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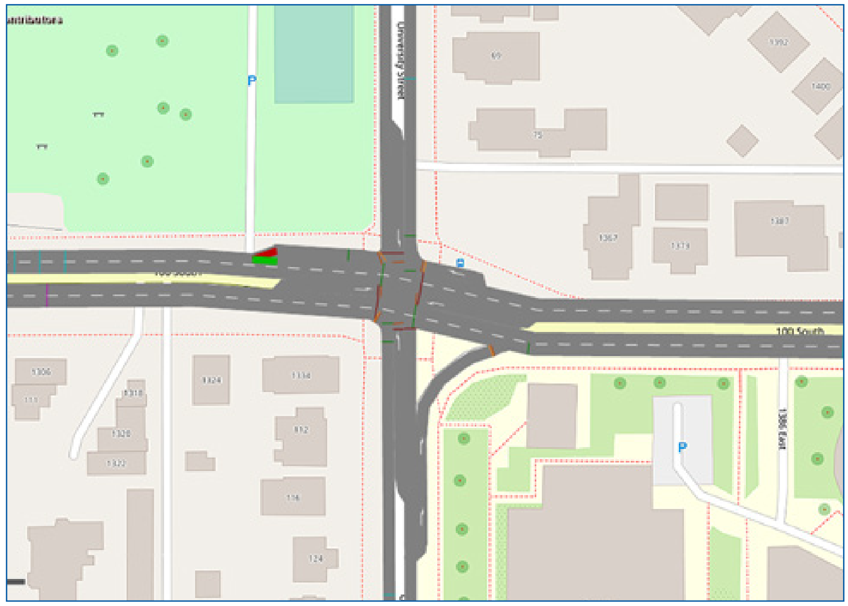
IMPACT OF CONNECTED VEHICLE TECHNOLOGY ON TRAFFIC SAFETY UNDER DIFFERENT HIGHWAY GEOMETRIC DESIGNS



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16. Abstract

Connected and automated vehicle (CAV) driving features can impact traffic safety in many aspects owing to their improved driving behavior. On the other hand, road geometric design elements are mainly based on human reactions and behavior, which might affect safety depending on road layout and the parties involved. However, automation and connectivity can convey more data about the driving environment that will reduce confronting unexpected driving conditions and driving load on drivers. Therefore, the risk of crashes due to roadway geometries will be reduced. The main objective of this study is to focus on the performance of the traffic flow, including CAVs with different geometric designs addressing the potential crash spots. This study aims to determine the efficacy of CAVs on traffic network safety quantitively and qualitatively. For this purpose, multiple scenarios with different geometric features are designed and simulated. Simulations include varied CAV shares in traffic composition and employ driving features of CAVs. Using the surrogate safety assessment model (SSAM), simulation results are evaluated for potential conflicts. Crash severity, frequency, and classification are studied to determine the safety effects of CAVs on potential crash hot spots. Results indicated that higher penetration rates of CAVs could improve the safety performance of traffic networks in multiple cases by reducing deceleration rates, cooperative lane changing, and adjusted speed in required situations. However, due to the interaction of CAVs and HDVs in a signalized intersection, safety performance might not benefit from CAV presence.

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ABSTRACT

Connected and automated vehicle (CAV) driving features can impact traffic safety in many aspects owing to their improved driving behavior. On the other hand, road geometric design elements are mainly based on human reactions and behavior, which might affect safety depending on road layout and the parties involved. However, automation and connectivity can convey more data about the driving environment that will reduce confronting unexpected driving conditions and driving load on drivers. Therefore, the risk of crashes due to roadway geometries will be reduced. The main objective of this study is to focus on the performance of the traffic flow, including CAVs with different geometric designs addressing the potential crash spots. This study aims to determine the efficacy of CAVs on traffic network safety quantitively and qualitatively. For this purpose, multiple scenarios with different geometric features are designed and simulated. Simulations include varied CAV shares in traffic composition and employ CAV driving features. Using the surrogate safety assessment model (SSAM), simulation results are evaluated for potential conflicts. Crash severity, frequency, and classification are studied to determine the safety effects of CAVs in potential crash hot spots. Results indicated that higher penetration rates of CAVs could improve the safety performance of traffic networks in multiple cases by reducing deceleration rates, cooperative lane changing, and adjusted speed in required situations. However, due to the interaction of CAVs and HDVs in a signalized intersection, safety performance might not benefit from CAV presence.

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LIST OF ACRONYMS

AADT	Average annual daily traffic
AASHTO	Association of State Highway Transportation Officials
ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver-Assistance Systems
ADOT	Arizona Department of Transportation
AEB	Automatic Emergency Braking
ATSPM	Automated Traffic Signal Performance Measures
AV	Automated vehicle
BSM	Basic Safety Message
CAV	Connected and Automated Vehicle
CACC	Cooperative Adaptive Cruise Control
CICAS	Cooperative Intersection Collision Avoidance System
CV	Connected vehicle
DGPS	Differential Global Positioning System
DNPW	Do Not Pass Warning
DSRC	Dedicated-Short-Range-Communications
FCC	Federal Communications Commission
FCW	Forward Collision Warning
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GPS	Global Positioning System
HDV	Human-Driven Vehicles
LCW	Lane Changing Warning
MAP	MAP Message
MCDOT	Maricopa County Department of Transportation
MMITSS	Multi-Modal Intelligent Traffic Signal System
NCHPR	National Cooperative Highway Research Program
NHTSA	National Highway Transportation Safety Administration
NYCDOT	New York City Department of Transportation
OBU	Onboard Unit
PATH	Partners for Advanced Transportation Technology
PHT	Person Hours of Travel
PET	Post Encroachment Time
PSM	Priority Status Message
RDW	Road Departure Warning
RSU	Roadside Unit
SAE	Society of Automotive Engineers
SRM	Signal Request Message
SPaT	Signal Phase and Timing
SSAM	Surrogate Safety Assessment Model
SSD	Stopping Sight Distance

SSM	Signal Status Message
SWSIS	Spot Weather Impact Warning
TRB	Transportation Research Board
TSP	Transit Signal Priority
TTC	Time To Collision
UDOT	Utah Department of Transportation
USPEA	U.S. Environment Protection Agency
UTA	Utah Transit Authority
VMT	Vehicle Miles Traveled
VSL	Variable Speed Limit
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
WFRC	Wasatch Front Regional Council
WYDOT	Wyoming Department of Transportation

EXECUTIVE SUMMARY

Road safety is one of the areas that has been the point of interest for many years in traffic engineering. Road design and driving behaviors have been the main contributors to crashes over the years. As geometric designs keep changing to promote safety, new vehicles such as connected and automated vehicles (CAVs) also develop with new driving technologies to enhance safety and limit the human role in driving. The driving assistance feature creates a bond between vehicles, infrastructures, and roads to exchange data and provide more driving information. Automation helps reduce drivers' misconceptions of roads and can enhance road performance by improving safety. These two features can create a safe infrastructure for the traffic network to reduce crash possibilities and severity. CAV safety features are handy on roads with inconsistent geometric design or unexpected driving conditions that require a faster reaction with sufficient data about the driving situation. Therefore, this study tries to find the consequence of adding CAVs in traffic flow on safety performance and its relationship with geometric design parameters.

As CAV driving behavior has shown to be more certain, it is expected that, compared with conventional vehicles, CAVs can upgrade flow capacity, travel time, and, most importantly, traffic safety. Road elements that can impact drivers' performance include the number of lanes, lane width, design speed, curves, and road slope. To reflect CAV behavior and roadway elements, multiple simulation scenarios are designed that contain road features that can cause crashes. These scenarios are simulated with traffic composition, including conventional vehicles and CAVs with different penetration rates. Also, the driving behavior of each class of vehicle is included to account for their effect on traffic performance. These simulations are done in VISSIM with scenarios that study the effect of the number of lanes, design speed, intersection, limited sight distance, conflict zone, and road grade on road safety. The trajectory of roads is used to analyze the safety performance quantitively. Safety analysis includes potential crash rates and severity. Flow characteristics of conflicts are also evaluated for flow performance under different traffic combinations.

This study is basically developed to investigate how CAVs can affect safety performance under different geometric designs and find the level when this safety is constructive. Scenarios are designed based on the Salt Lake City, Utah, traffic network. Locations are picked based on recent crash locations and roadways that include the main contributor to crashes. Results indicate that CAVs' presence in traffic flow can elevate safety performance, especially on freeways. Signalized intersections do not show an improvement in traffic safety, which is due to the limited information available on the interaction of conventional vehicles and CAVs. Also, potential CAV safety features might not be fully applicable in controlled roadways. However, the reduced number of rear-end and lane changing conflicts proves that CAVs successfully reduce crash rates. In addition, potential crash results demonstrate that crashes will be less severe due to smaller speed variance and reduced decelerations. Evaluation of safety performances shows that safety improvements with CAVs will be significant.

1. INTRODUCTION

1.1 Problem Statement

In recent years, with the rapid increase of car ownership, current traffic control systems across the country are suffering from many issues, such as traffic congestion, air pollution, and low travel reliability. As presented in the 2019 Urban Mobility Report, 8.8 billion hours of extra time and 3.3 billion gallons of fuel were wasted in 2017 (Schrank, Eisele, & Lomax, 2019). Moreover, the U.S. Environmental Protection Agency (EPA) estimated that about 34% of carbon dioxide emissions and about 28% of total greenhouse gas emissions were produced by daily transportation (Hockstad & Hanel, 2018). Hence, urban traffic conditions are critical to business, people’s lives, and the economy, and it is essential to take measures to address those transportation problems. In-vehicle distraction is one of the major causes of crashes, and it impacts road safety performance. Reduced safety can be related to road design layout and high interaction between drivers and road requirements. According to the National Highway Traffic Safety Administration (NHTSA), about 95% of crashes are human-related; among those, about 18% are distracted driving (NHTSA, 2018).

With today’s rapid and continuous improvements in communication and perception technologies, CAV features are being introduced to the transportation community; they have also developed rapidly and have been maturing in the past few years. With the applications of CAV, transportation issues will be solved in a promising way. Emerging CAV and driving assistant technologies could help to alleviate human errors that lead to crashes. CAVs are a combination of connected vehicles (CV) and automated vehicles (AV). With onboard units (OBU), CVs can communicate with each other (V2V) and with infrastructure (V2I) in real time. Early implementations of CV technology have shown great potential in mitigating traffic congestion and improving the efficiency of transportation systems. Specifically, V2V technology allows CVs to exchange critical vehicle status data such as vehicle speeds, location, and acceleration; the V2I platform supports communications with infrastructure (e.g., receiving signal phase and timing – SPaT data from the signal controller). On the other track, AVs are operated with automation and self-driving functions, supporting different types of sensors, e.g., LIDAR, ultrasonic, radar, and cameras. The sensor technologies allow vehicles to observe and analyze their surroundings and automatically take suitable driving maneuvers (e.g., deceleration, acceleration, lane-changing). When connectivity is added to the AV-based system, a CV will become a CAV equipped with both OBUs for communications and sensors for detection.

Advanced technologies in CAVs, such as V2V and V2I communications, can aid drivers in providing hazardous warnings or, in some cases, act accordingly to prevent crashes. Driver assistance technologies in CAVs will assist with prompt reaction in response to geometric road designs that will depend less on drivers’ input. The dependence of vehicles on humans decreases as automation increases and more driver assistance technologies become available in vehicles. The foundation of CAV technologies is V2I, and V2V enables communication with roads and other vehicles on the network and makes more data available to vehicles compared with solely human perceptions, especially in unusual road conditions. Many studies have analyzed the safety performance of these technologies, and it has been proven they improve the reliability and safety efficiency of vehicles over manually driven vehicles. Moreover, driving behaviors of CAVs, such as smoother accelerations and decelerations, have been shown to affect traffic flow efficiency and safety. CAV driving behaviors can increase capacity, reduce travel times, and reduce reaction time.

Road design elements are primarily based on human drivers and are justified for drivers’ reactions. Geometric factors that drivers influence include design speed, lane width, horizontal and vertical curve radius, road grade, and stopping sight distance (SSD). Due to the combination of drivers’ lack of attention and poor geometric design, road safety might decrease and cause crashes and unsafe driving conditions.

Unpredictable driving conditions can exacerbate risky driving situations and increase the probability of collisions. Even though improving road geometry elements can reduce the human-related impact in crashes, introducing CAVs in roadways can tackle this barrier and improve safety performance. However, changing design elements based on CAV is not practical due to the presence of human-driven vehicles (HDV) in the foreseeable future of the traffic network. The CAV market is forecast to grow by 63.1% by 2030 (Grand View Research Inc., 2020). Therefore, a quantitative analysis of their performance in traffic networks is required to predict their performance in the system and plan accordingly for adoption.

This study aims to analyze the safety performance of corridors with geometric design-related crashes and the influence of CAV on tackling it. To this end, Salt Lake City has been taken on as a case study, and significant geometric design causes of historical crash data have been analyzed. Next, five scenarios are designed and simulated using the same contributors in VISSIM software. Network traffic in scenarios includes CAVs and HDVs, and CAV driving behaviors are adjusted to address the technologies employed. To measure the level of effectiveness of CAVs in traffic network performance, different CAV penetration rates are applied. Using the trajectory data of simulated scenarios from VISSIM, the crash severity and frequency probability are evaluated by the Surrogate Safety Assessment Model (SSAM). The results of this study demonstrate a CAV's effects on traffic for safety performance and the potential technologies that can improve road safety. In addition, the effect of CAV penetration rate on safety and crash prevention is analyzed.

1.2 Objectives

This research objective is to study the performance of CAVs in response to various geometric designs and focus on the interaction of CAV and HDV traffic operations in different situations. By simulating multiple scenarios, the safety impact of CAVs' presence is evaluated and compared to cases without CAVs. The objectives of this study are as follows:

1. Analyze the correlation between crash statistics and geometric road design
2. Represent potential crash spots through scenarios, including CAV in traffic, by reflecting driver assistance technologies in their driving behavior
3. Analyze the safety performance of simulated scenarios with multiple CAV penetration rates and without CAVs
4. Quantitatively measure the safety effectiveness of CAVs in traffic under different geometry designs
5. Correlate CAV safety performance and road design elements

1.3 Outline of Report

This report is structured as follows:

- Chapter 2 reviews all past studies on CAV technologies and their safety performance. Also, studies that focus on the connection between geometry design and safety performance are explored.
- Chapter 3 summarizes technologies embedded in CAV that have affected their performance compared with conventional vehicles.
- Chapter 4 provides a section on technologies from the previous chapter in various fields.

- Chapter 5 describes how scenarios are developed and the driving features of both HDVs and CAVs in VISSIM.
- Chapter 5 reports the simulation setup and modification added to each scenario to reflect the actual cases.
- Chapter 6 analyzes the safety performance of scenarios with statistical tests and provides numerical safety results.
- In the last chapter, using the obtained results, a conclusion is presented to show the finding of this study on CAV safety performance in various geometric designs.

2. LITERATURE REVIEWS

Road safety has been one of the critical concerns of the transportation field in the history of traffic engineering. Geometric design factors are developed to provide safe driving conditions for drivers. As road elements are mainly based on driver reaction, poor driver performance is the leading cause of crashes. However, driver behavior is not the only cause of crashes, and typically, crashes originate from a series of factors. Driving speed is a significant parameter in road safety performance, and a 1 mph reduction of speed design can decrease crash rates by 5% (Finch, Kompfner, Lockwood, & Maycock, 1994). Among the road variables, lane width impacts maneuverability, shoulder width helps to regain control after losing control, superelevation helps with stability, and sight distance influences the driver's visibility (Mohammed, 2013). Moreover, the type of road can also affect crash rates. The number of lanes on the road is shown to directly affect their safety (O'Cinneide, 1998). Yet, due to changing vehicle features and drivers' adaption to the road, design parameters will be updated correspondingly through time. Driver assist technologies can improve a vehicle's driving functions to assist the driver in safer behavior.

CAVs can change driving behavior through smart technologies embedded in them. Driving assistance technologies can address the shortcomings in drivers' reactions to road conditions. In a study by Funke et al., multiple crash prevention technologies were simulated to evaluate the safety performance of these technologies in traffic networks (Funke, Srinivasan, Ranganathan, & Burgett, 2011). Further, other studies showed the effectiveness of warning systems in reducing crash rates and severity (Gordon et al., 2010; Harding & Powell, 2014; Perez et al., 2011; Wilson H., Stearns D., Koopmann, & Yang, Y. David, 2007). Advanced driver-assistance systems (ADAS) equipment in CAVs are used to warn drivers about imminent dangers on the road and are deployed for various purposes. Adaptive cruise control (ACC), anti-lock braking system (ABS), and collision avoidance systems are among ADAS technologies. Analysis of pre-crash scenarios with forward collision warning (FCW) combined with cooperative adaptive cruise control (CACC) has been found to have the highest potential to reduce crashes (K. Kockelman et al., 2016). Besides the latest technologies mentioned, other driver assistance technologies such as do not pass warning (DNPW), cooperative intersection collision avoidance system (CICAS), and control lost warning (CLW) have also been shown to boost road safety. Among all driver assistance technologies, automatic emergency braking (AEB) has been shown to be most effective in rear-end crashes, and electronic stability control can prevent off-road crashes. Lane changing warning (LCW) systems reduce side crash probabilities (Wang, Zhong, Ma, Abdel-Aty, & Park, 2020). Nevertheless, V2V cannot perform optimally when messages are congested, and traffic is dense, as the communication might get disrupted (He et al., 2020). The benefits of these technologies are not limited to safety aspects, they also have financial benefits for transportation networks (K. M. Kockelman & Li, 2016).

