STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV 10/98)

1. REPORT NUMBER

2. GOVERNMENT ASSOCIATION NUMBER

3. RECIPIENT'S CATALOG NUMBER

4. TITLE AND SUBTITLE

Interactive Simulation of Coopertive Adaptive Cruise Control (CACC) Vehicle Matching

Increasing the effectiveness of the CACC system

5. REPORT DATE

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

California PATH Program, Institute of Transportation Studies,
University of California, Berkeley,
Richmond Field Station,
1357 S. 46th Street, Richmond, CA 94804

10. WORK UNIT NUMBER

11. CONTRACT OR GRANT NUMBER

Contract 65A0682
Task ID 3128

12. SPONSORING AGENCY AND ADDRESS

Division of Research, Innovation and System Information
California Department of Transportation
1727 30th Street, 3rd Floor, MS-83
Sacramento, CA 94273-0001

13. TYPE OF REPORT AND PERIOD COVERED

Technical Report
July 01, 2017 to June 30, 2020

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Work under this research studied the solutions (e.g., dynamic displays) to help drivers who drive Cooperative Adaptive Cruise Control (CACC) vehicles to find other communication-equipped vehicles to follow, thereby helped to overcome one of the main impediments to early deployment of CACC at low market penetration.

The CACC model and the platoon forming strategy have been implemented with a microscopic simulation for an arterial corridor with multiple signalized intersections on San Pablo Ave. near Berkeley, California. The arterial corridor extends from south of Ashby Avenue to north of Gilman Street with 10 signalized intersection. The simulation environment is Aimsun. Simulations showed that proper platoon forming maneuvers could reduce total travel time.

17. KEY WORDS

Cooperative Adaptive Cruise Control, Deployment, Aimsun,

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIFICATION *(of this report)*

Unclassified

20. NUMBER OF PAGES

112

21. COST OF REPORT CHARGED

Free

DISCLAIMER STATEMENT

Project Title:

Interactive Simulation of CACC Vehicle Matching

Final Report

Caltrans Contract Number: 65A0682

Project Team:

Dr. Xiao-Yun Lu – Principal Investigator
Benjamin McKeever, Alex A. Kurzhanskiy, Soomin Woo, and EVite team

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June 27, 2020

Key words: *Connected Automated Vehicles (CAV), arterial intersection microscopic simulation of traffic with CAVs, platoon forming, CAV development, CAV deployment, CAV strategic Plan*

Abstract

This report documents the research results under the Interagency Agreement under Contract Number: 65A0682 with California Department of Transportation (Caltrans), Division of Research & Innovation and System Information (DRISI). This study includes the works in three aspects: (a) extensive literature review of platoon formation of Connected Automated Vehicles (CAV) – the approaches adopted and the findings; The review is conducted according to the lifecycle of a CAV string – string formation, maintenance, and dissolution; (b) preliminary implementation of Cooperative Adaptive Cruise Control (CACC) car-following model in a microscopic simulation of mixed traffic at an intersection and analyzed the benefit for the mixed traffic with CAVs compared to the current baseline traffic; and (c) strategic planning for CAV development and deployment in California. This strategic planning has covered almost all aspects.

Acknowledgements

This work was performed by California Partners for Advanced Transportation Technology (PATH) at the University of California at Berkeley, in cooperation with the California Department of Transportation (Caltrans), Division of Research & Innovation and System Information (DRISI) through the Interagency Agreement under Contract Number: 65A0682. The contents of this report reflect the views of the author, who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California.

Executive Summary

This study includes the works in three aspects:

- extensive literature review of platoon formation of Connected Automated Vehicles (CAV);
- preliminary implementation of Cooperative Adaptive Cruise Control (CACC) car-following model in a microscopic simulation of mixed traffic at an arterial with multiple signalized intersections;
- strategic planning for CAV development and deployment in California.

The following summarizes the approaches and finding in those three aspects.

(a) Literature Review of CAV Platoon Formation

Wide application of connected automated vehicles (CAVs) has the potential to increase the roadway capacity, improved safety, and reduced energy consumption and emission. However, CAV market penetration can only be increased progressively in many years. Therefore, mixed traffic with CAVs and manually driven vehicles will coexist practically. In the mixed traffic, how to aggregate the CAVs to for platoons so that the potential benefit of CAV could be realized is a very important issue which needs rigorous investigation. CAVs share their information through V2V (vehicle-to-vehicle communication) including the vehicle states and control information to reduce the delays and perception error. The CAVs can achieve safety even in a platoon of CAVs with shorter time gaps than previously possible. The consecutive CAVs driving with a cyber connection is termed a CAV string in this chapter [1]. However, different string formation strategies may result in different performances, reduction in headways, impact on the traffic. It is necessary develop approaches to maximize the benefit of string formation on the traffic. This chapter attempts to provide an overview of the current state of research on the string operations of CAVs and provide a guide for future research. There are three stages of string operation as the lifecycle of a CAV string – string formation (e.g. after entrance form onramp), maintenance (keeping the string formation for traffic stability), and dissolution (e.g. lane changing or leaving from off-ramp). In addition to giving a literature survey in general, this chapter provides a literature survey for each stage of the lifecycle because each stage has different assumptions and parameters to consider. For each part of the survey, this chapter also suggests future research that may improve the performance of CAV strings in a traffic stream.

(b) Microscopic Traffic Simulation with CAVs for Arterial with Signalized Intersections

A platoon formation model on an arterial was proposed for arterial intersections. The proposed platoon forming approach is a global list of CACC-enabled vehicles with their attributes including ID, location, dynamics and position in a platoon, maintained on the simulation level. This list is updated every simulation step and has most current information about all CACC vehicles in the modeled network. Every simulation step, each CACC vehicle performs the following sequence of actions:

- Obtain information of other CACC vehicles nearby
- Filter out vehicles that are within a given radius from the current vehicle.
- For every vehicle in the filtered list, check if it is a vehicle right in front of the current vehicle. If it is, and it is ready to form a platoon, join the platoon assigning a position in the platoon to itself.

In this platoon forming approach, the leader does not know if it has followers, and how many. A CACC vehicle that has no CACC vehicle in front, assumes platoon position 0. CACC vehicles joining from behind, assume the platoon position of their leading car incremented by 1. If a CACC vehicle finds itself in a platoon with a position equal to the maximum platoon length, it switches to the ACC car following model and declares its new platoon position as 0 – becoming a new platoon leader. Thus, platoons exceeding the maximum length are broken up into two.

The CACC model and the platoon forming strategy have been implemented with a microscopic simulation for an arterial corridor with multiple signalized intersections on San Pablo Ave. near Berkeley, California. The arterial corridor extends from south of Ashby Avenue to north of Gilman Street with 10 signalized intersection. The simulation environment is Aimsun. Some initial simulation showed that proper platoon forming maneuvers could reduce Total Travel Time.

(c) strategic planning for CAV development and deployment in California

Among many changes being experienced by public sector transportation agencies, and notably by state departments of transportation (DOTs), the development of connected and automated vehicles (CAVs) is potentially transformational. The deployment of CAV technology on our streets and highways will create opportunities and uncertainties in planning, managing and operating the transportation infrastructure. In parallel with a very large automated vehicle (AV) research and development effort by automotive and related industries, government agencies at the federal, state, regional and local levels are beginning to deploy connected vehicle (CV) technology to support AVs and undertaking related policy discussions. Caltrans, along with other Californian agencies and peer organizations in other states, is actively considering its options for CAV planning.

This chapter complements a Caltrans executive-level workshop that was held on April 18, 2019 to assist in the development of a framework for CAV readiness. The objectives of the workshop were to:

- Assist Caltrans in accelerating the state of preparation for CAV technologies (including specific CV and AV activities);
- Promote CV/AV initiative and leadership on the part of Caltrans;
- Promote CV/AV outreach on the part of Caltrans;
- Obtain internal feedback on key CV/AV questions; and
- Assist in initiating a Caltrans CAV planning framework.

This chapter describes CV, AV and CAV technologies, their potential benefits and known steps to CAV deployment. It also summarizes the main findings from the workshop and presents next steps for Caltrans to consider in their CAV planning process.

CV Technology

The purpose of CV technology is to share real-time data wirelessly between vehicles and other vehicles (V2V) and vehicles and infrastructure (V2I), upon which various crash risks can be quantified, and warnings provided to drivers as required. CV is not intended to provide automatic intervention; however, CV technology can support AV technology as another source of information. Standardized packets of data (position, speed and direction) are used in numerous on-board applications to derive warnings related to specific types of traffic conflicts and resulting crashes.

AV Technology

Automated vehicle (AV) technology provides driving control in relation to steering, acceleration and braking. Depending on its intended functionality – from conditional to full automation – the automated driving system (ADS) includes the elements of sensing, communication, monitoring, navigation, decision-making, behavior and driving control required for its progression in traffic. The term AV covers a very broad range of both automated function, in terms of the extent to which it replaces functions of the human driver, and the intended operating environment. ADSs are designed and evaluated for certain types of operation on public roads and to satisfy safe driving guidelines. ADSs have designated Operational Design Domains (ODDs); ODDs may include geofenced areas, and may speak to road class, traffic conditions, time of day or weather.

Convergence of CV and AV

The major national stakeholders, including U.S. DOT and state agencies, are actively considering both CV and AV and are encouraging a supportive relationship between the technologies. DOTs are carrying out pilot deployments of CV through the provision of roadside communication technology with the understanding that this technology will support future AV deployments.

Levels of Automation and Guidance to Manufacturers

The Society of Automotive Engineers (SAE) Standard J3016 (Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems) identifies five levels of driving automation, from Driver Assistance and Partial Automation (Levels 1&2) through Full Automation (Level 5). The National Highway Traffic Safety Administration (NHTSA) Federal Automated Vehicles Policy for safe testing and deployment of automated vehicles applies mainly to the higher levels of automation. This voluntary guidance indicates best practices in the design, testing and operation of ADSs and their intended operating environments, or operational design domain (ODD).

Deployment of CAV and Infrastructure Preparation

There are many examples of pilot tests of CAV, involving state and local agencies, the CAV industry and research organizations. These include off-roadway test sites, closed campuses and on-roadway corridors and zones. These efforts show great diversity and their number and scale is increasing.

Continued engagement by infrastructure owners and operators (IOOs) is crucial to preparing roads for automated vehicles. While AVs may be tested in off-roadway facilities, all companies engaged in AV development place high value on miles logged on public roadways. Most manufacturers maintain a position of non-reliance on infrastructure assistance, although improved road maintenance in relation to markings, signage and road surface condition – and their national consistency - is an important factor in the deployment of AVs.

Early Adopters

Prime examples for early adoption of AVs include:

- Automotive comfort, convenience and safety: Relief from driving chores in simple, predictable highway travel. Moderate levels of automation promote stable traffic behavior.
- Mobility as a service. Full automation is being targeted in city-based vehicle, geo-fenced fleets providing on-demand mobility services. The potential cost reductions with driverless, on demand vehicles are compelling.
- Long-haul trucking: Platooning and other higher levels of automated truck technologies can provide a clear and near-term return on investment. Platooning provides significant fuel savings.
- Closed communities and campuses: Health care, retirement communities and universities are serving as early deployment zones for automated vehicles. In these scenarios, conditions are suited to simple, small, low-speed automated vehicles and shuttles.

Policy Positions and Actions

CAV policies may originate at any level of government: federal, state or local. Generally speaking, policy initiatives tend to lag behind technological developments. This is especially true in the case of AVs, and the sheer rate of technological change has militated against AV regulations and legislation. Despite decades of motor vehicle safety regulation at the federal level, AVs have been approached with a light regulatory touch, relying mainly on guidance and voluntary disclosure. Some states, including California, require the disclosure of limited ADS performance data – such as ADS disengagements – during the testing and early operational phases of AVs.

Generally speaking, federal and state research and deployment programs in CAV have been motivated by safety. The U.S. DOT has consistently promoted research and industry guidance to advance the deployment of connected CV technology (both V2V and V2I) and AVs. U.S. DOT research has shown that CV could address 80% of serious multi-vehicle crashes, and AV at the higher levels could avoid more than 90% of serious crashes, given the huge preponderance of human errors in crashes. Such findings have influenced the U.S. DOT to vigorously promote AV and CV in the surface transportation system. We have also seen CV programs on the part of many states, and active encouragement of AV deployment by numerous states and cities.

At the same time, CV and AV have profound implications for traffic efficiency, energy use and vehicle emissions. Both CV and AV tend to smooth traffic flow and may allow vehicles to operate with shorter headways, promoting more efficient use of road space. Experience so far has shown that even small percentages of CVs and AVs in the traffic stream have a beneficial effect on traffic flow, provided that they effectively mimic human drivers in their response to traffic signals and rules of the road.

A number of unknowns still exist for AVs, including mature norms for safety evaluation, cybersecurity, liability, impacts on professional drivers and city economics including land use. Nevertheless, the potential contribution of AVs to safety, mobility and sustainability remains highly respected and supported by accumulating experience and evidence.

Deployment Activities and Controls in California

Considerable experience has been obtained with CV deployments, AV testing, platooning research and applicable legislation at the state level. Since 2005, Caltrans and PATH have operated a CV testbed in the heart of Silicon Valley that is used by several automakers and Tier 1 auto suppliers. The testbed spans 11 consecutive intersections along a 2-mile stretch of State Route 82 (El Camino

Real) in Palo Alto. Aside from the CV testbed, there are four other CV deployment sites in California that have been installed by local transportation agencies. These include:

- LA DOT deployment of DSRC and transit signal priority along 50 intersections near Hollywood Blvd (supported by a USDOT grant);
- City of Anaheim deployment of DSRC at 10+ intersections near Disneyland;
- LA Metro, LA County, and the City of Carson deployment of DSRC and freight signal priority at 10+ intersections; and
- San Diego Port Tenants Association deployment of DSRC and freight signal priority at 12 intersections near the Port of San Diego.

California has been a leading state in the area of partially-automated truck platooning. Caltrans, PATH, and Volvo recently completed an FHWA-funded research project to develop and demonstrate a 3-truck platoon using cooperative adaptive cruise control (CACC) technology. Caltrans and the I-10 Corridor Coalition are supporting a new PATH/Volvo project that will deploy and assess truck platooning in an operational setting.

California has taken strong initiative in setting regulations for the safe operations of AVs. California DMV has been the lead agency for setting AV regulations in the state. A new round of regulations took effect on April 2, 2018 which allowed for true driverless testing and deployment. DMV requires all companies who wish to test or operate AVs to acquire a testing or operations permit and report all accidents and disengagements to DMV.

California has two major AV testing sites that allow for controlled AV testing. GoMentum Station in Concord is currently the largest secure testing ground for CAVs in the country. AV testing takes place in a controlled environment on the facility’s roadways, and CV testing takes place by using the facility’s smart (V2I) infrastructure. The San Diego Regional Proving Grounds (RPG) are managed by SANDAG, in partnership with Caltrans District 11 and City of Chula Vista. San Diego RPG includes the following facilities: I-15, State Route 125, Chula Vista, and Miramar Marine Corps Air Station. The RPG consortium kicked off in October 2017 with a goal of facilitating testing and validation of CAV technologies while ensuring public safety and security.

CAV Leadership and Deployment Actions in Selected States

While some actions by states are relatively well-publicized, the full range of activities is less well documented, and rarely aggregated in an impartial manner. The full range of such actions shows a certain degree of commonality and covers many aspects such as planning, testing, deployment, research, industry collaboration and legislation. Several states were selected for consideration based on the breadth (and depth) of their CAV activities, and California was included in the analysis. The states included were:

- California;
- Colorado;
- Florida;
- Michigan;
- Pennsylvania; and
- Virginia.

Eight major themes of CAV preparation were looked at in our analysis. These were:

1. AV legislation
2. Embracing CAV in mainstream transportation planning processes
3. CV test beds, pilots, and consortia
4. CAV strategic, business, or program plan
5. AV testing and CAV test beds
6. State collaboration and partnership with technology companies
7. Systematic infrastructure methodology for CAV deployment
8. CAV Advisory Council

The Chapter provides multiple examples of CAV actions across each of these themes by individual states, providing an information base for CAV planning by Caltrans. The Chapter also shows how California's actions to date compare with those of other states.

A Path Forward for CAV Readiness in California

The CAV Readiness Workshop held at Caltrans Headquarters on April 18 was widely considered a success in terms of starting a discussion on how California can maintain its leadership position in this field. The workshop was organized by Division of Research, Innovation and System Information (DRISI) and facilitated by California Partners for Advanced Transportation Technology (PATH) and their partners CAVita. There were over 30 attendees at the event including Caltrans Director Laurie Berman and other executive level representatives from Caltrans Headquarters, Caltrans Divisions, California State Transportation Agency (CalSTA) and California Department of Motor Vehicles (DMV). The lively discussion that took place throughout the workshop and high level of audience participation is a clear indication that Caltrans executive leadership is fully engaged in the topic of CAV preparation and leadership.

Based on findings from the CAV Workshop, there are a number of potential actions that could take place as California considers next steps on the road to CAV readiness. They include short-term (0-2 years) and medium-term (3-5 years) considerations. Since some of the medium-term actions are more complicated and costly and have the potential to impact multiple Caltrans departments or other state agencies, they require more thorough vetting through a formal CAV planning process.

Short-Term Actions

Internal to Caltrans

- Formulate an internal executive leadership team at Caltrans to guide CAV policy
- Formulate an internal working group at Caltrans to execute CAV activities
- Identify a comprehensive picture of the stakeholder community for CAV in California both within Caltrans and external to Caltrans
- Establish a Caltrans CAV Strategic Plan
- Develop a CAV Implementation Plan that complements the Strategic Plan and provides a tactical list of near-term CAV activities for Caltrans operating units
    - As an example, Caltrans should install and maintain clear and conspicuous pavement markings and standardized roadway signage.
- Continue to expand and enhance the California CV testbed in Palo Alto and partner with local agencies and industry to deploy and test CV applications in an operational environment (e.g. CV-based transit signal priority)

- Support and/or participate in a high-profile demonstration of CAV technology at the 2020 ITS World Congress in Los Angeles
- Integrate CAV considerations in all aspects of transportation planning in the state
- Explore availability of federal funding and track federal CAV policy to support and inform California CAV implementation
- Influence future policy (state/federal) to enhance transition to CAV
- Recruit and retain a technical workforce that is equipped to handle CAV technology

Partnerships with other California agencies

- Launch a Governor's Office lead statewide CAV task force/advisory group for policy, technology, and infrastructure:
    - Develop a charter to provide direction, responsibilities, and priorities.
    - Include: OPR, CalSTA, Caltrans, CHP, DMV, OTS, CPUC, CalEPA, CARB, CDPH, CEC, DGS and other agencies as necessary
- Develop a statewide CAV planning framework with high-level goals that incorporate both traditional transportation goals with environmental, energy, and social equity considerations
- Establish a CAV Strategic Plan for California that includes more State agencies and complements the one developed for Caltrans
- Develop a return-on-investment for CAV that will help make decisions for prioritization, funding, and stakeholder involvement
- Strengthen the state partnerships with the California AV test beds, learning from their efforts to inform the state's own CAV initiative
- Identify (in order to leverage) technologies/capabilities already available to develop a phased CAV implementation plan
- Provide incentives and even financial support to encourage regional, county and local agencies to do more
- Identify workforce challenges and needs and embolden state efforts to recruit and retain the workforce of the future to sustain CAV
- Encourage widespread deployment of CAV infrastructure

- Support efforts produced by the AV Visioning sessions

Collaborations with Private Sector

- Hold AV Summit and engage the AV industry to establish partnerships with OEMs and related AV companies
- Survey the private sector on their priorities for infrastructure enhancements that are needed to support AV operations
- Maintain effective links with the research community and private sector to enhance CAV implementation
- Integrate findings from collaborations with the private sector into CAV Plans

Medium-Term Actions

- Adapt/evolve the CAV Strategic Plan(s) to learn from early implementation efforts
- Restructure Caltrans to better support and manage CAV
- Enhance the state's advisory mechanisms meant to inform CAV
- As directed in Senate Bill 1 (SB1), to the extent possible, and where feasible, install advanced technology on the transportation infrastructure to support CAVs
- Install and operate CAV systems at key roadside locations such as signalized intersections and ramp meters
- Facilitate high precision digital mapping of the state's roadway infrastructure
- Provide infrastructure-based sensing to identify hazardous conditions that can be communicated to CAVs
- Incorporate AV technology into state fleets
- Provide a comprehensive real-time database about work zone operations and emergency response actions that may impede travel of AVs
- Provide smart parking facilities that can facilitate use of automated valet parking systems by vehicles

- Support reconfiguration of urban or suburban streets to provide some separation between conventional traffic, low-speed AVs, and bicyclists and pedestrians to improve safety for all of them.
- Reframe funding channels for CAV in light of state-wide engagement with the stakeholder community
- Establish and maintain California's role as a leader in CAV in the United States and around the world

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List of Acronyms and Abbreviations

5G	Fifth Generation Wireless
AACVTE	Ann Arbor Connected Vehicle Test Environment
AAMVA	American Association of Motor Vehicle Administrators
AASHTO	American Association of State Highway and Transportation Officials
ACC	Adaptive Cruise Control
ACM	American Center for Mobility
ADAS	Advanced Driver Assistance System
ADS	Automated Driving System
AI	Artificial Intelligence
AIMSUN	A traffic simulation package and the name of the company
ASCT	Adaptive Signal Control Technologies
AV	Automated Vehicle *A vehicle that has one or several of a very wide range of automated driving features and replaces certain aspects of driver perception and control.*
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CalSTA	California State Transportation Agency
CAMP	Collision Avoidance Metrics Partnership
CAT	Cooperative Automated Transportation
CAV	Connected and Automated Vehicle(s)
CDOT	Colorado Department of Transportation
CHP	California Highway Patrol
CPLEX	IBM ILOG Optimization Studio is an optimization software package
CV	Connected Vehicle *A vehicle enabled for standardized communication between vehicles or with the roadside, to enable driver assistance applications for the purposes of safety, traffic efficiency, reduced fuel consumption or reduced emissions.*
C-V2X	Cellular V2X
DMV	Department of Motor Vehicles
DOT	Department of Transportation

DSRC	Dedicated Short Range Communication
EAD	Eco-Approach Directive
EV	Electrified Vehicle
FAVP	Federal Automated Vehicles Policy
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FTA	Federal Transit Administration
HAV	Highly automated vehicle, of SAE Level 3 or above
HOS	Hours of Service rules (applicable to truck drivers)
ID	Vehicle identification
GID	Geometric Intersection Description
GMU	George Mason University
ICM	Integrated Corridor Management
IOO	Infrastructure Owner Operator
IT	Information Technology
ITE	Institute of Transportation Engineers
ITSA	Intelligent Transportation Society of America
JPO	Joint Program Office
LA DOT	Los Angeles Department of Transportation
LiDAR	Light Detection and Ranging
LTE	Long-Term Evolution (to 4G)
MAP	Map data
MCDOT	Maricopa County Department of Transportation
MDOT	Michigan Department of Transportation
MEDC	Michigan Economic Development Corporation
MMITSS	Multi-Modal Intelligent Traffic Signal System
MTA	Metropolitan Transit Authority (NYC)
MTC	Metropolitan Transport Commission
NCHRP	National Cooperative Highway Research Program
NCSL	National Conference of State Legislators

NHTSA	National Highway Traffic Safety Agency
NHTSA 3.0	Version 3 of NHTSA's Automated Vehicle Guidance
NLC	National League of Cities
NOCoE	National Operations Center of Excellence
NPRM	Notice of Proposed Rulemaking
NREL	National Renewable Energy Laboratory
NYC DOT	New York City Department of Transportation
OBD	On-board diagnostics
OBU	On-board unit
ODD	Operational Design Domain
ODU	Old Dominion University
OEM	Original Equipment Manufacturer
OMNeT++	A modular, component-based C++ simulation library and framework, primarily for building network simulators
PennDOT	Pennsylvania Department of Transportation
PFS	Pooled Fund Study
Platoon	*Comprising two or more vehicles enabled for V2V communication as well as automated longitudinal (and perhaps lateral) control functions*
REL	Reversible Express Lanes
RELLIS	Texas A&M Core Values
RSE	Road-Side Equipment (see RSE)
RSU	Road-Side Unit
RTCM	Radio Technical Commission for Maritime
SAE	Society of Automotive Engineers
SANDAG	San Diego Association of Governments
SB1	Senate Bill 1 (State of California Transportation Funding Bill)
SPAT	Signal Phase and Timing
SM	Shared Mobility
SUMO	An open source microscopic traffic simulation package
TAMUS	Texas A&M University System
TNC	Transport Network Company

TRB	Transportation Research Board
TRC	Transportation Research Center (Ohio)
TRI	Toyota Research Institute
TSMO	Transportation Systems Management and Operations
TSP	Transit Signal Priority
TTI	Texas Transportation Institute
UMTRI	University of Michigan Transportation Research Institute
UVA	University of Virginia
VDOT	Virginia Department of Transportation
VEINS	An open source framework for running vehicular network simulations
VTA	Valley Transit Authority
VTTI	Virginia Tech Transportation Institute
V2I	Vehicle-to-Infrastructure aspect of CV
V2I DC	V2I Deployment Coalition (AASHTO)
V2V	Vehicle-to-Vehicle aspect of CV
V2X	Vehicle-to-Everything *Includes V2V and V2I, and vehicle communication with road users such as motorcyclists, cyclists and pedestrians*
WLAN	Wireless Local Area Network

Chapter 1. Introduction

This report documents the work conducted under the California Department of Transportation (Caltrans) Project 65A0682 entitled "*Interactive Simulation of CACC Vehicle Matching*".

