Connected and Automated Vehicle Research Roadmap

For

Caltrans

January 2021

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Acronyms and Definitions

5G	Fifth generation cellular network technology
AC	Alternating Current (electricity)
ADAS	Advanced Driver Assistance Systems - are electronic systems that increase car and road safety by assisting the driver with specific tasks.
AEV	Automated Electric Vehicle
ADT	Annual Daily Traffic
AI	Artificial Intelligence - the theory and development of computer systems able to perform tasks that normally require human intelligence, such as visual perception and decision-making.
AV	Autonomous Vehicle
B2I	Connectivity between a bicyclist and roadside infrastructure
B2V	Connectivity between a bicyclist and vehicles operating in the roadway
BDD	Berkeley Deep Drive – is an industry funded artificial intelligence research program – focusing on the use of vision systems for vehicle control.
BSM	The basic safety message is defined by the SAE J2735 standard. It is broadcast by vehicles to provide situational data (location, heading, speed, etc.) to surrounding vehicles – used to assess potential safety threats.
C-V2X	Cellular vehicle to everything connectivity: This is a conceptual vehicle connectivity service that would potentially be offered by cellular service providers. The service would be based on the 5G cellular platform, which is now undergoing early deployment. Full deployment of 5G networks is expected to take more than 5 years. This C-V2X service is not be compatible with the current connectivity approach, based on DSRC.
CACC	Cooperative Adaptive Cruise Control: A system for road vehicles that automatically adjusts the vehicle speed to maintain a safe distance from vehicles ahead. CACC utilizes vehicle-to-vehicle communications so that the vehicle has information not just on the vehicle immediately in front (through sensors), but also on a leading vehicle or vehicles further in front, through vehicle-to-vehicle communications of key parameters such as position, velocity, acceleration

CAV	Connected and Automated Vehicle
CO2	Carbon Dioxide
CV	Connected Vehicle - Connected vehicles enable safe, interoperable networked wireless communications among vehicles, and among vehicles and roadside infrastructure
DC	Direct Current (electricity)
DMV	Department of Motor Vehicles
DOE	United States Department of Transportation
DSRC	Dedicated Short-Range Communications - two-way short-range to medium-range wireless communication channels specifically designed for automotive use – along with corresponding set of protocols and standards.
DSS	Decision Support System: a set of inter-related computer programs and data that assist with analysis and real time decision-making required to actively manage traffic, to achieve a particular outcome – like emissions reduction.
FHWA	Federal Highway Administration
GHG	Greenhouse Gas, a gas that absorbs and emits radiant energy within the thermal infrared range. The primary greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide and ozone.
GPS	Global Positioning System - is a satellite-based, radio-navigation system owned by the United States government and operated by the United States Air Force. It provides geolocation and time information to a GPS receiver anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites. Obstacles such as mountains and buildings block the relatively weak GPS signals.
ICM	Integrated Corridor Management - is a promising tool in the congestion management toolbox that seeks to optimize the use of existing infrastructure assets and leverage unused capacity along our nation's urban corridors. ICM is defined as a collection of operational strategies and advanced technologies that allow transportation subsystems, managed by one or more transportation agencies, to operate in a coordinated and integrated manner. With ICM, transportation professionals manage the transportation corridor as a multimodal system rather than taking the more traditional approach of managing individual assets.

IDTO	Integrated Dynamic Transit Operation (IDTO) applications are expected to have great potentials to improve transit operation by adjusting transit routing, extending stop waiting time, and facilitating first-mile and last-mile ride-sharing, to meet real-time and dynamic demands of travelers. The dynamic operations are enabled and functionalized by connecting the ends of agency, vehicles, drivers, passengers and cloud server. The concept of Dynamic Transit Operation can be interpreted as flexible operations, multi-mode linkages, traveler-centric, and demand-responsive.
ISA	Intelligent Speed Adaptation (ISA) is an in-vehicle system that uses information on the position of the vehicle in a network in relation to the speed limit in force at that particular location.
LIDAR	Lidar is a surveying method that measures distance to a target by illuminating the target with laser light and measuring the reflected light with a sensor. Differences in laser return times and wavelengths can then be used to make digital 3-D representations of the target. Lidar is commonly used to make high-resolution maps, with applications in control and navigation for some autonomous cars.
MaaS	Mobility-as-a-Service (MaaS) describes a shift away from personally-owned modes of transportation and towards mobility solutions that are consumed as a service.
MMITSS	Multi-Modal Intelligent Traffic Safety System - overarching system optimization that accommodates transit and freight signal priority, preemption for emergency vehicles, and pedestrian movements while maximizing overall arterial network performance.
MPO	Metropolitan Planning Organization - A metropolitan planning organization is a federally mandated and federally funded transportation policy-making organization in the United States that is made up of representatives from local government and governmental transportation authorities.
NHTSA	National Highway Traffic Safety Administration
NOx	Oxides of Nitrogen, a criteria pollutant that contributes toward photochemical smog formation.
OEM	Original Equipment Manufacturer
SAE	Society of Automotive Engineers, an industry association that (among other tasks) develops standards for vehicle manufacturer and performance.