More focus on the efficiency of CAV in geometry road designs is needed as humans might fall short in a secured performance. Substitution of drivers by cameras and detectors has certainly altered driving behaviors, which many road elements are based on. Consequently, when CAVs form traffic in the future, road design standards will need to be adapted (Aryal, 2017). Conversion of new road elements, such as SSD and curve lengths, can help reduce road construction costs and environmental footprints (Khoury, Amine, & Saad, 2019; Welde & Qiao, 2016). Though due to the presence of HDV in transportation networks for the foreseeable time, design practices will not be based on CAV driving behaviors. However, recent studies have demonstrated that traffic flow performance and operations will be improved with CAVs introduced to the transportation network (Asadi, Anwar, & Miles, 2019; He et al., 2020; Stanek, Huang, Milam, & Wang, 2018). Results of mixed traffic simulations demonstrate that CAVs in traffic flow can lower speed variance in the network (Ye & Yamamoto, 2019).

Furthermore, the safety aspects of CAVs were shown in other studies, such as a work by Virdi et al., which studied the safety improvements in multiple road types. Results indicated that CAVs in priority intersections significantly decrease crash rates (Virdi, Grzybowska, Waller, & Dixit, 2019). Conversely, results show that safety might decline in signalized intersections, which higher CAV penetration rates might compensate for (Virdi et al., 2019). A few studies have also analyzed the effect of increased CAV market share on traffic performance but were limited to exclusive CAV lane performance (Zhang et al., 2020). Also, the CAV conflicts will increase by increasing CAVs in traffic flow (Papadoulis, Quddus, & Imprialou, 2019). However, many studies prove the safety benefits of CAVs in transportation networks, and they enhance safety more in heavy trucks than in light vehicles (Yue, Abdel-Aty, Wu, & Wang, 2018). Finally, analysis proves that CAVs can reduce crashes by 48% in the United States. (Wang et al., 2020).

Despite all the studies in the literature, the correlation between road geometry and CAV safety performance is needed to be studied in more detail. Therefore, CAVs' effect on traffic safety under different roadway geometrical features is analyzed in this paper. For this purpose, multiple scenarios in roadway designs with high crash risks are simulated using the CAV features. By obtaining the outputs of microsimulations for different CAV penetration rates, the safety improvement of road segments is evaluated. Results will demonstrate the impact of CAVs on crash severity and frequency under different roadway geometric designs. This paper is organized as follows: The following section presents the scenarios designed based on crash data in Salt Lake City, Utah. Next, the simulation of designed scenarios and CAV features are described, and finally, the results of simulation outputs analyzed by SSAM are presented.

3. OVERVIEW OF CAV TECHNOLOGY

3.1 Overview

This chapter introduces the current state-of-the-art in CAV technology. We first present the current state of automated and connected vehicle technology development and then review the benefits of adopting CAV technologies. Finally, the current pilots or testbeds of CAV applications in the United States are summarized.

3.2 Automated Vehicles

AV refers to vehicles that can sense their surrounding environments and complete driving tasks independent of human involvement. The advancements that assist this technology in automotive technologies and on-board computations include advanced sensors, processors, and complex algorithms. The advent and deployment of those advanced technologies enable AVs to operate like human drivers.

Based on the functional features, an AV's automation levels can range from the simplest automation, such as adaptive cruise control, which involves several driving behaviors, to utterly automated driving, which means vehicles can operate themselves without the engagement of human drivers. Whether partly or fully automated, the achievement of automation relies on advanced technologies. For example, radar sensors monitor the surrounding environments; video cameras judge traffic lights and road signs. Table 3.1 summarizes the technologies leveraged to support automation and lists the limitations or opportunities (KMPG, 2012; Wagner, Baker, Goodin, & Maddox, 2014).

Table 3.1 Common AV Technologies

Technology	Definition	Limitations or opportunities
Radar	A system bounces radio waves around to see their surroundings and is especially good at spotting big metallic objects	Mature technology, cheap, reliable, and do not influence by fog, rain, snow, etc.
LIDAR	An optical remote sensing technology that measures the distance to a target or other properties of the target by illuminating it with light	LIDAR is expensive and is still trying to strike the right balance between range and resolution
Camera	A device that spots things like speed signs and lane marks	The camera can be used to identify subjects more accurately with a better machine version
Computer imaging	A process that uses a camera captures images of the world and feeds the images into a computer program. Then the program analyzes the images to understand better	Variation and diversity of environments can be challenging
Ultrasonic sensors	A system similar to radar that perceives the surrounding environments	Better accuracy than radar with short-range detection
Digital mapping	A process by which a collection of data is compiled and formatted into a virtual image	Only some parts of the world have been mapped (mainly urban areas), and there is a need for a critical mass of mappers to enter and cross-validate data to achieve a satisfactory degree of accuracy
Global positioning system (GPS)	GPS is a space-based satellite navigation system that provides location and time information anywhere on or near the earth	The accuracy of a GPS receiver is about +/- 10 meters, not practical for locating an object the size of an automobile, which is about 3 meters long
Differential global positioning system (DGPS)	It is an enhancement to GPS that improves location accuracy from +/- 10 meters to about 10 cm	The DGPS correction signal loses approximately 1 meter of accuracy for every 150 km. Shadowing from buildings, underpasses, and foliage causes temporary losses of signal
Real-time kinematic	Satellite navigation is based on the use of carrier phase measurements of the GPS, GLONASS, and/or Galileo signals where a single reference station provides the real-time corrections	The base station rebroadcasts the phase of the carrier that is measured; the mobile units compare their phase measurements with the ones received from the base station

As described above, many technologies and functions are applied in AV. Variation in the maturity and complexity of these technologies results in different levels of automation, from no automation to full automation. To make sense of the complexity of automotive features, government and industry have developed several standardized terminology and classification systems to adopt AV technology. Among those standards, the most widely accepted is the one defined by the NHTSA, which includes five levels ranging from no automation (Level 0) to full automation (Level 4). The brief introduction of each level is as follows:

3.2.1 Level 0 – No Automation

As it sounds, vehicles at Level 0 have no automated functions. NHTSA describes it as "the driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for the safe operation of all vehicle controls" (National Highway Traffic Safety Administration, 2013). At this level, drivers need to take complete control, and vehicles can only monitor the surrounding environment and provide specific warnings, such as blind-spot warnings.

3.2.2 Level 1 – Function, Specific Automation

According to NHTSA, one or more specific automation can function with vehicles at this level, but drivers still have the "overall control." NHTSA stated that "the vehicle may have multiple capabilities combining individual driver support and crash avoidance technologies, but does not replace driver vigilance and does not assume driving responsibility from the driver. The vehicle's automated system may assist or augment the driver in operating one of the primary controls – either steering or braking/throttle controls (but not both)" (National Highway Traffic Safety Administration, 2013). That is to say, drivers must take control of one driving behavior. They cannot simultaneously move their hands from steering and their foot from peddling. Example applications at this level include adaptive cruise control and automatic braking.

3.2.3 Level 2 – Combined Function Automation

Drivers at this level can disengage at least two automation functions simultaneously. For example, vehicles can assist with accelerating and steering simultaneously and relieve drivers from those tasks. However, drivers still need to monitor the surrounding environments and be ready to take control of vehicles in dangerous situations. An example of this level is the adaptive cruise with lane-centering simultaneously.

3.2.4 Level 3 – Limited Self-Driving Automation

At this level, drivers can avoid the "safety-critical" functions under certain traffic conditions. Vehicles can drive by themselves in those conditions and monitor the surrounding environments, but the drivers' attention is still crucial. Drivers are required to control the vehicle when traffic changes are monitored. For example, the vehicle monitors the accident ahead that it cannot handle and then send messages to let the driver retake control of the vehicle.

3.2.5 Level 4 – Full Self-Driving Automation

As stated by NHTSA, "The vehicle at this level is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip." The only operation drivers need is to provide the direction and destination at the beginning of the trip. During this trip, vehicles can accelerate, brake, steer, monitor the environment, and respond to the changes on the roadway.

The classification above is from a governmental perspective. In 2014, the Society of Automotive Engineers (SAE) announced another classification of AV from the industry perspective. The SAE standard includes six levels, also ranging from no automation to full automation. SAE defined the levels based on the role of the human driver or the automated driving system in four aspects of the driving task: steering and acceleration, monitoring of the environment, fallback responsibility for the driving task, and driving mode. The specific SAE classification is described in Figure 3.1 ("SAE J3016 automated-driving graphic," 2014).

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 3.1 Classification of Automation Levels Defined by SAE

3.3 Connected Vehicles

Connected vehicle refers to vehicles that can communicate with each other or with roadway infrastructure with a series of communication technologies applied. A CV environment includes vehicles, infrastructures, and information service systems. In a fully CV-deployed environment, vehicles can broadcast plenty of traffic information to infrastructure, including location, acceleration, and speed. At the same time, vehicles can also receive information transmitted by the infrastructure, such as the current traffic status. With the application of CV technology, travelers could make smarter decisions by receiving information from infrastructures, like warning about a potential hazard or providing speed advice about entering and leaving intersections with minimal stops.

3.3.1 CV Communication Technology

The most notable feature of CV is the application of wireless communication, which is a method of transferring information between two or more points. Rather than using physical mediums like cables and wires, wireless communication leverages electromagnetic waves to transmit data. Nowadays, there are a variety of wireless technologies in the market. Different techniques have different operating characteristics. The primary features are communication range and latency. The communication range is the distance the communication signal can travel. This range is influenced by several factors and may vary significantly from one point to another (Zeng, Balke, & Songchitruksa, 2012). Communication latency is defined as the time interval between stimulation and response. More specifically, it refers to the time a communication signal spends from the starting transmission point to the ending transmission point.

The degree of information connectivity in the transportation network is greatly affected by the communication range and communication latency. In general, longer-range is better because longer-range communication has broader information coverage. Since communication latency represents how fast the communication information is transmitted, it is desired when it is low. However, it should be noted that long-range and low latency cannot exist simultaneously. Communication range and latency are the most crucial criteria for selecting wireless technologies in various transportation applications. Currently, a variety of wireless technologies highlight these two characteristics of application in the transportation system, and they are briefly introduced as follows:

DSRC is a protocol for wireless communication dedicated by the Federal Communications Commission (FCC) in 2004 to utilize 75 MHz bandwidth at 5.9 GHz spectrum to support the communication between vehicles and infrastructures. DSRC has a low communication latency because it is intended for high-speed wireless communication. Therefore, the communication range of DSRC is relatively short. The range of DSRC is designed at about 3,000 feet (1,000 meters), but this range in the real world is usually less than 1,000 feet (300 meters) (Kandarpa et al., 2009).

Cellular communication is a form of communication achieved by using mobile phones. A cellular communication system leverages a large number of low-power wireless devices. The main problem with current cellular communication technology is that the communication delay is significant within the communication range. Moreover, the network will experience a buffer-based delay if the cellular networks are busy. Therefore, current cellular technologies are considered only suitable for supplemental applications. However, cellular communication may surpass DSRC in the near future due to the rapid development of this technology, such as 5G.

Bluetooth communication is another widely applied technology in the consumer market. The communication range varies with Bluetooth classes, ranging from 30 feet (10 meters) to 300 feet (100 meters). The communication latency of this technology is significantly higher than that of DSRC. Therefore, it is only suitable for communication between two relatively stationary objects.

Satellite communication is achieved by the artificial satellite, which creates a communication link between the transmitter and the receiver at different locations on Earth. Satellite communication consists of two main components: ground segment and space segment. The ground segment usually includes the equipment for transmission and reception. The space segment is mainly the satellite itself. The satellite receives signals transmitted by equipment on earth, amplifies the signal, and then retransmits it back to Earth (Labrador, 2020). However, this technology is also unsuitable for real-time safety-related applications because the capacity of this technology is limited, and the communication latency is high.

3.3.2 Hardware

To achieve successful V2V and V2I communication, several devices are required to be installed in vehicles and along roadways. According to the Federal Highway Administration (FHWA), those devices are defined as OBU and roadside units (RSU).

OBU is the equipment installed in mobile applications that enables information to be exchanged between mobile users and other applications. For example, a CV system requires at least two DSRC radios installed in vehicles or roadside infrastructures to support communication. Moreover, a device-based warning system should be installed to send warnings to drivers. Figure 3.2 shows a complete picture of OBU in vehicles (Harding & Powell, 2014).

In addition to OBUs, a fully deployed CV environment requires an RSU to support the communication between vehicles and infrastructures. RSU refers to the equipment that has been installed at the roadside and communicates with mobile devices via DSRC radio communications. RSE could employ DSRC or potentially use other communications mediums, such as existing 3G/4G cellular networks or Wi-Fi.

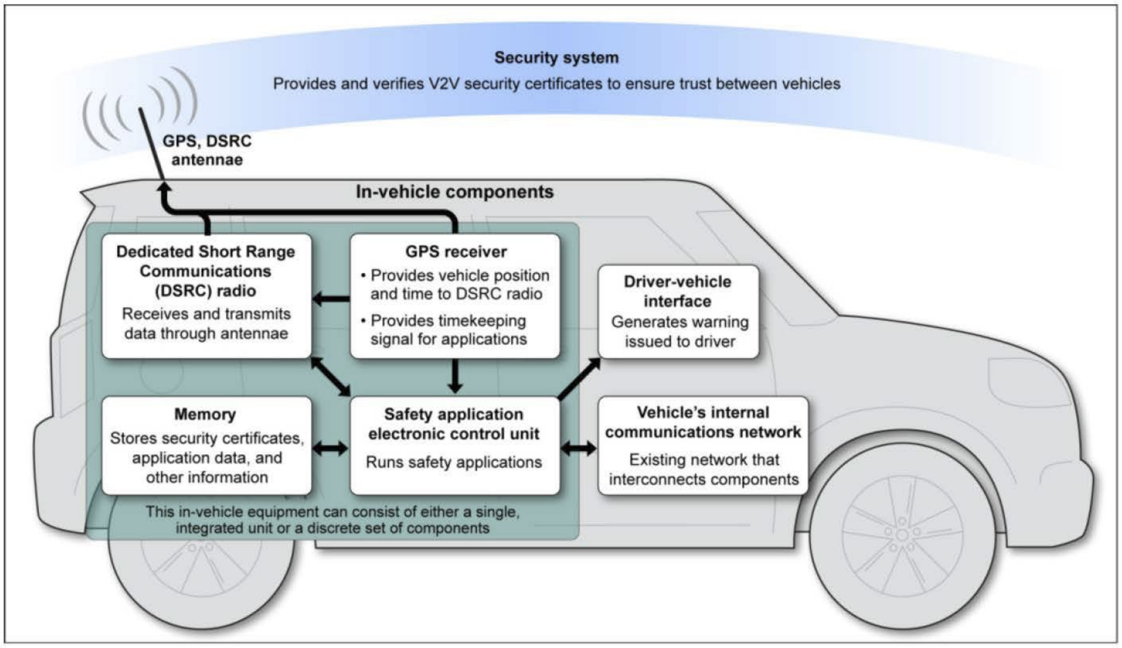

Figure 3.2 OBU of a CV System

3.4 CAV Benefits

To make the best use of the potential of CV and AV technologies, industry groups and researchers have dedicated themselves to developing a CAV system that combines CV technology and AV technology. The V2V communication and V2I communication provided by CV technology can provide helpful traffic information to the AV system to improve operational performance and safety. With V2V and V2I communication added, traffic information can be provided to the vehicle ahead so that it can take self-control (e.g., brake and accelerate) in advance to enable smooth traffic flow. Therefore, when connectivity is added to the AV-based system, vehicles would become CAVs, which are equipped with both OBUs for communications and sensors for detection.

Due to their communication and automated driving features, CAVs can provide a wide range of benefits for the transportation system and its users, including drivers, passengers, and pedestrians. The benefits can be summarized in the aspects of safety, mobility, environment, and data, which are outlined as follows:

- Safety: According to a USDOT survey, 94% of fatal vehicle crashes are caused by human errors. Higher levels of automation are capable of reducing dangerous driver behaviors, such as drugged driving, drunk driving, distracted driving, and speeding. If V2V and V2I communications can be achieved, the number of traffic accidents can be significantly reduced. Infrastructures like traffic signals and up-to-the-minute warning systems will send real-time information about potential dangers, impending collisions, diversions, and inclement weather conditions. That information could be used to avoid hazards.
- Mobility: Several innovative mobility applications supported by CAV technology can increase the mobility of the transportation system. For example, cooperative adaptive cruise control, enabling vehicles to operate with small gaps and the same speed as a platoon, is capable of increasing traffic throughput and alleviating congestion. With CAV technologies applied, vehicles can monitor the surrounding environment constantly and respond to changes by braking and accelerating quickly. Then CAVs can travel with small headway and higher speeds, and the traffic throughput can be increased.

- Environment: Traffic congestion often occurs not in the bottleneck due to errant human driver behaviors, such as changing lanes in the wrong place. With the application of CAV technology, such actions can be avoided, and traffic congestion can be reduced. Therefore, the emissions caused by frequent stop-and-go traffic can be decreased. Moreover, traffic congestion caused by crashes can also be reduced with the assistance of CAV technology, where vehicles and infrastructures can transmit real-time information to achieve coordination between vehicles and infrastructure. Then unnecessary braking and stopping can be avoided at some locations, like intersections, resulting in lowered emissions.

3.5 AV and CV Applications and Pilot in the USA

3.5.1 AV Application

Various automated features can be achieved with the application of AV technology according to the purpose. Some are developed to warn the driver of potential hazards. Some are designed to assist drivers with several driving tasks in specific situations, such as parallel parking. Based on the function of AV technology, Table 3.2 summarizes the AV applications (Wagner et al., 2014).

