles, Weather, CV

1. Introduction

Vehicles equipped with advanced technologies that allow them to interact with other vehicles, infrastructure, and external systems are known as connected vehicles (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. CVs 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.

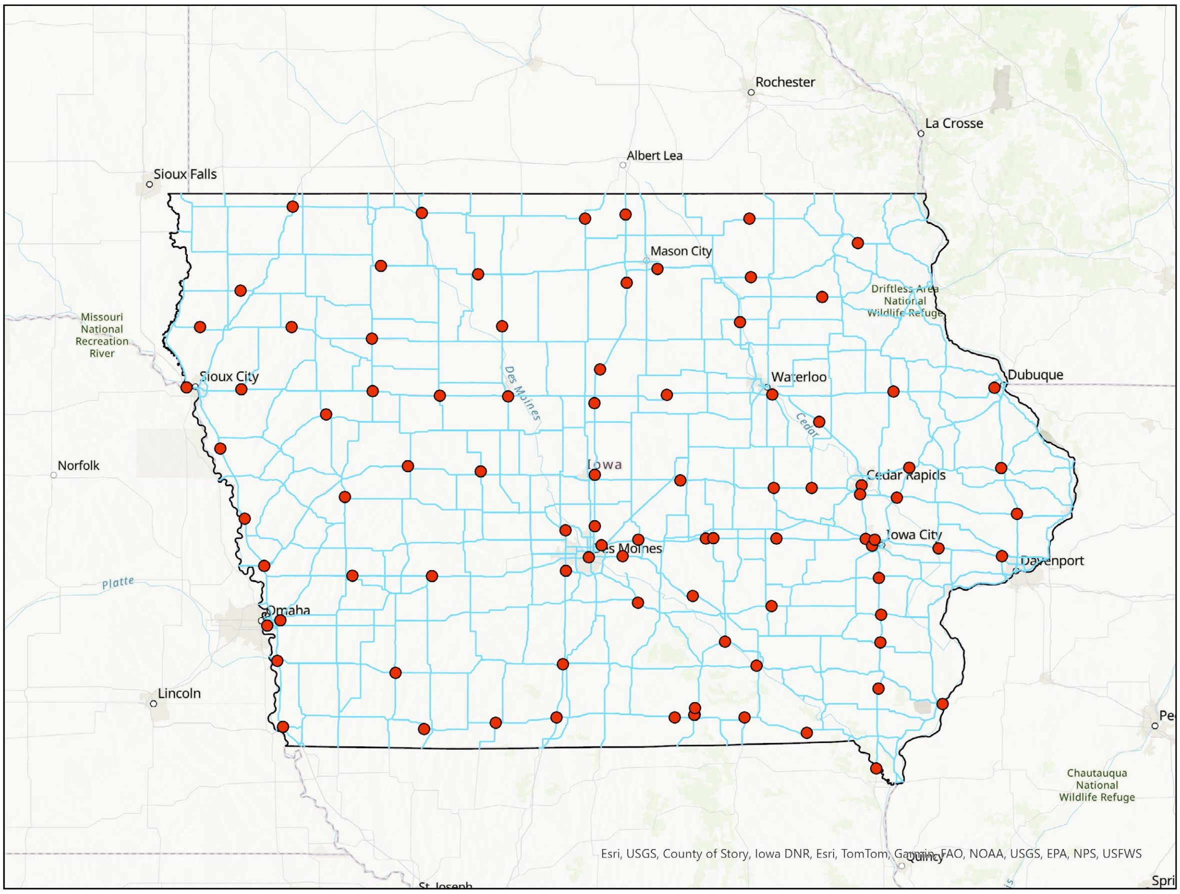
Aspect	CVs	CAVs
Connectivity	Primarily focuses on internet connectivity and communication capabilities	Combine connectivity with autonomy for autonomous operations
Human Intervention	Human drivers are responsible for driving and making decisions	Designed to operate with minimal or no human intervention
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

Transportation agencies across the US rely on Road Weather Information Systems (RWIS) to help predict and manage the impacts of weather on transportation safety and mobility. RWIS monitor weather and pavement surface conditions and communicates these conditions to agency personnel to facilitate maintenance operations and decision-making.

Typically, RWIS gathers general temperature, precipitation, and road surface condition information from fixed position roadside monitor stations. However, these conditions can change quickly and are often variable across a road corridor, to an extent that RWIS stations cannot capture. For instance, the Iowa DOT has about 200 RWIS stations deployed across 9,616 miles of state-maintained roadways as shown in Figure 1, translating to a resolution of one station per 49 miles. However, the effective range of each RWIS station is only a small fraction of this distance. Mobile, weather-capable CVs can provide improved and substantially more granular real-time data of the road weather conditions in conjunction with RWIS. Communication between these CVs and RWIS can enable more precise, better targeted, and more adaptive corridor management response plans. This study aims to identify emerging technologies required to support and take advantage of CV technology integration with RWIS. Table 2 compares the differences between CVs and RWIS.

Table 2. Comparison of CV and RWIS.