The project was sponsored by Caltrans and undertaken by the California Partners for Advanced Transportation Technology (PATH), of the University of California, Berkeley. The project duration was 19 months from 6/1/2018 to 12/30/2019.

This project has been focusing on the following three aspects related to Connected Automated Vehicles (CAV):

- Investigation of researches has been done on platooning forming through literature review
- Implementation of CAV in a microscopic simulation as a case study with the CAV car-following model PATH established in a previous project
- Extensive consideration of strategic planning for CAVs development and deployment in California

It has been simulated and generally accepted that CAV's such as Adaptive Cruise Control (CACC) or platooning could potentially increase traffic capacity due to synchronized behavior and shorter time-gap (distance-gap) in vehicle following. The market penetration of CAVs can only be increased progressively. It will a long period of time for CAV market penetration to reach a high level. Therefore, for traffic on highways, CAVs will generally randomly distributed in the mixed traffic with both manually driven vehicles and CAVs. The question is how to aggregate the CAVs so that they have better chances to form platoons to realize the expected benefit. On the other hand, lane changing maneuvers for platoon forming would affect other traffic which could counteract the benefit of CAVs. Therefore, judicious design and implementation for platoon forming through maneuvers on highways such as lane changing would be necessary.

Chapter 2. Implement Platoon Forming for Passenger Cars and Trucks in microscopic simulation

2.1 Introduction

The connected automated vehicles (CAVs) bring promise of improving the roadway capacity. CAVs share information about their driving decisions among each other and reduce reaction time and perception error. The CAVs achieve safety even in a platoon of CAVs with shorter headways than previously possible. The consecutive CAVs driving with a cyber connection is termed a CAV string [1]. However, different string formation strategies may result in different performances in the string formation, reduction in headways, and roadway capacity. Therefore, string operations need to be studied to find to maximize the benefit of string formation on the traffic. This chapter attempts to provide a overview of the current state of research on the string operations of CAVs and provide a guide for future research. This chapter defines three stages of string operation as the lifecycle of a CAV string – string formation, maintenance, and dissolution. In addition to giving a literature survey in general, this chapter provides a literature survey for each stage of the lifecycle because each stage has different assumptions and parameters to consider. For each part of the survey, this chapter suggests future research that may improve the performance of CAV strings in a traffic stream.

2.2 Lifecycle of a CAV string

This section briefly describes the three stages in the lifecycle of a CAV string. The life cycle is composed of string formation, maintenance, and dissolution. The three stages describe the evolution of a CAV string on the road. The definition and examples strategies and parameters are shown in Figure 2.1. Note that three stages are defined so that each stage has a relevant set of assumptions and parameters, which may be irrelevant to another stage of operation. For instance, the direction of a CAV travelling to join another CAV is an assumption to make for string formation, but not for string maintenance. In the next section, the literature will be surveyed according to the three stages of the lifecycle of CAV string operation with their relevant assumptions and parameters.

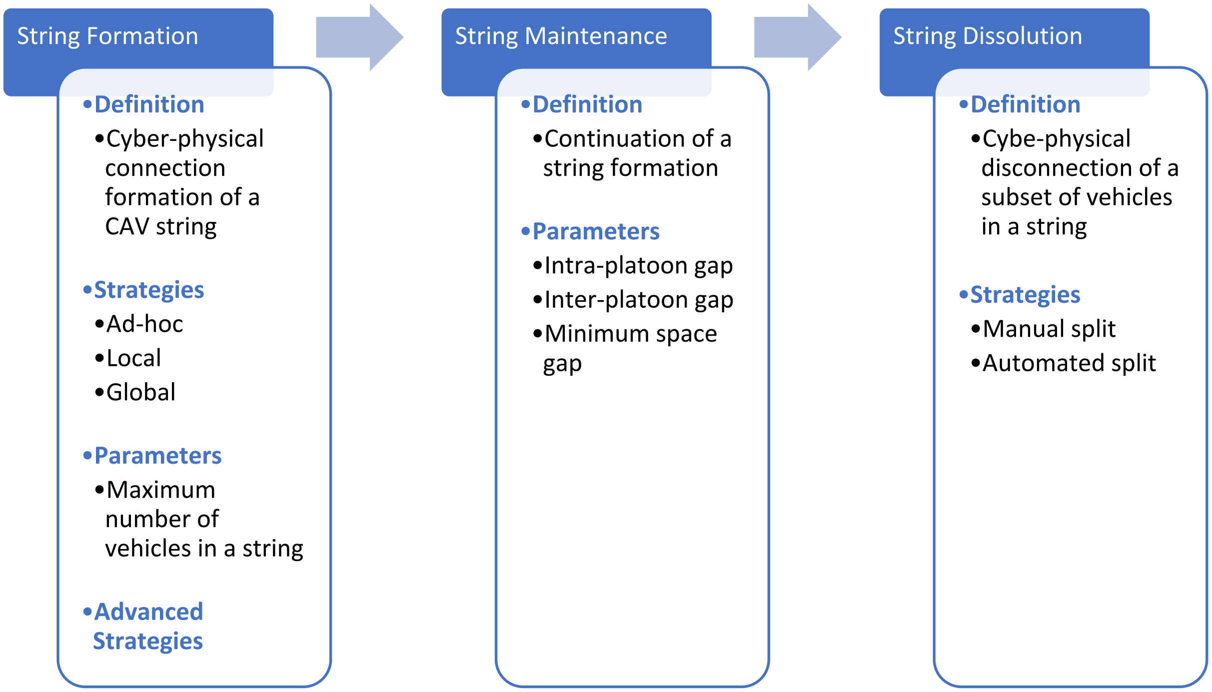

Figure 2.1 Three Stages of Lifecycle of a CAV String

Cyber-physical systems 'comprise interacting digital, analog, physical, and human components engineered for function through integrated physics and logic' [2]. The CAVs use communication and monitor the physical information of CAVs for CAV string operations. First stage of the lifecycle of a CAV string operation is string formation. In this stage, a cyber-physical connection is formed between a vehicle and a string, between two strings, or between two vehicles. This can be performed in three strategies – ad-hoc, local, and global – as defined in [1]. The direction that a subject CAV (or a subject CAV string) may be maneuvering to form a string with another CAV string can be front, rear, and side. For example, the front direction indicates that the subject CAV has another CAV string in the front of it.

Ad-hoc strategy describes string formation when a CAV or a string follows or leads another CAV or string without coordination. This strategy only allows the front and rear formation and requires no lane changing for coordination. At a low market penetration of CAVs, this strategy may be inefficient to form strings. Local strategy describes the string formation when a CAV or a string finds another in the neighborhood, which is not necessarily in the same lane or in a position immediately following (or leading?) the subject. After coordination that may include one or more lane changes, this strategy allows a CAV to form a string with another CAV from any directions – front, rear, or side. At a low market penetration of CAVs, this strategy may be efficient to form strings. However, this strategy may disturb the traffic stability by inducing additional lane changes and forcing neighboring vehicles to decelerate. Global strategy describes a strategy that plans for string formation before the participating CAVs enter the road by adjusting the departure times, routes, or vehicle speeds. The arrangement of time and location ahead of travel may reduce the solution space with the time and location constraints of trips, however it may be useful for the application of freights. Different parameters can be used for each strategy. Advanced strategies will be discussed in the following survey of literature.

Second in the string maintenance, the string formation is continued and maintained on the road. The parameters that describe this operation are related to the car-following behavior of the CAVs, including the desired speed, intra-platoon gap, inter-platoon gap. These parameters may influence the macroscopic traffic performance of the CAVs, for instance the smaller the platoon gaps, the larger the benefit to the roadway capacity at a high penetration rate of CAVs. Advanced strategies will be discussed in the following survey of literature. Third in the string dissolution, a subset of vehicles in a string physically departs away from the string and disconnects in communication. This split process can be initiated by manual split, for example, manual braking for a lane change. It can also be initiated by an automated split, i.e. the application of automated braking. The parameters and advanced strategies will be discussed in the following survey of literature.

2.3 Survey of the literature

This section provides a survey of literature on the operation of CAV strings. These literatures discuss the interaction among the CAVs and their impact to the traffic stream. A table for literature that consider CAV string operations is given first with their scope and assumptions. Next, literature for each stage of the CAV string lifecycle is presented with more details on the relevant assumptions and parameters considered.

2.3.1 Literature of CAV String Operations

Table 2-1 provides a list of literature that discuss CAV string operations and their methodology, objective, and assumptions on CAVs. The market penetration of CAVs indicates the stage of CAV adoption in the future. The interaction between the CAVs and non-CAVs is reflected during the intermediate penetration values greater than 0% and less than 100%. Macroscopic traffic scenario is also listed to understand the scope of work, such as congestion, free flow, and merge bottleneck. The CAV dedicated lane represents a special purpose lane on the road, in which only CAVs can travel but non-CAVs are banned from. This dedicated lane policy is often suggested to improve the roadway capacity and safety at a mixed traffic of CAVs and non-CAVs. In current studies, lateral control of the CAVs is often assumed to be manually executed or not specified, although the CAVs may change lanes differently to the human driver's behavior. This may be due to the lack of literature and field experiments of lane change behavior of CAVs. Lastly, vehicle types – passenger car or trucks – are sometimes specified in studies, when parameters, such as speed and acceleration, are important in the research discussion.

The market penetration of CAVs is an important parameter to consider in the literature review, as the traffic may macroscopically perform differently at each level due to the various mixture of different driving behaviors (with CAVs and non-CAVs). Table 2-1 shows that studies with an assumption of full penetration of CAVs often assume free flow traffic. Since a high market penetration of CAVs will be possible far in the future, it is more difficult to project the traffic congestion in the future. For instance, various automobile companies may present vehicles with different driving behaviors, which may result in different traffic behaviors in congestion. Also, uncertainty in future traffic demand, infrastructure to support CAVs, and policies in management of CAVs adds difficulty in predicting the traffic congestion at high penetration of CAVs. In order to improve the analysis of traffic congestion at a high penetration of CAVs, small-scale field experiments to learn driving behavior of CAVs in traffic congestion may help by predicting the future traffic more accurately.

For studies with a mixed traffic of CAVs and non-CAVs, realistic traffic scenarios have been analyzed, such as CAV dedicated lanes [3], merge bottlenecks [4], and multiple bottlenecks on a freeway network of California [5]. These studies often present some challenges in improving the traffic performance with a mixed traffic of CAVs and non-CAVS. For instance, a paper on the merge bottleneck shows that the CAV strings with tight headways can create large traffic shocks by blocking the on-ramp flow to the mainline [4]. The paper recommends the CAVs to automate the merging process and facilitate the entrance of the on-ramp flow. Another paper shows that a dedicated lane for CAVs may worsen the roadway capacity at a low penetration rate [5]. The paper recommends implementation of CAV-dedicated lanes only at a penetration rate around 50%, although the dedicated lanes are often proposed to improve the traffic performance and safety at a low CAV penetration. Therefore, there is a lack of research that provides possible solutions to the challenges of improving the traffic performance with a mixed traffic with CAVs and non-CAVs. Literature on such solutions, such as automated highway merging as proposed in [4] and various policies on CAV dedicated lanes, may help the implementation of CAVs in the near future.

In addition to the need for the future research described above, there is a gap in the literature on the lateral control of CAVs and its impact to the traffic flow. Whether performed manually or laterally, the CAVs may bring different impact to the traffic with the lane-changes because the CAVs may activate and deactivate the connection to a string. Therefore, the lateral behavior studies will be crucial to describe the future traffic with CAVs. Also, the analysis on the CAV string operations on the traffic is often limited to a simplified road configuration, such as a homogeneous road segment or isolated bottlenecks. Only one paper studies a freeway network [5]. With network-wide analysis of CAVs of various driving behaviors, the traffic performance will be better predicted.

Table 2-1 List of Research on Development of CAV Operation Strategies

	Methodology	Objective	Market Penetration of CAV	Macroscopic traffic condition	CAV Dedicated Lane	Lateral Control	Vehicle type
[6]	Field experiment	To design a latitude and longitude controller for vehicles in platoon	100%	Free flow	No	Automated	Passenger vehicle
[7]	Traffic simulator (VISSIM)	To increase lane capacity and maximize travel distance of platoons intact	100%	Varying flow below congestion, different free flow speed per lane	No	-	-
[8]	Field experiment	To design an interaction protocol for platoon merge	100%	Free flow based, lane closure	No	-	Passenger vehicle
[9]	Traffic simulator (Aimsun)	To investigate the capacity of multilane freeway merge bottlenecks	0% to 100% CACC	Varying traffic flow, traffic breakdown and capacity reduction, on-ramp	No	Manual	-
[10]	Traffic simulation (SUMO and OMNET)	To design platoon management protocol, merge, split, lane-change	100%	Saturation flow	Yes	Manual	-

	Methodology	Objective	Market Penetration of CAV	Macroscopic traffic condition	CAV Dedicated Lane	Lateral Control	Vehicle type
[11]	Optimization (CPLEX)	To determine the trajectories of trucks that lead to the successful formation of the platoon	-	Free flow with assumption of independent traffic flow with respect to platoon operations	-	-	Truck
[12]	Traffic simulation	To develop a realistic behavior of ACC vehicle and to develop strategies around traffic breakdown	0% to 50% ACC	Free flow, traffic breakdown and bottleneck	No	-	-
[13]	Traffic simulation (Veins)	To develop finite station machines for join maneuver to the middle of platoon string	Mixed traffic with non-platooning and platooning vehicles	-	No	Yes	-
[14]	Traffic simulation	To develop an interaction protocol to mimic human drivers in a distributed fashion	100%	Road closure	No	-	-
[15]	Optimization and Monte	To analytically characterize the	Mixed between platooning	-	No	-	-

	Methodology	Objective	Market Penetration of CAV	Macroscopic traffic condition	CAV Dedicated Lane	Lateral Control	Vehicle type
	Carlo simulation	timeout threshold for joining maneuver of platoons	vehicles and human vehicles				
[4]	Traffic simulation	To estimate merge bottleneck capacity under CACC deactivation to ACC	0 to 100% CACC	Merge bottleneck	No	Manual	-
[3]	Traffic simulation	To analyze the traffic flow and platoon operations with dedicated lanes for connected and automated vehicles	0 to 60% CACC	Various configurations of the dedicated lanes for CAVs	Yes		-
[16]	Traffic simulation (CTM)	To analyze the traffic flow with dedicated lanes for connected and automated vehicles	0 to 90% CAVs	Various configurations of the dedicated lanes for CAVs	Yes	CAV seeks optimal path with lane changes	-
[5]	Traffic simulation (MOTUS)	To analyze the traffic impacts of converting an HOV	0 to 50%	Multiple bottlenecks on a	Yes	Manual	-

	Methodology	Objective	Market Penetration of CAV	Macroscopic traffic condition	CAV Dedicated Lane	Lateral Control	Vehicle type
		lane into a dedicated CACC lane on SR 99 corridor in California		real freeway network			
[17]	Field Simulation	To calibrate the time-gap settings preferred by drivers on the road	16 drivers in CACC vehicles on a freeway	Real traffic on the highway in the field	No	Manual	Passenger cars

2.3.2 String Formation

This section provides literature survey with focus on the assumptions and parameters that the literature considers for string formation. Table 2-2 provides the common assumptions and parameters defined in the literature. Formation strategy describes whether the CAVs form a string with an ad-hoc, local, or global strategy from directions of rea, front, and side. The maximum string size is the maximum number of CAVs in a string. The assumption on the formation strategy and maximum string size are important as they can result in different string lengths of CAVs and result in different traffic capacities. For instance, increasing a CAV string length will reduce the average headways and improve the roadway capacity, however a string that is too long may disrupt the flow by blocking other vehicles from changing lanes. The string formation stage is especially important as the roadway capacity is expected to increase only minimally at a low penetration rate of CAVs due to the low probability in forming a string and significantly reducing the average headway [4],.

In the table, decision entity indicates the entity that evaluates and approves the decisions on string formation. The decision entities are analyzed in depth in papers that consider communication algorithms for string formation Micro-operation represents the detailed algorithms for the string formation operation, including the maneuvers to split from a string or join a string. The advanced strategy describes the algorithms proposed in the literature that facilitates string formation to improve its performance. The last column explains the papers' analysis on the impact of string formation to the traffic flow.

In the literature, there are various studies that consider the ad-hoc, local, and global strategies of string formation, but these studies most commonly consider rear or front direction of the CAVs to join another CAV string. The candidate members of string formation are only the immediate leaders or followers of a subject CAV in the same lane. However, the CAVs will have access to information of other CAVs nearby, for instance other CAVs that are in different lanes to the subject CAVs or that are blocked by non-CAVs in between. The CAVs can extend the pool of candidate members of a CAV string by using the information about the locations and movements other CAVs nearby to form a platoon.

However, the literature on string formation with extended pool of candidate members must take a caution. Some papers argue that the micro-operations relevant to string formation may have a negative impact to the traffic. The examples of the micro-operations are the activation of the cyber-physical connection among the CAVs in a string and the lane changes of the CAVs to join a CAV dedicated lane. A paper shows that these micro-operations make the traffic become unstable due to the acceleration and deceleration of the CAVs necessary to reach a stable state of distance, speed, and acceleration in string [4]. Another paper shows that the lane changes of CAVs to the dedicated lane may disrupt the traffic flow and counteract the benefit from reducing the headways with a CAV string [7], [5]. Therefore, it is necessary to investigate the strategies for a local string formation to extend the candidate members for the CAV string and improve the traffic performance, while understanding the potential disruption of their maneuvers to the traffic.

Table 2-2 Literature on String Formation

	Formation strategy	Maximum string size	Decision entity	Micro-operation	Advanced strategy	Impact to traffic flow
[1] Review	Discusses global/local/ad-hoc, rear/front/side	-	-	-	Discusses vehicle ordering	-
[18] Conceptual Overview	Defines ad-hoc, local, global strategies	Discusses the impact of maximum string size	-	-	-	Discusses vehicle ordering in a platoon
[19] Review	Global	-	Central service provider	-	Discusses fixed and flexible route, different level of automation Discusses arrangement of truck trips including platoon members, order of members, location and time to form, and route	-
[6]	Ad-hoc	-	Leader vehicle	Split and join maneuver	-	-
[7]	Local (rear)	6 to 30 vehicles	Distributed	-	Lane assignment of platoon based on the	"Platooning gives greater traffic flow at

	Formation strategy	Maximum string size	Decision entity	Micro-operation	Advanced strategy	Impact to traffic flow
					travel time as an intact platoon.	the cost of increased lane changes"
[8]	Ad-hoc (front)	-	Distributed	Join maneuver	-	-
[9]	Ad-hoc (rear/front/side)	10 vehicles	-	Split and join maneuver	-	Discussion of merging strategies of a string with incoming vehicles from on-ramp, to fill the 'white space' in time space diagram
[10]	Local (rear)	1 to 20 vehicles	Leader vehicle	Split, join, and lane change maneuver	Platoon selection based on route and cost	Throughput is an increasing function of the maximum string size.
[11]	Local (rear)	-	Distributed	Join maneuver	Speed and slow-down to close gap, time-out for string formation	-
[13]	Local (side)	-	Leader vehicle	Join maneuver	-	Interference of non-platooning vehicles
[14]	Ad-hoc, local (side)	-	Distributed	Gap making, join maneuver	-	-

	Formation strategy	Maximum string size	Decision entity	Micro-operation	Advanced strategy	Impact to traffic flow
[15]	Ad-hoc (rear)	-	Leader vehicle	Join maneuver	Time-out for string formation	-
[4]	Ad-hoc	10 vehicles	Distributed	Split and join maneuver	-	Discussion on the impact of deactivation of CACC to ACC on traffic flow
[3]	Ad-hoc	-	Distributed	Split and join maneuver	-	Discussion of the impact of various configurations of managed lanes on traffic flow
[16]	Ad-hoc	-	Distributed	Split and join maneuver	CAVs change lanes to increases the probability of string formation, Use of 2 lanes with 3 CAVs in parallel	Discussion of the impact of various configurations of managed lanes on traffic flow, and the impact of deactivation of CAVs to AVs on traffic flow
[5]	Ad-hoc	10 vehicles	Distributed	Split and join maneuver	-	Conversion of HOV lane to dedicated CACC lane

	Formation strategy	Maximum string size	Decision entity	Micro-operation	Advanced strategy	Impact to traffic flow
[17]	Ad-hoc	-	Distributed	Field experiment, split and join maneuver	-	Calibration of the CAV string parameters from the freeway experiment
[20]	Ad-hoc (front/rear/side)	-	Leader vehicle and 'merging performer' vehicle	Split and join maneuver	Change of leader for fuel consumption	-
[21]	Ad-hoc (rear/front)	15 vehicles	-	Join maneuver	-	-
[22]	Ad-hoc, local (Rear, side, or front	Rear, side, or front	Leader vehicle, Potential follower vehicle, and Back Office guidance to target a vehicle	Join and dissolve maneuver	Vehicle ordering by vehicle type, with heavy vehicle in front	-

2.3.3 String Maintenance

This section provides literature survey with focus on the assumptions and parameters that the literature considers for string maintenance. Intra-platoon time gap indicates the time gap between the CAVs in a string, whereas the inter-platoon time gap indicates the time gap between two CAV strings. These two parameters are the most commonly found parameters in the studies of string maintenance, as they distinguish the car-following behavior of the CAVs from the human car-following behavior. Some papers adopt both the intra-platoon time gap and the minimum space gap. This is because the intra-platoon gap based on time allows CAVs to travel with a headway that is unrealistically small at a low speed. The values for acceleration and speed are assumed to be similar for the car-following behavior of human drivers. Although a short reaction time is a key property of CAVs that allows them to achieve safety even with short headways, many papers omit this parameter because their driving models do not take this parameter as a variable.