Table 3.2 Application of AV Technology (Wagner et al., 2014)

Applications	Function
Antilock brakes	Prevent wheels from locking up and skidding when a driver brakes, particularly on wet or slippery roadway surfaces
Blind-spot information systems	Sensors monitor the side of a vehicle for other vehicles approaching blind spots and transmit an alert to the driver. Typically, a visual alert appears on or near the side mirrors if a vehicle is detected
Electronic stability control	The system uses automatic computer-controlled braking to prevent loss of control if a vehicle loses directional stability or control during a skid
Park assist	Cameras and sensors detect rear objects and available space when a vehicle is backing up, reducing the difficulty of parallel parking or, in some cases, enabling the vehicle to nearly park itself
Adaptive cruise control	ACC allows the driver to set the desired speed that the vehicle maintains automatically. ACC uses sensors to track the distance from the vehicle ahead and maintain a safe gap by accelerating or braking to adjust to changes in traffic speed
Forward collision prevention	Collision warning systems alert a driver if the vehicle is accelerating at a rate at which it would be likely to crash into a vehicle ahead
Lane departure warning	A system using cameras to track vehicle position relative to a driving lane to provide feedback and/or steering assistance to help maintain the vehicle position in the lane
Steering assist	A system uses all of its sensors and cameras to steer itself for a certain period
Autopilot	Allows drivers to let the cars drive themselves on certain portions of the trip, like on freeways.

3.5.2 CV Application

Over the past few years, scholars, industry groups, and other institutes made efforts to conduct research on CV deployments. As a result, a variety of CV application concepts have been developed. They can be categorized into six aspects: safety, mobility, environment, agency data, road weather, and smart roadside assistance. The introduction of those applications in each category from the UDSOT website is shown in Table 3.3 – Table 3.8.

Table 3.3 Safety Application of CV Technology[1,2]

Safety applications	Description
Red Light Violation Warning	An application that broadcasts signal phase and timing (SPaT) and other data to the in-vehicle device, allowing warnings for impending red-light violations
Curve Speed Warning	An application where alerts are provided to the driver approaching a curve at a speed that may be too high for safe travel through that curve.
Stop Sign Gap Assist	An application that utilizes traffic information broadcasting from roadside equipment to warn drivers of potential collisions at stop sign intersections
Spot Weather Impact Warning (SWIW)	An application that warns drivers of local hazardous weather conditions by relaying management center and other weather data to roadside equipment, which then re-broadcasts to nearby vehicles
Reduced Speed/Work Zone Warning	An application that utilizes roadside equipment to broadcast alerts to drivers warning them to reduce speed, change lanes, or come to a stop within work zones
Pedestrian in Signalized Crosswalk Warning (Transit)	An application that warns transit bus operators when pedestrians within the crosswalk of a signalized intersection are in the intended path of the bus
Emergency Electronic Brake Lights	An application where the driver is alerted to hard braking in the traffic stream ahead. This provides the driver with additional time to look for and assess situations developing ahead
Forward Collision Warning	An application where alerts are presented to the driver to help avoid or mitigate the severity of crashes into the rear end of other vehicles on the road. Forward crash warning responds to a direct and imminent threat ahead of the host vehicle
Intersection Movement Assist	An application that warns the driver when it is not safe to enter an intersection—for example, when something is blocking the driver's view of opposing or crossing traffic. This application only functions when the involved vehicles are each V2V-equipped.
Left Turn Assist	An application where alerts are given to the driver as they attempt an unprotected left turn across traffic to help them avoid crashes with opposite direction traffic
Blind Spot/Lane Change Warning	An application where alerts are displayed to the driver that indicates the presence of same-direction traffic in an adjacent lane (blind spot warning) or alerts given to drivers during host vehicle lane changes (lane change warning) to help the driver avoid crashes associated with potentially unsafe lane changes
Do Not Pass Warning	An application where alerts are given to drivers to help avoid a head-on crash resulting from passing maneuvers
Vehicle Turning Right in Front of Bus Warning	An application that warns transit bus operators of the presence of vehicles attempting to go around the bus to make a right turn as the bus departs from a bus stop

[1] https://www.its.dot.gov/pilots/pilots_v2i.htm
[2] https://www.its.dot.gov/pilots/pilots_v2v.htm

Table 3.4 Mobility Application of CV Technology[3]

Mobility applications	Description
Advanced Traveler Information System	Enhanced traveler information services that record or infer user decisions and other contextual trip data that, when suitably processed, can improve or transform system management functions
Intelligent Traffic Signal System	An overarching system optimization application accommodating signal priority, preemption, and pedestrian movements
Transit Signal Priority and Freight Signal Priority	Two applications that provide signal priority to transit at intersections and along arterial corridors as well as signal priority to freight vehicles along an arterial corridor near a freight facility
Mobile Accessible Pedestrian Signal System	An application that allows for an automated call from the smartphone of a visually impaired pedestrian to the traffic signal, as well as audio cues to safely navigate the crosswalk
Emergency Vehicle Preemption	An application that provides signal preemption to emergency vehicles and accommodates multiple emergency requests
Dynamic Speed Harmonization	An application that aims to recommend target speeds in response to congestion, incidents, and road conditions to maximize throughput and reduce crashes
Queue Warning	An application that aims to provide drivers with timely warnings of existing and impending queues
Cooperative Adaptive Cruise Control	An application that aims to dynamically adjust and coordinate cruise control speeds among platooning vehicles to improve traffic flow stability and increase throughput
Incident Scene Pre-Arrival Staging Guidance for Emergency Responders	An application that provides input to responder vehicle routing, staging, and secondary dispatch decisions
Incident Scene Work Zone Alerts for Drivers and Workers	An application that warns on-scene workers of vehicles with trajectories or speeds posing a high risk to their safety. It also warns drivers passing an incident zone if they need to slow down, stop, or change lanes.
Emergency Communications and Evacuation	An application that addresses the needs of evacuees with and without special needs or their transportation
Connection Protection	An application that enables coordination among public transportation providers and travelers to improve the probability of successful transit transfers
Dynamic Transit Operations	An application that links available transportation service resources with travelers through dynamic transit vehicle scheduling, dispatching, and routing capabilities
Dynamic Ridesharing	An application that uses dynamic ridesharing technology, personal mobile devices, and voice-activated onboard equipment to match riders and drivers
Freight-Specific Dynamic Travel Planning and Performance	An application that enhances traveler information systems to address specific freight needs. Provides information such as wait times at ports, road closures, work zones, and route restrictions.

[3] https://www.its.dot.gov/pilots/pilots_mobility.htm

Drayage Optimization	An application that optimizes truck/load movements between freight facilities, balancing early and late arrivals

Table 3.5 Environment Application of CV Technology[4]

Environment applications	Description
Eco-Approach and Departure at Signalized Intersections	A V2I application where intersection traffic signals broadcast the current state of signal phasing (red, yellow, or green) and time remaining in that phase
Eco-Traffic Signal Timing	An application that uses data collected wirelessly from vehicles (and other sources) to optimize the performance of traffic signals, thus reducing fuel consumption and emissions
Eco-Traffic Signal Priority	An application that allows transit or freight vehicles approaching a signalized intersection to request signal priority, thereby adjusting the signal timing dynamically to improve service for the vehicle. Priority decisions are optimized for the environment by considering vehicle type, passenger count, or adherence to the schedule
Connected Eco-Driving	An application that uses V2I and V2V data to provide customized real-time driving advice to drivers, including recommended driving speeds and optimal acceleration/deceleration profiles, so that drivers can adjust their driving behavior to save fuel and reduce emissions
Wireless Inductive/Resonance Charging	An infrastructure application that uses magnetic fields embedded in the pavement to wirelessly transmit electric currents between metal coils, thus enabling the wireless charging of electric vehicles while the vehicle is stopped or in motion
Eco-Lanes Management	An application that establishes parameters and defines the operations of eco-lanes. Eco-lanes are similar to existing managed lanes but optimized for the environment
Eco-Speed Harmonization	An application that determines speed limits optimized for the environment based on traffic conditions, weather information, and GHG and criteria pollutant information, allowing for speed harmonization in appropriate areas
Eco-Cooperative Adaptive Cruise Control	A V2V application that uses connected vehicle technologies to collect speed, acceleration, and location information of other vehicles and integrates these data into a vehicle's adaptive cruise control system, thus allowing for automated longitudinal control capabilities and vehicle platooning that seek to reduce fuel consumption and emissions
Eco-Traveler Information Applications	A group of applications that disseminate information to support transportation choices that reduce fuel consumption and emissions
Eco-Ramp Metering	An application that collects traffic and environmental condition data to determine the most environmentally efficient operation of traffic signals at freeway on-ramps and to manage the rate of entering vehicles
Low Emissions Zone Management	An application that leverages connected vehicle technologies to enable the operation of low emissions zones. Low emissions zones are geographic areas that seek to incentivize green transportation choices and deter high polluting vehicles from entering the zone

[4] https://www.its.dot.gov/pilots/pilots_environment.htm

AFV Charging / Fueling Information	An application that informs travelers of locations and availability of alternative fuel vehicle charging and fueling stations and inductive/resonance charging infrastructure, thereby alleviating "range anxiety"
Eco-Smart Parking	An application that provides users with real-time location, availability, type, and price of parking, resulting in reduced parking search times and emissions
Dynamic Eco-Routing (Light Vehicle, Transit, Freight)	A navigation routing application that determines the most eco-friendly route, in terms of minimizing fuel consumption or emissions, for individual travelers
Eco-ICM Decision Support System	An application that uses historical, real-time, and predictive traffic and environmental data on arterials, freeways, and transit systems to determine operational decisions by system operators that are environmentally beneficial to the corridor

Table 3.6 Agency Data Application of CV Technology[5]

Agency data application	Description
Probe-based Pavement Maintenance	An application that allows the vehicle to automatically report potholes or other pavement anomalies
Probe-enabled Traffic Monitoring	An application that utilizes communication technology to transmit real-time traffic data between vehicles
Vehicle Classification-based Traffic Studies	An application that would allow sorting of vehicle behavior data by vehicle type
CV-enabled Turning Movement & Intersection Analysis	An application that uses paths self-reported by vehicles to track turning ratios, delay, and other intersection metrics
CV-enabled Origin-Destination Studies	An application that uses connected vehicle technology to monitor the beginning and endpoints of a vehicle's journey and extrapolate the route in between
Work Zone Traveler Information	An application that monitors and aggregates work zone traffic data

[5] https://www.its.dot.gov/pilots/pilots_agency_data.htm

Table 3.7 Road Weather Application of CV Technology[6]

Road weather application	Description
Motorist Advisories and Warnings	An application that will use road-weather data from connected vehicles to provide information to travelers on deteriorating road and weather conditions on specific roadway segments
Enhanced MDSS	An application that will acquire road-weather data from connected and other general public vehicles to recommend treatment plans and weather response plans to snowplow operators and maintenance vehicle drivers
Vehicle Data Translator	A complementary application that, when installed on-road service vehicles such as snowplows, collects road and atmospheric conditions data and transmits them to other portions of the road weather management network
Weather Response Traffic Information	An application that will use connected vehicle data and communications systems to enhance the operation of variable speed limit systems and improve work zone safety during severe weather events

Table 3.8 Smart Roadside Application of CV Technology[7]

Smart roadside application	Description
Wireless Inspection	An application that will utilize roadside sensors to transit identification, hours of service, and sensor data directly from trucks to carriers and government agencies
Smart Truck Parking	An application that will provide information such as hours of service constraints, location and supply of parking, travel conditions, and loading/unloading schedules to allow commercial drivers to make advanced route planning decisions

3.5.3 Current Pilot in the USA

As described above, many concepts about CV and AV applications have been developed across the United States. To test the effectiveness and feasibility of those applications, various institutes, including government, research organizations, and industries, have deployed or begun to deploy related pilots to do field tests of CV and AV technologies. The following sections will briefly introduce those pilot tests.

(a) CV Pilots

- New York

New York City Department of Transportation (NYCDOT) intends to deploy a CV pilot to evaluate a series of CV applications on safety and mobility. The deployment site is located in tightly-spaced New York intersections, which are shown in Figure 3.3[8].

[6] https://www.its.dot.gov/pilots/pilots_roadweather.htm
[7] https://www.its.dot.gov/pilots/pilots_smart_roadside.htm
[8] https://www.its.dot.gov/pilots/pilots_thea.htm

Figure 3.3 New York CV Pilot

The CV pilot led by NYCDOT deployment includes three different areas in the boroughs of Manhattan and Brooklyn. As shown in the figure above, the first area consists of a four-mile segment of Franklin D. Roosevelt (FDR) Drive in the Upper East Side and East Harlem neighborhoods of Manhattan. The second area involves four one-way corridors in Manhattan, and the third area includes a 1.6-mile segment of Flatbush Avenue in Brooklyn. Using DSRC, V2I communication technology will be applied at nearby intersections. Also, approximately eight RSUs will be installed along the higher-speed FDR Drive to address issues such as short-radius curves and a weight limit, and 36 RSUs will be installed at other locations within the city to support traffic management.

- Florida

1) Tampa-Hillsborough Expressway Authority (THEA)

To alleviate traffic congestion, reduce collisions, and prevent wrong-way entry at the Selmon Reversible Express Lanes (REL) exit, THEA plans to deploy a CV pilot that integrates various CV applications. This deployment site is located in downtown Tampa, shown in Figure 3.4[9].

Figure 3.4 Connected Vehicle Pilot Deployment—Downtown Tampa

DSRC technology has been applied in the THEA CV pilot to enable transmissions among 10 buses, 8 trolleys, approximately 1,000 cars of individual volunteers, and about 47 roadside units along city streets. This deployment pilot is used to enhance pedestrian safety, improve transit operations, and reduce conflicts of mixed traffic. To support this initiative, THEA will work with its primary partners, the City of

[9] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/i75-frame.shtm

Tampa, the Florida Department of Transportation (FDOT), and the Hillsborough Area Regional Transit, to create a region-wide connected vehicle task force.

2) I-75 Florida's Regional Advanced Mobility Elements (FRAME)

The I-75 FRAME project is located on the I-75 and US 301/441 corridors, connecting east-west arterials between these two corridors, as shown in Figure 3.5[10]. The purpose of this project is to reroute the I-75 traffic in the case of emergencies and incident management and to transfer real-time information to drivers when freeway incidents happen. The project impact area comprises FDOT Districts 2 and 5 jurisdictions. Each district will lead the efforts to leverage CV technologies to manage better, operate, and maintain the multi-modal system and generate an integrated corridor management solution.

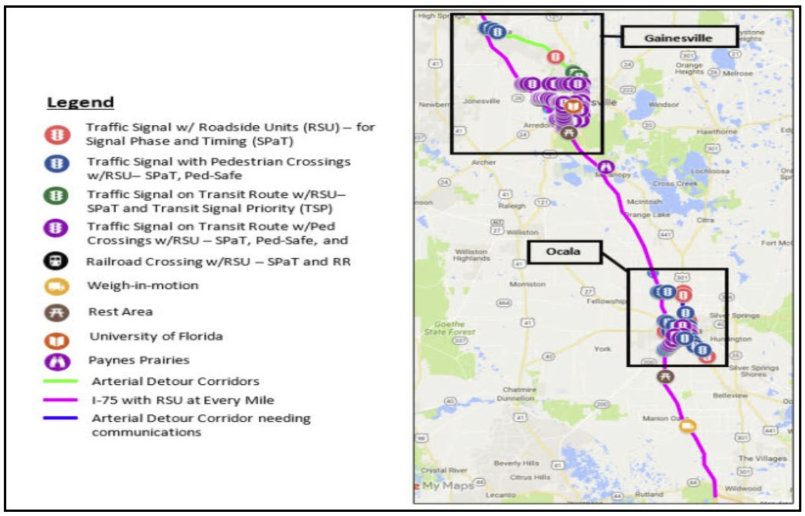

Figure 3.5 Exhibition of FRAME Testbed

3) Lake Mary Boulevard CV testbed

The Lake Mary Boulevard CV testbed is located along seven signalized intersections from International Parkway to Rinehart Road in Lake Mary, Florida, as shown in Figure 3.6[11]. DSRC technology is deployed to evaluate many CV applications, including red light violation warning, signal phase and timing, forward collision warning, target classification (identifying other OBUs), and traffic incident messages.

[10] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/i75-frame.shtm
[11] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/lake-mary-boulevard-cv

Figure 3.6 The Lake Mary Boulevard CV Testbed

4) Orlando Smart community 2017 ATCMTD

Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) was announced in 2017 by the FDOT in partnership with MetroPlan Orlando, the University of Central Florida, the City of Orlando, and Orange County. This project consists of three components in the East Orlando Communities: PedSafe, GreenWay, and Smart Community.

PedSafe is a collision-avoidance system designed by the FDOT to protect pedestrians. The basic idea of PedSafe is to use CV technologies to connect the advanced signal controller to reduce the crash ratio of pedestrians and bicycles. The overview of the technical framework is shown in Figure 3.7[12]. The project designed 33 RSUs and is expected to be completed by the end of 2020.

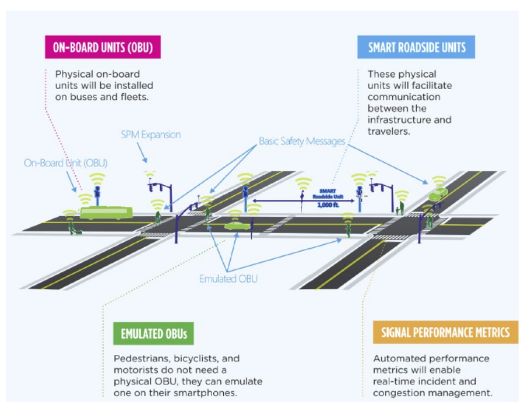

Figure 3.7 Overview of the Technical Framework of Pedsafe

Greenway is also developed by the FDOT to actively manage over 1,000 traffic signals within the region by leveraging the multi-modal transportation system. Greenway aims to connect advanced sensor technology, conditional TSP, adaptive deployment traffic signal interface with track positive train control (SunRail), smart parking technology with signal performance metrics, integrated corridor management, and signal control analytics and visualization. The control framework is shown in Figure 3.8[13]. This will allow strategic planning for special events considering all modes and users and offer a unified system operation and management strategy.