Category	CV	RWIS
Real-Time Data & Coverage	Provides real-time communication between vehicles (V2V) and infrastructure (V2I). Relies on a high number of connected vehicles for effectiveness.	Monitors road conditions in real time but is limited to fixed sensor locations.
Weather & Road Conditions	Detects localized weather and road hazards.	Cannot track moving weather patterns or localized conditions.
Data Reliability & Accuracy	More vehicles improve data accuracy, but sensor reliability varies by manufacturer.	Provides stable, high-accuracy weather data using calibrated sensors.
Infrastructure Needs	May require roadside units (RSUs) for full functionality, especially in areas with low adoption.	Expensive to install and maintain, limiting widespread deployment.
Traffic & Safety	Improves crash prevention, alerts drivers to hazards, but has privacy and connectivity concerns in low-signal areas.	Supports road maintenance and winter safety but lacks real-time driver alerts and hazard detection.



Esri, USGS, County of Story, Iowa DNR, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS

Figure 1. RWIS Locations, Iowa DOT.

2. Methods

The study first conducted a comprehensive literature review to obtain full understanding of the state-of-the-art and state-of-the-practice literature on CV applications for winter road weather management and CV applications for multimodal travel. Then a survey was conducted to determine investments made by state DOTs, regional and metropolitan planning organizations in RWIS technologies for the purpose of supporting CV integration. To augment the agency outreach, the research team conducted follow-up interviews based on the survey responses, targeted at the agencies that appeared the most mature in their accommodation of CV technology according to the survey responses.

3. Literature Review

The literature review provided a comprehensive analysis of the integration of CVs and RWIS across three themes which are discussed below.

3.1. Applications for and Practical Feasibility of CV-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 booted drones 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 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 random forest, polynomial, and linear regression models. The DNN model outperformed the other models by having the highest R2 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 [13].

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.

3.2. Practical Considerations for CV-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 [18] 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.* [19], 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 [20] 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 Rehrl [21] 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.* [22] 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*. [23] 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*. [24] 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*. [25] 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.* [26] 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.

3.3. Mode 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 [27].

In a study to explore ways of sending safety messages from one vehicle to another with high reliability and low delay, Xu *et al.* [28] 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.* [29] 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 [30]. 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.* [31] 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 [30].

The most crucial issue at this moment may be how superior C-V2X is to DSRC. To determine this, Nguyen *et al.* [32] 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 [33] 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.* [23], 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 [30] 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.* [34], the effectiveness of a heterogeneous network (HetNet) 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 [35].

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.* [36] 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 [37] 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 [38].

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.

3.4. 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 [39]-[41].

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 [42].

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 [40].

Some DOTs have plans to integrate CAVs into their systems for detecting road surface conditions and forecasting road weather [43]-[46]. 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 [44].

Integrating CAVs and RWIS will involve upgrading the skills of agency workforces. In a report by Fard *et al.* [47], 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.* [48] 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 [49].

Since local agencies generally do not have the resources to prepare for the widespread implementation of CAVs, Hallmark *et al.* [50] 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 [51], 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.* [38], 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.

3.5. Overview of the Current Practices

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 [52].

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 [53].

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 [54].

The federal government's involvement in research on transportation automation is mentioned in a recent U.S. DOT report [55]. 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 [56] 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.

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 [57].

Other Caltrans CAV projects include projects in Districts 11 and 12 [58]. 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 is 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 of 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) [59].

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, which is expected to be operational by the end of 2024, 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 [60]. 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 [60].

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 [61].

511 Traveler Information System

The 511 traveler information system, designated by the Federal Communications Commission (FCC) in 2000, provides real-time traffic, road conditions, and weather-related updates through phone calls, websites, and mobile applications. Managed by state and regional transportation agencies, it helps travelers navigate road closures, construction zones, major traffic incidents, and, where available, public transit information to enhance safety, reduce congestion, and improve transportation efficiency [62] [63]. However, the system has limitations, including incomplete weather data, lacks details like visibility, precipitation type, and forecasted pavement temperature, which can impact the reliability of road condition reports, especially in severe weather-prone areas. Additionally, not all states have implemented 511, and coverage varies, sometimes being restricted to specific regions rather than statewide [64]. For instance, the Iowa 511 app provides statewide updates for interstates and major highways but excludes county roads and city streets, limiting its usefulness for local travelers [65]. These inconsistencies in coverage and data availability can affect the system's overall effectiveness in providing timely and accurate travel information.

ClearPath Weather

Many state departments of transportation (DOTs) in the United States use ClearPath Weather, a winter road information service within the Data Transmission Network (DTN)'s ClearPath suite of traffic and weather solutions [66]. Designed to assist decision-makers in managing winter road conditions before, during, and after weather events, it provides site-specific forecasts, real-time data, and customizable alerts for observed and predicted weather and pavement conditions. It also integrates National Weather Service (NWS) watches, warnings, and advisories to enhance preparedness and response efforts. However, coverage gaps, particularly in rural or less-monitored areas, can affect forecast accuracy, and its reliance on third-party data sources, may impact effectiveness. Despite these limitations, ClearPath Weather remains a vital tool for winter maintenance operations, helping agencies improve road safety and mobility during severe weather conditions.