One field experiment on the CAVs have calibrated the intra-platoon time gaps preferred by drivers on a freeway [17], which is often used in the following literature to depict the car-following behavior of the CAVs [9], [4], [5]. While many studies try to adopt the most realistic parameters and predict the future traffic with CAVs, one paper considered the CAV parameters as controllable variables to improve the traffic performance [12]. This paper proposes that the CAVs may vary their parameters dynamically with the traffic condition. For instance, the CAVs temporarily drive aggressively when leaving a bottleneck queue to increase the discharge flow. The literature can further extend this idea to manage the traffic with the CAVs. One example is to use the communication capability of the CAVs to the roadside infrastructure to monitor for a bottleneck downstream. The CAVs can proactively slow down to reduce the shock in arriving at a bottleneck queue.

Table 2-3 Literature on String Maintenance

	Intra-platoon time gap	Inter-platoon time gap	Minimum space gap	Acceleration	Speed	Reaction time
[6]	-	-	6.5 m	-	Desired speed 60mph	-
[7]	-	5 s	10 m	-	Free flow speed from 80 to 120km/h, varying desired speed per individual	-
[9]	0.6 to 1.1 s	1.5 s	-	Maximum acceleration 2.0m/s^2, maximum deceleration -2.5m/s^2	Desired speed 30m/s	0.4s
[10]	0.55 s	3.5 s	2 m	Maximum acceleration 3 m/s^2, maximum deceleration 5 m/s^2	Maximum speed 30m/s, desired speed 20m/s	0.4s
[4]	0.6 to 1.1s	1.5s	3m	For CACC/ACC vehicles, Maximum acceleration 2.0m/s^2, maximum deceleration -4m/s^2	Free flow speed follows Normal(125, 8.75)km/h	-
[3]	1s	1.2s	1m	Max acceleration 2m/s^2	Desired speed 105km/h	-
[16]	-		-	Deceleration under 3m/s^2	Maximum speed 108 km/h	-
[5]	0.6 to 1.1s	1.5s	-	Maximum acceleration 2.0m/s^2, maximum deceleration -4m/s^2	Free flow speed follows Normal(125, 8.75)km/h	-
[17]	0.6 to 1.1 s	-	-	-	Calibration data with speed over 35mph	-

[21]	0.71s	2.0s	-	Maximum acceleration 2.0m/ s2, Maximum deceleration 4 m/s2	Average desired speed 30.5m/s	0.8s
[12]	Adapt parameters depending on the local traffic condition: - Free traffic: default for maximal comfort - Upstream of jam front: reduce velocity gradient and enhance safety - Congested traffic: default - Downstream of jam front: increase acceleration and reduce time gap temporarily to increase capacity Bottleneck: increase acceleration and reduce time gap temporarily to increase capacity					

2.3.4 String Dissolution

This section provides literature survey with focus on string dissolution, often termed in the literature as a string split maneuver. The literature does not have a large variety in the assumptions for this stage. Most studies assume that the split of a CAV string occurs when braking is applied to the CAV. The literature often describes the reasons for the CAVs to depart from the current string (i.e. dissolution purpose) and some details on the micro-operation algorithms, such as the number of vehicles allowed to leave a string at a time, and a time-out threshold for the dissolution. In the study that shows a negative impact of the CAV maneuvers to activate the cyber-physical connection, the CAVs are also shown to worsen the traffic stability when deactivating the cyber-physical connection of a string [4]. Since a CAV may change lanes after braking and dissolving a string, the disruption to the traffic flow may be more severe than a human driver changing lanes. Therefore, the literature may develop strategies for string dissolution that may reduce the shock to the traffic stream. One possible study is to develop a cooperation algorithm among the CAVs to absorb the shock of a CAV splitting from the string. For instance, when a subject CAV brakes to split away from a string, the other CAVs left in the string can temporarily adopt a shorter headway setting.

Table 2-4 Literature on String Dissolution

	Dissolution purpose	Micro-operation
[6]	Manual split for mandatory and optional departure	Split maneuver, one vehicle at a time while platoon is cruising
[9]	Automated split to keep the maximum string size, Manual split for mandatory and optional departures	Split maneuver to accommodate merging vehicles
[10]	Automated split to keep the maximum string size	Split maneuver with a time-out threshold
[4]	Safety, lane changes, route-related (i.e. exiting and merging freeway), lane-drops,	Split maneuver

	platoon disruption due to limited acceleration and deceleration of CACC	
[3]	Exiting freeway, non-CACC vehicles cut in, communication disruption	Split maneuver
[5]	Purposes are related to lane-changes, safety, and route	Split maneuver
[20]	-	Split maneuver
[22]	-	Leave maneuver from front, side, and rear (individual vehicle), dissolve maneuver from rear (platoon)

2.3.5 Conclusion

The current literature reveals that there are some challenges yet to be overcome in improving the traffic capacity with CAVs. Traffic capacity is expected to grow very slowly or even worsen at a low penetration rate of CAVs, for instance at a merge bottleneck or on the road with CAV dedicated lanes at a low CAV penetration. Some studies propose string formation strategies to increase the traffic capacity by increasing the string lengths and reducing the average headways. However, the maneuvers for such strategy like acceleration, deceleration, and lane-changes may disrupt the flow and counteract the benefit of a formed string. Therefore, there is a crucial need in developing algorithms and strategies to analyze and resolve these challenges. The literature also shows potential in utilizing the CAV communication capability to manage the traffic. The CAVs may share information with other CAVs and roadside infrastructure to gather information about the traffic and cooperate to increase traffic stability. Examples include the CAVs that proactively slow-down upstream to reduce the deceleration at arrival of a bottleneck queue and the CAVs that temporarily adopt short headway settings to absorb a shock of a leader CAV decelerating.

2.4 References of Chapter 2

[1] C. Nowakowski, S. E. Shladover, X.-Y. Lu, D. Thompson, and A. Kailas, “Cooperative Adaptive Cruise Control (CACC) for Truck Platooning: Operational Concept Alternatives,” *Calif. PATH, Univ. Calif.*, no. March, pp. 1–37, 2015.

[2] “Framework for Cyber-Physical Systems: Volume 1, Overview.”

[3] Z. Zhong and J. Lee, “The effectiveness of managed lane strategies for the near-term deployment of cooperative adaptive cruise control,” *Transp. Res. Part A Policy Pract.*, vol. 129, pp. 257–270, 2019.

[4] L. Xiao, M. Wang, W. Schakel, and B. van Arem, “Unravelling effects of cooperative adaptive cruise control deactivation on traffic flow characteristics at merging bottlenecks,” *Transp. Res. Part C Emerg. Technol.*, vol. 96, no. October, pp. 380–397, 2018.

[5] L. Xiao, M. Wang, and B. Van Arem, “Traffic Flow Impacts of Converting an HOV Lane into a Dedicated CACC Lane on a Freeway Corridor,” *IEEE Intell. Transp. Syst. Mag.*, vol. 12, no. 1, pp. 60–73, 2020.

[6] R. Rajamani, H. S. Tan, B. K. Law, and W. Bin Zhang, “Demonstration of integrated

longitudinal and lateral control for the operation of automated vehicles in platoons," *IEEE Trans. Control Syst. Technol.*, vol. 8, no. 4, pp. 695–708, 2000.

[7] T. S. Dao, C. M. Clark, and J. P. Huissoon, "Distributed platoon assignment and lane selection for traffic flow optimization," *IEEE Intell. Veh. Symp. Proc.*, pp. 739–744, 2008.

[8] H. H. Bengtsson, L. Chen, A. Voronov, and C. Englund, "Interaction Protocol for Highway Platoon Merge," *IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC*, vol. 2015-Octob, pp. 1971–1976, 2015.

[9] H. Liu, X. (David) Kan, S. E. Shladover, X. Y. Lu, and R. E. Ferlis, "Impact of cooperative adaptive cruise control on multilane freeway merge capacity," *J. Intell. Transp. Syst. Technol. Planning, Oper.*, vol. 22, no. 3, pp. 263–275, 2018.

[10] M. Amoozadeh, H. Deng, C. N. Chuah, H. M. Zhang, and D. Ghosal, "Platoon management with cooperative adaptive cruise control enabled by VANET," *Veh. Commun.*, vol. 2, no. 2, pp. 110–123, 2015.

[11] M. Saeednia and M. Menendez, "Analysis of Strategies for Truck Platooning: Hybrid Strategy," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2547, no. 1, pp. 41–48, 2016.

[12] A. Kesting, M. Treiber, and D. Helbing, "Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 368, no. 1928, pp. 4585–4605, 2010.

[13] M. Segata, B. Bloessl, S. Joerer, F. Dressler, and R. Lo Cigno, "Supporting platooning maneuvers through IVC: An initial protocol analysis for the JOIN maneuver," *11th Annu. Conf. Wirel. On-Demand Netw. Syst. Serv. IEEE/IFIP WONS 2014 - Proc.*, pp. 130–137, 2014.

[14] E. S. Kazerooni and J. Ploeg, "Interaction Protocols for Cooperative Merging and Lane Reduction Scenarios," *IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC*, vol. 2015-Octob, pp. 1964–1970, 2015.

[15] M. Khaksari and C. Fischione, "Performance Analysis and Optimization of the Joining Protocol For a Platoon of Vehicles," *Proc. 5th Int. Symp. Commun. Control Signal Process.*, no. May, 2012.

[16] K. Ma and H. Wang, "Influence of Exclusive Lanes for Connected and Autonomous Vehicles on Freeway Traffic Flow," *IEEE Access*, vol. 7, pp. 50168–50178, 2019.

[17] C. Nowakowski, J. O'Connell, S. E. Shladover, and D. Cody, "Cooperative adaptive cruise

control: Driver acceptance of following gap settings less than one second," *Proc. Hum. Factors Ergon. Soc.*, vol. 3, pp. 2033–2037, 2010.

[18] S. E. Shladover, C. Nowakowski, X.-Y. Lu, and R. Ferlis, "Cooperative Adaptive Cruise Control: Definitions and Operating Concepts," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2489, pp. 145–152, 2015.

[19] A. K. Bhoopalam, N. Agatz, and R. Zuidwijk, "Planning of truck platoons: A literature review and directions for future research," *Transp. Res. Part B Methodol.*, vol. 107, pp. 212–228, 2018.

[20] S. Maiti, S. Winter, and L. Kulik, "A conceptualization of vehicle platoons and platoon operations," *Transp. Res. Part C Emerg. Technol.*, vol. 80, pp. 1–19, 2017.

[21] H. Liu, X. (David) Kan, S. E. Shladover, X. Y. Lu, and R. E. Ferlis, "Modeling impacts of Cooperative Adaptive Cruise Control on mixed traffic flow in multi-lane freeway facilities," *Transp. Res. Part C Emerg. Technol.*, vol. 95, no. December 2017, pp. 261–279, 2018.

[22] C. Bergenhem, A. B. Qihui Huang, and T. Robinson, "Challenges of platooning on public motorways," *17Th World Congr. Intell. Transp. Syst.*, pp. 1--12, 2010.

[23] J. Laval, M. Cassidy, and C. Daganzo, "Impacts of Lane Changes at Merge Bottlenecks: A Theory and Strategies to Maximize Capacity," in *Traffic and Granular Flow'05*, 2007.

Chapter 3. Implement Platoon Forming for Passenger Cars and Trucks in microscopic simulation

3.1 Basics

Vehicles equipped with CACC technology can communicate with one another to form platoons. These platoons can increase the throughput of intersections by decreasing headways between successive vehicles. In simulation, platoon management and formation is divided into three phases:

1. Identifying vehicles that can be grouped into platoons;
2. Adjusting parameters of leaders and followers in platoons; and
3. Performing maintenance on the platoon.

This scheme is modeled by the state machine shown in Figure 3.1.

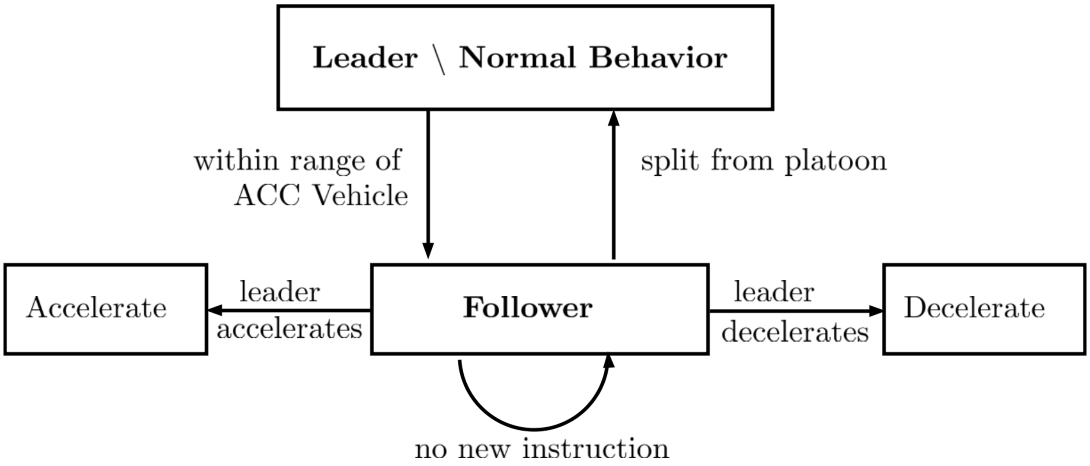

Figure 3.1 State machine describing the behavior of a platoon vehicle.

A platoon's lead vehicle has the same properties as ACC vehicles. An isolated CACC vehicle is a leader of a platoon of size 1. When a platoon leader comes into range of another CACC vehicle in front, it joins the platoon becoming a follower. Followers have reduced headway and travel much closer to one another than standalone vehicles. In addition, followers are able to receive information from the leader, such as to accelerate after a green light at an intersection or to decelerate approaching an obstacle, e.g. red light downstream.

Since followers are not bound to the same route as the platoon leader, they are free to separate. After leaving the platoon, the headway and acceleration parameters are restored to their original values. This can happen for example when the follower changes its route or becomes separated from the rest of platoon, e.g., due to switching traffic signal as it crosses an intersection.

To implement this behavior in Aimsun microsimulator, we use the Aimsun facility called *microSDK*, which allows modelers to program their own longitudinal and lateral controllers for simulated vehicles. Our simulation model has three types of vehicles: ordinary cars, ACC-enabled cars and CACC-enabled cars. Figure 3.2 presents an Aimsun simulation screenshot where these three types of vehicles are present.

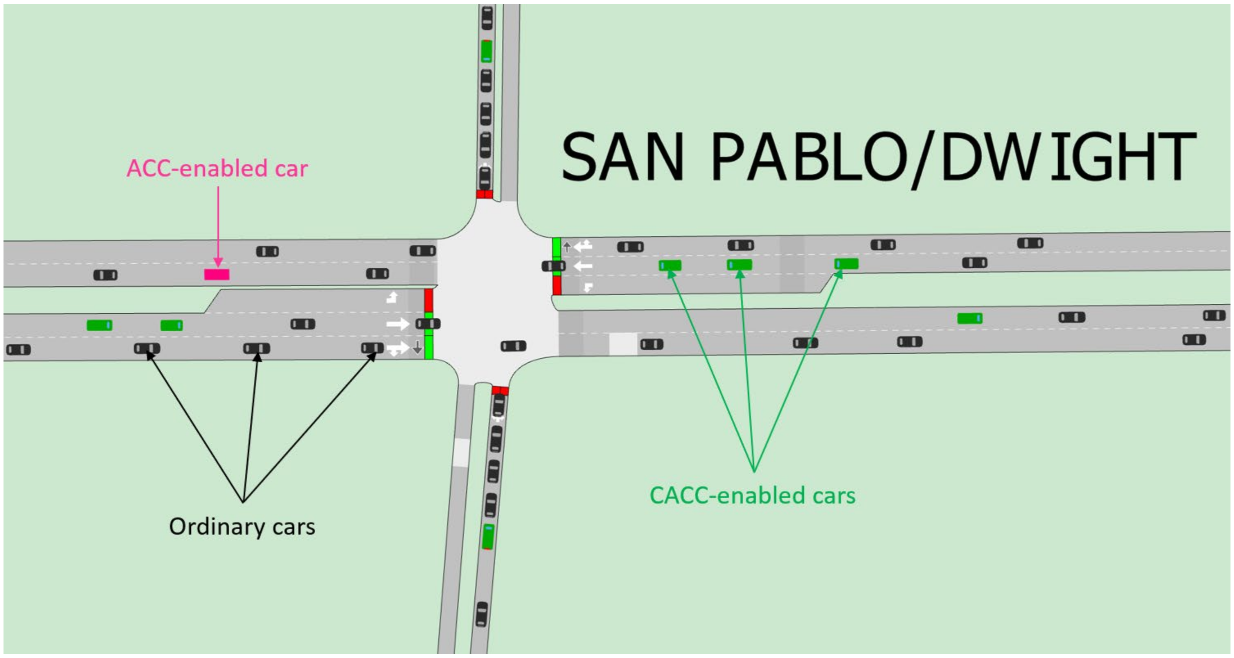

Figure 3.2 Aimsun screenshot of San Pablo traffic network: ordinary, ACC- and CACC-enabled cars near the intersection of San Pablo Avenue and Dwight Street in Berkeley.

Using Aimsun microSDK, every simulation step for each CACC-enabled vehicle we perform the algorithm outlined in Figure 3.3.

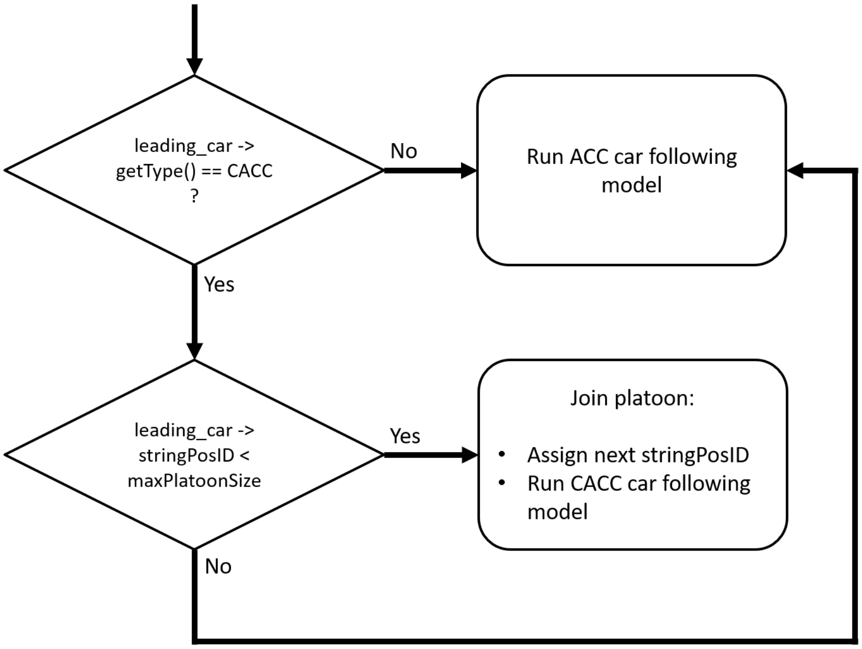

Figure 3.3 Block diagram summarizing CACC vehicle model, executed every simulation step.

Here the variable *leading_car* indicates a vehicle in front of the current one. Aimsun microSDK gives us the full information about the vehicle in front – its ID, type, location and dynamics. In the real world, however, there is no access to this information. Connected vehicles must inform the environment about themselves by broadcasting Basic Safety Messages (BSM) and identify positions of CACC-enabled vehicles around them from the pool of recent BSM broadcasts. This is described next.

3.2 Model of Platoon Organization

Building upon the basic platoon model described above, in this project we developed a more realistic model for platoon organization that has an exchange of information between CACC-enabled vehicles through BSMs.[1] The approach is summarized in Figure 3.4.

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[1] We only modeled the information exchange, not the wireless communication. In our model the information flow is ideal: there is no packet loss or communication delay.

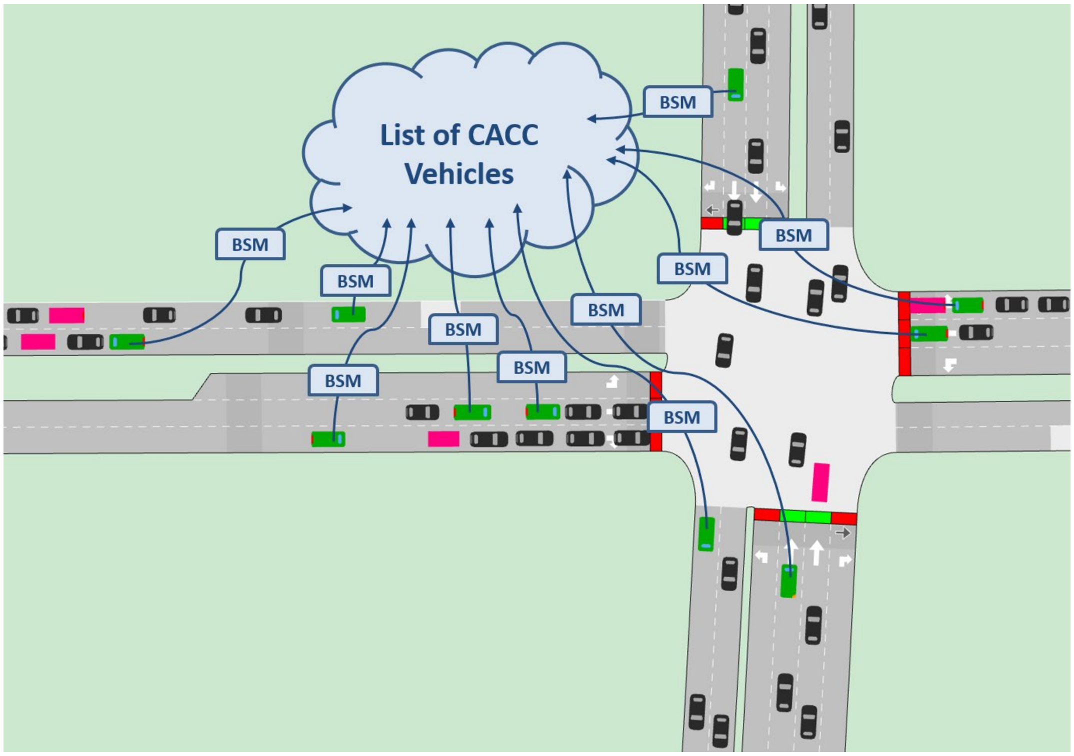

Figure 3.4 CACC-enabled vehicles inform the environment about themselves through Basic Safety Messages.

The centerpiece of this approach is a global list of CACC-enabled vehicles with their attributes including ID, location, dynamics and position in a platoon, maintained on the simulation level. This list is updated every simulation step and has most current information about all CACC vehicles in the modeled network. Every simulation step, each CACC vehicle performs the following sequence of actions:

- Read the global list of CACC vehicles.
- Filter out vehicles that are within a given radius[2] from the current vehicle.
- For every vehicle in the filtered list, check if it is a vehicle right in front of the current vehicle. If it is, and it is ready to form a platoon, join the platoon assigning a position in the platoon to itself.