[12] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/atcmtd-orlando.shtm
[13] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/atcmtd-orlando.shtm

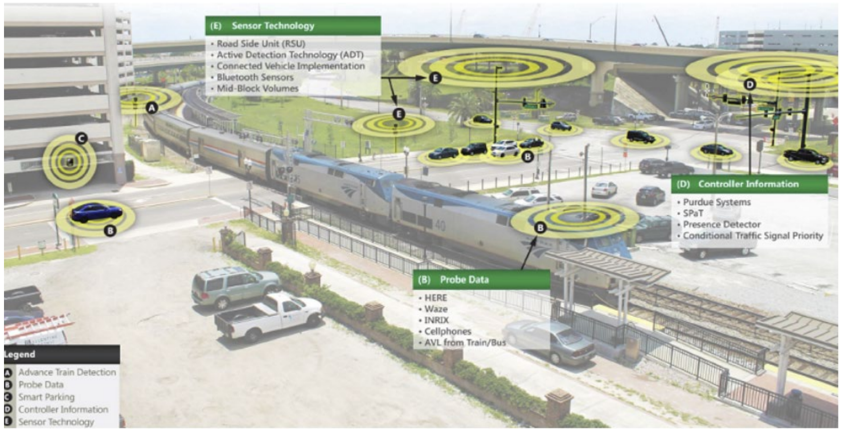

Figure 3.8 Control Framework of Greenway

SmartCommunity is a program that integrates CAV technology, connected infrastructure, renewable energy, and mobility on demand framework to alleviate day-to-day challenges like traffic congestion. With this program applied, travelers can share information and coordinate trips to their destinations. Moreover, multimodal travel information integrating trip planning with modal choice options can be accessed by this program.

5) Gainesville signal phase and timing (SPaT) Trapezium

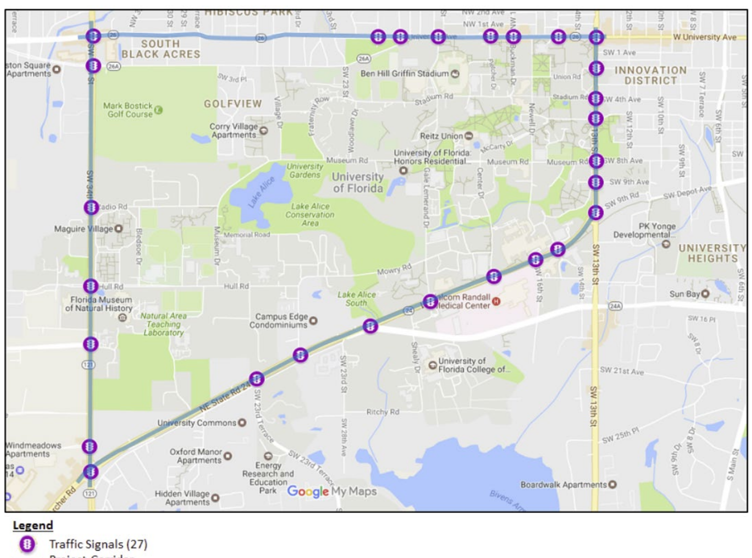

Figure 3.9 Gainesville SPaT Testbed

This deployment site is located along four roads, SR 121 (SW 34th St), SR 26 (W University Ave), US 441 (SW 13th St), and SR 24 (SW Archer Rd), surrounding the University of Florida main campus, as shown in Figure 3.9[14]. The four roads form a trapezium shape. This testbed consists of 27 traffic signals equipped with 27 roadside units. This testbed aims to improve travel time reliability, safety, and throughput and provide traveler information with the application of CV technology.

[14] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/gains-trapezium.shtm

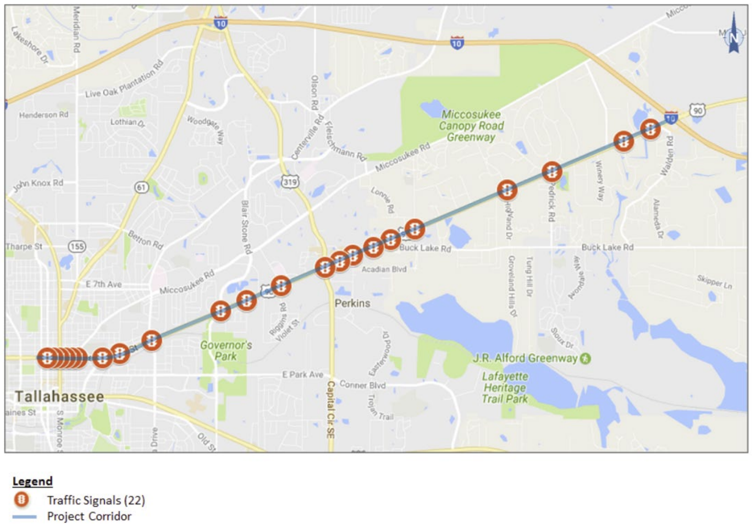

Figure 3.10 US 90 SPaT Tallahassee Deployment

6) US 90 SPaT Tallahassee

This SPaT deployment site is located along the corridor that runs from Duval Street in downtown Tallahassee to Walden Road, west of Interstate 10 (I-10), Florida, as shown in Figure 3.10[15]. SPaT equipment and CV-ready traffic signal controllers were integrated and installed at 22 signalized intersections along this corridor. The short-term goal is to confirm whether SPaT performs effectively in the hilly and forested regions. The long-term goal is to assess DSRC effectiveness and safety for road users traveling along a signalized arterial corridor.

- Wyoming

Wyoming is critical for freight transport across the country and between the United States, Canada, and Mexico, as shown in Figure 3.11[16]. Every year more than 32 million tons of freight are transported across this 6,000-foot long corridor, where the crash rate in winter is three to five times higher than that in summer due to high wind speeds and wind gusts. Therefore, the Wyoming Department of Transportation (WYDOT) announced the deployment of a CV pilot to reduce the number of blow-over incidents and adverse weather-related incidents in the corridor. WYDOT will deploy approximately 75 roadside units (RSUs) along various sections of this corridor. Moreover, around 400 vehicles will be equipped. Of the 400 vehicles, at least 150 would be heavy trucks that are expected to be regular users of I-80. Also, 100 WYDOT fleet vehicles, snowplows, and highway patrol vehicles will be equipped with OBUs and mobile weather sensors.

[15] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/us90-spat.shtm
[16] https://www.its.dot.gov/pilots/pilots_wydot.htm

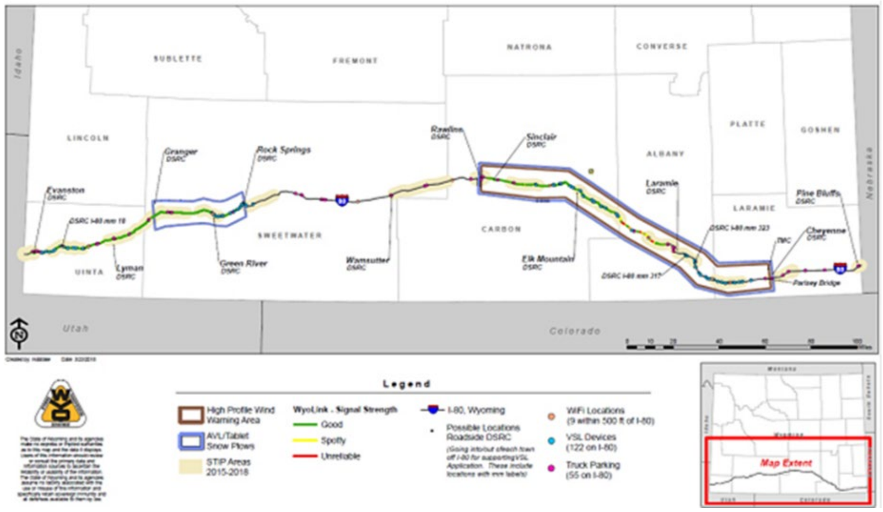

Figure 3.11 Wyoming CV Deployment

- Michigan

1) M-city

Figure 3.12 M-city CAV Deployment

M-city involves about 16 acres of roads and traffic infrastructure, located on a 32-acre ground on the North Campus Research Complex of the University of Michigan, as shown in Figure 3.12[17]. M-city is a full-scale out laboratory that is able to provide traffic simulations involving various complex situations that vehicles may encounter in reality. This testbed can be used for a variety of CV and AV applications, such as driverless shuttle testing, accelerated evaluation of AVs in lane change scenarios, and accelerated evaluation of AVs in car-following maneuvers.

[17] https://mcity.umich.edu/our-work/mcity-test-facility/

2) Southeast Michigan Connected Vehicle Test Bed

This testbed is a roughly 125-mile-long road near the General Motors Milford Proving Grounds, I-94 from Ann Arbor to metro Detroit, and U.S. 23 from Arbor to Brighton, as shown in Figure 3.13[18]. Approximately 115 sensors and other wireless equipment are installed on roadsides to broadcast signals to CVs to help alleviate traffic congestion.

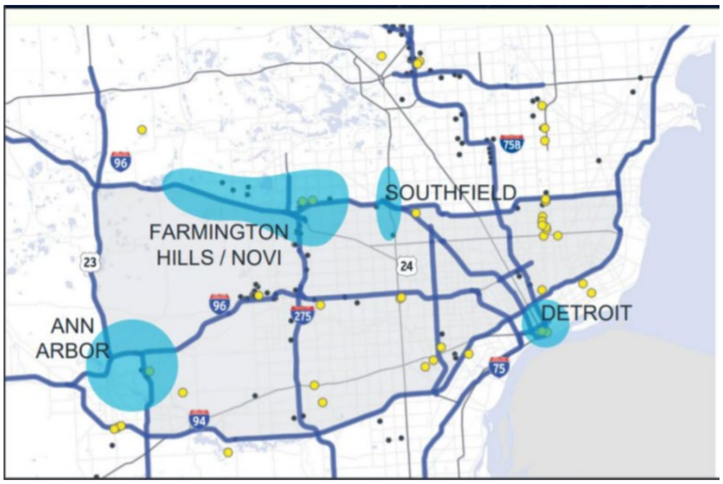

Figure 3.13 Southeast Michigan Connected Vehicle Testbed

- California

In 2005, the nation's first public CV testbed was developed by Caltrans, which partnered with the Metropolitan Transportation Commission and the California Partners for Advanced Transportation Technology (PATH) program at UC Berkeley. This testbed is along El Camino Real (state route 82), a major arterial and state highway connecting South San Francisco to San Jose through the heart of Silicon Valley, as shown in Figure 3.14[19]. In 2018, to comply with the latest CV standards, technologies, and implementation architecture, Caltrans and PATH worked with USDOT to update this testbed. These improvements were successfully used to demonstrate the multi-modal intelligent traffic signal system (MMITSS), including CV-based traffic signal control and signal priority for transit, freight, and pedestrians, and environmentally friendly driving.

[18] https://www.gomobilemichigan.org/planetm/southeast-michigan-connected-vehicle-test-bed.html
[19] http://caconnectedvehicletestbed.org/index.php/about.php

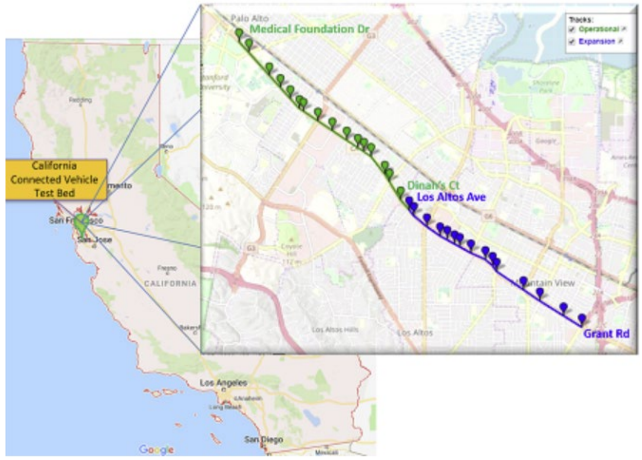

Figure 3.14 El Camino Real CV Testbed

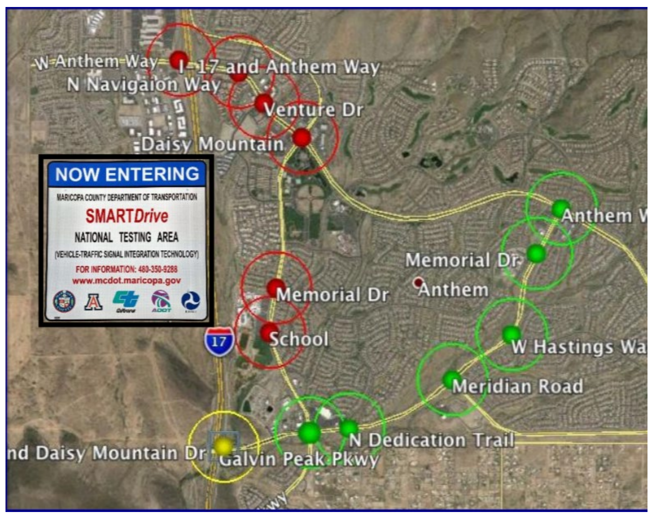

Figure 3.15 Arizona CV Testbed

- Arizona

In 2007, the Maricopa County Department of Transportation (MCDOT), in partnership with the University of Arizona and the Arizona Department of Transportation (ADOT), deployed a testbed for connected vehicle (CV) technologies in Anthem, Arizona, to field test DSRC deployments, as shown in Figure 3.15[20]. This testbed includes six intersections designated to test MMITSS with CV technology, such as transit signal priority and emergency vehicle preemption.

[20] http://itswisconsin.org/wp-content/uploads/2017/07/2015-Forum-Khoshmagham.pdf

- Ohio

In 2014, Ohio State University initially launched a 33 Smart Mobility Corridor; since then, the Ohio Smart Mobility Initiative has quickly evolved to become a collaborative effort among several organizations to deploy this corridor. The corridor is centered around a 35-mile stretch of US-33, beginning in Dublin through Marysville and continuing to East Liberty, Ohio, in the northwest portion of the Central Ohio region, as shown in Figure 3.16[21]. The corridor serves as a testbed for real-world demonstrations of a range of CV technologies.

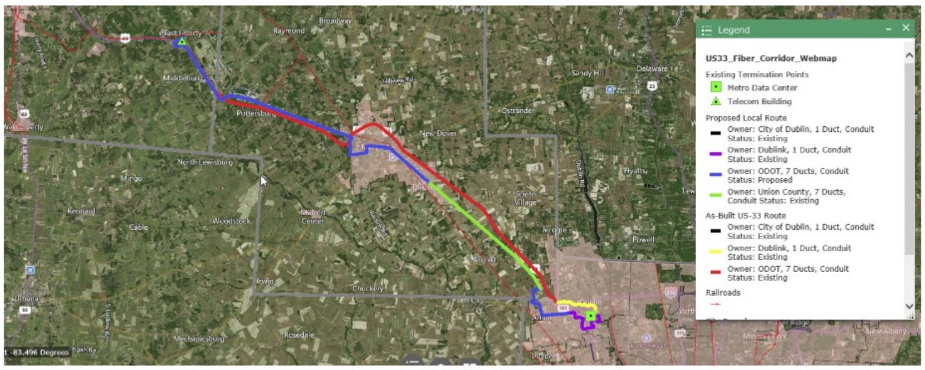

Figure 3.16 33 Smart Mobility Corridor in Ohio

- Utah

Starting in 2016, UDOT planned to build an entire DSRC corridor for CV technology testing. The deployment site is located along Redwood Road in Salt Lake City, as shown in Figure 3.17[22]. This UDOT-owned urban corridor stretches for 11 miles and includes around 30 signalized intersections. As an initial application, this CV deployment project equipped transit vehicles with OBUs and GPS for V2I communications, which can provide intelligent TSP to late buses. When a bus comes into the DSRC communication range of intersections, the V2I function will gather CV information, and TSP control algorithms will be activated if the bus is behind in its schedule.

[21] https://drive.ohio.gov/wps/portal/gov/driveohio/know-our-projects/projects/03-33-smart-mobility-corridor

[22]https://transops.s3.amazonaws.com/uploaded_files/Utah%20DSRC%20MMITSS%20Project%20Overview%2002.14.18%20-%20NOCoE%20Peer%20Exchange.pdf

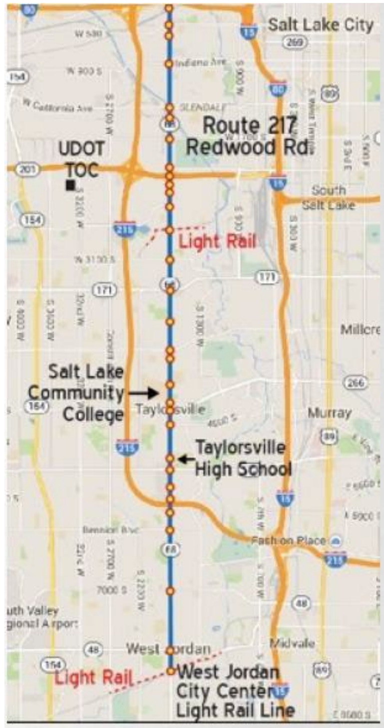

Figure 3.17 Utah CV Corridor

(b) **AV Testbed**

Figure 3.18 AV Testbeds in Lake Nona, Florida

Two AV shuttles were operating in Lake Nona, Florida. The AV shuttles transported passengers along Tavistock Lake Boulevard from behind the Pixon Apartments outside the Lake Nona Town Center to Canvas Restaurant and Market in the Village Center, as shown in Figure 3.18[23]. The length of this route is 1.2 miles, and the shuttle frequency is 10 to 15 minutes. The AV shuttle service started on September 18, 2019.