SB1 A 2017 California transportation bill that funds road maintenance and rehabilitation, active transportation, freeway service patrol, (among other programs) transportation research

SB375 SB 375 builds on the existing framework of regional planning to tie together the regional allocation of housing needs and regional transportation planning in an effort to reduce greenhouse gas (GHG) emissions from motor vehicle trips. Air Resources Board to set regional targets for the reduction of greenhouse gas emissions. Aligning these regional plans is intended to help California achieve GHG reduction goals for cars and light trucks under AB 32, the state’s landmark climate change legislation.

V2I Vehicle-to-Infrastructure - is a communication model that allows vehicles to share information with the components that support a country's highway system. Such components include cameras, traffic lights, lane markers, streetlights, signage and parking meters

V2V Vehicle-to-Vehicle - Vehicular communication systems are computer networks in which vehicles serve as communicating nodes, providing each other with information, such as safety warnings and traffic information. They can be effective in avoiding accidents and traffic congestion.

V2X Vehicle to everything (V2X) is a term that refers to high-bandwidth, low latency and highly reliable communication between a broad range of transport and traffic-related sensors

VMT Vehicle Miles Traveled – is a performance statistic of highway usage. It is calculated as the total annual miles of vehicle travel divided by the total population in a state or in an urbanized area.

VSL Variable Speed Limit - A variable speed limit is a flexible restriction on the rate at which motorists can drive on a given stretch of road. Conventional speed limit signs, in contrast, usually list a single speed, generally the maximum rate.

CAV RESEARCH ROADMAP

Introduction

The purpose of this document is to develop a roadmap for advancing research in the area of connected and automated vehicles (CAV) at Caltrans. In recent years, the amount of attention and funding being focused on CAVs has grown immensely, particularly in the private sector, as CAVs have gone from being a "pie-in-the-sky" concept to a reality. Some observers consider CAVs to be a tipping point in transportation, of a magnitude only seen at intervals of many decades. With this increased level of attention and advancement in CAVs, comes great opportunity for Caltrans to leverage this technology to fulfil their strategic goals.

The following CAV research roadmap identifies actionable research activities that build on Caltrans and PATH's past research experience to help guide CAVs towards a successful deployment in California. Caltrans and the PATH Program have been leaders in the CAV field and one of the primary centers of expertise on road vehicle automation for over thirty years. For many of those years, PATH was the only research program in the U.S. to focus heavily on road vehicle automation, and over the years the PATH research staff, faculty, and graduate students have invested over 600 labor years of effort researching CAV and its impacts. These efforts have included development of operational concepts; design, development, and testing of a wide range of connected and automated vehicle systems; assessments of human driver usage of vehicle automation systems; modeling and simulation of the transportation system impacts of automation; and studies of the policy and institutional aspects of automation. The roadmap presented here builds on these past efforts and aims to keep Caltrans and PATH at the forefront of this rapidly advancing industry.