In this approach, the platoon leader does not know if it has followers, and how many. A CACC vehicle that has no CACC vehicle in front, assumes platoon position 0. CACC vehicles joining

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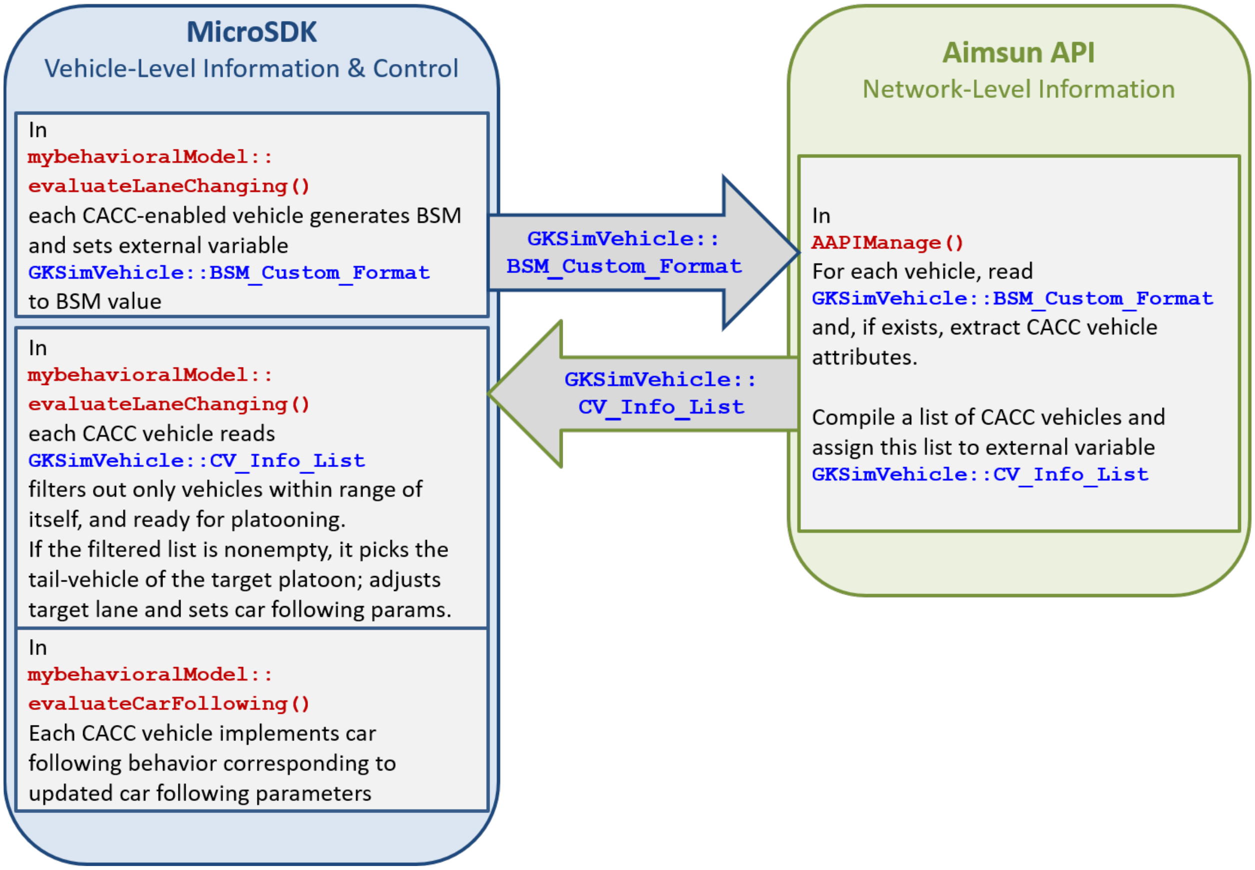
[2] We used 250 meters as a default radius.

from behind, assume the platoon position of their leading car incremented by 1.[3] If a CACC vehicle finds itself in a platoon with a position equal to the maximum platoon length, it switches to the ACC car following model and declares its new platoon position as 0 – becoming a new platoon leader. Thus, platoons exceeding the maximum length are broken up into two.

This model cannot be implemented in Aimsun using microSDK alone. It requires the use of Aimsun API module to maintain the global list of CACC vehicles, from where it could be requested by microSDK. Diagram in Figure 3.5 summarizes the implementation of the platoon organization.



In `mybehavioralModel::evaluateLaneChanging()` each CACC-enabled vehicle generates BSM and sets external variable `GKSimVehicle::BSM_Custom_Format` to BSM value

In `mybehavioralModel::evaluateLaneChanging()` each CACC vehicle reads `GKSimVehicle::CV_Info_List` filters out only vehicles within range of itself, and ready for platooning. If the filtered list is nonempty, it picks the tail-vehicle of the target platoon; adjusts target lane and sets car following params.

In `mybehavioralModel::evaluateCarFollowing()` Each CACC vehicle implements car following behavior corresponding to updated car following parameters

In `AAPIManage()` For each vehicle, read `GKSimVehicle::BSM_Custom_Format` and, if exists, extract CACC vehicle attributes.

Compile a list of CACC vehicles and assign this list to external variable `GKSimVehicle::CV_Info_List`

Figure 3.5 Diagram of Aimsun implementation of platoon organization.

To ensure that a simulation runs without failures, the Aimsun scenario must have the following attributes of type String or CString, defined by a modeler:

- *GKSimVehicle::BSM_Custom_Format*;

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[3] In our model, we assume maximum platoon length to be 5.

- *GKSimVehicle::CV_Info_List.*

3.3 Extending Basic Safety Message

As mentioned above, CACC vehicles update their information in the global list using BSM. According to SAE J2735 standard,[4] BSM contains the following parameters relevant to platoon application:

- TemporaryID;
- Latitude;
- Longitude;
- Elevation;
- Speed;
- Heading;
- AccelerationSet4Way;
- BrakeSystemStatus;
- VehicleSize.

These are not enough to form and maintain a CACC platoon.

A group of V2V researchers and practitioners proposed an extension of SAE J2735 dedicated to platooning.[5] In this proposal additional parameters necessary for coordination of maneuvers within platoon are listed. These parameters are usually defined by a control system designer. They are not from sensors. The control designer could define a particular meaning of a number which could represent a particular maneuver. To avoid confusion for the communication between vehicles of different makes, it is necessary to standardize this set of data. Broadcasting the current maneuver status is very important for control of individual vehicles and safety so that all the vehicles in the same string know what the others are doing right now. Obviously, one of the control

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[4] SAE J2735 Standard: https://www.sae.org/standardsdev/dsrc

[5] X.Y. Lu, S. Shladover, A. Kailas, O. Atlan. *Messages for Cooperative Adaptive Cruise Control Using V2V Communication in Real Traffic*. Fei Wu Eds., Taylor & Francis Group, CRC Press, 2018.

strategies for the subject vehicle is to avoid any space-time conflict with other vehicles in the same string for safety, maneuvering efficiency and string stability.

Parameters for maneuver coordination include:

- Vehicle position in platoon;
- Vehicle maneuver;
- Distance to car in front;
- Distance to platoon leader.

To determine, whether the car in front is a CACC vehicle and to match the correct CACC vehicle from our global list, we need to perform its localization using its coordinates and heading. Doing it properly is a rather complex task. Therefore, for the purpose of simulation modeling, we extended the BSM even further by adding parameters:

- Road section ID of the vehicle;
- Vehicle’s position in section;
- Vehicle’s lane ID.

Each BSM must be timestamped.

3.4 Simulation Results

We conducted our simulation experiments on a 2.2-mile segment of San Pablo Avenue stretching from south of Ashby Avenue to north of Gilman Street with 10 signalized intersection, shown in Figure 3.6.

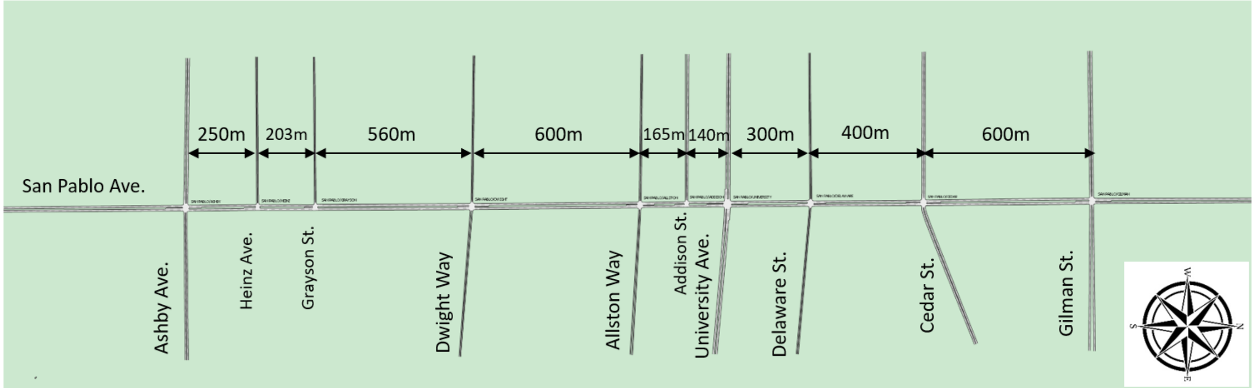

Figure 3.6 San Pablo simulation network.

First, we compared the performance of our platoon organization model (Section 3.2) with the basic platoon model (Section 3.1). In the basic model, platoons are formed every time there is an opportunity. In this case, CACC vehicle obtains full information about the car in front. In the real-world platoon organization model platoons are formed only when a CACC vehicle correctly identifies a CACC vehicle right in front of it. Mistakes are possible, because here a CACC vehicle only knows about other CACC vehicles around, but it does not know whether the car in front is CACC-enabled. Instead, it makes a guess. Figure 3.7 shows the percent of erroneous guesses by CACC vehicles about their leading cars depending on the penetration rate of CACC-enabled traffic.

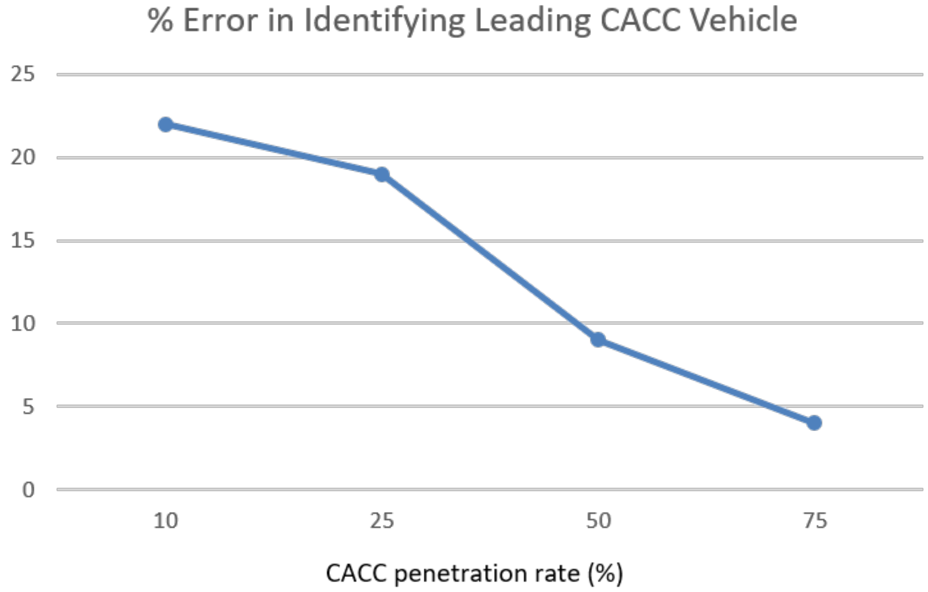

Figure 3.7 Percent of erroneous guesses by CACC vehicles about their leading cars.

These errors refer to situations when a CACC vehicle assumes that a car in front is not CACC-enabled and proceeds using the ACC car following model. In other words, these error statistics reflect the lost opportunities by CACC vehicles to join/form a platoon.

Related statistics are displayed in Figure 3.8. Here we show the percent of CACC vehicles that were driving in a platoon some time during their trip. Platoons may be restricted only to certain streets or road sections. The second curve in Figure 3.8 reflects the case when platoons are enabled only on the road section between Allston Way and University Avenue. Forming platoons everywhere may not always be wise. Obviously, increasing traffic flow upstream of a bottleneck is a bad idea. Therefore, platoons should be enabled only at bottleneck locations – to improve vehicle throughput at those places. In our traffic network, such a bottleneck exists for the northbound direction at the intersection of San Pablo Avenue with University Avenue. Thus, platooning is recommended upstream of the University Avenue.

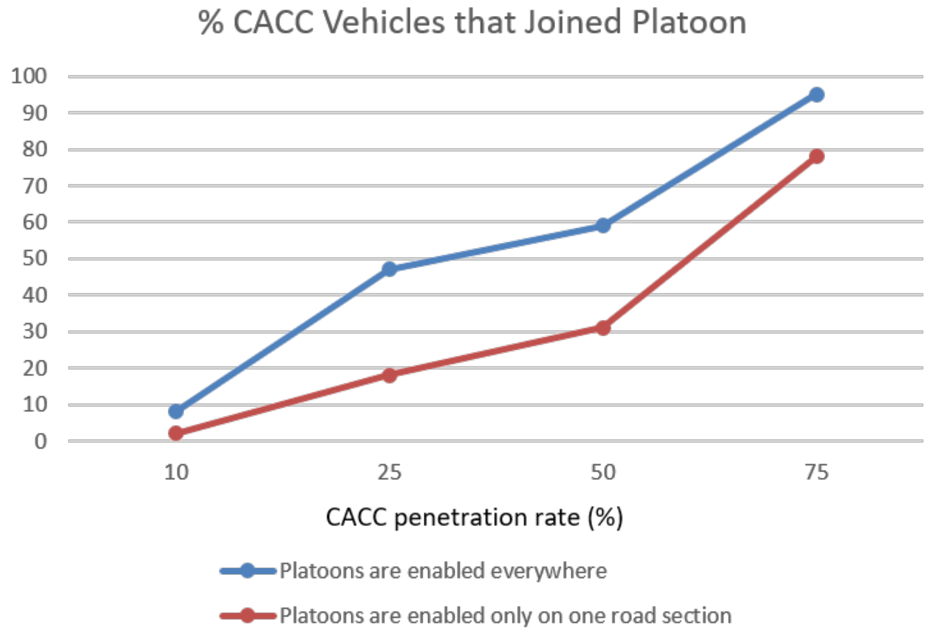

Figure 3.8 Percent of CACC vehicles that made a part of their trip in a platoon.

Our next experiment analyzed the intersection throughput when there is a long distance to the next intersection – that is, a free road ahead; and when the next intersection is near, so that vehicles do not have enough time to accelerate before they reach the end of the downstream queue. Figure 3.9 and Figure 3.10 display the flow, the gap between the cars, speed and acceleration of vehicles passing through the stop bar detectors in single lanes of the northbound direction at Dwight Way and Alston Way intersections with San Pablo Avenue. These quantities are measured within the first 60 seconds after the signal switches from red to green.

As one can see, the northbound flow from Allston Way is hindered by a downstream vehicle queue formed at the Addison intersection. Therefore, even if we enable platooning there, it does not improve the intersection throughput dramatically. On the other hand, when there is a relatively long distance to the next intersection, such as in the northbound direction of Dwight Way, platoons can significantly increase intersection throughput. Figure 3.11 summarizes the throughput analysis of these two intersections by presenting the aggregate vehicle counts for he first 60 seconds after the signal switches from red to green for different penetration rates of CACC vehicles in the overall traffic flow. The vehicle counts are given per lane.

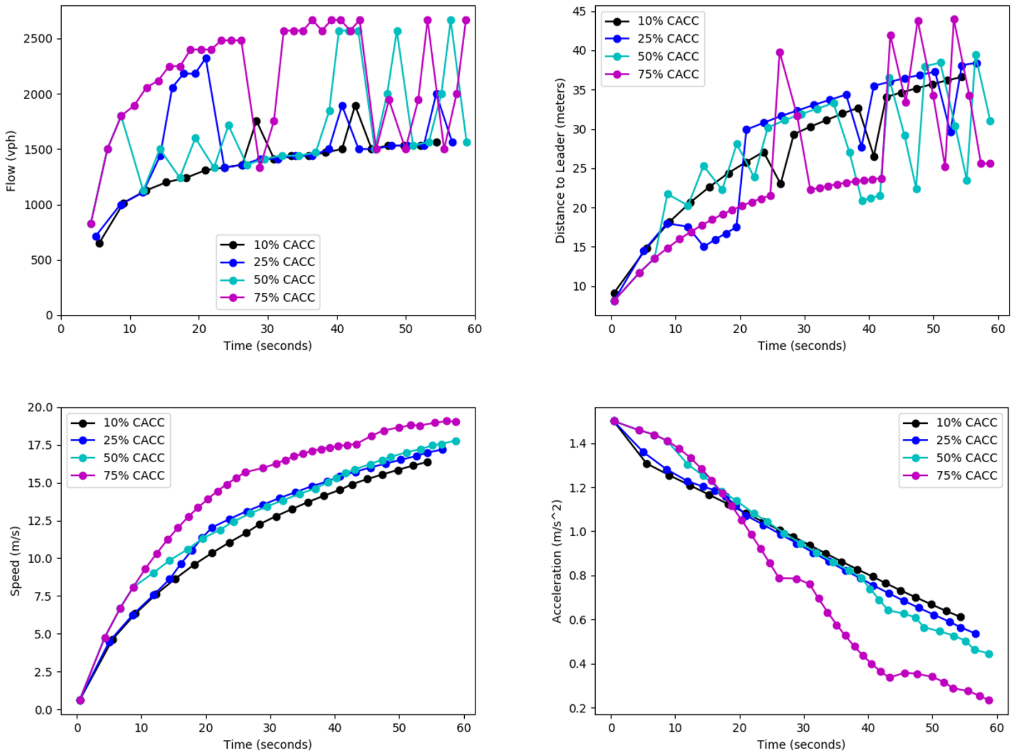

Figure 3.9 Throughput analysis of the North Bound direction of Dwight Way intersection.

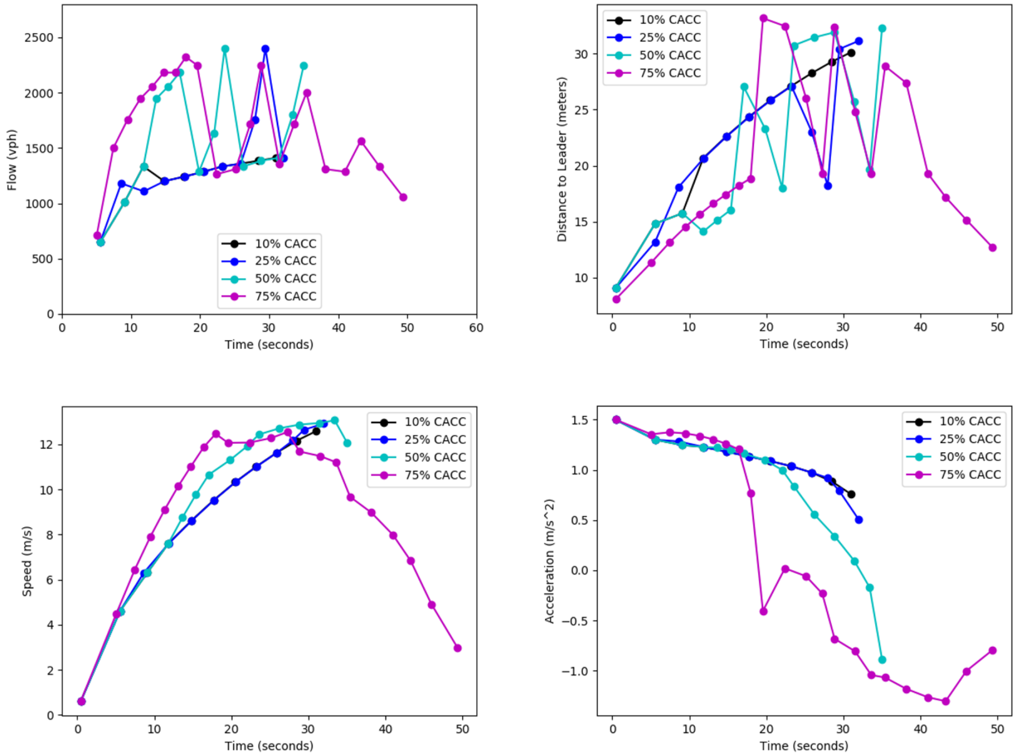

Figure 3.10 Throughput analysis of the North Bound direction of Allston Way intersection.

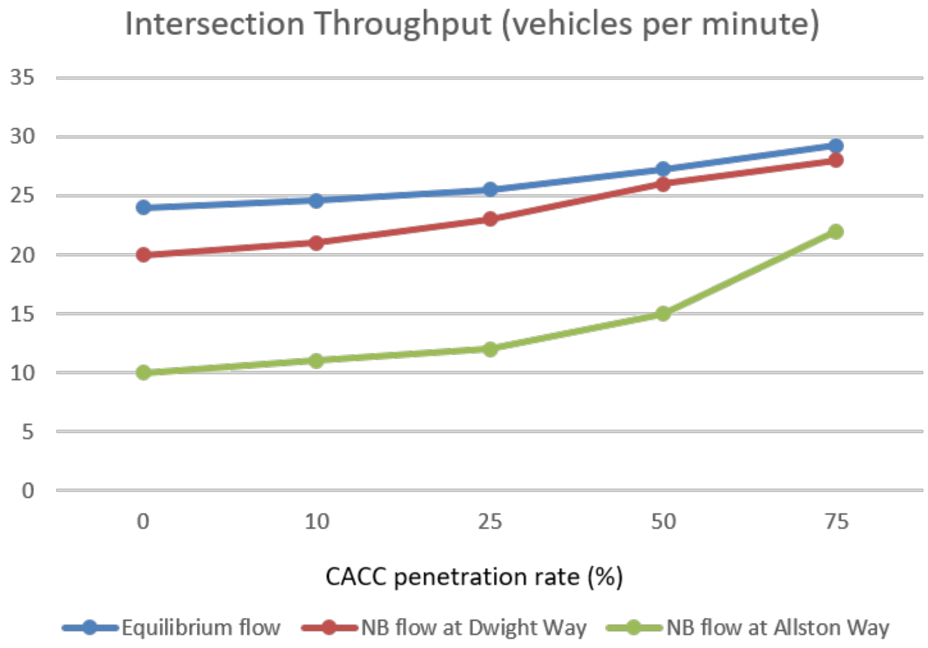

Figure 3.11 Comparison of intersection throughputs with equilibrium flow.

Note that on the plot in Figure 3.11, there is a curve corresponding to the *equilibrium vehicle flow*. This equilibrium flow is computed as follows. Denote λ, $0 \leq \lambda \leq 1$, a portion of CACC vehicles in the traffic flow (e.g., $\lambda = 0.25$ corresponds to 25% of CACC penetration rate); τ – reaction time for ordinary vehicles, τ^{CACC} – reaction time for CACC vehicles; g – minimum gap for ordinary vehicles; g^{CACC} – minimum gap for CACC vehicles; ℓ – average vehicle length; v – desired speed. The average headway in the equilibrium traffic flow is obtained from the expression:

$$\theta(\lambda) = \lambda \tau^{CACC} + (1-\lambda)\tau + \frac{\lambda g^{CACC} + (1-\lambda)g + \ell}{v}.$$

Then, the equilibrium flow in vehicles per minute is given by:

$$f(\lambda) = 60 / \theta(\lambda).$$

In our calculations, we used the following values:

- $\tau = 2$s, $\tau^{CACC} = 1$s;
- $g = 4$m, $g^{CACC} = 2$m;
- $\ell = 4$m;

- $v = 20$ m/s.