Other State-Level Connected Vehicle Deployments

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

Table 3. Operational connected vehicle deployments

State	Deployment
Alabama	• University of Alabama, ACTION Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) • University of Alabama, Center for Advanced Vehicle Technologies and Alabama DOT
Arizona	• Arizona Connected Vehicle Test Bed (Anthem)
California	• California Connected Vehicle Test Bed, Palo Alto • Prospect Silicon Valley Technology Demonstration Center ITS Lab • San Jose Connected Vehicle Pilot Study
Colorado	• Denver ATCMTD • US RoadX Connected Vehicle Project
Delaware	• Delaware DOT SPaT Challenge Deployment
Florida	• 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
Georgia	• 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

Continued

Hawaii	• Hawaii DOT DSRC Deployment
Idaho	• Ada County Highway District
Indiana	• Indiana Connected Vehicle Corridor Deployment Project
Maryland	• I-895 Baltimore Harbor Tunnel DSRC • I-95 Fort McHenry Tunnel DSRC • US 1 Innovative Technology Corridor
Massachusetts	• Hope TEST
Michigan	• 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	• MnDOT DSRC • Roadway Safety Institute Connected Vehicle Test Bed
Nevada	• Las Vegas Freemont Street SPaT Corridor • I-580/Washoe County, Nevada
New Hampshire	• New Hampshire DOT SPaT, Dover
New Jersey	• City of New Brunswick Innovation Project • Integrated Connected Urban Corridor, Newark
New York	• 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	• North Carolina DOT DSRC
Ohio	• City of Columbus—Smart City Challenge • NW US33 Smart Mobility Corridor • Ohio Turnpike and Infrastructure Commission DSRC Project
Pennsylvania	• 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

Continued

Tennessee	• Tennessee DOT SPaT Challenge Project (Knoxville)
Utah	• Provo Orem Bus Rapid Transit • Salt Lake Valley Snowplow Preemption • Utah Transit Authority DSRC Traffic Signal Pilot Project
Virginia	• Fairfax County Connected Vehicle Test Bed • Virginia Smart Roads
Washington	• Washington State Transit Insurance Pool Safety-Collision Warning Pilot Project
Wisconsin	• Connected Park Street Corridor
Wyoming	• Wyoming Connected Vehicle Project Deployment

Table 4 shows the planned connected vehicle deployments by state according to the U.S. DOT [64].

Table 4. Planned connected vehicle deployments.

State	Deployment
Alaska	• Alaska University Transportation Center
Arizona	• Loop 101 Mobility Project
California	• 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	• Colorado Better Utilizing Investments to Leverage Development (BUILD) • Colorado Transportation Investment Generating Economic Recovery (TIGER) • Colorado DOT Wolf Creek Pass ATCMTD
Delaware	• Delaware DOT ATCMTD
Florida	• 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

Continued

Georgia	• CV-1K+ Project
Hawaii	• Hawaii DOT C-V2X Project
Indiana	• Indiana DOT SPaT Deployment—Greenwood • Indiana DOT SPaT Deployment—Merrillville
Iowa	• Iowa City ADS
Kentucky	• Louisville TIGER
Maine	• Maine BUILD • Maine DOT 2020 ATCMTD
Massachusetts	• Mass DOT DSRC Route 9 DSRC Corridor
Michigan	• Michigan ADS • Michigan BUILD • Michigan TIGER • MDOT Intelligent Woodward Corridor Project • University of Michigan 2020 ATCMTD
Missouri	• Kansas City US 69 Corridor SPaT Challenge • Springfield, Missouri, SPaT Project • St. Louis SPaT Deployment Project
Nebraska	• Nebraska Integrated Corridor Management (ICM) • Nebraska TIGER
Nevada	• Las Vegas BUILD • RTC 2020 ATCMTD
New Jersey	• 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	• Connected Region: Moving Technological Innovations Forward in the Niagara International Transportation Technology Coalition (NITTEC) Region
North Carolina	• North Carolina DOT Multimodal CV Pilot
Ohio	• Ohio ADS • Smart Belt Coalition (Ohio)
Oregon	• Oregon ATCMTD
Pennsylvania	• Pennsylvania ADS • PennDOT I-76 Multimodal Corridor Management Project
South Carolina	• South Carolina Connected Vehicle Test Bed
Tennessee	• Chattanooga Smart City Corridor Test Bed • Metro Nashville 2020 ATCMTD • Tennessee DOT I-24 Corridor Nashville

Continued

Texas	• 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	• Utah DOT Connected Utah ATCMTD • Utah 2020 ATCMTD • Utah DOT CV Data Eco-system Project
Virginia	• Virginia ADS • Virginia Port 2020 ATCMTD • Virginia Truck
Washington	• 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	Wyoming BUILD

Source: [64].

3.6. 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

CV technology relies on message exchange to create mutual awareness, which requires a high CV 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

CVs produce enormous amounts of data, which makes CV 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 CVs, 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

CV 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 CV users' privacy in terms of identity and location arises from the ways CV data are used [26].