[23] https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/LakeNonaAVshuttles

Gainesville Autonomous Transit Shuttle deployed an autonomous transit system connecting the City of Gainesville Innovation District and downtown with the University of Florida campus. The goal of this shuttle is to guarantee a maximum headway of 10 minutes. These AV routes include SW 4th Avenue, SW 13th Street, SW 2nd Avenue, and S Main Street, as shown in Figure 3.19[24].

Figure 3.19 AV Testbeds on the University of Florida Campus, Florida

Two fully-automated, 11-seat, all-electric shuttles manufactured by the French firm NAVYA were operated in M-city from June 4, 2018, through December 19, 2019[25]. The goal of operating these two AVs is to understand better how passengers, pedestrians, bicyclists, and other drivers interact with the shuttle. Therefore, consumer acceptance of the technology can be identified.

Figure 3.20 Exhibition of AV-Shuttle in M-city

Waymo LLC is an American autonomous driving technology development company[26]. In April 2017, Waymo started a limited trial of a self-driving taxi service in Phoenix, Arizona. During recent years, Waymo has tested its autonomous vehicles in several cities, including Mountain View Sunnyvale, Los Altos Hills, and Palo Alto in California and Phoenix in Arizona.

[24] https://www.fdot.gov/traffic/its/projectsdeploy/cv/maplocations/gainsav.shtm
[25] https://mcity.umich.edu/shuttle/
[26] https://www.wired.com/story/waymo-self-driving-taxi-service-launch-chandler-arizona/

Figure 3.21 Exhibition of Waymo AV

4. POTENTIAL IMPACT OF CAV ON TRANSPORTATION PLANNING

4.1 Overview

Transportation planning is a collaborative process to determine future goals, policies, investments, and designs for future events regarding traffic movement, facility usage, and impact analysis. Transportation planners conduct transportation planning by defining goals and objectives, identifying problems, generating and evaluating alternatives, and developing plans. This chapter will state the potential impacts of CAV technology on transportation planning with three aspects: transportation systems, land use patterns, and infrastructure investment decisions.

4.2 Impacts on the Transportation System

The impacts that CAVs exert on the transportation system are thorough and profound. Although the magnitude of the effects depends on the market penetration rate of CAVs, management policy, and regulation, CAVs will bring different levels of impact on the following aspects.

4.2.1 Motorized Traffic

When the market penetration of CAVs increases due to the improvements in the maturity of the technology and the reduction in the economic burden, one of the most important things we need to consider is how much and how often we will drive. The most common measurements to evaluate are traffic demand and vehicle miles traveled (VMT), which are miles traveled by vehicles within a specified region for a specified period, as defined by the FHWA.

Recently, various research has been conducted to study the potential impact of CAV on VMT (Auld, Verbas, Javanmardi, & Rousseau, 2018; Cottam, 2018; Shladover, Su, & Lu, 2012; Taiebat, Stolper, & Xu, 2019). These studies show that VMT is influenced by various factors that are most likely to be affected by CAV technologies, which are summarized as follows:

- **Travel demand:** With the application of CAV technology, citizens' travels have become more convenient. CAVs will enable travelers to access other activities while traveling, such as reading, working, and playing. Thus, people will have fewer incentives to optimize or minimize their travel costs, which will potentially increase vehicle travel. Moreover, CAVs can reduce crash risk due to shorter reaction times and advanced warning systems. Therefore, vehicles can be operated more smoothly on the road network, and vehicle travel will increase. Since CAV enables vehicles to drive in a platoon with a relatively short headway, the traffic throughput can also be generally boosted.

- **Shift between traffic modes***:* Compared with transit, biking, and walking, a CAV will be more attractive due to its increased convenience and affordability. Travelers are more likely to choose CAVs when traveling. The shift from high-occupancy public transportation to low-occupancy CAVs will increase travel demand. CAVs are also an optimal means to solve the first-and-last-mile problem. Therefore, travelers will select CAVs even for short trips normally completed by walking or biking.

- **Urban form***:* Since travelers are capable of doing other things traveling by CAV, they may be more willing to accept a longer work commute to live in a more affordable home. This would give an incentive for urban sprawl and, in turn, would generate more miles of travel (Public Sector Consultants & Center for Automotive Research, 2017).

- **Increased mobility of non-drivers**: CAV can enable people without driving abilities, such as the disabled, under age 16, and senior citizens, to drive. Although this will benefit society, it will also increase travel demand.

- **Increased vehicle occupancy**: With CAV technology applied, several traffic modes like car-sharing will be more convenient and practical. CAV is capable of optimizing traffic routes in real-time, making sharing a part with other passengers much cheaper and more convenient. Therefore, carpooling will be more attractive to CAV. If CAV car-sharing becomes prolific in the future, there will be fewer vehicles on the road.

- **Less travel related to searching**: CAV can search for a particular location or a parking site easily and quickly. This will reduce the miles spent searching for desired locations.

4.2.2 Nonmotorized Traffic

CAV applications will bring benefits and challenges to nonmotorized traffic (bicycle and pedestrian). Planners should understand those impacts to develop good planning for nonmotorized traffic.

Information provided by CAVs will change the nature of bicyclists and pedestrian experiences when they use transportation facilities. For example, the safety of bicyclists and pedestrians can be improved because CAV technology can send messages to warn vehicles of the presence of bicyclists and pedestrians. Bike-sharing stations can send information about their locations and availabilities in real time. Bicyclists will then have less chance to arrive at a station where all bikes have been taken, or all spots are full (Krechmer et al., 2009).

Various information, such as bicycle travel times, bicycle occupancy, pavement conditions, and routing data, is expected to be available by application of CAV technologies. This information can enrich the real-time data; thus, the database can help identify system gaps and deficiencies. It can also assist in developing bicycle and pedestrian plans (Krechmer et al., 2009).

4.2.3 Public Transportation

CAVs pose complex impacts on public transportation. Planners need to clarify and analyze those impacts and the required investments to meet future needs.

In the short term, the application of CAV technologies will provide plentiful traffic information that can improve the quality and timeliness of traveler information, resulting in enhanced transit operations and higher ridership. In the medium term, since CAV is optimal to operate with car-sharing and ridesharing alternatives, ridership on traditional transit will decline. Planners should consider the potential trends when conducting alternative analyses.

In the long term, with the development of CAV technology, travelers can be increasingly connected with the transit system with smart devices, and transit can be more connected with road infrastructures. Therefore, dynamic operations and optimization can be achieved, such as intermittent bus lanes, which enable transit to request exclusive bus lanes when required.

4.3 Impacts on Land Use

The study and deployment of CAV technologies rely on current land use. In the short term, the deployment of CAV technology could still be based on land use. However, in the medium to long term, planners need to thoroughly analyze the impacts that CAVs exert on land use to provide crucial advice to policymakers and governments. Depending on the purpose of CAV utilization and how CAVs interact with others, CAV technology will result in low or high density of land use.

One of the main CAV technology benefits is that it can relieve travelers from physically driving. Thus, travelers will have more time to engage in other tasks, such as working, meeting, or relaxing. A CAV is also capable of reducing travel time due to the reduction of traffic congestion and improving traffic safety. These aspects will enable people who are willing to travel long distances. Therefore, people are more likely to search for apartments or houses with lower prices, usually far from the urban center. This will result in incentives for more sprawling, low-density urban development.

Apart from the low-density scenario, CAVs can also produce high-density areas. For example, on-site parking needs, especially in urban cores, will be reduced with the assistance of CAV technology. Thus, valuable space can be freed and planned for other purposes, which will then increase density.

4.4 Impacts on Infrastructure

The currently used infrastructure on the roadway network is designed for human-driven vehicles, which may not be suitable for CAVs. Therefore, the infrastructure needs of CAVs should be understood to make future investment decisions.

For many CAVs, their operations are achieved by identifying road markings with vision systems such as cameras. In 2017, a research study funded by the Transportation Research Board was conducted to study the impacts that the characteristics of pavement markings exert on the ability of CAV's vision system. As reported in this research, it is not a feasible strategy to control CAVs by solely relying on lane marking recognition since it is unrealistic to expect that lane markings on the road are in perfect condition all the time, and several road markings cannot be identified by CAVs (Porcari, 2017). Therefore, to better deploy CAV technology, government agencies should require that road markings be maintained in good condition and avoid markings that CAVs cannot identify.

Since CAVs can communicate with RSU and 3D mapping inside the vehicle to provide real-time traffic conditions and related information, several road signs and signals, such as speed limit signs, will no longer be required.

In addition to those infrastructures that require maintenance, many new infrastructures will need deployment to develop CAV technology. For example, maps with higher resolution need to be provided to ensure a safe drive. New types of RSUs need to be installed to support communication with CAVs.

5. METHODOLOGY

Road geometric features affect driver behaviors and reactions, including SSD, speed, headway length, and gap acceptances. On the other hand, if driving conditions are not aligned with drivers' expectations, they might cause crashes. In Utah, due to the geographic situation, a significant number of highways are located on superelevated layers and mountains. This layout results in steep vertical alignments and curves. Also, driving conditions might worsen due to the frequent snow and inclement weather in cold seasons. Driver assistance technologies in CAV might concur with the shortcomings drivers will experience in these cases. In Salt Lake County, the top five leading crash causes from 2016 to 2019 are reported to be (UDOT, 2021b; UDPS, 2021):

- Short headway
- Failure to yield the right of way
- High speed
- Failure to maintain lane
- Signalized intersections

Any of the reasons for crashes originated either from driver distractions or the incompatibility of drivers with road design. In order to investigate the correlation between road factors and safety performance, five scenarios are designed based on the above causes. These scenarios use road segments with geometric features that are experiencing crashes due to the geometric design elements involved. To mark the role of CAVs in traffic safety performance, a microsimulation in VISSIM 10 by the PTV group is established using actual traffic data from PeMS (UDOT, 2021a). Next, each scenario is simulated with different CAV market penetration rates to study the safety impact quantitively. These scenarios account for impact factors such as desired speed, sight distance, and SSD in vertical and horizontal alignments and a varied number of lanes. Scenarios include:

1. Scenario 1: Due to various constructional projects in Salt Lake County, numerous work zones are assigned in roadways. The number of lanes and speed limit in work zones will generally be reduced, requiring correspondent signs upstream and drivers' proper lane changing in advance. Improper deceleration and gap acceptance for lane changing might cause crashes. A highway segment, including work zones, is simulated in this scenario, including a drop in the number of lanes and speed limit. The presence of CAVs in the network will demonstrate the safety impacts of automation in lane changing behavior and speed adaption. The results of this study also can imply roadways with a reduced number of lanes due to geometry features.

2. Scenario 2: Based on UDPS, 46% of crashes happen at intersections. As Salt Lake County is located in a valley, multiple traffic intersections are located on steep slopes. The steep vertical alignment will restrict stopping sight distance and increase the dilemma zone for drivers. So, an actual signalized intersection situated in an elevated roadway is simulated to analyze the CAV's safety performance. Results can show the CAV performance in controlled intersections and speed control in congested areas.

3. Scenario 3: As stated earlier, sight distance drops notably on mountain highways during cold seasons. Implementation of a variable speed limit (VSL) improves road safety, yet slippery road surfaces might prevent a vehicle's deceleration in correspondent time. V2I technology can be used to alert drivers for situations with smaller sight distances and lower road friction to modify their speed in time. Even though inclement weather might reduce visibility for cameras and the accuracy of sensors, it has been shown that CAVs can still improve safety more than HDV traffic in unusual driving conditions. The results of this scenario can prove this finding.

4. Scenario 4: Routing and suitable guidance sign is another element that potentially improves traffic safety. The short distance between two successive ramps will intensify a vehicle's potential conflicts and reduce maneuverability. As a result, a highway section with consecutive on-ramps and off-ramps is simulated to study CAV lane changing behavior and routing close to ramps. V2I will reduce reaction time by providing correspondent routing and actions to drivers. This scenario focuses on the in-advance lane changing effect in potential lateral crashes.

5. Scenario 5: Mountain roads with sequential horizontal and negative gradient vertical alignments leading to reduced SSD are simulated. Limited SSD has caused numerous crashes due to high speed and run-off road crashes. Roadway departure warning (RDW) systems in CAVs can prevent the last type of crashes on such roadways. Being aware of the road layout and other vehicles on the road can reduce the risk of conflicts, which is the goal of scenario 5.

5.1 CAV Driving Behavior Features

The connectivity and automation of CAVs convey extra data from roadways and surroundings to the driver, in which a higher level of automation might take control of driving in response to collected data. Different levels of automation and availability of data control the driving behavior of a CAV, which results in various driving parameters used in the micro-simulations. In this study, the driving parameters of simulated vehicles were adjusted internally with predefined parameters. These variables include parameters involved in car following, lane change, and lateral and signalized intersection behavior. Depending on the automation level, several driving behaviors can be defined. Nevertheless, as a higher level of automation is still not common in the traffic network, a CAV with driver and vehicle automation integration is considered. PTV has recommendations for simulating AV (Sukennik, 2018) driving behaviors which account for different levels of automation and driving approaches. Moreover, many studies have suggested driving parameters for VISSIM simulation according to their objectives (Asadi et al., 2019; He et al., 2020; Stanek et al., 2018).

Despite diverse defined parameters, most recommendations have a few points in common. First, it is clear that CAV driving is more explicit than HDV due to automation's involvement. The stochastic feature of acceleration and deceleration will be removed, and vehicles will drive more smoothly. The same holds for driving speed, as drivers tend to move in a closer range to the speed limit. Connectivity to infrastructure and vehicles brings more information about the surroundings and driving environment to the driver. Therefore, the number of possible interacted vehicles and objects and sight distance will be increased. More information about the road will allow the vehicle to have a smaller headway distance from other vehicles. This study, however, assumed headway would change according to driving conditions. Other common driving features in CAV involve smaller gap acceptance in lane changing and cooperative lane changing with increased acceleration. The driving behaviors picked for sample CAVs in this study are presented in the following sections.

5.1.1 Following Behavior

In VISSIM, car following behavior is based on the Wiedemann car-following model. The Wiedemann 99 model is used for freeways, and Wiedemann 74 for urban and signalized areas. Previous studies and field data have evaluated the car following behavior of CAVs. Based on their results and the objectives of this study, corresponding adjustments to models have been made to create a sample neutral and cautious CAV in harsh driving conditions. Primarily, as CAV includes radar and cameras, more roadway information will be conveyed to the driver. Therefore, look-ahead distance and look-back distance have been increased for CAVs as the vehicle cameras can detect a more extensive range compared with human eyes.

Field data have found that this value can be more than twice that in HDVs. As a result, observed vehicle value has been increased, accounting for both vehicles and objects.

Next, CAVs tend to have a closer gap with other vehicles in a complete stop, as shown in the *CC0* value. Yet, it is assumed that this value will remain unchanged for a cautious CAV due to possible harsh driving conditions. Headway is also observed to be lower in CAVs compared with HDVs due to less reaction time. Smaller reaction time results in quicker following and reaction to the leading vehicle as well. Shorter headway time in CAVs will reflect in SSD and deceleration in vertical curves. Despite the faster response in CAVs, the headway time for cautious driving is suggested to be more than the default value. A shorter gap between vehicles results in a smaller car following distance and its variation, as shown in *CC4* and *CC5*. On the other hand, reduced oscillation has removed speed dependency on fluctuation and following threshold speed. Even though acceleration-related values have been assumed to be similar to HDV in natural CAV, cautious CAV might have slower acceleration for increased headway with the leading vehicle. Values for each car following parameters for all HDVs and CAVs are both neutral, and cautious driving behaviors are shown in Table 5.1.

Table 5.1 Car Following Parameters for HDV and CAV in VISSIM

Parameters	HDV	CAV Cautious	CAV Normal
General Behavior			
Look ahead distance (ft)	0-820.21	0-1640.42	0-1640.42
Look back distance (ft)	0-820.21	0-1640.42	0-1640.42
Observed vehicles	2	4	10
Wiedemann 99 Model			
CC0, Standstill Distance (ft)	4.92	4.92	4.1
CC1, Headway Time (s)	0.9	1.5	0.5
CC2, Following Variation (ft)	13.12	9.84	9.84
CC3, Threshold for Entering Following	-8	-12	-12
CC4, Negative Following Threshold	-0.35	-0.1	-0.1
CC5, Positive Following Threshold	0.35	0.1	0.1
CC6, Speed Dependency of Oscillation	11.44	0	0
CC7, Oscillation Acceleration (ft/s^2)	0.82	0.49	0.82
CC8, Standstill Acceleration (ft/s^2)	11.48	10.82	11.48
CC9, Acceleration with 50 mph (ft/s^2)	4.92	4.92	4.92

5.1.2 Lane Changing and Lateral Behavior

A shorter distance to other vehicles also appears in lateral movements. Therefore, the safety reduction factor that controls the gap acceptance for lane changing is assumed to be lowered in CAVs. This assumption results in higher lane changing possibility chances for CAVs than HDVs. However, cautious CAV requires more gaps for lane changing for secured maneuvers. Also, the same feature is observed in headway after lane changing when reduced headway is allowed between vehicles. Secondly, cooperative lane changing in CAVs is another prominent driving feature. Furthermore, increased deceleration in cooperative braking is required for better conformity of trailing vehicles. Adjusted values in lateral and lane changing behavior for sample vehicles in simulations are presented in Table 5.2.

Table 5.2 Lane Changing and Lateral Parameters for HDV and CAV in VISSIM

Parameters	HDV	CAV Cautious	CAV Normal
Lane Changing Behavior			
Minimum Headway (front/rear) (ft)	1.64	2.05	1.23
Safety Distance Reduction Factor	0.6	0.7	0.45
Cooperative Lane Change	No	Yes	Yes
Maximum Deceleration for Cooperative Braking (ft/s^2)	-9.84	-13.12	-13.12
Lateral Behavior			
Minimum Lateral Distance Standing (ft)	0.66	0.49	0.49
Minimum Lateral Distance Driving (ft)	3.28	2.46	2.46

It is worth noting that the deterministic behavior of CAVs, such as desired speed, acceleration, and deceleration functions, is also accounted for in simulations. Unlike HDV dynamics functions in VISSIM, which have a range of values to account for the stochasticity of vehicles, a CAV's acceleration and deceleration functions follow a single function. Speed distribution also falls into a more limited range to show that a CAV drives closer to the speed limit.