Finally, Figure 3.12 presents the average travel time for ordinary and CACC-enabled cars on the route from Ashby Avenue to Gilman Street, computed for different penetration rates of CACC vehicles in the overall traffic. In this figure, there are two curves representing CACC-vehicle travel time: CACC-basic corresponds to the basic platoon model (Section 3.1), and CACC-modified refers to the more realistic platoon model (Section 3.2).

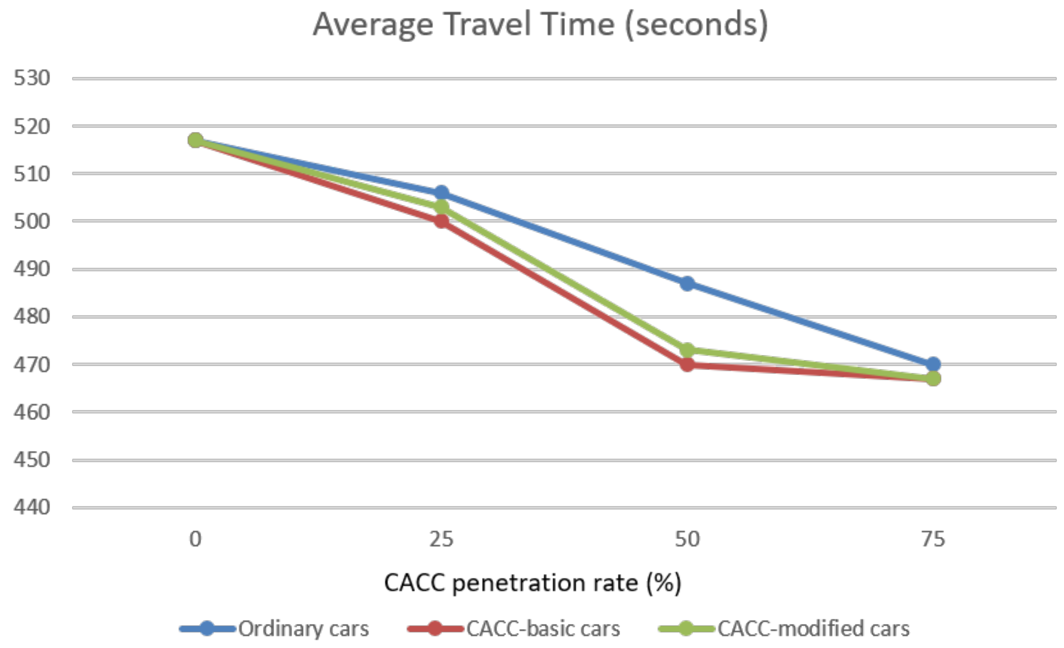

Figure 3.12 Average travel time on the route on San Pablo Ave. from Ashby Ave. to Gilman St.

3.5 Conclusion

A platoon formation model on an arterial was proposed for arterial intersections. The proposed platoon forming approach is a global list of CACC-enabled vehicles with their attributes including ID, location, dynamics and position in a platoon, maintained on the simulation level. This list is updated every simulation step and has most current information about all CACC vehicles in the modeled network. In this platoon forming approach, the leader does not know if it has followers, and how many. A CACC vehicle that has no CACC vehicle in front, assumes platoon position 0. CACC vehicles joining from behind, assume the platoon position of their leading car incremented by 1. If a CACC vehicle finds itself in a platoon with a position equal to the maximum platoon length, it switches to the ACC car following model and declares its new platoon position as 0 – becoming a new platoon leader. Thus, platoons exceeding the maximum length are broken up into two.

The CACC model and the platoon forming strategy have been implemented with a microscopic simulation for an arterial corridor with multiple signalized intersections on San Pablo Ave. near Berkeley, California. The arterial corridor extends from south of Ashby Avenue to north of Gilman Street with 10 signalized intersection. The simulation environment is Aimsun. Some initial simulation showed that proper platoon forming maneuvers could reduce Total Travel Time.

Chapter 4. Develop a Prospectus for Caltrans' Strategic Approach to CAV Preparation

4.1 Introduction

Among many changes being experienced by public sector transportation agencies, and notably by state departments of transportation (DOTs), the development of connected and automated vehicles (CAVs) is potentially transformational. Some observers consider CAVs to be a tipping point in transportation, of a magnitude only seen at intervals of many decades. Therefore, CAVs create significant opportunities and uncertainties in planning, managing and operating the transportation infrastructure.

This Chapter aims to provide background on CAV technologies, their potential benefits and steps to CAV deployment. Scenarios for CAV deployment include applications such as on-demand mobility services and CAV applications such as platooning in the trucking industry. The paper considers potential ramifications for policy makers, planners and regulators and presents findings from a Caltrans executive-level workshop that was held on April 18, 2019 to assist in the development of a framework for CAV readiness.

The objectives of the CAV readiness workshop were to:

- Assist Caltrans in accelerating the state of preparation for CAV technologies (including specific activities in connected vehicles (CV) and automated vehicles (AV));
- Promote CV/AV initiative and leadership on the part of Caltrans;
- Promote CV/AV outreach on the part of Caltrans;
- Obtain internal feedback on key CV/AV questions; and
- Assist in initiating a Caltrans CAV planning framework.

The paper draws on the continuing connected vehicle (CV) and automated vehicle (AV) research and deployment programs of the U.S. Department of Transportation (U.S. DOT) as well as the evolving body of literature on CAV technologies. Of particular note are recent publications by the Transportation Research Board's (TRB's) National Cooperative Highway Research Program

(NCHRP), including its "Connected and Automated Vehicle Research Roadmap for AASHTO" (project 20-24(98)) (*3*), "Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies" (project 20-102) (*4*), and "Challenges to CV and AV Applications in Truck Freight Operations" (project 20-102(03)) (*5*), among others. Also of note is TRB's transportation research circular E-C208, "Transformational Technologies in Transportation" (*6*).

The paper is also informed by the on-going efforts of national stakeholders such as the American Association of State Highway Transportation Officials (AASHTO), and its Cooperative Automated Transportation (CAT) Coalition, the Institute of Transportation Engineers (ITE) and ITS America.

Caltrans wishes to accelerate its leadership and outreach in the field of CAV. In addition to presenting the current status of CAV technology and deployment, this paper will discuss examples of CAV preparation. It will also help to identify the potential scope of a Caltrans planning framework for CAV and the type of coordination structure needed for consistent CAV leadership and support to be provided by Caltrans and its partners.

4.2 CAV Technology Status

The quantity and maturity of CAV activities continue to grow and evolve. In fact, CAV activities in U.S. states, regions and cities are by now extremely numerous, diverse and ever-changing. While an exhaustive description would evade a chapter such as this, we will concentrate on clearly distinguishing the CV and AV technologies and providing a sense of deployment activities, as well as approaches to governance. We partly draw on two papers prepared by CAVita LLC: a TRB publication on transformational technology in transportation *(1)* and a CAV chapter prepared for a DOT CEO Leadership Forum (2).

4.2.1 Connected and Automated Vehicle Technologies

4.2.1.1 Overview of CV, AV and CAV

Connected vehicle (CV) technology refers to robust, standardized vehicle-to-vehicle communication (V2V), vehicle-to-infrastructure communication (V2I), and "V2X", broadly representing communication between vehicles, infrastructure and other road users (such as pedestrians and cyclists). V2I involves deployment of connectivity in the infrastructure and potentially interfaces with advanced traffic applications utilizing Intelligent Transportation Systems (ITS).

The purpose of CV technology is to provide certain real-time data, upon which various crash risks can be quantified, and warnings provided to drivers as required. CV is not intended to provide automatic intervention; however, CV technology can support AV technology as another source of information. Standardized packets of data (position, speed and direction) are used in numerous on-board applications to derive warnings related to specific types of traffic conflicts and resulting crashes. The same data can be used in further applications that are not directly relevant to safety: to smooth traffic flow, reduce energy use and reduce emissions. Regardless of the end purpose, CV is only intended to provide warnings to drivers, and does not automatically take corrective action.

Automated vehicle (AV) technology does provide driving control in relation to steering, acceleration and braking. Depending on its intended functionality – from conditional to full automation – the automated driving system (ADS) includes the elements of sensing, communication, monitoring, navigation, decision-making, behavior and driving control required for its progression in traffic. The term AV covers a very broad range of both automated function, in terms of the extent to which it replaces functions of the human driver, and the intended operating environment. ADSs are designed and evaluated for certain types of operation on public roads and to satisfy safe driving guidelines. ADSs have designated Operational Design Domains (ODDs); ODDs may include geofenced areas, and may speak to road class, traffic conditions, time of day or weather. Highly-automated vehicles (HAVs) include those closest to driverless capabilities and are of particular significance in enabling disruptive change in the mobility of people and freight.

Currently, CV and AV are pursuing parallel technological and policy paths, and their relationship is evolving. The major national stakeholders, including U.S. DOT and state agencies, are actively considering both CV and AV and are encouraging a supportive relationship between the technologies. DOTs are carrying out pilot deployments of CV through the provision of roadside communication technology with the understanding that this technology will support future AV deployments.

The common use of the term “connected and automated vehicle” (CAV) allows for the beneficial combination of the two technologies as shown in Figure 4.1. In this context, CV may be regarded as an additional data input or “sensor” in the ADS’s suite of sensors. Many uses of the term “CAV” are driven mainly by the “AV” component. The terms CV and AV are often used in their own right as well.

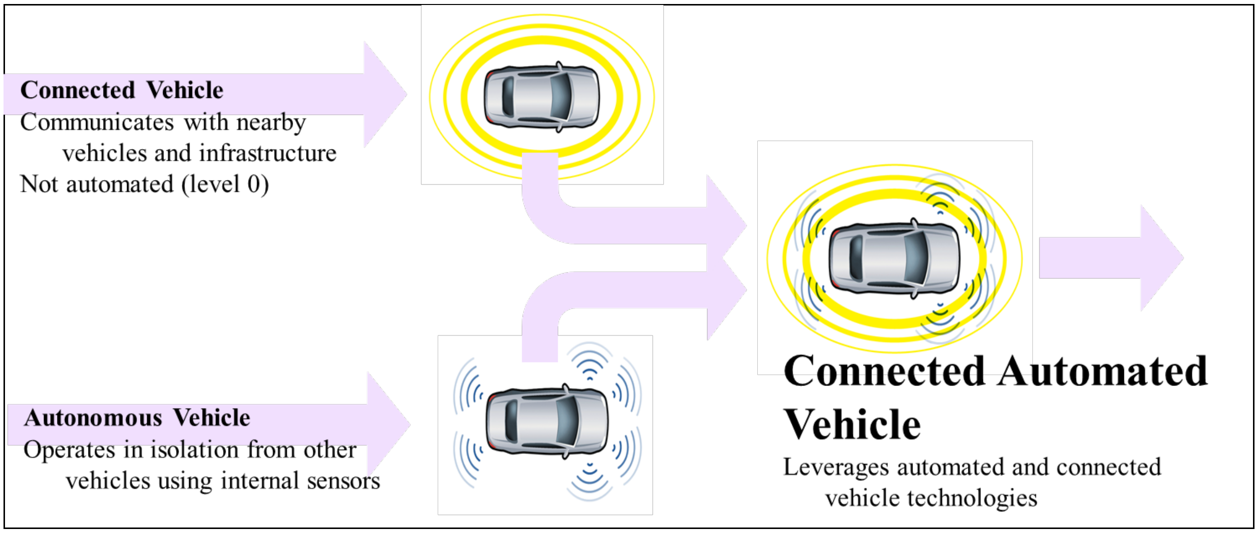

Figure 4.1 CAV Concept (source: USDOT)

4.2.1.2 Functions of CV and AV technology

“CV” generally refers to both connected vehicles and infrastructure, and to connection among all ground vehicle players: cars, freight trucks, and buses – and potentially motorcycles, bicycles, and pedestrians. Connected technologies include wireless local area networks (WLAN) licensed wireless regimes such as dedicated short-range communication (DSRC), as well as the newer cellular technologies, such as “C-V2X” (a form of LTE) and the forthcoming 5G. Collectively these regimes are often referred to as V2X.

The “connected” part of “connected and automated” generally refers to a V2X-enabled capability that creates machine awareness of the trajectories of equipped vehicles in the immediate vicinity. This machine awareness applies to vehicles as well as specific features of the infrastructure, such as intersections and curves. Such machine awareness may be used to identify safety risks, but also to condense or smooth traffic flow. Importantly, these applications of the technology require warnings or notifications for drivers, in order for the driver to make the required vehicle corrections.

The components of connected vehicle systems are well-defined, and include the following elements:

- The on-board unit (OBU) fitted to the vehicle, for broadcasting and receiving defined message sets (principally the Basic Safety Message (BSM));
- The road-side unit (RSU) fitted to roadside furniture at intersections and typically connected to a traffic signal controller for broadcasting and receiving defined message sets (principally signal phase and timing (SPAT) and the BSM);
- The V2X applications that process messages and devise driver warnings; certain applications may require vehicle data via connection to the vehicle's on-board diagnostics (OBD) port; vehicles may contain both V2V and V2I (or I2V) applications;
- The interface between the OBU and driver in the vehicle;
- The interface between the RSU and signal controller; and
- The data backhaul from RSUs to a central location.

Figure 4.2 shows the architecture of a typical V2I deployment. In this depiction, the RSU is referred to as "RSE" but the meaning is the same. Many states and cities have developed CV test beds on real roads that include V2I installations like the one shown in Figure 4.2.

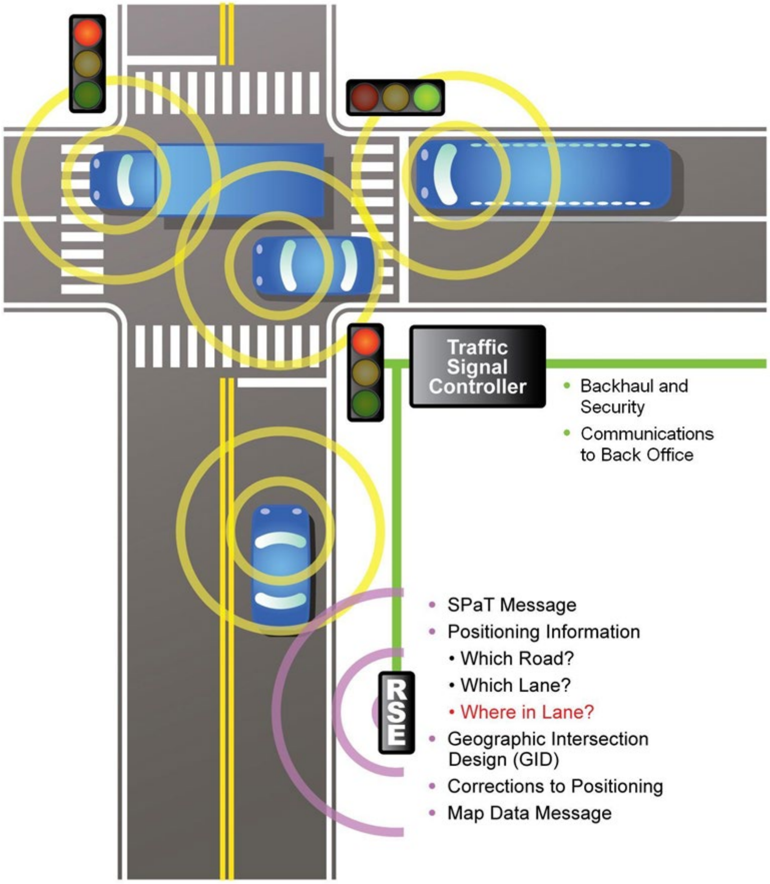

Figure 4.2 Typical V2I Deployment Concept (source: USDOT)

The “automated” part of “connected and automated” refers to various levels of replacement of human perception and control, and is currently applicable to cars, freight trucks, and buses. Note that platoons of vehicles utilize simple forms of both connected and automated technologies. By way of further background, automated vehicle features have to some extent evolved from a class of advanced driver assist systems (ADAS).

The terms “automated” and “autonomous” are often used interchangeably. However, autonomous usually means a vehicle that relies entirely on its own onboard sensors for situation awareness in the roadway, and therefore for exercising vehicle control functions. Automated vehicles may cover a very wide range of automated driving features, from partially-automated driver assist systems to fully automated capabilities.

The Society of Automotive Engineers (SAE) Standard J3016 (Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems) (*7*) is widely referenced and identifies **six driving automation levels**[6], comprising:

- Level 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;
- Level 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 performs all remaining aspects of the dynamic driving task;
- Level 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 performs all remaining aspects of the dynamic driving task;
- Level 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;
- Level 4 – High Automation: The driving mode-specific performance by an Automated Driving System of all aspects of the dynamic driving task, within a defined set of driving environments, with no expectation that a driver will intervene; and
- Level 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.

The U.S. DOT adopted this standard into the National Highway Traffic Safety Administration (NHTSA) Federal Automated Vehicles Policy (FAVP) for safe testing and deployment of automated vehicles,[7] thereby aligning and formalizing a commonly used shorthand for quickly and concisely categorizing automated vehicle technologies and capabilities (i.e. L3, L4, etc.). Updated

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[6] http://standards.sae.org/j3016_201401/

[7] https://www.sae.org/news/3544/

and revised versions of this guidance, including the recent NHTSA 3.0, retain these fundamental definitions of automated driving functionality.

4.2.1.3 Further Technological Developments

Connected Vehicles

While the vehicular side of CV is ready for production vehicles (as evidenced by GM's deployment in selected 2017 models and positive announcements by Toyota), considerable R&D effort has been devoted recently to V2I technology and applications. Work led by the Federal Highway Administration (FHWA) and the Collision Avoidance Metrics Partnership (CAMP) has developed an increased range of V2I applications. Work by FHWA has developed standards for the connections between RSUs and traffic controllers, and ITS/controller companies have developed products based on these standards. R&D has been carried out to develop "pseudo BSMs" that broadcast BSMs on behalf of unequipped vehicles present in an intersection.

In early 2017, NHTSA issued a Notice of Proposed Rule Making (NPRM) for V2V communications that would require all future vehicles to install DSRC technology. However, after the change in administrations, this NPRM was never acted upon. With the apparent shelving of NHTSA's NPRM for V2V (DSRC), original equipment manufacturers (OEMs) will determine the applicable standards and timing for inclusion of V2V and V2I functionality in new vehicles. It appears that some OEMs, including GM and Toyota, will use WLAN (DSRC), and some (such as Ford) prefer the cellular methodology.

Automated Vehicles

With many of the basic challenges associated with enabling Level 1 and 2 driving solved, technology developers focused attention on developing the ability for AVs to recognize and safely respond to unconventional and unanticipated road conditions, paving the way for Level 4 and 5 automated driving. These efforts have largely been oriented around developing artificial intelligence (AI) software for vehicular control. Developers have achieved meaningful advancements within two particular categories of AI best positioned to solve the complex challenges associated with higher levels of automated driving: machine learning and, more importantly, deep learning.

The importance developers place on advancing machine and deep learning has created fierce competition for quality software and talented computer scientists and engineers. Recent years have seen large corporate transactions driven primarily by this competition. Examples include:

- The staffing and ramping up of activities at the $1B Toyota Research Institute Inc. (TRI)[8], an R&D enterprise established with a $1B investment by Toyota in 2015, focused on artificial intelligence and robotics.[9]
- General Motors' March 2016 $581M acquisition of Cruise Automation,[10] a company that at the time was known for having developed promising AV control software. GM has since allocated responsibility for GM's AV development to Cruise.

Many view Light Detection and Ranging (LiDAR) units, which are able to accurately gauge a vehicle's surroundings in many complex situations, as essential to enabling higher levels of automation. Major efforts continue to reduce the size and cost of historically bulky and expensive units. The sensor suites utilized in AVs are changing rapidly and will continue to do so.

Infrastructure

Continued engagement by infrastructure owners and operators (IOOs) is crucial to preparing roads for automated vehicles. While AVs may be tested in off-roadway facilities, all companies engaged in AV development place high value on miles logged on public roadways. Most manufacturers maintain a position of non-reliance on infrastructure assistance, although improved road maintenance in relation to markings, signage and road surface condition – and their national consistency - is an important factor in the deployment of HAVs. Other important infrastructure issues include provision of real-time information regarding work zones and other road conditions, pick-up and drop-off areas (including curb design and access), use of dedicated or managed lanes and dynamic lane assignment.

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[8] http://www.tri.global/

[9] http://newsroom.toyota.co.jp/en/detail/10171645/

[10] http://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2016/mar/0311-cruise.html

4.2.2 Scenarios for Deployment

4.2.2.1 <u>The Ecosystem Driving CAV Development and Adoption</u>

The advent of CAVs brings a wider range of players than we have seen previously in transportation. All of the following broad categories of stakeholders are involved in the development and adoption of CAVs:[11]

I. <u>Policy development</u>. Largely carried out by government at the federal, state, and local levels. Industry, academia, and research play a supporting and advisory role. Policy development applies to motor vehicles, infrastructure equipment, and telecommunications.

II. <u>Vehicles</u>. Designed, manufactured, and distributed by original equipment manufacturers and suppliers in several tiers. Certain equipment is also designed, manufactured, and distributed in the aftermarket.

III. <u>Infrastructure</u>. The nation's system of streets, roadway structures, and associated equipment and roadside furniture. Designed, constructed, maintained, and operated by state and local agencies, with federal government assistance. Equipment such as traffic management systems is designed, manufactured, and supplied by ITS companies and traffic equipment suppliers.

IV. <u>Personal technology ("tech")</u>. Manufacturers and providers of personal devices and services to consumers, and to other business sectors such as vehicle manufacturers. Includes inroads by "tech" companies into vehicle development: tech cars that are automated, connected, and electrified.

V. <u>Communications, computation, and big data</u>. The underlying telecommunications technology, the carriers, and the retail providers of phone and data services. Included are cellular and wireless regimes such as Wi-Fi, as well as the Internet and computation services on the vehicle and in the cloud. Also included are big data services creating information and applications in and around the high velocity and high-volume data streams being created by CVs and infrastructure.

VI. <u>Insurance, standards, and security</u>. Motor vehicle insurers are active in data- intensive insurance products and may develop new insurance concepts for automated vehicles. This

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[11] http://onlinepubs.trb.org/onlinepubs/circulars/ec208.pdf

refers to national and international standards bodies covering automotive and communications and to the cybersecurity approaches adopted by vehicle and equipment manufacturers.

VII. Mobility services. A diverse range of on-demand services, including transport network companies (TNCs), smart parking, carsharing, ridesharing, ridesourcing, and trip planning. This includes the on demand, networked ride services constituting shared mobility (SM) (e.g. Uber, Lyft).

VIII. Convening, deployment, and evaluation. The more traditional aspects of convening are carried out by industry associations and professional bodies. Universities and local agencies also organize efforts for deployment and economic development. Such consortia usually carry out evaluation activities.