Communication Range, Sensing Range, and Latency

Communication range and latency are of utmost importance for CV applications. For example, CVs 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 CV applications [16] [34] [35]. Since mmWave technology produces lower latencies than other technologies [36], extensive research should be conducted on improving this technology's range and line of sight qualities.

Communication Standards

The lack of standards for V2V safety communications may be a cause of the delays in CV integration. Developing and implementing national standards for CV applications will provide guidance on V2X communication protocols and promote effective communication between different CV system components made by different manufacturers [17] [37].

4. Survey of Agencies

State and local transportation agencies were surveyed to investigate their investments in RWIS technologies to support CV integration and the impact of these investments on leveraging the rapidly expanding CV space. The survey was developed using Qualtrics, and a link to the survey was emailed to various state and national committees. While the primary target was state DOTs, the survey was also shared with local government agencies, consultants, and toll authorities. In total, 54 responses were received from 46 organizations. The survey was sent to organizations in all 50 states, and responses were obtained from 32 state DOTs, representing about 64% of all state DOTs. **Figure 2** shows the states participating in the survey.

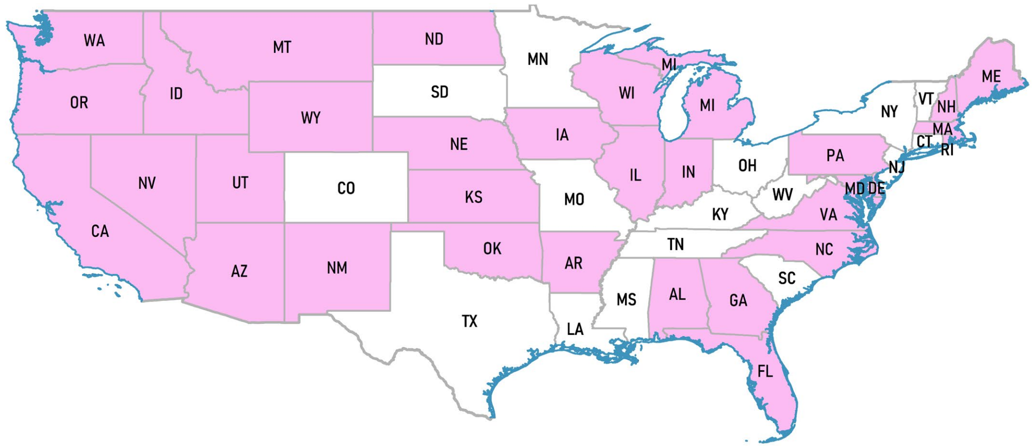


Figure 2. States participating in the survey.

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 CVs. Section II concentrated on investments in information technology (IT) and data management technologies to enable data exchange between RWIS and CVs. Section III investigated maintenance practices that would benefit from CV-RWIS integration and changes in maintenance practices required to facilitate seamless leveraging of CV infrastructure for RWIS applications. Section IV explored agencies' investments in workforce development and collaborations with various stakeholders to adapt or leverage the CV industry for RWIS applications, and Section V examined agencies' investments in developing standards and protocols to accommodate CVs. Figure 3 shows the six sections of the survey.

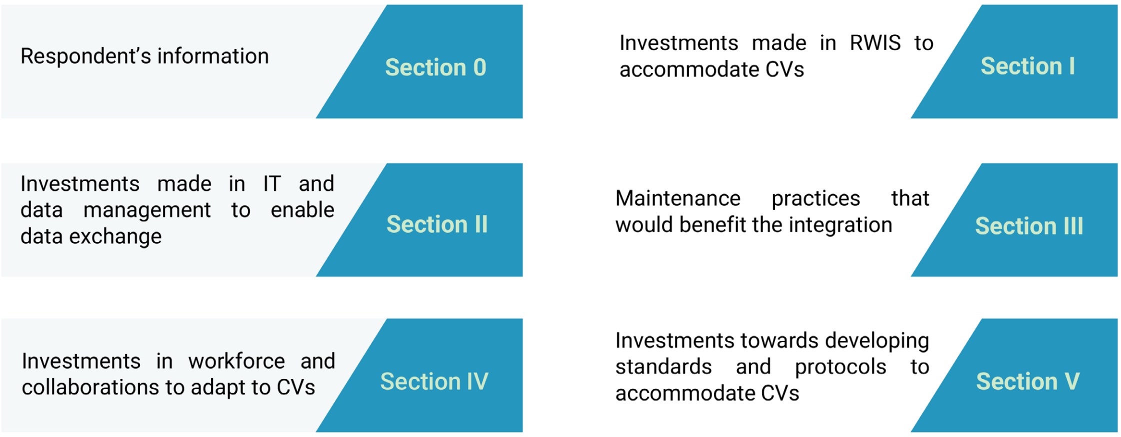


Figure 3. Sections of the survey.

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.

5. Targeted Interviews

Follow-up interviews were conducted based on the survey responses to augment the survey described above. Agencies that participated in the survey and appeared to be the most mature in their accommodation of CV technology were ranked, 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.