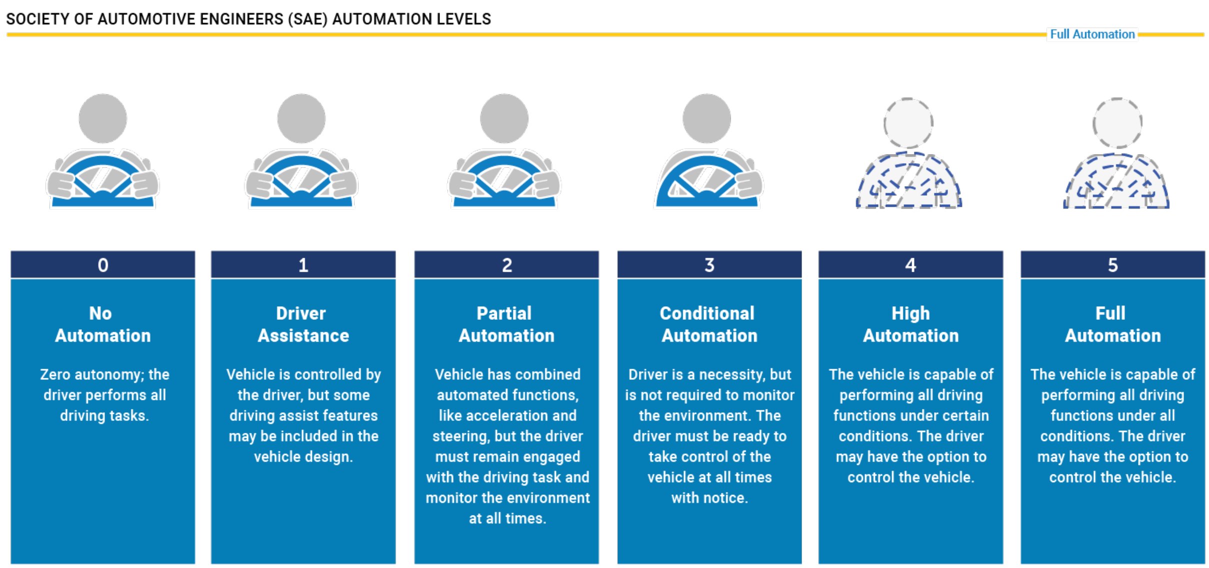
Background

Before presenting the CAV Research Roadmap, it is important to recognize that there are some differences between connected vehicles (CV), automated vehicles (AV) and their combination as connected and automated vehicles (CAV). These concepts are likely to have different implications for the transportation system and they are likely to develop along different time lines. Each of these concepts incorporates a wide range of technology and applications, which will be implemented as distinct products and services.

CV technology refers to robust, standardized vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) communication, broadly representing wireless communication between vehicles, infrastructure and other road users (such as pedestrians and cyclists). V2V technology is typically applied to in-vehicle safety applications while V2I involves connectivity between vehicles and the infrastructure and interfaces with traffic signals, dynamic message signs and other traffic control devices.

The purpose of CV technology is to provide real-time data, upon which various crash risks can be quantified, and warnings delivered, to allow road users to avoid crashes. Although CV is not intended to provide automatic intervention, CV technology can provide AV technology with an additional 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 related 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 other road users and does not automatically take corrective action.

AV technology provides driving control in relation to steering, acceleration and braking. Depending on its intended functionality – from partial to full automation – the automated driving system (ADS) includes the elements of sensing, communicating, monitoring, navigating, decision-making, behavior and driving control required for its progression in traffic. The term AV covers a very broad range of automated functions, both in terms of the extent to which it replaces functions of the human driver, and the intended operating environment. The Society of Automotive Engineers (SAE) Standard J3016 (Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems) is widely referenced and identifies six driving automation levels[1], from no automation (level 0) to full automation, all of the time (level 5). See Figure 1 for an explanation of the six levels of automation.