6. MICROSIMULATION SETUP

Employing the CAV driving behavior explained in Chapter 3, they have been added as a new type of vehicle to the VISSIM vehicle composition. As described earlier in Salt Lake City, five scenarios addressing the potential crash hot spots, including the leading causes of crashes, were simulated in VISSIM. Traffic data are obtained from PeMS, which is a detector-based platform that records real-time traffic data. Each scenario has been simulated 10 times with different random seeds. Using the trajectory data output file of each simulation, the conflicts probability was analyzed with SSAM. SSAM is software developed by the Federal Highway Administration (FHWA) that uses trajectory data of microsimulations to analyze and classify conflicts. SSAM evaluated the trajectory data file of microsimulations to identify the conflicts in the network with CAVs mixed in traffic. To estimate the performance of CAVs' impact on road safety, each simulation was run with mixed traffic of HDVs and CAVs with penetration rates of 10%, 20%, 40%, and 60% and excluding CAVs (zero penetration rate). The following are the detailed designs of each simulation.

6.1 Scenario 1

Failure to yield right of way, improper gap acceptance or high-speed work zones can reduce safety and cause crashes. As a result, a section of I-15 northbound within the intersection of I-80 and 1300 South Street was simulated in the first scenario. It was assumed a work zone was in place for a quarter of a mile with reduced lanes from six to five. It was also assumed that the speed limit along this section was reduced from 65 mph to 50 mph. Simulation was run for two hours (7,200 seconds) for five different CAV penetration rates. The CAV deceleration rate for reduced speed area was set to a lower value compared with HDV to represent the earlier declaration for CAV. The main objectives of this scenario were to study the lane changing behavior of CAVs in reduced lanes and their impact on angle crashes. Also, the reduction of desired speed requires proper speed adjustment upstream to prevent rear-end crashes. By implementing regular CAV driving parameters during simulation, it is noted that CAVs made the lane change farther from the work zone than HDVs. The designed network in the VISSIM environment is shown in Figure 6.1.

6.2 Scenario 2

As a signalized intersection is one of the crash causes, scenario 2 is designed to depict a signalized intersection on a highly elevated layout. It replicated the intersection of 100 South and University Street, which has relatively higher traffic flow due to its location close to campus. The vertical grade of the east-west approach is 10%, while the north-south direction is almost level. The simulated network is shown in Figure 6.2. Traffic flow was simulated for one hour (3,600 seconds) for a fixed signal timing with permitted left turns on all approaches. This network's superelevated vertical curve might result in slower reaction time due to limited sight distance that requires higher deceleration for an on-time break.

Further, vehicles might travel faster westbound due to a negative slope, which reduces the gap for an opposing approach for a left-turn move. The network condition increases the possibility of angle and head-on crashes. Assuming normal CAVs have V2I technology, they will drive at a lower speed while approaching the red light. For this purpose, the desired driving speed of CAVs was lowered from 35 mph to 25 mph in the east-west direction and 30 mph to 20 mph in the north-south direction.

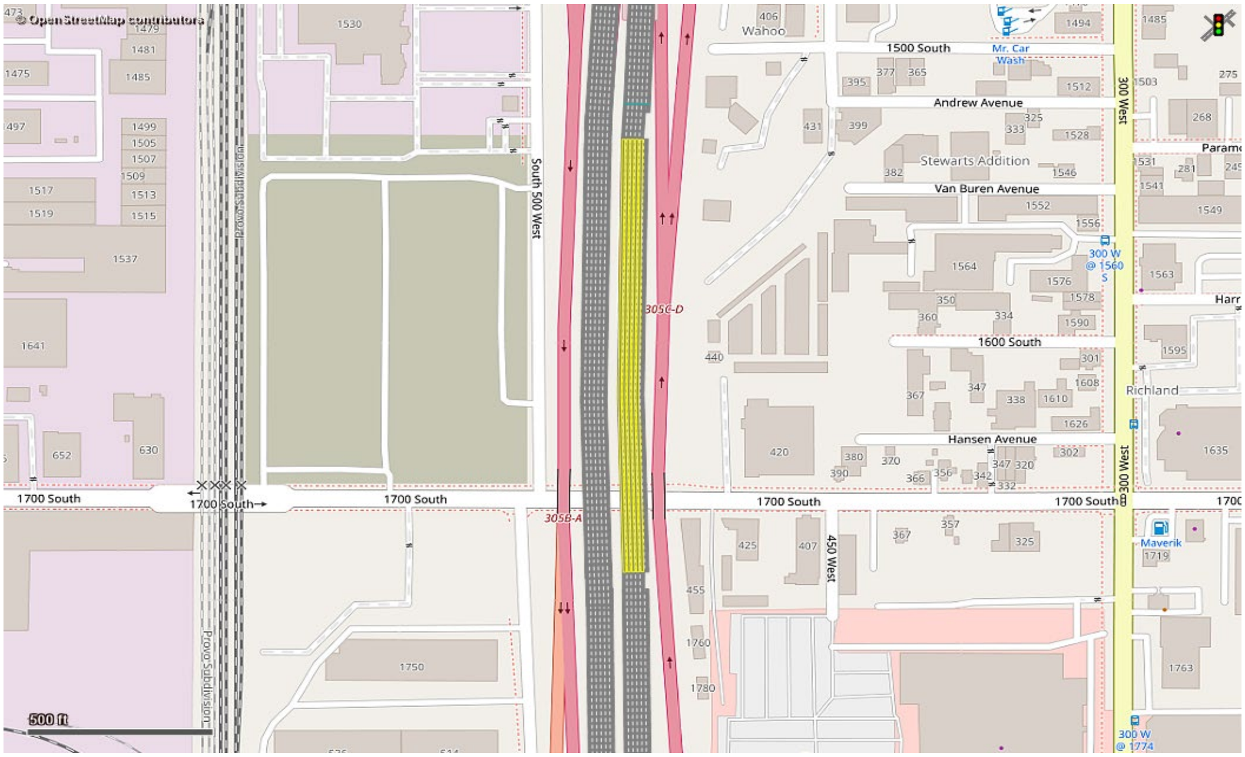

Figure 6.1 Work Zone Network Simulation Layout in VISSIM

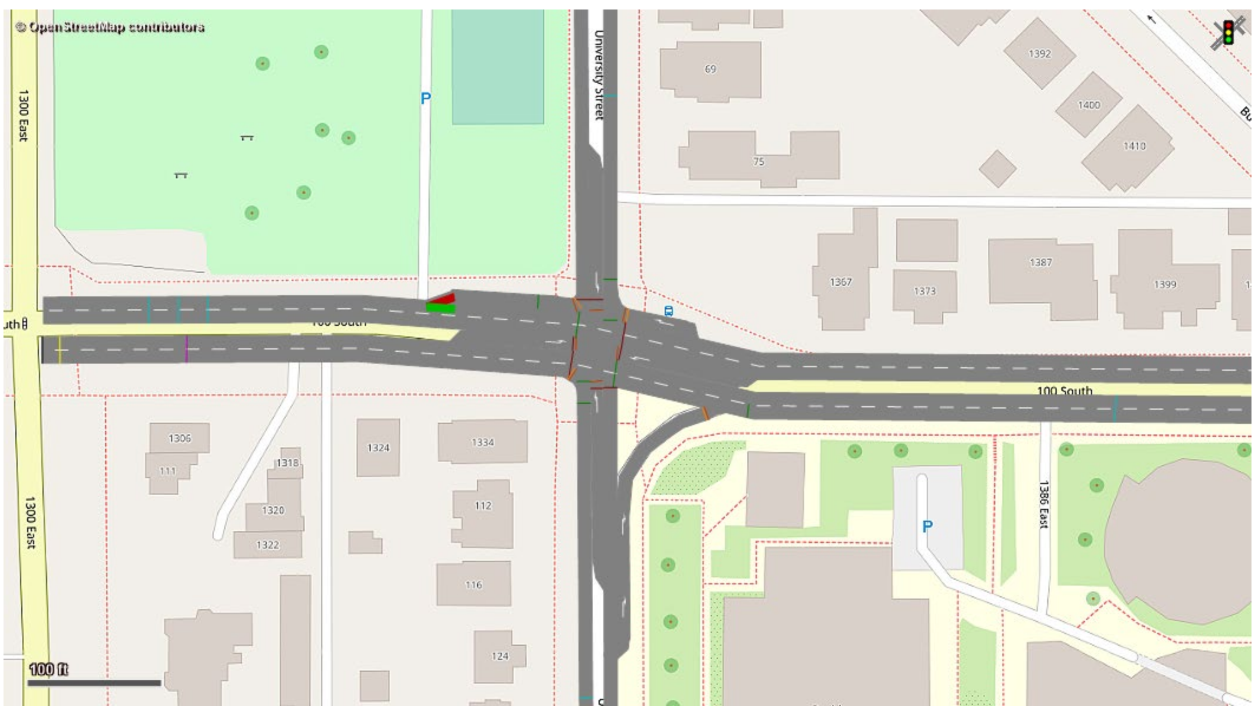

Figure 6.2 Superelevated Signalized Intersection Network Simulation Layout in VISSIM

6.3 Scenario 3

The unique location of I-80 from Salt Lake City toward Parleys Canyon experiences reduced visibility in cold seasons due to snowstorms and fog. Successive horizontal curves also reduce sight distance and maneuverability. Variable speed limit (VSL) signs are located in this corridor. Scenario 3 simulated eastbound of this corridor in severe driving conditions. Also, it was assumed that the road surface was not dry due to precipitation, and cautious driving behavior was picked for CAVs in the network. As mentioned in the driving features section, cautious CAVs will drive with longer headway and secured acceleration and deceleration. As shown in Figure 6.3, the yellow section demonstrates the reduced speed area by VSL for 1.2 miles, lowering the speed limit from 65 mph to 40 mph. Again, CAV declarations were set to occur farther away from reduced speed areas compared with regular vehicles. Microsimulation was done for two hours for all CAV penetration rate scenarios. This simulation aims to evaluate whether V2I can overcome drivers' obstacles in limited vision spots.

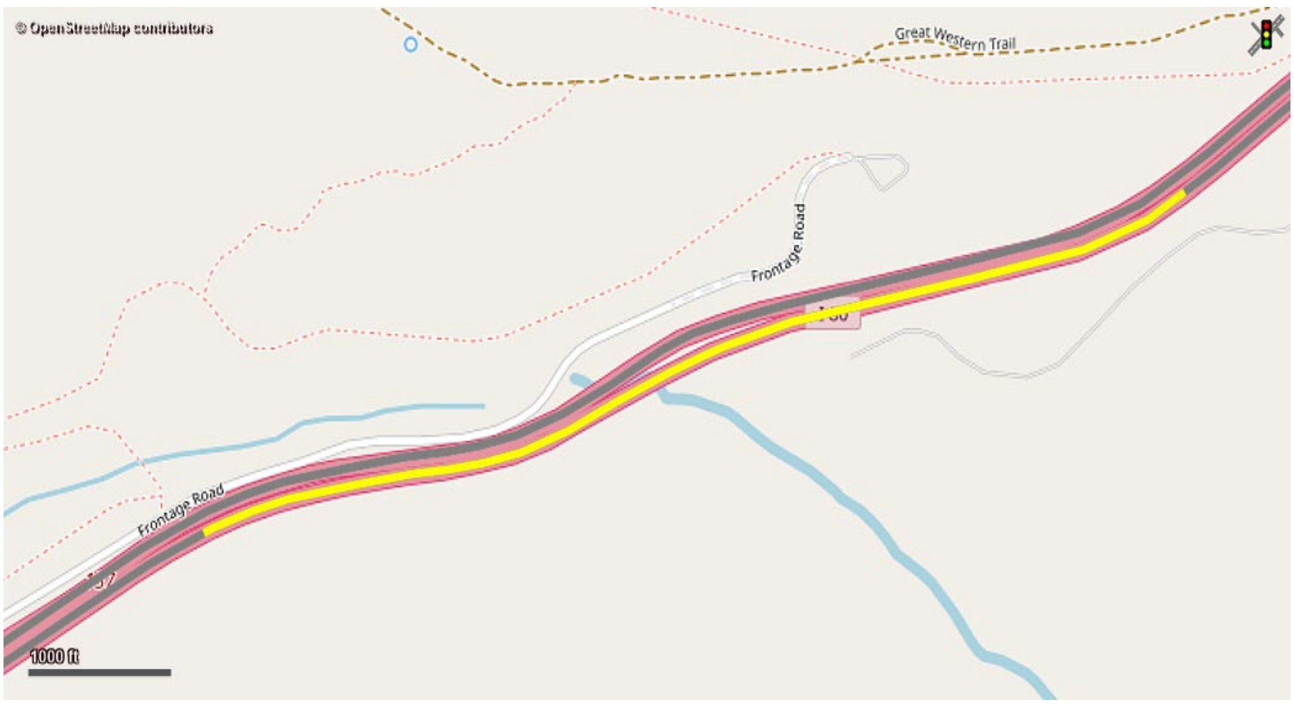

Figure 6.3 Freeway with Weather Advisory Network Simulation Layout in VISSIM

It should be noted that to reflect the driving features of HDV in inclement weather, driving features in snow are also obtained (Chen et al., 2019) to account for uncertainty in driving. The driving behavior in car following is derived from simulation in the snow where friction is lower and will reflect in driving behavior. As the simulated section is on a positive slope, the values for uphill are used. Driving in inclement weather results in larger headway and higher variance in driving. Due to lower visibility, reaction time becomes critical, resulting in a less safe car following behavior. Values used in this simulation are shown in Tables 6.1 and 6.2.

Table 6.1 Car Following Parameters for HDV in VISSIM in Adverse Weather

Parameters	HDV
General Behavior	
Look ahead distance (ft)	0-820.21
Look back distance (ft)	0-820.21
Observed vehicles	1
Wiedemann 99 Model	
CC0, Standstill Distance (ft)	2.46
CC1, Headway Time (s)	4.33
CC2, Following Variation (ft)	39.4
CC3, Threshold for Entering Following	-7
CC4, Negative Following Threshold	-0.15
CC5, Positive Following Threshold	0.15
CC6, Speed Dependency of Oscillation	11.44
CC7, Oscillation Acceleration (ft/s2)	1
CC8, Standstill Acceleration (ft/s2)	14.92
CC9, Acceleration with 50 mph (ft/s2)	4.92

Table 6.2 Lane Changing and Lateral Parameters for HDV in VISSIM in Adverse Weather

Parameters	HDV
Lane Changing Behavior	
Minimum Headway (front/rear) (ft)	2.72
Safety Distance Reduction Factor	0.9
Cooperative Lane Change	No
Maximum Deceleration for Cooperative Braking (ft/s^2)	-9.84
Lateral Behavior	
Minimum Lateral Distance Standing (ft)	0.66
Minimum Lateral Distance Driving (ft)	3.28

6.4 Scenario 4

The short distance between successive ramps reduces the maneuverability for lane changing and lateral movement on freeways. In a segment of the southbound I-15 freeway, from 500 South Street to the I-80 off-ramp, multiple consecutive on-ramps and off-ramps are located. Based on UDOT crash reports, more than 25 angles and side sweep crashes happened annually, on average, from the intersection of the freeway with 800 South Street to the I-80 off-ramp. In scenario four, this corridor was designed and simulated to analyze traffic performance between the successive on-ramp and off-ramp distanced less than 1,800 ft (0.32 miles), as shown in Figure 6.4. Traffic data for through traffic and flow on both ramps are obtained from PeMS and simulated for two hours. This microsimulation aims to study the effect of CAV driving behavior in lateral moves and safe routing.

6.5 Scenario 5

In this scenario, the influence of a combination of horizontal and vertical alignments on road safety is evaluated. For this purpose, part of the I-80 freeway westbound from Parleys Canyon toward Salt Lake City, located within mountains, is chosen. The vertical slope of this route ranges from 3% to 8%, requiring on-time and frequent deceleration. Due to negative grades laid on multiple horizontal curves, sight distance is restricted, which will affect the deceleration rate along the road. Outputs of this simulation demonstrate the CAV driving behavior results in run-off-road incidents and front-to-rear crashes. The layout of the network is depicted in Figure 6.5.