5.1. 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 CVs, 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 CVs", "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 CVs	**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 shows the top 10 organizations that have already invested or plan to invest in technology for CV 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 CV 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

5.2. Agency Selection and Findings

Of the top six organizations listed in Table 3, the Delaware DOT had yet to make plans for significant investments in CV-RWIS integration soon. 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 key findings of the survey and targeted interviews are summarized as follows:

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

When addressing the issues associated with the integration of RWIS and CVs, agencies continually emphasized resource constraints as a common challenge. Given this limitation, investment decisions for CV-RWIS integration were prioritized based on certain conditions. Caltrans, for example, underlined the importance of upgrading existing RWIS technology to ensure readiness for CV 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 CV master plan that includes RWIS integration.

Regarding 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 CV-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 CV-RWIS integration efforts. Plans were in the works to develop a CV academy to fully train Caltrans workers on CV technology and deployment. PennDOT highlighted an in-house division dedicated to emerging technologies that provided personnel with access to training, which is helpful for CV-RWIS integration. Specific skills in areas such as networking, communications, and equipment troubleshooting were identified as important for enabling staff to effectively support CV-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 CV-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.

6. Challenges and Recommendations for Future Research

Efforts to integrate CVs 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.

6.1. Data Standards to Enhance Interoperability and Interpretability

The integration of CVs 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, are an ongoing challenge that hinders data interoperability and poses integration challenges. Furthermore, the lack of standard protocols for data exchange and processing between CVs 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 CVs 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.

6.2. 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 CV-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 CV-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 CV-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 CV-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 CV.

6.3. Investments in RWIS Technologies to Support CV Integration

Efficient data handling by RWIS and RSUs requires robust computational capabilities for swift processing and exchange, and determining the optimal number of CVs 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 CVs and RWIS stations for cost-effective integration.

6.4. Investments in IT and Data Communication and Management Technology

The literature review indicated that CVs 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 CV applications was another identified challenge. CV-RWIS integration also raises privacy concerns, necessitating a balance between data interchange and user privacy preservation [26]. The survey identified common challenges in implementing IT and data management systems for CV 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 CVs and RWIS necessitates the development of a strong communication infrastructure [33] [35] [47]. Investments in high-speed networks, particularly the deployment of technologies such as 5G, are critical for enabling real-time data transmission between CVs 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 CVs and RWIS, resulting in a more secure and efficient integration system.

6.5. 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 CV-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 [28] [38]. To ensure the reliability of data, the sensors in both CVs 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 CV-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 CVs 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.

6.6. Workforce Development

The integration of CVs and RWIS requires agencies to upgrade the skills of their workforce, as indicated in the literature review [47]. 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 CV-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 CV integration process.

Another challenge is the 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 could pay higher salaries. This is primarily due to insufficient existing position classifications and pay ranges for recruiting and retaining new talent.

6.7. Implementation Framework and Technical Guidance

While this paper outlines key barriers to CV-RWIS integration, future research must also focus on the development of a structured implementation framework to guide agencies through the integration process. Such a framework would include phases of deployment, key decision points, stakeholder roles, and feedback loops for iterative improvement. A decision-support model or roadmap that helps agencies move from planning to full-scale implementation—tailored by context (e.g., rural vs. urban)—is needed to guide adoption across diverse regions and agency capacities.

In addition, future efforts should provide comparative technical analyses of hardware and software options, including roadside units, onboard communication technologies, edge computing hardware, and sensor packages. These comparisons should include specifications on data throughput, latency, environmental durability, cost, power requirements, and interoperability. Research that develops standardized evaluation criteria or performance benchmarks would improve agencies' ability to select appropriate technologies for integration with their existing RWIS infrastructure.

By combining a structured implementation framework with technical performance comparisons, agencies will be better equipped to make evidence-based decisions and allocate resources efficiently. This dual approach also ensures that integration strategies are not only visionary but also practical and grounded in current technological realities.

Acknowledgments

The authors would like to thank Colby Fortier-Brown (Team Chair), Mohammad Iraki, Jason Norville, Kevin Duby, James Roath, Jon Bjorkquist, Tonya Lohman, Cody Opperman, Jimmy White, and Theresa Litteral for insightful discussions. The work present in this manuscript was supported by the Federal Highway Administration (FHWA) Transportation Pooled Fund Aurora program and the Iowa Department of Transportation (DOT).

Authors' Contributions

The authors confirm contribution to the paper as follows: study conception and design: I. Nlenanya, S. Hallmark; data collection: I. Nlenanya, A. Inusah; analysis and interpretation of results: I. Nlenanya, A. Inusah, S. Hallmark; draft manuscript preparation: I. Nlenanya, A. Inusah. All authors reviewed the results and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] MnDOT. CAV-State Aid-MnDOT. https://www.dot.state.mn.us/stateaid/cav.html

[2] Aecom, M.B. and Information Logistics, and Texas Transportation Institute (2017) Connected and Automated Vehicles (CAV) Program Roadmap Prepared for Pennsylvania Turnpike Commission.