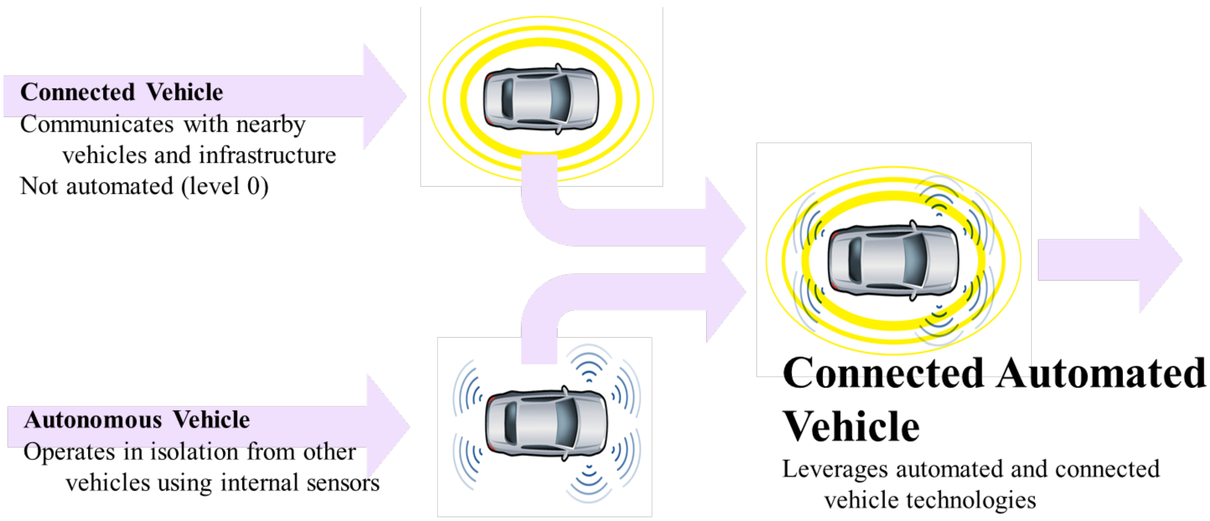


USDOT has integrated this standard into their guidelines for safe testing and deployment of AVs, thereby aligning and formalizing a commonly used shorthand for quickly and concisely categorizing automated vehicle technologies and capabilities (i.e. L3, L4, etc.). Highly Automated Vehicles (HAVs), those comprising levels 3, 4 and 5, are often distinguished from the lower levels of automation (levels 0-2) that we see on the roadway today. The term "autonomous vehicle" is often used to refer to a fully automated vehicle or level 5 vehicle.

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

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

The common use of the term "connected and automated vehicle" or "CAV" allows for the beneficial combination of the two technologies as shown in Figure 2. 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 separately as well.



The term Cooperative Automated Transportation (CAT) is used in the U.S. and Europe to encompass CAV technologies, but also to bring elements of usage into the picture. This expands the scope considerably, from just vehicles to the possible inclusion of trips, traffic and transportation systems comprising several modes. Considerable attention is being focused on ride hailing, ride sharing and Mobility on Demand (MoD), or Mobility as a Service (MaaS). Other terms with a similar overall meaning are being used overseas, including Connected and Automated Driving (CAD), and C-ITS (Cooperative Intelligent Transportation Systems). In this report, consider CAT as a broader multimodal mobility concept encompassing MoD. CAT nevertheless relies on CAV as its most central enabler and we will refer to CAV throughout this document.

How CAV Supports Caltrans Strategic Goals

Caltrans is currently in the process of developing a new Strategic Plan for the department. The new Caltrans Strategic Plan is expected to be completed in early 2021. In their plan, Caltrans has established the following six goals as an organization:

- Safety first;

- Cultivate excellence;
- Enhance and connect the multi-modal transportation network;
- Strengthen stewardship and drive efficiency;
- Lead climate action; and
- Advance equity and livability in all communities.

CAV technology has the potential to address each of these goals by saving lives, providing greater mobility for all people, making our transportation system more efficient, making California more economically competitive, and making our environment and people healthier. For example, research from USDOT has shown that more than 90 percent of traffic-related fatalities are caused by human error[2]. Connectivity and automation have the capacity to mitigate human errors and save lives on a scale well beyond other safety countermeasures. Also, CAVs have the potential to reduce traffic congestion and increase the efficiency of use of our transportation infrastructure. Research has shown that when fully deployed, CAVs can increase freeway capacity by 92%.[3] Finally, CAV technology may provide an opportunity to improve upon, and ease the movement of, people, goods, and services, and also provide opportunities for job creation and new public-private partnerships in a growing industry.

These potential benefits directly support California's State priorities and the six Caltrans organizational goals listed above. The recently completed Caltrans CAV Strategic Plan has established CAV program goals that align with these six organizational goals as follows:

Safety First

- Partner with industry and other agencies to deploy CAV in a manner that enhances the safety of the traveling public and the Caltrans workforce.