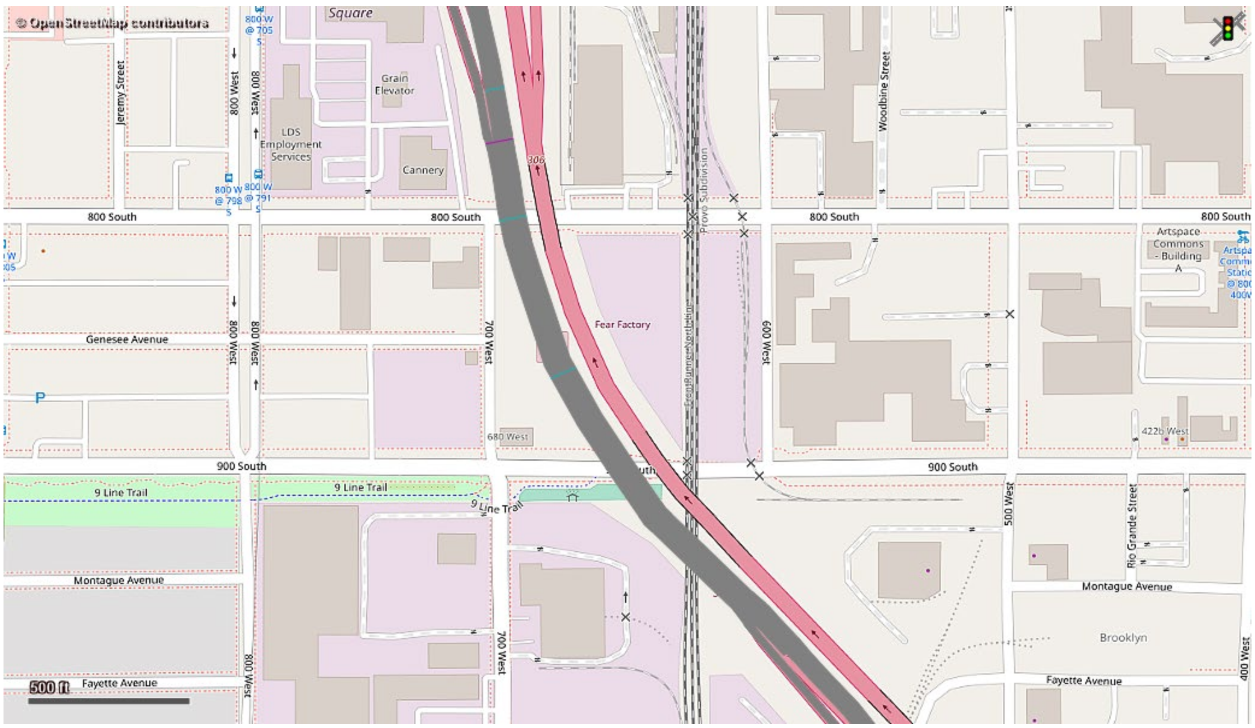

Figure 6.4 On-Ramp and Off-Ramp Network Simulation Layout in VISSIM

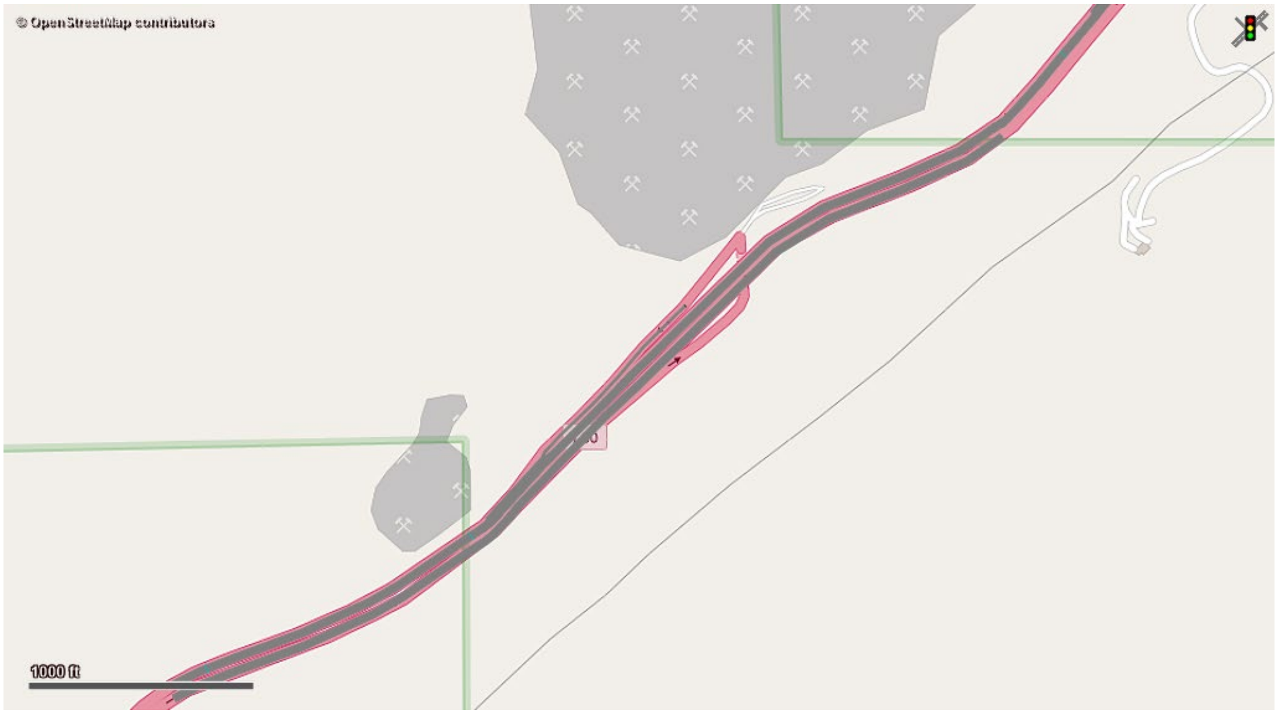

Figure 6.5 Horizontal and Vertical Alignment in Roadway Simulation Layout in VISSIM

7. SSAM RESULTS AND ANALYSIS

SSAM is a safety analysis tool that takes trajectory file data and defines and classifies conflicts in the traffic network. Conflicts convey the situation where two vehicles collide and would be classified depending on their relative angle. Conflict types in SSAM include unclassified, crossing, rear-end, and lane changing types. For classification and definition criteria purposes, multiple parameters need to be set before analysis. The minimum time to collision (TTC) is one of the values determined by the trajectory data of vehicles and, by default, is 1.5 sec. The second parameter is maximum post encroachment time (PET), which describes the time difference between two consecutive vehicles passing a point. When PET is equal to zero, an actual collision will happen; however, according to a study, the threshold was set to 5 (Pu & Joshi, 2008). The angle threshold for rear-end and crossing conflict types was also set to 30º and 80º.

SSAM uses PET and TTC to determine potential conflicts from trajectory data. However, CAVs tend to have shorter headways, which might impact the settings of these two values, i.e., SSAM might record shorter headways as conflicts. Based on analysis of all scenarios for, different penetration rates of CAV conflicts are determined by SSAM. Figure 5.1 demonstrates the evaluation output of each scenario for potential conflicts.

As shown in Figure 7.1, conflicts have been reduced by the increase in CAV penetration rate in most cases. In the first scenario, which reduced the number of lanes and what the deceleration relation of driving is focused on, a reduction in the number of conflicts is observed as the penetration rate increases. A 90% decline in conflicts improves the secure lateral movement of CAVs in bottlenecks. Besides a significant reduction in the number of conflicts in scenario 3, it also demonstrates the effect of CAV presence in performing timely deceleration. Conflict trends are descending in scenarios 4 and 5 as well; however, the decline is less significant compared with scenarios 1 or 3.

It can be concluded from the results of scenarios 1 and 3 that a CAV is successful in performing safe lateral movements and can affect safety performance. Also, scenarios 3 and 4 prove the improved performance of CAVs in comparison with HDVs in small sight distances and where shorter reaction times are required for deceleration. On the other hand, CAV performance in signalized intersections does not indicate improvement in safety, which requires further analysis. Potential conflicts of scenario 2 show that CAVs do not remarkably affect the safety performance in a signalized intersection. Reduced safety might be due to more conflicts between CAVs and HDVs caused by shorter headways in intersections. The number of conflicts in most scenarios indicates that higher CAV penetration rates in freeways and higher traffic allow CAVs to employ more potential safety features.

To study the effect of CAVs' driving behavior along HDVs in traffic flow, classifications of the conflict types for scenarios are analyzed. Since all crashes were classified as rear-end, lane change, or crossing, unclassified conflicts are not included in graphs, as shown in Figure 7.2. As depicted in Figure 7.2 (a), in general, the introduction of CAVs in traffic could reduce rear-end conflicts on freeways due to their faster reactions. This trend is demonstrated in all scenarios except for scenario 2. One explanation of increased rear-end crashes in scenario 2 is that due to shorter headway in CAVs, SSAM will pick the shorter headways to have lower TTC; therefore, they will be categorized as conflicts by SSAM. With reduced rear-end crashes in scenarios 1 and 3, one can conclude that a higher deceleration rate can result in sufficient time for reaction. Higher deceleration comes from CAV connectivity, which provides more information about road driving settings.

Lane change conflicts on freeways have also decreased significantly in scenarios 1 and 4, originating from lower safety factors in lane changing gap acceptance in CAVs. In these two scenarios, where more lane changing is required due to the road layout of simulations, results can determine that CAV performance in lane changing is safer than an HDV. Again, with the trend of lane changing conflicts in scenario 2, there are no solid conclusions. Still, as the crossing conflicts have been removed in high penetration rates, it can be concluded that CAVs with high penetration rates can be effective in signalized intersections in some respects. Even though harsh weather can also affect the visibility of radars and sensors, a reduced number of rear-end conflicts indicates that driver assistance features can still exceed HDV performance in inclement weather. Fewer lane changing conflicts also show safe lateral moves and reduced probability of angle crashes in lower visibilities.

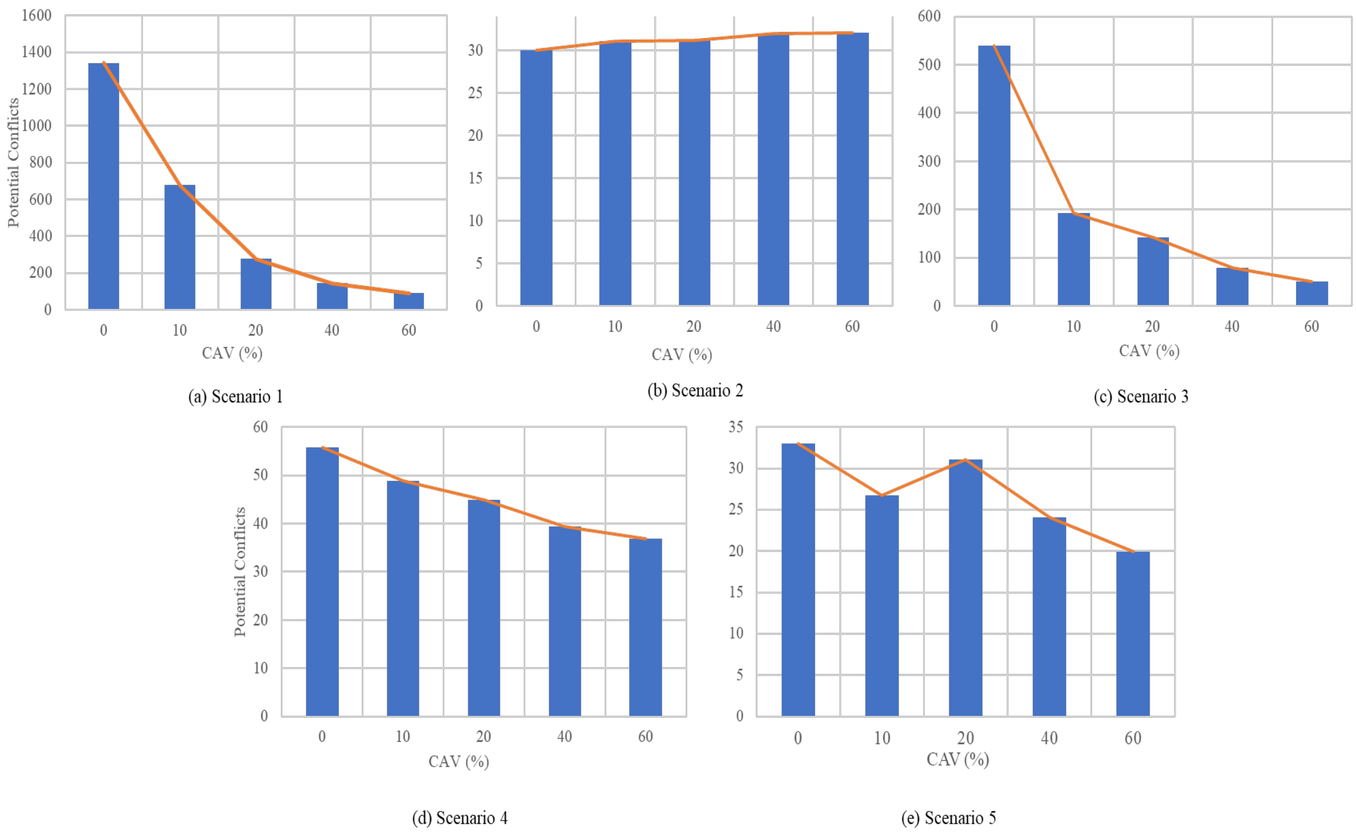

Figure 7.1 Conflict Rates for Simulated Scenarios by CAV Penetration Rates

In both scenarios 4 and 5, rear-end and lane changing conflicts are shown to be lessened. However, it is worth noting that in scenario 4, where lane changing and lateral moves are the points of interest, lane changing conflicts have been affected. This illustrates that CAV's ability in routing and decision making is superior to drivers. On the other hand, rear-end conflicts resulting from short sight distance and successive curves in scenario 5 have been changed more. Based on the latest two observations, it can be concluded that the CAV driving feature can convert the safety efficiency in short maneuverability and limited sight distance in roadway design. It is noticed that higher penetration rates have been successful in reducing the impact of these two geometric factors.

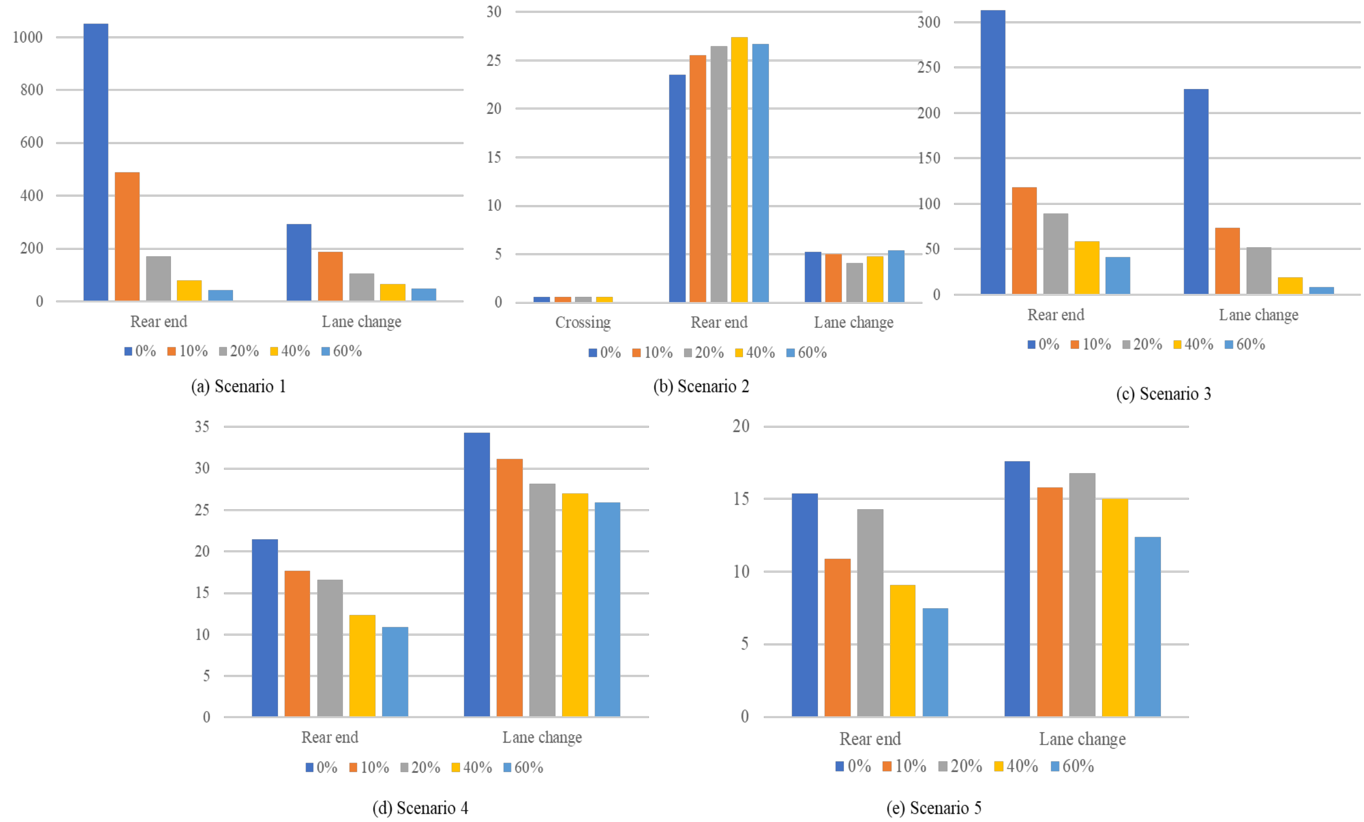

Figure 7.2 Conflict Classification for Simulated Scenarios by CAV Penetration Rates

Other than crash frequency, crash severity was also analyzed to evaluate the safety performance of the roadway. For this purpose, SSAM has multiple variables showing the severity of conflicts. The measurements indicating the severity of collisions are:

- *MaxS*: the maximum speed of vehicles in the conflict
- *DeltaS*: maximum speed difference of vehicles in conflict
- *DR*: initial deceleration rate of the second vehicle in conflict
- *MaxD*: maximum deceleration rate of the second vehicle in the conflict

Table 7.1 summarizes the SSAM safety measurements of scenarios. For all cases, PET and TTC values have been reduced by more CAVs in the network, which is an indicator of shorter headway by CAVs. However, as rear-end conflicts were shown to be reduced, smaller headway will result in a safer roadway if the reaction time is proportional. It is noticeable that for most scenarios, MaxS has increased slightly, which signifies a CAV's deterministic desired speed in driving and less fluctuation from the speed limit. However, in scenario 1, a decline in the DeltaS indicates that less severe conflicts have happened. DeltaS has been lowered due to lower speed differences between vehicles, which implies less severe conflicts. Results of scenario 2 show an insignificant higher deceleration and speed variance as more CAVs are present in traffic. The increase is due to the rise of HDVs following CAVs, which is attributed to smoother CAV driving, causing harder braking for HDVs. Escalation of this interaction might not be beneficial to roadway safety, and full automation may be required to fix this issue. However, changes in deceleration rate and speed in conflicts do not show an improvement in safety in intersections, which can reveal that CAV technologies might not be most beneficial in controlled roadways.