[3] Vaidya, B., Kaur, P.P. and Mouftah, H.T. (2021) Provisioning Road Weather Management Using Edge Cloud and Connected and Autonomous Vehicles. 2021 *International Wireless Communications and Mobile Computing* (*IWCMC*), Harbin, 28 June-2 July 2021, 1424-1429. https://doi.org/10.1109/iwcmc51323.2021.9498869

[4] Shi, X., Wang, Y., Wang, H. and Akin, M. (2020) Exploring Weather-Related Connected Vehicle Applications for Improved Winter Travel in the Pacific Northwest.

[5] Bento, L.C., Parafita, R. and Nunes, U. (2012) Intelligent Traffic Management at Intersections Supported by V2V and V2I Communications. 2012 15*th International IEEE Conference on Intelligent Transportation Systems*, Anchorage, 16-19 September 2012, 1495-1502. https://doi.org/10.1109/itsc.2012.6338766

[6] Outay, F., Kammoun, F., Kaisser, F. and Atiquzzaman, M. (2017) Towards Safer Roads through Cooperative Hazard Awareness and Avoidance in Connected Vehicles. 2017 31*st International Conference on Advanced Information Networking and Applications Workshops* (*WAINA*), Taipei, 27-29 March 2017, 208-215. https://doi.org/10.1109/waina.2017.17

[7] Shi, M., Lu, C., Zhang, Y. and Yao, D. (2017) DSRC and LTE-V Communication Performance Evaluation and Improvement Based on Typical V2X Application at Intersection. 2017 *Chinese Automation Congress* (*CAC*), Jinan, 20-22 October 2017, 556-561. https://doi.org/10.1109/cac.2017.8242830

[8] Hoque, M.A., Hasan, R. and Hasan, R. (2021) R-CAV: On-Demand Edge Computing Platform for Connected Autonomous Vehicles. 2021 *IEEE* 7*th World Forum on Internet of Things* (*WF-IoT*), New Orleans, 14 June-31 July 2021, 65-70. https://doi.org/10.1109/wf-iot51360.2021.9595160

[9] Varghese, J.Z. and Boone, R.G. (2015) Overview of Autonomous Vehicle Sensors and Systems. *International Conference on Operations Excellence and Service Engineering*, Orlando, 10-11 September 2015, 178-191.

[10] Bogaerts, T., Watelet, S., Thoen, C., Coopman, T., Van den Bergh, J., Reyniers, M., *et al*. (2022) Enhancement of Road Weather Services Using Vehicle Sensor Data. 2022 *IEEE* 19*th Annual Consumer Communications & Networking Conference* (*CCNC*), Las Vegas, 8-11 January 2022, 1-6. https://doi.org/10.1109/ccnc49033.2022.9700658

[11] Chapman, L., Young, D.T., Muller, C.L., Rose, P., Lucas, C. and Walden, J. (2014) Winter Road Maintenance and the Internet of Things. 17*th International Road Weather Conference*, La Massana, 30 January-1 February 2014, 1-7. https://www.researchgate.net/publication/263443890

[12] Ho, C., Snyder, M. and Zhang, D. (2020) Application of Vehicle-Based Sensing Technology in Monitoring Vibration Response of Pavement Conditions. *Journal of Transportation Engineering*, *Part B*: *Pavements*, **146**, Article ID: 04020053. https://doi.org/10.1061/jpeodx.0000205

[13] Petty, K.R. and Mahoney, W.P. (2007) Enhancing Road Weather Information through Vehicle Infrastructure Integration. *Transportation Research Record*: *Journal of the Transportation Research Board*, **2015**, 132-140. https://doi.org/10.3141/2015-15

[14] Mercelis, S., Watelet, S., Casteels, W., Bogaerts, T., Bergh, J.V.d., Reyniers, M., *et al*. (2020) Towards Detection of Road Weather Conditions Using Large-Scale Vehicle Fleets. 2020 *IEEE* 91*st Vehicular Technology Conference* (*VTC*2020-*Spring*), Antwerp, 25-28 May 2020, 1-7. https://doi.org/10.1109/vtc2020-spring48590.2020.9128484

[15] Khadka, S., Wang, P., Li, P. and Torres, F.J. (2023) A New Framework for Regional Traffic Volumes Estimation with Large-Scale Connected Vehicle Data and Deep Learning Method. *Journal of Transportation Engineering*, *Part A*: *Systems*, **149**, 1-14. https://doi.org/10.1061/jtepbs.teeng-7536

[16] He, J., Tang, Z., Fu, X., Leng, S., Wu, F., Huang, K., *et al*. (2019) Cooperative Connected Autonomous Vehicles (CAV): Research, Applications and Challenges. 2019 *IEEE* 27*th International Conference on Network Protocols* (*ICNP*), Chicago, 8-10 October 2019, 1-6. https://doi.org/10.1109/icnp.2019.8888126

[17] Kwon, T.M. (1999) Next Generation RWIS. https://ntlrepository.blob.core.windows.net/lib/22000/22300/22307/PB99176919.pdf

[18] Linton, M.A. and Fu, L. (2015) Winter Road Surface Condition Monitoring: Field Evaluation of a Smartphone-Based System. *Transportation Research Record*: *Journal of the Transportation Research Board*, **2482**, 46-56. https://doi.org/10.3141/2482-07