Cultivate Excellence

- Leverage Caltrans CAV activities to cultivate excellence in the Caltrans workforce and operations.

Multi-modal Transportation

- Utilize CAV technologies to enhance the effectiveness of all transportation modes and reduce VMT.

Strengthen Stewardship and Drive Efficiency

- Partner with industry and other agencies to deploy CAV in a manner that maximizes efficient use of the infrastructure and long-term value from public investment.

Lead Climate Action

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[2] https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety

[3] http://www.virginiadot.org/vtrc/main/online_reports/pdf/21-r1.pdf

- Partner with industry and other agencies to deploy CAV and related technologies to reduce greenhouse gas emissions and improve resilience of the transportation system to climate change.

Advance Equity and Livability

- Foster the equitable deployment of CAV technologies to advance accessibility and livability in all communities.

The following CAV Research Roadmap presents a list of activities that are consistent with the Caltrans organizational goals and the Caltrans CAV Program goals.

Recommended CAV Focus Areas

The CAV research field is quite broad and cuts across many academic disciplines. As such, it is important to identify the key CAV focus areas that build on all of Caltrans and PATH's strengths and allow us to have the greatest impact and the most success. As noted above, PATH has been involved in CAV research for over three decades but our role has evolved during that time. Because the CAV area is so broad, PATH has focused on a few specialized areas such as truck platooning, partial automation for transit, CAV modeling and simulation, and development and testing of CV applications and Level 1 automated systems integrated with CV technology. More recently, the private sector has taken a lead role in developing and testing higher levels of automated driving (Levels 4 and 5) and PATH has adapted by starting up Berkeley Deep Drive (BDD), an industry consortium investigating state-of-the-art technologies in computer vision and machine learning for automotive applications[4]. BDD brings together UCB faculty, researchers and private industry partners including Audi/VW of America, Bosch, Ford, Honda, NVIDIA, Samsung, Panasonic, Qualcomm, and Toyota to advance CAV technologies.

With these facts in mind, and recognizing our traditional strengths in the CAV field and the strengths of our faculty partners on campus, the following ten focus areas are proposed for the CAV Research Roadmap:

1. Connected Vehicle Development and Testing
2. CAV Development and Testing
3. Heavy Vehicle Platooning and Automation
4. Critical Enabling Technologies for Highly Automated Driving
5. Analysis, Modelling and Simulation of CAV Impacts
6. CAV Policy and Planning
7. CAV Public Awareness and Education
8. Automated Electric Vehicles
9. Highway Automation and Control
10. Multimodal CAV Research

[4] https://deepdrive.berkeley.edu/

It is important to recognize that there will inevitably be some cross-over and overlap between these focus areas and it is likely that many PATH researchers and staff will work in several of the focus areas. These focus areas are not intended to operate as silos. It is also likely that these focus areas may change or evolve over time as PATH grows and the CAV industry changes. The proposed CAV focus areas are described in greater detail in Table 1. The left column of Table 1 provides an identifier (ID) for each CAV focus area and the right column provides a description of the type of research that fits in that focus area. The Focus Area ID is used to organize the CAV research roadmap and identify the various projects defined in Table 2. Table 2 provides the CAV Research Roadmap, which is a listing of proposed research activities/projects grouped by CAV Focus Area.

Table 1: CAV Focus Areas

Focus Area ID	Focus Area Description
CAV1	***Connected Vehicle (CV) Development and Testing***. Connectivity, communication between vehicles and vehicles and roadside infrastructure, provides real-time information to vehicles about operational risks – allowing drivers to avoid hazards that are responsible for a large percentage of accidents. Connectivity is also required to capture societal benefits (improved safety, reduced congestion and emissions) from all vehicles, including vehicles with automation. Connectivity also provides a critical layer of safety redundancy for highly automated driving systems, which cannot always rely on sensors performance. CAV1 research will focus on technology and applications that deliver societal benefits without automation (SAE Level 0) to passenger vehicles. Higher levels of automation and other modes of transportation are covered in other focus areas.
CAV2	***Connected and Automated Vehicle (CAV) Development and Testing.*** Vehicle connectivity in concert with vehicle automation expand safety and system performance benefits, over that which can be captured by connectivity alone. Under CAV2 applications will be developed and tested that leverage the benefits of combined CV and AV technology to improve safety and trip reliability. Multiple levels of automation (SAE 1-5) will be considered but this area is limited to light vehicles (heavy vehicle automation is covered in CAV3).
CAV3	***Heavy Vehicle Platooning and Automation.*** When vehicles are coupled closely in platoons, using CAV technology, trucks and buses have the potential to greatly reduce their fuel consumption and emissions. Heavy-duty vehicles such as trucks and buses have unique vehicle dynamics that must be considered when developing algorithms, models or technologies