Prime examples for early adoption of AVs include:

- Automotive comfort, convenience and safety: Relief from driving chores in simple, predictable highway travel. Moderate levels of automation promote stable traffic behavior.
- Mobility as a service. Higher levels of automation are increasingly appearing in city-based vehicle fleets providing on-demand mobility services. The potential cost reductions with driverless, on demand vehicles are compelling.
- Long-haul trucking: Platooning and other higher levels of automated truck technologies can provide a clear and near-term return on investment. For example, testing done by the National Renewable Energy Laboratory (NREL) demonstrated fuel savings up to 5.3 percent in the lead truck while the trailing truck saved up to 9.7 percent.[12] Automated trucks are estimated to save about $1.67 per mile compared to standard trucks.[13] Given hours of service (HOS) constraints on human drivers, automated trucks could allow more hours of operation.
- Closed communities and campuses: Health care, retirement communities and universities are serving as early deployment zones for automated vehicles. In these scenarios, the

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[12] https://www.nrel.gov/transportation/fleettest-platooning.html

[13] https://insights.samsung.com/2017/04/17/telematics-lays-the-foundation-for-autonomous-trucking/

demand for mobility solutions is more predictable. Additionally, conditions are suited to simple, small, low-speed automated vehicles and shuttles.

4.2.2.2 Examples of CV, AV and CAV Deployments

In recent years, vehicle and technology manufacturers, the U.S. government, and universities (and other third parties) have contributed to CAV testing and demonstration programs. While some initiatives have targeted both CV and AV, many are oriented to one or the other.

Connected Vehicle Deployments

The U.S. DOT has overseen a tightly integrated program of CV research, bench testing, test beds, field trials, standards development, and model deployment.[14] Prominent CV test sites already in operation, or getting underway, tend to have a specific, local university partner and an explicit component dedicated to private industry participation and collaboration. These CV test sites include a combination of federally funded efforts and state led efforts. Some of the better known CV testbed sites are described below.

- Arizona Connected Vehicle Program identified how new technology applications could enhance traffic signal operations, incident management and traveler information. It led to what became the Maricopa County Department of Transportation (MCDOT) SMARTDrive^{SM} Program, which provides emergency vehicle pre-emption at signalized intersections. The technology developed by Arizona's Connected Vehicle Program contributed to the development of the U.S. DOT’s Multi-Modal Intelligent Traffic Signal System (MMITSS). The program has now expanded its testing to include new applications such as a pedestrian traffic signal crosswalk application, transit priority application and a trucking priority application.[15]
- Ann Arbor Connected Vehicle Test Environment (formerly Safety Pilot) has been operated by the University of Michigan Transportation Research Institute (UMTRI) since 2012 with a large contingent of DSRC-connected cars, trucks and buses. The USDOT-funded Safety

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[14] http://onlinepubs.trb.org/onlinepubs/circulars/ec208.pdf

[15] https://www.maricopa.gov/640/Connected-Vehicles-Program

Pilot served as a catalyst for further related developments in Southeast Michigan, including Mcity (launched in 2015), and the American Center for Mobility (ACM).

- Ohio's Smart Mobility Corridor comprised of advanced highway technology along a 35-mile stretch of US 33 northwest of Columbus. The Smart Mobility Corridor is a key component of the state's Smart Mobility Initiative.[16]
- California Connected Vehicle Test Bed has been in operation since 2005 when it was established by a partnership between Caltrans, UC Berkeley Partners for Advanced Transportation Technology (PATH) and the Metropolitan Transportation Commission (MTC). Located in Palo Alto, the testbed spans 11 consecutive intersections along a 2-mile stretch of State Route 82 (El Camino Real) with plans to expand to 31 intersections by the end of 2019. The Test Bed exchanges live data with a Caltrans 2070 traffic controller at each intersection for populating the SPAT messages and commanding adaptive signal and priority timing.

In 2015, USDOT awarded cooperative agreements collectively worth more than $45 million to three pilot sites - in New York City, Tampa and Wyoming - to implement a suite of connected vehicle applications and technologies tailored to meet their region's unique transportation needs. These pilot sites are helping connected vehicles make the final leap into real-world deployment so that they can deliver on their promises to increase safety, improve personal mobility, enhance economic productivity, reduce environmental impacts and transform public agency operations. A summary of the three CV pilot sites is provided below.

- New York City DOT Pilot comprised of approximately 5,800 cabs, 1,250 MTA buses, 400 commercial fleet delivery trucks, and 500 city vehicles to evaluate CV technologies and applications in tightly spaced intersections typical in a dense urban transportation system.[17]
- Tampa-Hillsborough Expressway Authority Pilot employs DSRC to enable V2X transmissions among approximately 1,500 cars, 10 buses, 10 trolleys, 500 pedestrians with smartphone applications, and approximately 40 roadside units along the Selmon Reversible

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[16] https://www.dot.state.oh.us/news/Pages/SmartMobilityCorridor.aspx

[17] https://www.its.dot.gov/pilots/pilots_nycdot.htm

Express Lanes (REL) to relieve congestion, reduce collisions, and prevent wrong way entry.[18]

- Wyoming DOT pilot focuses on the needs of commercial vehicle operators by using a variety of V2X technologies along Interstate 80 to support a flexible range of services from advisories including adverse weather conditions, roadside alerts, parking notifications and dynamic travel guidance.[19]

Automated Vehicle Testing and Deployment

Examples of AV test facilities and consortia established and operated in recent years include:

- Berkeley DeepDrive, an industry consortium headed up by UC Berkeley's PATH program developing advanced computer vision and machine learning. Berkeley DeepDrive involves collaboration with 22 industrial partners, including Original Equipment Manufacturers (OEMs), Tier 1 suppliers, tech companies, communications, IT, and consumer electronics.
- GoMentum Station in Concord, California currently is the largest secure testing ground for CAVs in the country. AV testing takes place on the facility's roadways, and CV testing takes place by using the facility's smart (V2I) infrastructure, including traffic signals.
- The Texas A&M University System (TAMUS) is creating a large off-roadway test facility for CAV and smart infrastructure at its 3,000-acre RELLIS facility in Bryan, Texas. Companies are forming consortia to carry out CAV-related R&D in collaboration with the Texas Transportation Institute (TTI). RELLIS is of sufficient scale and built environment for companies to locate large R&D efforts on-site.
- The University of Michigan's Mcity is a 32-acre facility in Ann Arbor, Michigan with diverse roadways, roadside features and infrastructure is a closed, controlled environment that allows researchers to safely test emerging concepts in connected and automated vehicles.[20] The facility includes 13 signalized intersections and incorporates urban, suburban and highway settings, and was opened in July 2015. The Mcity consortium

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[18] https://www.its.dot.gov/pilots/pilots_thea.htm

[19] https://www.its.dot.gov/pilots/pilots_wydot.htm

[20] http://energy.umich.edu/research/partner-programs/mcity

brought together more than 70 companies involved in research and deployment programs in and around Mcity. These companies include OEMs, Tier 1 suppliers, ITS, tech companies, communications, IT, insurance, and mobility services.

- The American Center for Mobility (ACM) was created by the Michigan Economic Development Corporation (MEDC), MDOT and the University of Michigan, utilizing the former GM transmissions facility at Willow Run. A 300-acre multi-environment AV test facility, with attached freeway and interchange sections, has been constructed and is available to manufacturers. A comprehensive range of test environments and situations for object and event detection are being provided for safety validation of ADSs.
- The Transportation Research Center (TRC) is a long-standing 4,500-acre test facility in central Ohio, with added capabilities for CAV testing. TRC is owned and operated by Honda and the Ohio State University, and has NHTSA as a long-term resident user. US Route 33, connecting TRC with Marysville, is being equipped for V2I testing, providing a link to the Columbus Smart City deployments in CAV.
- Virginia Automated Corridors feature more than 70 miles of interstates and arterials roadway supported by academia, the state's DOT, and private industry that establish an environment and significant research support to create, test, and deploy CAV systems.[21]
- Virginia Smart Road is a 2.2-mile, controlled-access test track research facility managed by the Virginia Tech Transportation Institute (VTTI) and owned and maintained by the Virginia Department of Transportation (VDOT).[22] Extensions to the Smart Road provide structured environments for CAV testing.

Vehicle and technology manufacturers have received considerable attention for their activities, given that most are highly-publicized and on public roadways. In some cases, these deployments allow for public passengers. Just a few examples of privately led AV applications and deployments include:

- Waymo in Mountain View, CA and Phoenix, AZ has deployed tens of thousands of HAV minivans with full-scale fleet management.

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[21] http://www.vtti.vt.edu/featured/?p=260

[22] http://www.vtti.vt.edu/facilities/virginia-smart-road.html

- General Motors is testing thousands of HAVs in Detroit, MI, San Francisco, CA, and Scottsdale, AZ.
- Peloton has undergone thousands of miles of highway testing of a system that allows pairs of trucks to "platoon" in Utah, Nevada, Michigan, Ohio, Florida and California.[23]

4.2.2.3 Geography of U.S. Deployments and Consortia

As illustrated by Figure 4.3 and Figure 4.4, manufacturer, government, academic, and other prominent testing and deployment efforts are located in various regions throughout the country, and are thus exposed to a variety of geographic environments, roadway scenarios, weather conditions, and stakeholder groupings.

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[23] https://www.trucks.com/2016/08/28/truck-platooning-technology-advances/

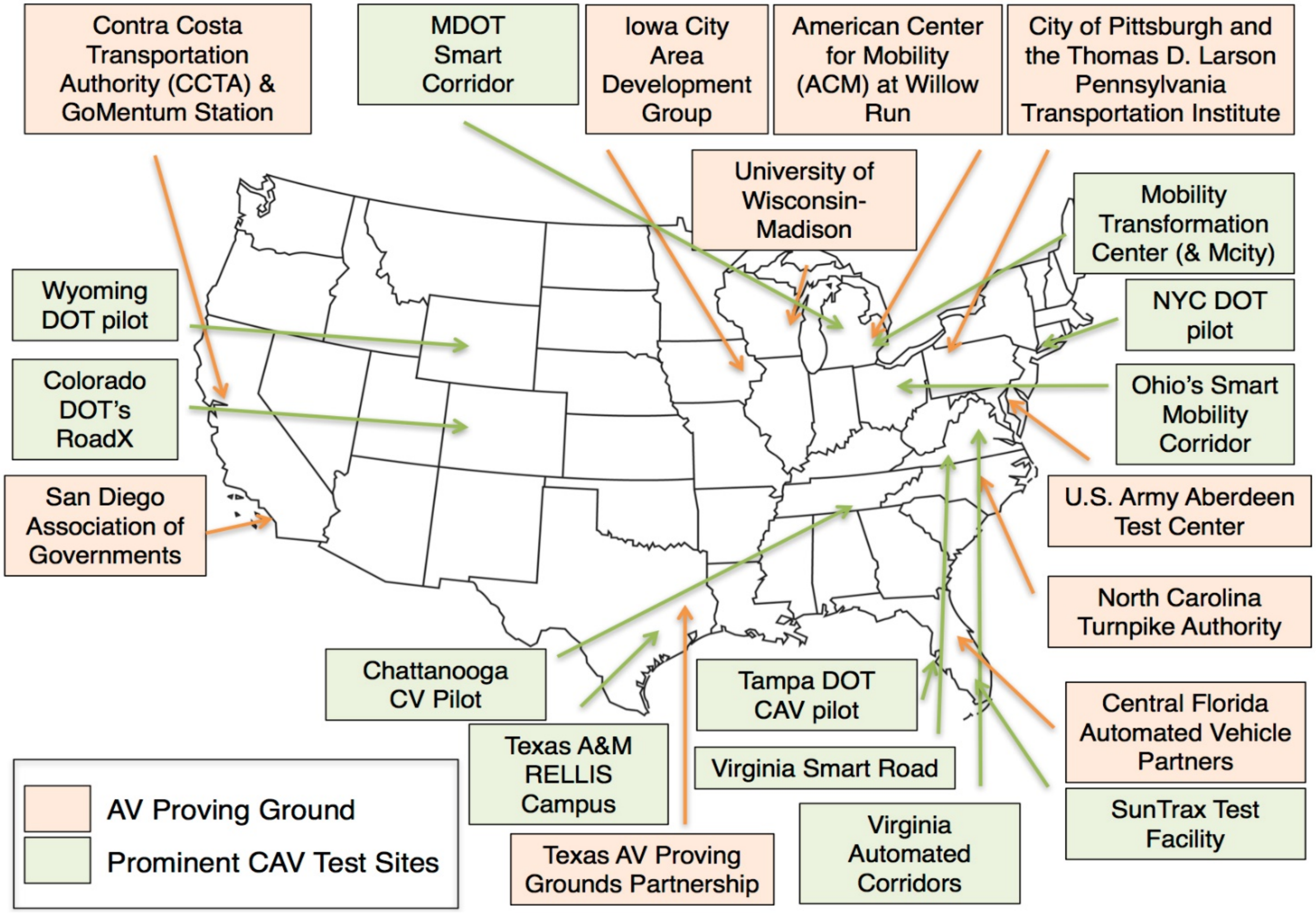
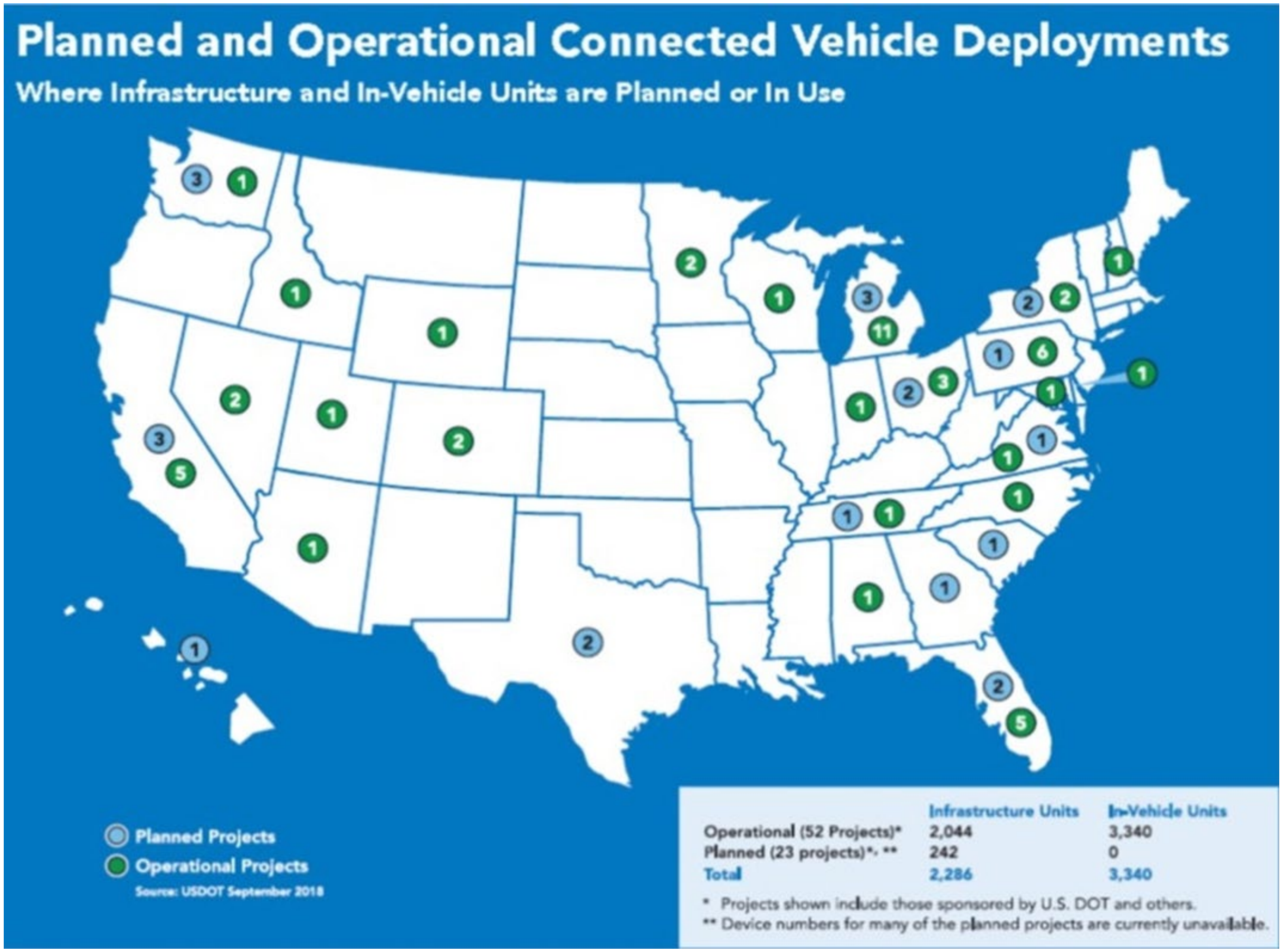


Figure 4.3 U.S. CAV Consortia Locations



	Infrastructure Units	In-Vehicle Units
Operational (52 Projects)*	2,044	3,340
Planned (23 projects)*, **	242	0
Total	2,286	3,340

* Projects shown include those sponsored by U.S. DOT and others.
** Device numbers for many of the planned projects are currently unavailable.

Figure 4.4 U.S. CV Deployment Locations (source: USDOT)

4.2.3 National CAV Policy Activities

Federal policy actions may build upon a substantial body of research conducted by the U.S. DOT, including the programs of the National Highway Traffic Safety Administration (NHTSA), FHWA, the ITS Joint Program Office (JPO), The Federal Motor Carrier Safety Administration (FMCSA), the Volpe Center and the Federal Transit Administration (FTA).

However, CAV policies may originate at any level of government: federal, state or local. Generally speaking, policy initiatives tend to lag behind technological developments. This is especially true in the case of AVs, and the sheer rate of technological change has militated against AV regulations and legislation. Despite decades of motor vehicle safety regulation at the federal level, AVs have been approached with a light regulatory touch, relying mainly on guidance and voluntary disclosure. Some states, including California, require the disclosure of limited ADS performance data – such as ADS disengagements – during the testing and early operational phases of AVs.

Generally speaking, federal and state research and deployment programs in CAV have been motivated by safety. The U.S. DOT has consistently promoted research and industry guidance to advance the deployment of connected CV technology (both V2V and V2I) and AVs. U.S. DOT research has shown that CV could address 80% of serious multi-vehicle crashes, and AV at the higher levels could avoid more than 90% of serious crashes, given the huge preponderance of human errors in crashes. Such findings have influenced the U.S. DOT to vigorously promote AV and CV in the surface transportation system. We have also seen CV programs on the part of many states, and active encouragement of AV deployment by numerous states and cities.

At the same time, CV and AV have profound implications for traffic efficiency, energy use and vehicle emissions. Both CV and AV tend to smooth traffic flow and may allow vehicles to operate with shorter headways, promoting more efficient use of road space. Experience so far has shown that even small percentages of CVs and AVs in the traffic stream have a beneficial effect on traffic flow, provided that they effectively mimic human drivers in their response to traffic signals and rules of the road. Note that many AVs are also likely to be electrified vehicles (EVs) with associated benefits – in many cases - for energy use and emissions.

A number of unknowns still exist for AVs, including mature norms for safety evaluation, cybersecurity, liability, impacts on professional drivers and city economics including land use.

Nevertheless, the potential contribution of AVs to safety, mobility and sustainability remains highly respected and supported by accumulating experience and evidence.

4.2.3.1 Actions of the Federal Government in the Introduction of CAVs

U.S. DOT CAV activities include sponsored research funded by NHTSA, FHWA, and the ITS JPO. These activities have focused on automated vehicle technology development and evaluation, policy assessment, and impact evaluation, among others. A sampling of sponsored research topics includes:[24]

- Safety standards – identifying where there may be challenges to certifying a range of AV concepts;
- Liability and insurance – synthesizing how AVs potentially impact current liability and insurance models; summarizing possible risk management or policy strategies;
- Legislation – reviewing existing vehicle safety legislation and pending state/local CAV legislation;
- Cooperative Adaptive Cruise Control (CACC) – looking at the ways to overcome the technical, institutional, and market barriers to deployment of this technology, which aims to increase traffic throughput by safely permitting shorter following distances between vehicles;
- Truck platooning – evaluating performance, technology, and commercial viability of truck-based CACC and Driver Assistive Truck Platooning applications;
- Enabling technologies – providing guidance with respect to the underlying enabling technologies common across automated and connected vehicles;
- Driver acceptance – examining critical human factors issues such as workload, situational awareness, and distraction for automation applications; and
- Best practices – developing a guide for jurisdictions in regulating AVs and driver testing.

In 2016, the U.S. DOT released its "**Federal Automated Vehicles Policy**" (*10*) that envisaged far-reaching principles and guidelines for the safety evaluation of HAVs. The policy package included a 15 Point Safety Assessment for the safe design, development, testing and deployment of

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[24] https://ops.fhwa.dot.gov/regulationpolicy/avpolicyactivities/

automated vehicles. In subsequent releases by NHTSA – titled *Automated Driving Systems: a Vision for Safety 2.0* and *Preparing for the Future of Transportation: Automated Vehicles 3.0* – refinements have been introduced, including:

- ADS Safety Elements (including voluntary safety self-assessment in the form of the Safety Assessment Report);
- Best practices for state highway safety officials;
- Focus on SAE Levels 3-5 – Automated Driving Systems (ADSs) – Conditional, High, and Full Automation; and
- Introduction of a "balance of capabilities" approach between the HAV and the infrastructure it operates upon.

At the time of writing, 12 Safety Assessment reports have been posted on NHTSA's website. These reports vary widely in scope and depth, but do provide an overall window on the nature of the design and testing process for ADSs, and its complexity and scale, as well as the steep rate of change in ADS design, particularly for sensors.

4.2.3.2 Actions of National Stakeholders

The **National Operations Center of Excellence (NOCoE)** is a partnership of AASHTO, ITE, and ITSA that also receives support from the FHWA. The NOCoE serves the transportation systems management and operations (TSMO) community by offering an array of technical services such as peer exchange workshops and webinars, ongoing assessments of best practices in the field, and on-call assistance.[25] It has two primary components: The Operations Technical Services Program, and a web portal that contains case studies, resources, links to information, discussion forums, and a calendar of TSMO-related events.

The goal of the NOCoE is to provide convenient access to key knowledge resources and the opportunity to discuss topics related to transportation systems management and operations. Included in these key knowledge resources are publications and other tools to help organize CAV stakeholders and share knowledge on CAV technologies and policies. By way of example, an

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[25] http://www.transportationops.org/overview-nocoe-and-its-programs

April 2017 FHWA study looked at how CAVs can be incorporated into an integrated corridor management (ICM) approach.[26]

The **Vehicle to Infrastructure Deployment Coalition (V2I DC)** - where the U.S. DOT joined with AASHTO, the ITE, and ITS America to create a single point of reference for stakeholders to meet and discuss V2I deployment issues – was rolled into **AASHTO's CAT Coalition** in 2018. The CAT Coalition facilitates cooperation between the infrastructure owners and operators (state, county, and local level transportation agencies), the automobile industry OEMs, aftermarket manufacturers and other stakeholders required to deploy and operate CAVs nationwide.

In 2017, the V2I DC (now the CAT Coalition) started a new initiative called the **AASHTO SPAT Challenge.** The charge of this group is to mobilize state and local public sector infrastructure owners and operators to achieve deployment of DSRC infrastructure with SPAT, MAP, and RTCM broadcasts in at least one corridor or network (approximately 20 signalized intersections). The goal is a SPAT Corridor in each of the 50 states by January 2020. Ideal SPAT Challenge corridors are envisioned to have:[27]

- Signalized intersection scope of approximately 20 signals;
- Modern controllers with in-cabinet equipment to support the interface with a DSRC radio (the "roadside unit" or "RSU");
- Backhaul communications with sufficient bandwidth from the corridor either from each signal or from a master; and
- The ability to broadcast MAP/GID (Geographic Intersection Description) data.