[19] Qian, Y., Almazan, E.J. and Elder, J.H. (2016) Evaluating Features and Classifiers for Road Weather Condition Analysis. 2016 *IEEE International Conference on Image Processing* (*ICIP*), Vol. 2016, 4403-4407. https://doi.org/10.1109/icip.2016.7533192

[20] Linton, M.A. and Fu, L. (2016) Connected Vehicle Solution for Winter Road Surface Condition Monitoring. *Transportation Research Record*: *Journal of the Transportation Research Board*, **2551**, 62-72. https://doi.org/10.3141/2551-08

[21] Brunauer, R. and Rehrl, K. (2016) Supporting Road Maintenance with In-Vehicle Data: Results from a Field Trial on Road Surface Condition Monitoring. 2016 *IEEE* 19*th International Conference on Intelligent Transportation Systems* (*ITSC*), Rio de Janeiro, 1-4 November 2016, 2236-2241. https://doi.org/10.1109/itsc.2016.7795917

[22] Raddaoui, O., Ahmed, M.M. and Gaweesh, S.M. (2020) Assessment of the Effectiveness of Connected Vehicle Weather and Work Zone Warnings in Improving Truck Driver Safety. *IATSS Research*, **44**, 230-237. https://doi.org/10.1016/j.iatssr.2020.01.001

[23] Tahir, M.N., Leviäkangas, P. and Katz, M. (2022) Connected Vehicles: V2V and V2I Road Weather and Traffic Communication Using Cellular Technologies. *Sensors*, **22**,

Article No. 1142. https://doi.org/10.3390/s22031142

[24] Stepanova, D., Sukuvaara, T. and Karsisto, V. (2020) Intelligent Transport Systems—Road Weather Information and Forecast System for Vehicles. 2020 *IEEE* 91*st Vehicular Technology Conference* (*VTC*2020-*Spring*), Antwerp, 25-28 May 2020, 1-5. https://doi.org/10.1109/vtc2020-spring48590.2020.9129368

[25] Ma, B., Li, W., Zhang, Z. and Song, R. (2020) Research on Weather Condition Influence Factors on Intelligent Connected Vehicle. *Journal of Physics*: *Conference Series*, **1550**, Article ID: 032021. https://doi.org/10.1088/1742-6596/1550/3/032021

[26] Atmaca, U.I., Maple, C. and Dianati, M. (2019) Emerging Privacy Challenges and Approaches in CAV Systems. *Living in the Internet of Things* (*IoT* 2019), London, 1-2 May 2019, 1-9. https://doi.org/10.1049/cp.2019.0141

[27] Li, Y. (2015) An Overview of the DSRC/WAVE Technology. *International ICST Workshop on Dedicated Short-Range Communications*, Vol. 15, 9-21.

[28] Xu, Q., Mak, T., Ko, J. and Sengupta, R. (2004) Vehicle-to-Vehicle Safety Messaging in DSRC. *Proceedings of the* 1*st ACM International Workshop on Vehicular Ad Hoc Networks*, Philadelphia, 1 October 2004, 19-28. https://doi.org/10.1145/1023875.1023879

[29] Outay, F., Kamoun, F., Kaisser, F., Alterri, D. and Yasar, A. (2019) V2V and V2I Communications for Traffic Safety and CO_2 Emission Reduction: A Performance Evaluation. *Procedia Computer Science*, **151**, 353-360. https://doi.org/10.1016/j.procs.2019.04.049

[30] Ansari, K. (2020) Joint Use of DSRC and C-V2X for V2X Communications in the 5.9 GHz ITS Band. *IET Intelligent Transport Systems*, **15**, 213-224. https://doi.org/10.1049/itr2.12015

[31] Gheorghiu, R.A., Iordache, V. and Minea, M. (2018) Messaging Capabilities of V2I Networks. *Procedia Manufacturing*, **22**, 476-484. https://doi.org/10.1016/j.promfg.2018.03.073

[32] Nguyen, T.V., Shailesh, P., Sudhir, B., Kapil, G., Jiang, L., Wu, Z., *et al.* (2017) A Comparison of Cellular Vehicle-to-Everything and Dedicated Short Range Communication. 2017 *IEEE Vehicular Networking Conference* (*VNC*), Vol. 2018, 101-108. https://doi.org/10.1109/vnc.2017.8275618

[33] Bey, T. and Tewolde, G. (2019) Evaluation of DSRC and LTE for V2x. 2019 *IEEE* 9*th Annual Computing and Communication Workshop and Conference* (*CCWC*), Las Vegas, 7-9 January 2019, 1032-1035. https://doi.org/10.1109/ccwc.2019.8666563

[34] Dey, K.C., Rayamajhi, A., Chowdhury, M., Bhavsar, P. and Martin, J. (2016) Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) Communication in a Heterogeneous Wireless Network—Performance Evaluation. *Transportation Research Part C*: *Emerging Technologies*, **68**, 168-184. https://doi.org/10.1016/j.trc.2016.03.008

[35] Abboud, K., Omar, H.A. and Zhuang, W. (2016) Interworking of DSRC and Cellular Network Technologies for V2X Communications: A Survey. *IEEE Transactions on Vehicular Technology*, **65**, 9457-9470. https://doi.org/10.1109/tvt.2016.2591558

[36] Chen, X., Leng, S., Tang, Z., Xiong, K. and Qiao, G. (2019) A Millimeter Wave-Based Sensor Data Broadcasting Scheme for Vehicular Communications. *IEEE Access*, **7**, 149387-149397. https://doi.org/10.1109/access.2019.2932428

[37] AASHTO Surface Transportation Reauthorization (2019) Transportation Policy Forum White Paper.