	that support automated driving. This focus area will include development and testing of all levels of automation (SAE Levels 1-5) for heavy vehicles.
CAV4	***Enabling Technologies for Highly Automated Driving.*** Some industry leaders predict that highly automated vehicles (SAE Levels 3-5) will be on the road in the 2020's. However, recent incidents and fatal accidents have proven that highly automated driving is not yet safe enough for widespread deployment. Recently introduced computer visioning and machine learning technologies, as well as other enabling technologies, need to evolve to achieve safe automated driving. Research focus areas include the underlying technologies for safety assurance, software verification and the validation of fault detection systems.
CAV5	***Analysis, Modeling and Simulation of CAV Impacts.*** So that state and local decision makers are able to make well-informed decisions about CAV infrastructure investments, it is critical that the research community conduct careful and comprehensive assessments of CAV technology impacts on the transportation network. The CAV5 topic area will encompass a variety of methods for assessing the impacts of CAVs, including: human factors studies that assess the impact of CAVs on driver behavior; safety studies using driving simulators; or, small-scale field tests. This topic area will also environmental impact assessments, using traffic simulation models (microscopic or macroscopic) to assess how CAVs can improve mobility or reduce emissions.
CAV6	***CAV Policy and Planning.*** State, regional and local agencies need to consider a wide range of federal and state policies in allocating resources for the implementation of CVs, AVs and CAVs. Conscious decisions need to be made about Infrastructure modification for CAV; deployment to maximize risk reduction; automation impact on traffic, possible source of congestion and emission reduction potential; CAV costs and benefits; data exchange for public benefit and goods movement. The CAV6 focus area will consider a variety of planning tools for CAV such as CAV Strategic Plans, CAV Implementation Plans, CAV Deployment Plans, cost-benefit analyses and other studies.
CAV7	***CAV Public Awareness and Education***. As state, regional and local agencies begin to test and deploy CAV technologies in their jurisdictions, it will be critical to educate the public on both the potential risks and benefits of CAV technologies. In order to do this, understandable public outreach and education materials needs to be created that is based on actual research results.

CAV8	***Automated Electric Vehicles (AEVs).*** AEV advocates, including the DOE, General Motors and Tesla see automated electric vehicles as the foundation for a future, where electric vehicles dominate personal transportation. There are many energy management concerns that will need to be addressed before EVs can be deployed at scale. AEV recharging is one such concern – AEVs would need to be routed and scheduled to mitigate roadway congestion, utilize energy produced from renewable resources as well as prevent the consequences of excessive demand on the electric grid.
CAV9	***Highway Automation and Control***. In addition to highly automated vehicles, the future of transportation will include similar advances to the traffic management discipline. Dynamic control and automation could be applied to managing lanes that facilitate freight movement while simultaneously managing general-purpose lanes that minimize the growth in VMT. When active transportation management technologies are combined with highway control systems (aka a decision support system) at traffic management centers a practical approach emerges to control transportation as a system, and achieve the objectives of reducing emissions, congestion and improving safety.
CAV10	***Multimodal CAV Research.*** Transit and active transportation modes such as walking and biking have an important role in achieving California's goals in both mobility improvement and emissions reduction. Transit operators are continuously looking for ways to improve their operational safety, operational effectiveness, and travel efficiency. Connectivity and automation offer multiple paths to achieve improved mobility service and safety for public transportation. When the vehicles are connected, transit operations can be improved to be flexible and dynamic beyond the convention, offering traveler-centric and demand-responsive travel services. Similarly, CAV technologies also have the potential to make active transportation modes safer and more efficient. By connecting pedestrians, bicycles and micro-transit with vehicles and infrastructure, vulnerable uses will be able to more safely and efficiently navigate todays' complex transportation system.