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[26] http://www.transportationops.org/publications/leveraging-promise-connected-and-autonomous-vehicles-improve-integrated-corridor

[27] http://www.transportationops.org/sites/transops/files/SPaT%20challenge%20Folio%20imposed.pdf

4.3 Preparatory Activities by States

The previous section summarized the current state of CV and AV technology and deployment in the United States. The focus of that section was primarily on nationally led (or nationally recognized) deployment and policy activities but there are also a number of state-led activities that provide good examples of CAV preparation and leadership.

In this section, we first provide a summary of the CV and AV activities that have been conducted in California to date. Next, we give a summary of CAV progress being made in other leading states. The section concludes with an analysis of how California compares to the states that are leading the way in CAV preparation and leadership.

4.3.1 CV and AV Activities in California

4.3.1.1 California CV Activities

Caltrans and PATH have developed a partnership over the past 20 plus years as leaders in research and testing of CV technology. California's involvement in CV research and testing dates back to 2005 when the nation's first ever state-funded CV testbed was established on State Route 82 (El Camino Real) in Palo Alto and the surrounding area. In addition, Caltrans has been an active member of the CV Pooled Fund Study[28] (PFS), a group of 18 state and local transportation agencies focused on preparing for the deployment of connected vehicle infrastructure. The PFS members are in their eighth year of a multi-phase program that facilitates field demonstration, deployment and evaluation of connected vehicle infrastructure and applications at the local level.

One of the more high-profile PFS projects, the development and field testing of a Multi-modal Intelligent Traffic Signal System (MMITSS), was successfully demonstrated on California's CV Testbed in 2015. This demonstration is noteworthy since it involved the integration of MMITSS software and Dedicated Short-Range Communications (DSRC) technology into Caltrans-operated traffic signal controllers in a live traffic environment. Further, MMITSS demonstrated the

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[28] http://www.cts.virginia.edu/cvpfs/

potential to improve traffic operations along the corridor through better signal timing, reduced idling and offering safer conditions for pedestrians and cyclists.

In 2016, Caltrans initiated two new projects with UC Berkeley PATH and UC Riverside to enhance the CV testbed and applications on El Camino Real and improve the testbed's reliability for use by private sector partners. Under those efforts, each of the 11 testbed intersections was equipped with the latest CV technology and integrated with Model 2070 traffic signal controllers. This has enabled broadcasts of signal phase and timing (SPAT) and MAP messages over DSRC to CV-equipped vehicles. In addition, PATH and UC Riverside enhanced previously developed applications such as MMITSS with new algorithms for transit signal priority (TSP) and developed new applications such as Eco-Approach and Departure (EAD) at Signalized Intersections. In the near future these applications will be tested using CV-equipped buses from partner transit agency Valley Transit Authority (VTA)

Starting in January 2019, Caltrans has been working with PATH to expand its size from its current 11 intersections to 31 intersections between Medical Foundation Drive in Palo Alto and Grant Rd in Mountain View. This expansion is expected to be completed in late 2019 and will support future CV application testing including red-light violation warning, pedestrian safety and bicycle detection and priority. It is expected that this connected vehicle corridor will serve as a model deployment that can be duplicated on similar corridors in other urban regions of California.

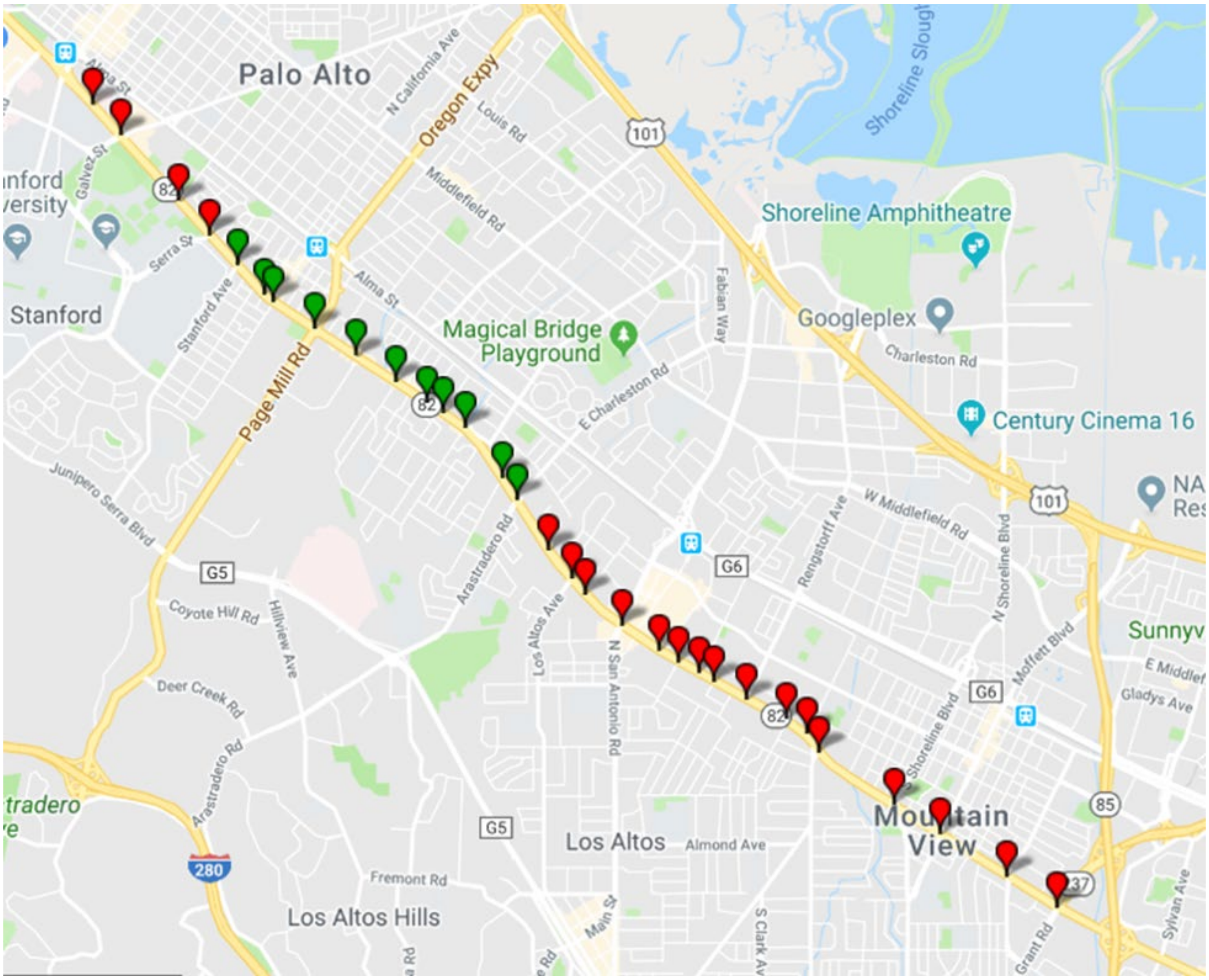

Figure 4.5 California CV Test Bed (existing in green, planned in red)

Aside from the CV Test Bed in Palo Alto, there are four other CV deployment sites in California that have been installed by local transportation agencies. These include:

- LA DOT deployment of DSRC and transit signal priority along 50 intersections near Hollywood Blvd (supported by a USDOT grant);
- City of Anaheim deployment of DSRC at 10+ intersections near Disneyland;
- LA Metro, LA County, and the City of Carson deployment of DSRC and freight signal priority at 10+ intersections; and
- San Diego Port Tenants Association deployment of DSRC and freight signal priority at 12 intersections near the Port of San Diego.

4.3.1.2 California AV Activities

AV Regulations

California has been a leading state in terms of setting regulations for the safe operations of AVs. California DMV has been the lead agency for setting AV regulations in the state. On September 16, 2014, they started allowing for HAV (Level 3-5) testing on public roadways with a safety driver in the driver's seat. The second round of regulations took effect on April 2, 2018 which allowed for true driverless testing and deployment. Waymo recently became the first company to receive permission to test on California roadways without a human driver.

DMV requires all companies who wish to test or operate AVs to acquire a testing or operations permit and report all accidents and disengagements to DMV. As of November 30, 2018, DMV had reported the following:

- 64 Manufacturer Testing Permits issued (60 Active);
- 638 AV's permitted for operation on public roads;
- 2092 qualified Test Drivers; and
- 115 collisions reported.

Truck Platooning

Aside from AV regulations, California has also been a leading state in the area of partially-automated truck platooning. Caltrans, PATH, and Volvo recently completed an FHWA-funded research project to develop and demonstrate a 3-truck platoon using cooperative adaptive cruise control (CACC) technology. CACC controls the speed of the truck using V2V communications and other sensors allowing them to follow at close headways. It has shown the potential to save 5-13% on fuel usage at gaps of 0.6-1.8 seconds. Caltrans and the I-10 Corridor Coalition are supporting a new PATH/Volvo project that will deploy and assess truck platooning in an operational setting. This new project is also funded by FHWA and it kicked off in March 2019.

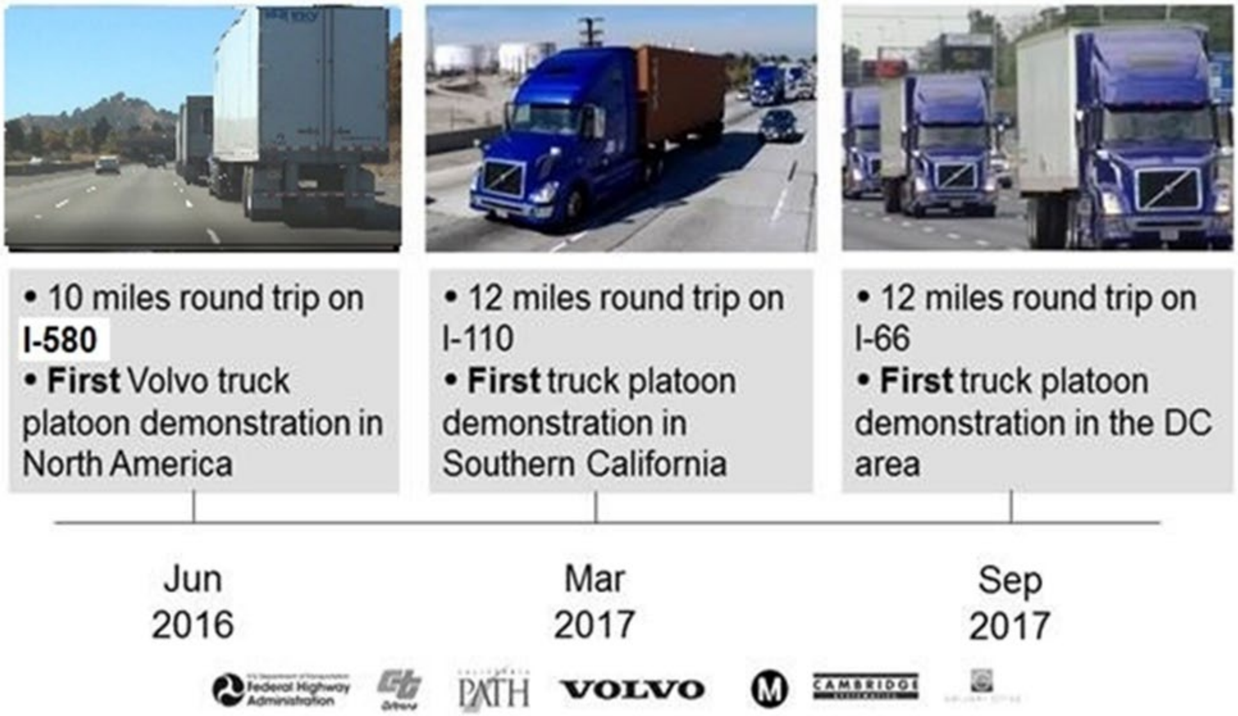

Figure 4.6 California Truck Platooning Project Milestones

AV Proving Grounds

California has two major AV testing sites that allow for controlled AV testing. As mentioned in Section 2, GoMentum Station in Concord, California currently is the largest secure testing ground for CAVs in the country. AV testing takes place in a controlled environment on the facility's roadways, and CV testing takes place by using the facility's smart (V2I) infrastructure, including traffic signals. GoMentum is currently being managed by AAA of Northern California and recent collaborators have included Toyota Research Institute, Honda, Uber, Lyft and Easymile.

The other AV testing site in California is the San Diego Regional Proving Grounds (RPG) which are managed by SANDAG, in partnership with Caltrans District 11 and City of Chula Vista. San Diego RPG includes the following facilities: I-15, State Route 125, Chula Vista, and Miramar Marine Corps Air Station (see Figure 4.7). The RPG consortium kicked off in October 2017 with a goal of facilitating testing and validation of CAV technologies while ensuring public safety and security. Key consortium partners include Ford, Qualcomm and others.

Figure 4.7 San Diego Regional Proving Grounds

AV Working Groups

Although a formal statewide council or advisory body focused on CAV issues has not yet been established by the governor's office or state legislature, California does have at least two informal AV working groups that have been meeting regularly for the past few years. The "California Transportation Agency AV Visioning Group" is comprised of representatives from Caltrans, CalSTA, CHP, DMV, OTS and other agencies. They meet periodically to discuss how to prepare for AV technology and to share information on each agency's activities related to AVs.

In addition, the "California Multi-Agency Work Group on AVs" develops draft public policies for AV's primarily related to sustainability and public health. They are comprised of staff from a number of California agencies including Caltrans, CalEPA, CalSTA, CARB, CDPH, CEC, DGS, DMV, OPR, and others. This multi-agency working group works to ensure that CV and AV transformation accelerates in California with clear environmental benefits and attention to equity issues. The group has established a list of AV principles for healthy and sustained communities that can be found here: http://opr.ca.gov/docs/20181115-California_Automated_Vehicle_Principles_for_Healthy_and_Sustainable_Communities.pdf

4.3.2 CAV Actions in other States

The project team has collaboratively investigated CAV actions taken by several states. While some actions by states are relatively well-publicized, the full range of activities is less well documented, and rarely aggregated in an impartial manner. The full range of such actions shows a certain degree of commonality (as discussed in the next section), and covers many aspects such as planning, testing, deployment, research, industry collaboration and legislation.

Several states were selected for consideration based on the breadth (and depth) of their CAV activities, and California was included in the analysis. The states included were:

- California;
- Colorado;

- Florida;
- Michigan;
- Pennsylvania; and
- Virginia.

Aspects of CAV activity included in our analysis were:

1) AV legislation: core legislation is in place, usually part of a dynamic process evolving with the state's experience of AVs;
2) Embracing CAV in mainstream transportation planning processes: it is recognized that CAV is potentially transformational, is not a stand-alone initiative, and should be fully tied into the state's overarching transportation efforts, including traffic systems management and operation (TSMO) and congestion management; CV is leveraged to advance CAV objectives;
3) CV test beds, pilots, and consortia: as a first step in CV programming, test beds provide learnings to expand CV and then CAV activities; test beds provide the groundwork for assessment and further CV deployment; as initiatives evolve, pilots and consortia involve significant numbers of vehicles and industry/academic partnerships;
4) CAV strategic, business, or program plan: a policy blueprint for CAV has been developed, bringing together CV, AV, and related transportation efforts, under one umbrella approach;
5) AV testing and CAV test beds: AV testing on public roads is underway, often prompted by the presence of a major company wishing to test its technology under a range of operating conditions; the state interfaces with test conditions and scenarios that speak to AV preparedness; CAV test beds are established where states and vehicle manufacturers work on the conditions for a successful deployment;
6) State collaboration and partnership with technology companies: unique deployments are developed, often with local companies of significance;
7) Systematic infrastructure methodology for CAV deployment: a longer-term, staged approach is taken to the deployment of CV underpinnings and technology layers in corridors, zones and roadway classes; and
8) CAV Advisory Council: multiple state agencies, industry and academia come together to consider CAV in a broad context of mobility, community access and economic development.

4.3.3 Examples of CAV Leadership Actions by Individual States

4.3.3.1 AV legislation

The passage of SB 17-213 directed the Colorado Department of Transportation (CDOT) and the Colorado State Patrol to develop a process whereby autonomous vehicles equipped with automated driving systems that are not able to fully obey the laws of the road may be approved for testing in

Colorado. According to CDOT's website, "Colorado is home to one of the friendliest policy environments in the country for operating autonomous driving systems, or autonomous vehicles."

Florida Statutes Section 316.85 allows for the operation (testing and use) of AVs on public roads without an "operator" physically in the vehicle. Florida had previously allowed AVs only for testing, but removed that limitation in 2016, along with the requirement that the vehicle "operator" be present in the vehicle.

Michigan passed new AV legislation in December of 2016 (S995, 996, 997, and 998), which establish regulations for the testing, use, and eventual sale of autonomous vehicle technology and are meant to more clearly define how self-driving vehicles can be legally used on public roadways. The law specifies the conditions under which driverless vehicles can be tested and used on public roads

Pennsylvania requires a seated and licensed driver able to assume control if necessary (unmanned and/or remote testing on public ways is prohibited). There are no current laws or regulations which require AV testers to report testing activities to PennDOT.

Virginia's legislation is minimal and is meant to create an environment in which Virginia is "open for business" with minimal regulations.

4.3.3.2 CAV in transportation planning

As part of its overarching planning efforts, Colorado intends to position CAV to turn roads into information freeways that need to be planned, built, managed, and maintained in a very different manner from the basics of asphalt or concrete. Florida's extensive commitment to Transportation Systems Management and Operations (TSMO) has led to a robust TSMO Strategic Plan that includes the CAV program as one of the priority focus areas.

Michigan's 5 Year Transportation Plan incorporates a CAV component and ties to the CAV Strategic Plan. As a state with significant experience in this area, given its unique partnership with the family of automakers within its borders, Michigan's "rolling" planning process continually updates its CAV focus with the latest improvements and initiatives captured through an MDOT/industry partnership.

CAV is tied to PennDOT's safety vision and addresses capacity management and congestion reduction. The work that has been taking place via a number of research initiatives within Pennsylvania has helped inform the state's role as a full partner in the field.

The Commonwealth of Virginia's statewide long-range plan, VTrans2040, and the 2017 Virginia Highway Safety Plan both include CAV topics as important elements. Virginia's CAV Program Plan was one of the first in the country.

4.3.3.3 CV test beds, pilots and consortia

In Colorado, an extensive effort is being made to establish a comprehensive CV program framework before building out how AV relates to - and can be based on - CV. It is a helpful reminder to get the CV side right, first, before amalgamating AV efforts integrally with infrastructure.

Florida's TSMO Plan addresses CV, including: DSRC for V2I communication, SPAT, Basic Safety Messages (BSMs), transit, pedestrian safety, freight and emergency vehicle priority. A U.S. DOT connected vehicle test bed is underway in Tampa and is helping to inform a more comprehensive network.

Michigan operates several CV test beds in corridors as well as urban zones and hosts federal research, such as the Ann Arbor Connected Vehicle Test Environment (AACVTE).

Pennsylvania and Virginia operate several CV test beds in corridors as well as urban zones. In the former case, the state is committed to a multistate corridor (including Ohio and Michigan) to further test and expand its network. Virginia seeks to make its corridors available to use by an array of research from both the private sector and academia, with its in-state institutions playing a strong role.

4.3.3.4 CAV strategic, business, or program plans

Michigan and Pennsylvania have CAV Strategic Plans in place that merit review for the methodology and approach, and relevance to the Californian environment. Virginia has a very robust CAV Program Plan; Florida's draft CAV Business Plan has been completed and Colorado has created a CAV Framework that is serving as the basis for both its TSMO efforts as well as cross-cutting considerations in all CDOT functions.

4.3.3.5 AV testing and CAV test beds

In Michigan, a range of activities is underway via MCity and the American Center for Mobility (ACM).

In Pennsylvania, testing is underway in Pittsburgh and selected sites via technology partners.

Florida, Colorado, and Virginia encourage partnerships with the private sector to bring testing to their states with the intention that it will assist, in part, the states' refinement of their infrastructure capabilities to embrace AV into a CAV framework.

4.3.3.6 State collaboration with technology companies

Colorado has established significant partnerships with Panasonic, QualComm, and Ford.

In Michigan, the automotive industry – especially GM, Ford and Toyota – have significant partnerships with Mcity, ACM and other locations.

In Pennsylvania, long-standing AV partners include: Aptiv, Argo AI, Aurora, Carnegie Mellon University, Royal Truck and Equipment, Uber and Volvo.

In Virginia, there is extensive collaboration with state and non-profit partners, academia, and the private sector, including: Virginia Transportation Research Council, GMU, ODU, and UVA. The Virginia Tech Transportation Institute (VTTI) works extensively with private sector and VDOT contracts.

Florida's newly created CAV Business Plan provides the basis for collaboration with industry. It notes "Collaborating with industry leaders, researchers, and the private sector can assist FDOT to better prepare for leveraging opportunities and addressing challenges of CAVs." A key action item is to "Provide Opportunities for Industry Partners to Test Hardware and Software."

4.3.3.7 Systematic infrastructure methodology for CAV deployment

Colorado has a comprehensive approach, with planned phases tackling their "Internet of Roads". According to its program overview, "In a world where vehicle decisions and movements are communicated wirelessly to humans or automated vehicles (AV), CDOT will have new tools to systematically improve safety and efficiency, while providing robust and timely information to both humans and vehicles."

Michigan's rolling five-year transportation plan and the Michigan Council on Future Mobility maintain a "live, ongoing setting" for innovation and implementation. This is reflected significantly in the continuous improvement the state brings to bear in its planning and execution, all to ensure it remains current, if not ahead of the curve when applying innovative solutions.

Pennsylvania's long-term goal is framed in their CAV 2040 Vision which is based on the "assumed condition that connected and autonomous technology will be incorporated into all motor vehicles by 2040." The Vision document goes on to state that "while the actual date for full incorporation will depend on the pace and scale of connected and autonomous technology adoption, the assumed 2040 date in this report provides context for PennDOT decision makers facing a future involving these vehicles."

Virginia states that "the deployment of CAV technology and applications will be a phased approach spread out over the next 20 years." The approach supports the state's pragmatic thinking about what works, while retaining a long term contextual setting in which key outcomes for safety and mobility remain in focus.

4.3.3.8 CAV Advisory Council

In Colorado, CDOT works extensively to partner with local, regional, and national stakeholders to reach consensus and align efforts. The state's Autonomous Mobility Task Force is actively involved in providing guidance on AV testing.

The Michigan Council on Future Mobility advises the Governor on transportation innovation, with CAV as a central set of technologies to benefit communities and the economy. Its first two annual reports reflect a deep awareness and engagement designed to respond to the rapid movement of the technologies and the importance of aligning solutions to meet the state's safety and mobility goals.

Pennsylvania has established the AV Policy Task Force, and Virginia the Connected and Automated Vehicle Executive Steering Committee. Although Florida has not yet created a similar entity, its business plan identifies education and outreach as essential, not just to disseminate information on CAV, but also to ensure feedback and collaboration with stakeholders.

It is important to note that these advisory bodies in one form or another are meant to ensure a more holistic, consensual approach toward greater CV/AV/CAV deployment. And while each state has taken its own approach, the absence of a state-wide body comprising DOT and other entities, and constituted to provide high-level CAV vision, advice, consensus, and coordination can impede effective solutions.