[38] McGuckin, T., Lambert, J., Newton, D., Pearminee, A. and Hubbard, E. (2017) Leveraging the Promise of Connected and Autonomous Vehicles to Improve Integrated

Corridor Management and Operations: A Primer. https://www.dksassociates.com/wp-content/uploads/2018/07/fhwahop17001.pdf

[39] Alaska DOT & PF, "About RWIS". https://roadweather.alaska.gov/about-rwis

[40] Pennsylvania DOT, "TSMO Business Areas". https://www.penndot.pa.gov/ProjectAndPrograms/operations/Pages/TSMO-Business-Areas.aspx

[41] TranSmart/EJM, AECOM, Parsons, and CDM Smith (2019) Illinois Statewide Intelligent Transportation Systems (ITS) Architecture and ITS Strategic Plan Concept of Operations.

[42] Minnesota DOT, "Maintenance—Road and Weather Information System—MnDOT". https://www.dot.state.mn.us/maintenance/rwis.html

[43] Kittleson & Associates and Alaska DOT & PF (2021) Connected & Automated Vehicle Working Group Strategic Plan.

[44] AECOM and MnDOT (2020) Systems Engineering Analysis for Road Weather Information System Test Plan.

[45] MDOT (2018) 2018-2022 Five-Year Transportation Program.

[46] Nevada DOT, "Automated and Connected Vehicles|Nevada Department of Transportation". https://www.dot.nv.gov/mobility/avcv

[47] Fard, Z.B., Dennis, E.P., Fiorelli, T., Gregory, S. and Torrence, D. (2021) High-Tech Workforce for Emerging Technologies. https://www.michigan.gov/mdotresearch

[48] Fard, Z.B., Spulber, A. and Reed, B. (2018) Implementation Recommendations for Management Procedures for Data Collected via CAV.

[49] NYSDOT (2020) Transportation Systems Management and Operations Strategic Plan.

[50] Hallmark, S., Veneziano, D. and Litteral, T. (2019) Preparing Local Agencies for the Future of Connected and Autonomous Vehicles (No. MN/RC 2019-18).

[51] Systems Performance Operations and Technology Subcommittee (2020) Connected and Autonomous Vehicles (CAVs) White Paper—Planning Considerations for the National Capital Region Transportation Planning Board.

[52] US DOT and FHWA, "Automated Vehicle Activities and Resources|FHWA". https://highways.dot.gov/automation

[53] US DOT and FHWA, "National Dialogue on Highway Automation—FHWA Office of Operations". https://ops.fhwa.dot.gov/automationdialogue/

[54] US DOT and FHWA, "Policy and Strategy Analysis Team—Policy|Federal Highway Administration". https://www.fhwa.dot.gov/policy/otps/otpsstaff.cfm

[55] US DOT (2018) Preparing for the Future of Transportation—Automated Vehicles 3.0.

[56] US DOT and NSTC (2020) Ensuring American Leadership in Automated Vehicle Technologies.

[57] Caltrans and PATH of UC Berkeley, "California Connected Vehicle Testbed—Home". https://caconnectedvehicletestbed.org/home

[58] Caltrans, "Connected and Automated Vehicles|Caltrans". https://dot.ca.gov/programs/traffic-operations/cav

[59] VDOT, "Home|Virginia Connected Corridors". https://www.vtti.vt.edu/vcc/index.html

[60] PennDOT and PTC, "CAV Initiatives".

https://www.penndot.pa.gov/ProjectAndPrograms/ResearchandTesting/Autonomous%20_Vehicles/Pages/CAV-Initiatives.aspx

[61] Davis, A. (2021) Georgia Connected Vehicles.

[62] 511: What Is It? National Traffic and Road Closure Information. Federal Highway Administration. https://www.fhwa.dot.gov/trafficinfo/511what.htm

[63] FHWA Traveler Information—About 511. https://ops.fhwa.dot.gov/travelinfo/about/about511.htm

[64] Lindly, J.K. and Hill, S.E. (2003) Overview Study—511 Traveler Information Services for the Alabama Department of Transportation.

[65] Iowa's 511 Website and Apps. Iowa DOT. https://iowadot.gov/511/

[66] ClearPath Weather Service. Transportation Industry. DTN. https://www.dtn.com/weather/transportation/clearpath-weather/

[67] Hallmark, S., Smadi, O., Markt, J., Plapper, E., Carlson, P., Zimmerman, K. and Duncan, G. (2024) NCHRP Research Report 1084: Connected and Autonomous Vehicle Technology; Determining the Impact on State DOT Maintenance Programs. National Cooperative Highway Research Program.