Results of scenario 3 demonstrate increased MaxD resulting from more CAVs in the network braking faster to prevent crashes. A higher deceleration rate might result from low visibility, which restricts decision making and camera performance. On the other hand, DeltaS has decreased, indicating less severe conflicts with lower speed differences. Reduced DeltaS, DR, and MaxD in safety measurements from scenario 4 also illustrate a secure and smoother lane change resulting in less severe crashes. The trend of these variables with increased penetration rates shows safer maneuverability of CAVs in the network. Measurements from scenario 5 also demonstrated that the speed variance reduces with the higher CAV penetration rate, indicating a CAV's ability to adapt to a steep slope in response to other vehicles, as shown in DeltaS. Reduced speed and deceleration improve safety and increase driver reaction time, preventing severe conflicts.

Table 7.1 SSAM Safety Measures for Five Scenarios with Different CAV Penetration Rates

	CAV Penetration Rate (%)				
Parameter	0	10	20	40	60
Scenario 1					
TTC	0.846	0.736	0.552	0.413	0.296
PET	1.787	1.475	0.928	0.618	0.360
MaxS	12.395	14.976	19.134	21.635	24.139
DeltaS	5.984	6.519	6.553	5.688	5.108
DR	-3.557	-3.868	-4.271	-4.351	-4.803
MaxD	-5.021	-5.368	-5.597	-5.548	-5.626
MaxDeltaV	3.200	3.500	3.509	3.030	2.730
Scenario 2					
TTC	1.181	1.175	1.212	1.112	1.106
PET	2.135	2.043	2.101	1.932	1.880
MaxS	5.348	5.572	5.414	5.569	5.660
DeltaS	4.071	3.984	3.980	3.973	4.027
DR	-2.071	-2.027	-1.999	-1.945	-2.166
MaxD	-2.174	-2.115	-2.191	-2.205	-2.485
MaxDeltaV	2.144	2.101	2.088	2.078	2.120
Scenario 3					
TTC	0.658	0.533	0.462	0.269	0.120
PET	1.125	0.784	0.635	0.350	0.134
MaxS	14.795	18.833	20.746	24.331	26.047
DeltaS	7.348	7.797	7.417	6.505	5.407
DR	-4.154	-4.042	-3.436	-2.406	-1.528
MaxD	-5.434	-5.182	-4.617	-3.094	-1.898
MaxDeltaV	3.887	4.145	3.960	3.505	2.964
Scenario 4					
TTC	0.217	0.165	0.181	0.113	0.054
PET	0.280	0.207	0.218	0.122	0.063
MaxS	26.171	26.594	26.388	27.424	27.406
DeltaS	4.936	4.487	4.665	3.908	3.472
DR	-4.783	-4.980	-4.980	-5.288	-5.549

MaxD	-5.836	-5.992	-5.953	-5.957	-6.086
MaxDeltaV	2.652	2.404	2.498	2.080	1.854
Scenario 5					
TTC	0.261	0.282	0.341	0.240	0.167
PET	0.364	0.363	0.463	0.282	0.176
MaxS	25.150	25.322	24.251	25.170	26.534
DeltaS	5.481	5.099	5.631	5.213	4.466
DR	-4.513	-4.534	-4.605	-4.741	-5.001
MaxD	-5.418	-5.452	-5.496	-5.476	-5.349
MaxDeltaV	2.966	2.724	3.050	2.770	2.354

Although the safety effect of CAVs highly depends on the automation level, road type, and driving approach, the aggregated results of all five scenarios above reveal that higher penetration rates of CAVs can reduce potential conflicts. As depicted in Figure 7.3, rear-end conflicts are the type that have been most affected by CAVs. Although, as discussed earlier, shorter headways of CAVs might be misclassified as rear-end conflicts by SSAM, an 83% reduction in this type of conflict is observed. The reason behind lower rear-end conflicts can be described as cooperative driving by CAVs with a shorter reaction time. However, more CAVs in the vehicle composition leads to more interactions of CAVs and HDVs, which might diminish this CAV safety effect, especially in signalized intersections. Cumulative conflict rates also show reduced lane changing conflicts, which emerge from CAVs taking smaller gaps for changing lanes. Cooperative lane changing by CAVs reduces the chance of conflicts through proper deceleration, which enhances road safety. Based on individual results from scenarios, it was observed that lateral movements in CAVs are the most significant driving feature in dealing with geometric design variables that impact vehicle sideways movements.

The analysis indicates the network's safety performance with CAV mixed traffic quantitively and the correlation of the CAV penetration rate with crash rate and severity. However, to check whether these changes are significant, using SSAM, a t-test with a 95% confidence interval is done on the results of scenarios with HDVs only and 60% CAVs included in the traffic. The results of these tests can show if CAVs can significantly improve road safety in each scenario.

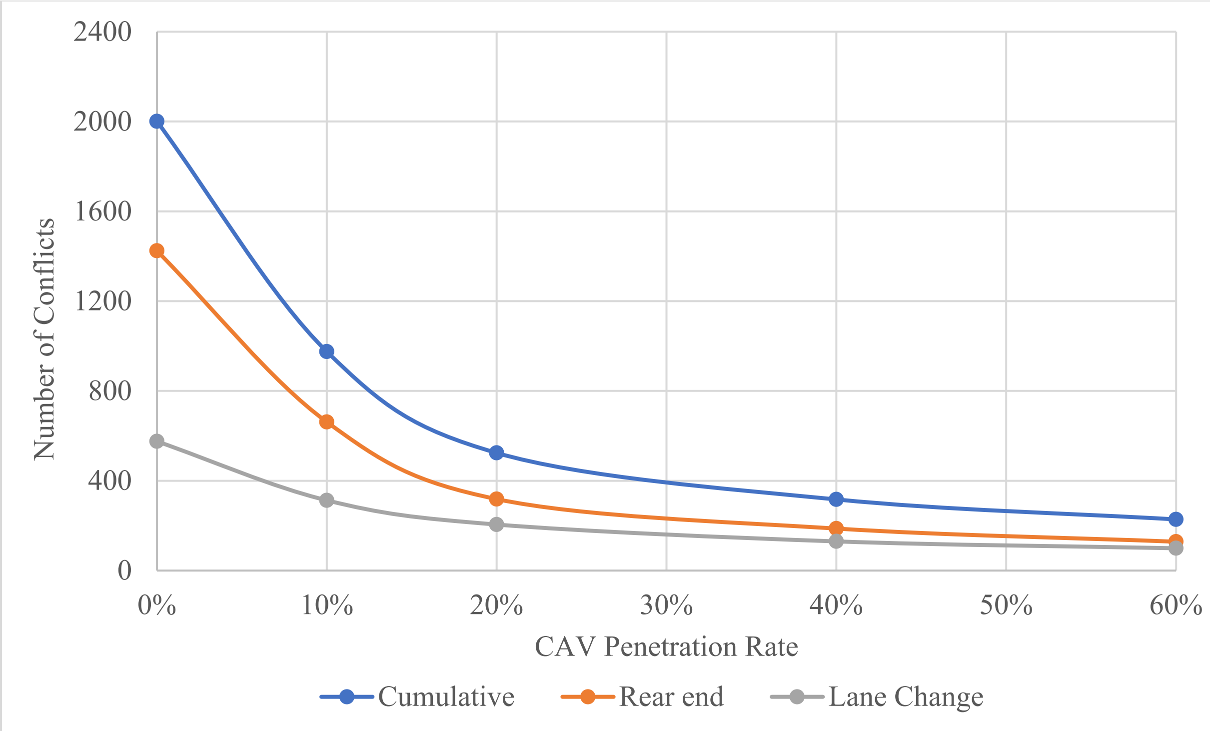

Figure 7.3 Cumulative Conflict Rates by All Scenarios vs. Penetration Rates

Table 7.2 T-test of Safety Performance in Scenario 1 with 0% and 60% CAV

Measures	0% CAV	60% CAV	T value	Significant	Mean Difference
SSAM Measures					
TTC	0.85	0.3	29.13	YES	0.55
PET	1.79	0.36	49.6	YES	1.43
MaxS	12.39	24.14	-49.73	YES	-11.74
DeltaS	5.98	5.11	5.3	YES	0.88
DR	-3.56	-4.8	13.33	YES	1.25
MaxD	-5.02	-5.63	7.38	YES	0.6
MaxDeltaV	3.2	2.73	5.24	YES	0.47
Conflict Types					
Crossing	0.2	0	1.5	NO	0.2
Rear-end	1050.4	41.8	9.9	YES	1008.6
Lane changing	292.3	47.3	15.96	YES	245
Total	1342.9	89.1	10.77	YES	1253.8

Table 7.2 indicates that both PET and TTC have decreased significantly, reflecting the shorter headway of CAV. Even though the MaxS has increased notably, DeltaS has also reduced considerably, indicating less severe conflicts. The changes in DR, MaxD, and MaxDeltaV demonstrate that as CAVs increase in a network, drivers accelerate faster, and traffic flow characteristics become more deterministic. The latter conclusion, plus the significant changes in crash rates, prove that CAVs will improve safety in work zones and locations that require speed adaption and lane changing.

Table 7.3 T-test of Safety Performance in Scenario 2 with 0% and 60% CAV

Measures	0% CAV	60% CAV	T value	Significant	Mean Difference
SSAM Measures					
TTC	1.18	1.07	2.33	YES	0.11
PET	2.13	1.83	2.57	YES	0.3
MaxS	5.35	5.69	-1.38	NO	-0.35
DeltaS	4.07	4.08	-0.05	NO	-0.01
DR	-2.07	-2.02	-0.29	NO	-0.05
MaxD	-2.17	-2.28	0.55	NO	0.1
MaxDeltaV	2.14	2.15	-0.04	NO	0
Conflict Types					
Crossing	0.6	0.6	0	NO	0
Rear-end	23.5	25.6	-2.04	YES	-2.1
Lane changing	5.2	5	0.33	NO	0.2
Total	29.3	31.2	-1.49	NO	-1.9

On the other hand, the results of Table 7.3 show that increased CAVs in signalized intersection does not make a notable improvement in safety performance. This may be due to a CAV not being able to use its driving assistance technologies in intersections completely. Also, increased rear-end crashes result from short headways in CAVs that SSAM will detect as rear-end crashes.

Table 7.4 T-test of Safety Performance in Scenario 3 with 0% and 60% CAV

Measures	0% CAV	60% CAV	T value	Significant	Mean Difference
SSAM Measures					
TTC	0.66	0.12	29.77	YES	0.54
PET	1.12	0.13	40.67	YES	0.99
MaxS	14.8	26.05	-48.08	YES	-11.25
DeltaS	7.35	5.41	10.2	YES	1.94
DR	-4.15	-1.53	-19.33	YES	-2.63
MaxD	-5.43	-1.9	-24.03	YES	-3.54
MaxDeltaV	3.89	2.96	8.35	YES	0.92
Conflict Types					
Crossing	0	0	0	NO	0
Rear-end	313.2	41.6	21.2	YES	271.6
Lane changing	226.1	8.3	24.88	YES	217.8
Total	539.3	49.9	24.09	YES	489.4

In scenario 3, reduced DeltaS shows crash severity has been lowered. However, increased deceleration is the main contributor to reduced crashes, as shown by statistical test results in Table 7.4. The results of this test prove that CAVs could better adapt to perilous driving conditions in harsh weather and lower visibility conditions.

Table 7.5 T-test of Safety Performance in Scenario 4 with 0% and 60% CAV

Measures	0% CAV	60% CAV	T value	Significant	Mean Difference
SSAM Measures					
TTC	0.26	0.17	2.24	YES	0.09
PET	0.36	0.18	3.32	YES	0.19
MaxS	25.15	26.53	-2.56	YES	-1.38
DeltaS	5.48	4.47	2.31	YES	1.01
DR	-4.51	-5	2.56	YES	0.49
MaxD	-5.42	-5.35	-0.43	NO	-0.07
MaxDeltaV	2.97	2.35	2.57	YES	0.61
Conflict Types					
Crossing	0	0	0	NO	0
Rear-end	15.4	7.5	4.14	YES	7.9
Lane changing	17.6	12.4	3.3	YES	5.2
Total	33	19.9	5.24	YES	13.1

The difference between DeltaS and crash rates between the two cases in Table 7.5 demonstrates improved safety in locations with multiple ramps requiring frequent lateral movements. In addition, the deceleration rate is shown to be decreased, addressing a CAV's ability to find a route in advance to prevent conflicts in lane change moves. A similar trend is seen in scenario 5 results in Table 7.6, showing less severe crashes as well as a reduced number of conflicts. Enhanced safety performance in limited sight distances is related to steadier traffic flow and vehicles with lower deceleration rates, averting running into unexpected barriers on the road.

Table 7.6 T-test of Safety Performance in Scenario 5 with 0% and 60% CAV

Measures	0% CAV	60% CAV	T value	Significant	Mean Difference
SSAM Measures					
TTC	0.22	0.05	6.9	YES	0.16
PET	0.28	0.06	6.41	YES	0.22
MaxS	26.17	27.41	-3.46	YES	-1.24
DeltaS	4.94	3.47	5.13	YES	1.46
DR	-4.78	-5.55	4.7	YES	0.77
MaxD	-5.84	-6.09	2.09	YES	0.25
MaxDeltaV	2.65	1.85	5.09	YES	0.8
Conflict Types					
Crossing	0	0	0	NO	0
Rear-end	21.5	10.9	4.74	YES	10.6
Lane changing	34.3	25.9	5.05	YES	8.4
Total	55.8	36.8	5.61	YES	19

8. CONCLUSIONS

The introduction of CAVs into traffic flow has brought many privileges to traffic flow performance. Moreover, automation and connectivity can convey more data about the driving environment, reducing the chance of drivers making uncomfortable decisions. As the driving assistance technologies in CAVs have made driving patterns smoother and reduced the driver decision load, it can be beneficial to road safety and crash rates. On the other hand, geometric design elements are mainly based on human reactions and behavior, which from time to time, drivers might fall short in timely response to road layout changes. Therefore, CAVs can provide a safer performance by carrying more data from roads and infrastructure. This study investigates the effect of CAVs on different road geometry designs, and the relation of CAV safety performance with road design parameters is analyzed. Considering Salt Lake County as a case study, multiple scenarios are proposed in potential hot spots with high crash rates. Scenarios include freeway segments and a signalized intersection. Road design variables involved in these scenarios include the number of lanes, reduced speed areas, sight distance, horizontal and vertical alignments, road friction factor, and ramps. For safety performance evaluation, the scenarios are first simulated in VISSIM using the CAV driving behavior parameters for two driving approaches, namely neutral and cautious CAVs. Next, obtained trajectory data from simulations for different CAV market penetration rates are fed into SSAM software to analyze crash severity and frequency by different safety measurements.

Based on SSAM analysis results, it was observed that CAVs' appearance on freeways could affect safety more than a controlled intersection. Cumulative results illustrate that increased CAVs in traffic will improve safety and reduce the chance of conflicts, especially rear-end crashes. CAVs' presence on roadways is shown to be most effective in work zones and during severe weather conditions. Based on statistical tests and conflict analysis, safety could be improved to 90% in crash rates in these cases. On the other hand, higher CAV and HDV interaction in intersections might not be practical due to the incompatibility of driving behaviors. Shorter headways in CAVs will influence human-driven vehicles and increase potential conflicts. For the improved performance of CAVs in controlled roadways, a higher penetration rate and full connectivity are required. However, as the interaction of HDVs and CAVs is not studied enough, the safety performance of intersections might need more study to reflect results closer to reality. It is also found that a CAV's lateral movements can impact safety significantly. As CAVs tend to have cooperative lane changing and shorter reaction times, it will provide more opportunities for safe lane changing to all vehicles. Safer lateral movements are also related to the data available for the driver in advance for a timely reaction.

Studying the measurements of performance on conflict severity showed that in all cases, TTC and PET are going to be reduced with the increase of CAVs on the road as they will have shorter headways. As the maximum speed of vehicles involved in potential conflicts increases, it can be concluded that CAVs create a more uniform traffic flow, making vehicles drive at less varied speeds. As a result, speed variance will be less, reducing crash severities. Deceleration rates are also shown to be reduced in most cases, illustrating vehicles will lower their speed in advance, which prevents harsh braking. Lower deceleration rates give drivers an extended reaction time to stop promptly. An increased deceleration rate in scenario 3 is caused by low visibility, which is inevitable. However, as conflicts have decreased, it can be concluded that sudden braking is used to prevent crashes. Moreover, maximum deceleration rate changes with the introduction of CAVs in scenario 5 were insignificant, which might originate from shorter reaction time in CAVs minimizing crash rates.

Cautious driving added as a CAV driving behavior during inclement weather, also showed improvements in rear-end conflicts. However, more field data on CAV performance in such cases are required to model their behavior in comparison to human drivers, as low visibility can also affect cameras and sensors. Even though the shorter headway is one of the CAV features in driving, the findings of this study have shown that in the case of shorter sight distance due to roadway alignments, CAVs tend to adapt better to vehicle control, thereby reducing crashes. A notable conclusion of this investigation was that more CAVs in traffic flow positively impacts roadway safety performance and can reduce conflict severity depending on road design. The improvement has been significantly seen in rear-end crashes due to a lower deceleration rate. Finally, lateral movements of CAVs have been noted in most scenarios that appear to benefit from cooperative lane changing behavior and lower angle crashes. It should be noted that the interaction of CAVs and HDVs requires a more detailed exploration, as results illustrated that it might affect the operational safety aspects of roadways.

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