4.3.4 Comparison of California with Other States

When assessing CAV activity and leadership state by state, one can look at the critical themes of CAV preparation and planning that were introduced in section 3.2. In the previous section the project team investigated CAV actions taken by several states. Section 3.1 introduced a number of CAV activities taking place in California. The full range of such actions shows a certain degree of commonality, and covers many aspects such as planning, testing, deployment, research, industry collaboration and legislation.

Table 4-1 below summarizes the CAV preparation progress made by California and the six states investigated in the previous section. The other states were selected because of the breadth (and depth) of their CAV activities, and California was included in the analysis for comparison purposes. The matrix shows where progress has been made state by state across each of the eight critical themes.

Table 4-1 Matrix of CAV Initiatives in Key States

Theme	CA	CO	FL	MI	PA	VA
1. AV Legislation	Y	Y	Y	Y	Y	Y
2. Embracing CAV and aligning it with Existing Transportation Plans	N	Y	Y	Y	Y	Y
3. CV Test Beds, Pilots, and Consortia	Y	Y	Y	Y	Y	Y
4. CAV Strategic, Business, or Program Plan	TBD	Under Dev.	Y	Y	Y	Y
5. AV testing/CAV Test Beds	Y/TBD	Y	Y	Y	Y	Y
6. Prominent Role of Technology, Collaboration, and Partnerships	Y	Y	Y	Y	Y	Y
7. Comprehensive Approach and Long Term View	N	Y	Y	Y	Y	Y
8. CAV Advisory Body	N	N	Y	Y	Y	Y

In short, California has made great progress and has a solid foundation in terms of CAV preparation, but there is still work to be done to further the work across the eight thematic areas. In particular, California needs to develop a CAV Strategic Plan that is authentic to the state's strengths and special circumstances and consider integrating CAV into their existing planning processes. They should also look for more opportunities to engage with the private sector on AV testing activities to better understand how infrastructure can be adapted to support AV operations. Caltrans could take a lead role in these activities.

4.4 Caltrans CAV Workshop Findings and a Path Forward

On April 18, 2019 Caltrans held an all day workshop focused on planning and preparing for connected and automated vehicle (CAV) technology. The workshop was held in the Basement Board Room at Caltrans Headquarters in Sacramento and was organized by Division of Research, Innovation and System Information (DRISI). The morning session was moderated by Pete Hansra from Caltrans DRISI. The afternoon session was facilitated by California PATH and their partners CAVita. There were over 30 attendees at the event including Caltrans Director Laurie Berman and other executive level representatives from Caltrans Headquarters, Caltrans Districts, California State Transportation Agency (CalSTA) and California Department of Motor Vehicles (DMV). A full list of attendees is included in Appendix A.

The CAV Workshop was designed to help Caltrans address a CAV planning framework that will:

- Accelerate California's state of preparation for CAV technologies;
- Promote best practice in state-level actions in CV, AV and CAV; and
- Facilitate the development of a CAV strategic plan and alignment with other state transportation plans.

An earlier version of this chapter was provided to all workshop invitees in advance of the event to serve as a primer. The one-day workshop was mostly internal, with a wide representation of Caltrans divisions and districts, but it also included representatives from CalSTA and DMV. An outline of the workshop program is provided in Appendix B. The morning plenary session focused on the current status of CV and AV development in California and other leading states, progress at the national level, and Caltrans interests in better coordinating its CAV activities and in accelerating the agency's leadership position in CAV preparedness. In the afternoon, roundtable discussions were held to review CAV planning options and contribute to Caltrans CAV preparation and coordination structure. The workshop concluded with a summary of the key findings and next steps captured from the discussion.

4.4.1 Key Findings

There was lively discussion throughout the CAV Readiness Workshop and almost everybody in attendance participated in the discussions. This is a clear indication that Caltrans executive leadership is fully engaged in the topic of CAV preparation and leadership. As the afternoon discussions progressed, it became clear that there were a few major topic areas that were of greatest concern and became the focus of the group. These topic areas were:

- Perceived status of the technology;
- Opportunities and risks with CAV deployment;
- Positioning Caltrans for CAV deployment; and
- Coordination of Caltrans CAV activities.

The highlights of the discussions around each of these topic areas is provided below.

4.4.1.1 Perceived Status of the Technology

The group recognized that CV is, in certain respects, more developed and better understood than AV. While it is accepted that deployment of CV will eventually be beneficial for AV, there is some current confusion concerning the communication standard to be used. While the performance and benefits of CV technology such as DSRC have been proven, it is not clear how its parallel deployment in vehicles and infrastructure can be managed. There are also significant concerns that a cellular alternative to DSRC, often referred to as C-V2X, will be preferred by some major automakers.

Nevertheless, Caltrans' depth of experience in deploying CV, using DSRC in roadside equipment, provides some confidence in moving forward with such deployments. There is a likelihood that both DSRC and C-V2X will be used – by different OEMs, but also with both modes in the same vehicle.

On the AV side, California has experience with AV test beds, AV testing on public roads, and with AV legislation. However, the group is not satisfied with the extent of Caltrans' interaction with the industry's test programs and the exchange of information. Many feel that they are very much "in the dark" concerning industry intentions and needs. There is a strong desire for positive

Caltrans action in this respect. This was seen as a major positive for the state – in the light of federal inaction – and would fit with the progressive image of the state in matters automotive.

4.4.1.2 CAV Deployment – Opportunities and Risks

The urgency for action on CAV was present across the whole discussion, although many asked for clarifications to separate out elements that are ready to become operational, as distinct from those that remain in the domain of research. There is also a desire to understand both short-term implementation and long-term deployment. Part of the concern with getting started is that inventories of the current system are not sufficiently advanced to make decisions about deployment locations. There seems to be a backlog of preparatory activities that should not be delayed awaiting more clarity on the many CAV unknowns. This imperative fits with a general desire to "move CAV out of research and into operations", even though there is recognition that some aspects are still subject to research questions.

The group is extremely aware of AV safety risks – particularly in the early stages of deployment – but is also attracted to the long-term safety benefit of less human error. Caltrans' role in getting from today's human-dependent system to an autonomous future is not yet fully understood. It is not clear how the safety of workers, pedestrians and cyclists will be protected with increasing numbers of CAVs. How will they be detected, and the data sent to AVs? Social equity needs to be protected; how will those lacking the means for AVs and mobility as a service (MaaS) move around? Will there be new forms of liability for infrastructure owner operators (IOOs) who design roadways to favor AVs over human drivers?

However, there is a strong belief in the potential of properly-deployed AVs to reduce serious crashes in a way that has eluded OEMS and IOOs over a long period of automotive history. This would apply to Caltrans' own vehicle fleet, where employees would be a lot safer with CAVs. The group is less clear about AV impacts on VMT, traffic congestion, social equity and sustainability; a number of concerns were expressed in these areas.

The group is also extremely conscious of the broad mobility focus that needs to accompany a new CAV direction for Caltrans. It is important that the people of the state benefit broadly, including bikes, pedestrians, transit, and all age groups. A broad framework of state agencies should therefore be leading the conversation.

4.4.1.3 Positioning Caltrans for CAV Deployment

Some at the workshop advocated strongly for a greater Caltrans focus on the benefits of CAV, rather than the problems and the risks. The question was asked: what are the opportunities that we are not taking? How to we match up the CAV potential with the needs of California's population? It was suggested that Caltrans should take the focus off the physical infrastructure – where affordability is a perennial issue – and concentrate more on solutions in the domain of ITS.

There is a desire to convert the research into workable standards for basic items such as striping, signs and crack sealing, but there is "no one right way of doing it". Interaction with the industry "to ask what they want" is a basic first step. But it is necessary to mobilize an overall CAV course for Caltrans based on what we know now. This would include partnerships with entities that want to work with Caltrans. OEMs are designing AVs based on the state of the current infrastructure; likewise, Caltrans should be accommodating current AVs – and their manufacturers - in infrastructure maintenance and design. Similarly, Caltrans could provide a strong national voice for the deployment of DSRC, rather than waiting for the current spectrum stand-off to be resolved by others.

The overall impact of CAV on VMT and traffic congestion is a critical consideration for Caltrans. "Unregulated rollout of competing AV technologies" will lead to more congestion and unsustainable emissions and energy use. There is a need for Caltrans to "put a stake in the ground" so that the AV operating point – for example, vehicle speeds – will be more efficient and sustainable, not less. A more assertive role for Caltrans was a discernible part of the discussion. For example, should vehicles be designed for a lane type that suits Caltrans?

The trucking industry is an early adopter of CAV. The industry currently relies on information to fully exploit the state infrastructure. Projections of marked increases in freight truck traffic within the next five years point to exploitation of platooning technology. The deployment of truck platooning should be a major focus of Caltrans in the immediate term. Care is needed because we will see more truck VMT when the constraints of the driver shortage are lifted in favor of automation. Consideration of managed lanes for such freight vehicle technologies may be required. Again, it was suggested that Caltrans should take an assertive role with the freight applications of CAV and how they will impact Caltrans in the short term.

Organizational matters were also raised, especially related to a stronger involvement of traffic operations, in addition to DRISI. The need for a forum engaging traffic engineers was raised.

4.4.1.4 Coordination of Caltrans CAV Activities

Significant elements of the roundtable discussion focused on potential CAV roles and actions to be carried out by Caltrans' main operational entities: the divisions and districts. The discussion highlighted the need for collaboration between divisions, particularly the nexus between traffic operations, maintenance and planning.

Caltrans has difficulties in planning for 5-year and 10-year horizons given that CAV brings great promise, but also great uncertainties. For example, the central place of safety in Caltrans thinking demands a degree of certainty: will fatalities continue to be caused by human errors, or would a stronger focus on CAV provide a path to zero fatalities? Significant decisions are involved because they include recruit and retain technical workforce and coming up to speed with the technology. There is also a need for new planning tools and resources.

The use of historical data and travel demand models becomes problematic with CAV. Do we actually have alternative futures to deal with? There are too many questions. There is a desire to "abandon caution" and move quickly with joint planning efforts, perhaps beginning with a combined effort by *planning* and *operations*. From a maintenance perspective, the systems aspect of CAV presents challenges in monitoring and planning across divisions.

Internal cooperation was a major theme of the discussion. The need for close coordination between DRISI, operations and maintenance was raised as a prime example, along with *operations* and *planning*. And it was recognized that a certain degree of standardization would be needed to underpin such cooperation.

This need for coordination of CAV activities extends to programming. There is a need for a separate account for CAV, and a recognition that new inventory will be added. New money will be needed and there were various suggestions about new sources of revenue to fund CAV investments. This would need to be the subject of a further, less technological, group discussion.

Finally, the important issue of communication to the public was raised briefly. This was considered too large of a topic for the current discussion, but a consistent set of talking points will be needed, with an overall aim of "putting the safety of the public first and foremost".

4.4.2 Next Steps

Based on the findings from the CAV Workshop, there are a number of potential actions that could take place as California considers next steps on the road to CAV readiness. They include short and medium term considerations. Some can be accomplished in a straightforward manner and some will require greater time and effort and consensus building. A summary of recommended next steps is provided below.

4.4.2.1 Short Term Actions/Initial Steps

There are a number of actions that Caltrans can take in the short term (next two years) to initiate the CAV planning process. Caltrans should assess opportunities internally as well as plan for broader involvement by consulting with partner state agencies and the private sector. Short-term actions are grouped below as either internal actions, partnerships with other agencies or collaboration with the private sector.

Internal to Caltrans

- Formulate an internal executive leadership team at Caltrans to guide CAV policy
- Formulate an internal working group at Caltrans to execute CAV activities
- Identify a comprehensive picture of the stakeholder community for CAV in California both within Caltrans and external to Caltrans
- Establish a Caltrans CAV Strategic Plan
- Develop a CAV Implementation Plan that complements the Strategic Plan and provides a tactical list of near-term CAV activities for Caltrans operating units
    - As an example, Caltrans should install and maintain clear and conspicuous pavement markings and standardized roadway signage.
- Continue to expand and enhance the California CV testbed in Palo Alto and partner with local agencies and industry to deploy and test CV applications in an operational environment (e.g. CV-based transit signal priority)

- Support and/or participate in a high-profile demonstration of CAV technology at the 2020 ITS World Congress in Los Angeles
- Integrate CAV considerations in all aspects of transportation planning in the state
- Explore availability of federal funding and track federal CAV policy to support and inform California CAV implementation
- Influence future policy (state/federal) to enhance transition to CAV
- Recruit and retain a technical workforce that is equipped to handle CAV technology

Partnerships with other California agencies

- Launch a Governor's Office lead statewide CAV task force/advisory group for policy, technology, and infrastructure:
    - Develop a charter to provide direction, responsibilities, and priorities.
    - Include: OPR, CalSTA, Caltrans, CHP, DMV, OTS, CPUC, CalEPA, CARB, CDPH, CEC, DGS and other agencies as necessary
- Develop a statewide CAV planning framework with high-level goals that incorporate both traditional transportation goals with environmental, energy, and social equity considerations
- Establish a CAV Strategic Plan for California that includes more State agencies and complements the one developed for Caltrans
- Develop a return-on-investment for CAV that will help make decisions for prioritization, funding, and stakeholder involvement
- Strengthen the state partnerships with the California AV test beds, learning from their efforts to inform the state's own CAV initiative
- Identify (in order to leverage) technologies/capabilities already available to develop a phased CAV implementation plan
- Provide incentives and even financial support to encourage regional, county and local agencies to do more
- Identify workforce challenges and needs and embolden state efforts to recruit and retain the workforce of the future to sustain CAV
- Encourage widespread deployment of CAV infrastructure

- Support efforts produced by the AV Visioning sessions

Collaborations with Private Sector

- Hold AV Summit and engage the AV industry to establish partnerships with OEMs and related AV companies
- Survey the private sector on their priorities for infrastructure enhancements that are needed to support AV operations
- Maintain effective links with the research community and private sector to enhance CAV implementation
- Integrate findings from collaborations with the private sector into CAV Plans

4.4.2.2 Medium Term Actions/Integrative Steps

Medium term actions are those that should be taken in the next 3 to 5 years. These steps are often more complicated and costly and have the potential to impact multiple Caltrans departments or other state agencies. As such, these should be more thoroughly vetted through a formal CAV planning process.

- Adapt/evolve the CAV Strategic Plan(s) to learn from early implementation efforts
- Restructure Caltrans to better support and manage CAV
- Enhance the state's advisory mechanisms meant to inform CAV
- As directed in Senate Bill 1 (SB1), to the extent possible, and where feasible, install advanced technology on the transportation infrastructure to support CAVs
- Install and operate CAV systems at key roadside locations such as signalized intersections and ramp meters
- Facilitate high precision digital mapping of the state's roadway infrastructure
- Provide infrastructure-based sensing to identify hazardous conditions that can be communicated to CAVs
- Incorporate AV technology into state fleets

- Provide a comprehensive real-time database about work zone operations and emergency response actions that may impede travel of AVs
- Provide smart parking facilities that can facilitate use of automated valet parking systems by vehicles
- Support reconfiguration of urban or suburban streets to provide some separation between conventional traffic, low-speed AVs, and bicyclists and pedestrians to improve safety for all of them.
- Reframe funding channels for CAV in light of statewide engagement with the stakeholder community
- Establish and maintain California's role as a leader in CAV in the United States and around the world

4.5 References of Chapter 4

[1]. Mohaddes, A. Sweatman, P. (CAVita, LLC) *Transformational Technologies in Transportation – State of Activities*. Transportation Research Board, May 2016. http://onlinepubs.trb.org/onlinepubs/circulars/ec208.pdf

[2]. CAVita LLC (2017) Connected and Automated Technologies and Transportation Infrastructure Readiness. Prepared for NCHRP 20-24(111

[3]. *The Transforming Mobility Ecosystem: Enabling an Energy-Efficient Future*. U.S. DOT. January 2017. https://energy.gov/sites/prod/files/2017/01/f34/The%20Transforming%20Mobility%20Ecosystem-Enabling%20an%20Energy%20Efficient%20Future_0117_1.pdf

[4]. *Connected/Automated Vehicle Research Roadmap for AASHTO*. Project 20-24(98). http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-24(98)_RoadmapTopics_Final.pdf

[5]. *Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies*. NCHRP 20-102. http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3824

[6]. *Challenges to CV and AV Applications in Truck Freight Operations*. NCHRP 20-102(03). http://www.trb.org/Publications/Blurbs/175965.aspx

[7]. *Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems*. SAE International, September 2016. http://standards.sae.org/j3016_201609/

[8]. *U.S. Department of Transportation Designates 10 Automated Vehicle Proving Grounds to Encourage Testing of New Technologies*. U.S. DOT, January 2017. https://www.transportation.gov/briefing-room/dot1717

[9]. *Federal Automated Vehicles Policy*. U.S. DOT and NHTSA, September 2016. https://www.transportation.gov/sites/dot.gov/files/docs/AV%20policy%20guidance%20PDF.pdf

[10]. *Automated Driving Systems 2.0: A Vision For Safety*. U.S. DOT and NHTSA, September 2017. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf

[11]. *Preparing for the Future of Transportation: Automated Vehicles 3.0.* U.S. DOT and NHTSA, November 2018.

[12]. *FMVSS No. 150 – Vehicle-to-Vehicle Communication Technology For Light Vehicles*. U.S. DOT and NHTSA, November 2016. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/v2v_pria_12-12-16_clean.pdf

[13]. *Application Requirements for Autonomous Vehicle Tester Program*. California DMV. https://www.dmv.ca.gov/portal/dmv/?1dmy&urile=wcm:path:/dmv_content_en/dmv/vehindustry/ol/auton_veh_tester

[14]. *Autonomous Vehicles: A Policy Preparation Guide*. National League of Cities, April 2017. http://nlc.org/sites/default/files/2017-04/NLC%20AV%20Policy%20Prep%20Guide%20web.pdf

[15]. *Cybersecurity Best Practices for Modern Vehicles*. NHTSA, October 2016. https://www.nhtsa.gov/staticfiles/nvs/.../812333_CybersecurityForModernVehicles.pdf

[16]. *Automotive Cybersecurity Best Practices*. Auto-ISAC, July 2016. https://www.automotiveisac.com/best-practices/

[17]. *Beyond Traffic 2045*. U.S. DOT, 2017. https://www.transportation.gov/sites/dot.gov/files/docs/BeyondTraffic_tagged_508_final.pdf

[18]. *Federal Big Data Research and Development Strategic Plan*. National Science and Technology Council (NSTC), May 2016. https://www.nitrd.gov/PUBS/bigdatardstrategicplan.pdf

[19]. Shaheen, S. Cohen, A. Zohdy, I. *Shared Mobility – Current Practices and Guiding Principles.* U.S. DOT and FHWA, April 2016. https://ops.fhwa.dot.gov/publications/fhwahop16022/fhwahop16022.pdf

Appendix A: Caltrans CAV Workshop Attendees

	Name	Organization
1	Wheeler, Dara L (event host)	Caltrans
2	Berman, Laurie S	Caltrans
3	Davis, James E	Caltrans
4	Takigawa, Steve K	Caltrans
5	Briseno, Socorro A	Caltrans
6	Myers, Bob S	Caltrans
7	Bhullar, Jesse S	Caltrans
8	Kunzman, Lisa M	Caltrans
9	Brannon, Tom L	Caltrans
10	Wong, Deborah M	Caltrans
11	Dermody, Ryan A	Caltrans
12	Hansra, Gurprit S	Caltrans
13	Clark, Melissa L	Caltrans
14	Siddiqui, Asfand Y	Caltrans
15	Kress, Monica L	Caltrans
16	Simi, Brian R	Caltrans
17	Ward-Waller, Jeanie	Caltrans
18	Giovinazzi, Giles	Caltrans
19	Steinberg, Alan	Caltrans
20	Sah, Prakash	Caltrans
21	Benton, Janice I	Caltrans
22	Clark, Antonette C	Caltrans
23	Kopper, Karl	Caltrans
24	Anderson, Don	Caltrans
25	Alvarez, Juven	Caltrans
26	Reitz, Erik	Caltrans
27	Aboukhadijeh, Hassan	Caltrans
28	Perez, Jose	Caltrans
29	Hansen, Matt	Caltrans
30	Perron, Melanie M.	CalSTA
31	Fowler, Alicia M.	CalSTA
32	Moosavi, Darwin	CalSTA
33	Soriano, Bernard	DMV
34	Sweatman, Peter	CAVita
35	Kern, Tom	CAVita
36	Tom West	PATH
37	Ben McKeever	PATH

Appendix B: Outline of CAV Workshop Program

1. **Welcome and Opening** **9:30 – 10:00 am**

Dara Wheeler, Division Chief, DRISI
Laurie Berman, Director, Caltrans
Jesse Bhullar, Division Chief, Traffic Operations
Bernard Soriano, Deputy Director, Caltrans DMV
Tom West, Director, California PATH

2. **State of the Art for CAV Technology** **10:00 – 10:40 am**
“the technology is here”

2.1 Connected and Automated Vehicle Technology: What Is It? What is the Current Status?
Peter Sweatman (CAVita LLC)

2.2 CV and AV policy at federal level and current deployment status
Ben McKeever (Cal PATH)

Q&A

3. **Steps Toward CAV Preparation** **10:40 am – noon**
“how are CA (and other states) preparing?”

3.1 Caltrans CV and AV actions to date
Pete Hansra (Caltrans DRISI)

3.2 Integrating CAV Planning into Caltrans Processes
Coco Briseno (Deputy Director, Caltrans Planning and Modal Programs)

3.3 Impacts of CAV on how Caltrans does business
Brian Simi (Caltrans Division of Traffic Operations)

3.4 Steps in CV, AV and CAV undertaken by other states – lessons learned
Tom Kern (CAVita)

Q&A

Lunch Break **noon – 1:00 pm**

4 Roundtable Discussion 1:00 – 2:30 pm

Moderated by Peter Sweatman (CAVita). Four rounds of interactive discussion:

Round I. Building a CAV agenda for Caltrans – main imperatives (30 minutes)

Based on current activities, and taking steps to accelerate progress, what actions may Caltrans take in the next five years to prepare for CAV as a commercial reality?

Round II. Potential CAV influence across major Caltrans areas of operations (30 minutes)

How may Caltrans approach the potential impacts of CAV on Caltrans Divisions? Including but not limited to:

- Operations (including both the Office of Safety and the Office of Mobility);
- Maintenance;
- Planning (including Freight);
- Design (including potential impact changes to design standards);
- Local Assistance (supporting cities and counties with CAV deployment guidance); and
- Programming (factoring CAV needs into the funding process).

Round III. What may be Caltrans' future role in CAV policy and planning? (30 minutes)

How may CAV fit into Caltrans' on-going planning process? What are the implications of the CAV ecosystem – including public agencies at all levels, and the multi-faceted CAV industry – for policy development and transportation planning by Caltrans?

Break **2:30 – 3:00 pm**

Roundtable Discussion (cont.) **3:00 – 3:30 pm**

<u>Round IV. CAV coordination and leadership within Caltrans and the State (30 minutes)</u>

How may an improved CAV planning framework advance the highest-priority issues and initiatives? What are the key elements of such a framework? What measures need to be taken to ensure effective coordination and advisory functions? Should Caltrans set up a "CAV Working Group", as introduced by other states?

5 Workshop Outcomes for Further Consideration **3:30 – 3:50 pm**

Summary by Project Team

6 Closing Remarks and Next Steps **3:50 – 4:00 pm**

Dara Wheeler, Division Chief, DRISI

Workshop Close **4:00 pm**