Table 2: CAV Research Roadmap

Roadmap Area	Project ID	Keywords	Project Title and Summary
CAV1 **Connected Vehicle Development and Testing (V2V and V2I, SAE Level 0)**	CAV1.1	Ramp Meter Control; Congestion Mitigation; Safety Improvement; Congestion and Emissions Reduction	**Dynamic Ramp Meter Timing:** Simulation, prototype development and proof-of-concept testing of CV-based Signal Priority for Freight, Transit, Connected and Automated vehicles at Ramp Metering Signals. Ramp metering enabled by CV data collects traffic and environmental data to allow: on-ramp merge operations that minimizes overall congestion and emissions, on the ramp, and; on the freeway upstream and downstream of the ramp. Using this information, the application determines a timing plan for the ramp meter based on current and predicted traffic and environmental conditions **Deliverable:** Final Report: Dynamic Ramp Meter Timing
CAV1 **Connected Vehicle Development and Testing (V2V and V2I, SAE Level 0)**	CAV1.2	Improved Safety; Dynamic Signal Control;	**Improved Safety through Dynamic Intersection Control - Safety:** Feasibility analysis, development, testing on a controlled facility and field operational testing of (CV-based) Traffic Signal Adaptation for Intersection Safety, using dynamic all-red extension for red-light-running vehicles, dynamic pedestrian intervals for pedestrians with disability, etc. **Deliverable**: Final Report: Improved Safety through Dynamic Signal Control
CAV1 **Connected Vehicle Development and Testing**	CAV1.3	Improved Transit Mobility; Reduced Transit Emissions; Eco-Driving; Field Operational Test; Reduced Fuel	**Improved Mobility and Reduced Emissions through Dynamic Intersection Control:** Execute planning, simulation, field-testing and early deployment of connected vehicle dynamic signal control to improve the movement of transit and

(V2V and V2I, SAE Level 0)		Consumption; Signal Priority	freight through intersections, thus reducing emissions and fuel consumption. Field trials would be conducted collaboratively with transit and freight providers. **Deliverable:** Final Report: Improved Mobility Through Dynamic Signal Control
CAV1 **Connected Vehicle Development and Testing (V2V and V2I, SAE Level 0)**	CAV1.4	Improved Safety; Improved Light Rail Service Times; Signal Priority; Driver Assist;	**Improved Light Rail Mobility and Safety through Dynamic Intersection Control:** Development and Testing of CV-based Signal Priority and Preemption for light rail vehicles and traffic signal control countermeasures to reduce accidents at light rail grade crossing (light rail driver assist, public road user warning/alert, etc.) **Deliverable:** Final Report: Improved Light Rail Mobility and Safety
CAV1 **Connected Vehicle Development and Testing (V2V and V2I, SAE Level 0)**	CAV1.5	Field Operational Test; 5G Cellular Communications; DSRC Communications	**Evaluation of 5G Cellular Communications for Transportation Applications:** Assessment of feasibility, monitoring of development and deployment, small-scale and large-scale testing of 5G cellular, to develop objective economic and performance information on the potential for 5G cellular to serve the transportation market. Develop an objective method to test the two leading approaches to communications (performance and impact on safety) and analyze the resulting data to compose a realistic and comparable apple-to-apple comparison of DSRC and 5G cellular technologies. **Deliverable:** Final Report: Comparative Performance analysis of competing communication channels
CAV1 **Connected Vehicle Development and Testing**	CAV1.6	Improved Safety; Reduced Congestion; Traffic Management	**Cloud Based CAV Data Collection:** Feasibility investigation, small and large scale demonstration of cloud-based CAV data collection, data sharing, edge

(V2V and V2I, SAE Level 0)			computing, and transportation management. **Deliverable:** Final Report: Analysis and Demonstration of Cloud-Based CAV Data collection
CAV1 **Connected Vehicle Development and Testing (V2V and V2I, SAE Level 0)**	CAV1.7	Traffic Management, Congestion Management; Emissions Reduction	**Multi-Modal Intelligent Traffic Safety System (MMITSS):** Development of a long-term strategy for MMITSS based on its performance (determined through simulation, bench-scale testing and field operational testing) and the needs of transportation community for intersection control (peri-urban, suburban, and urban settings). Signal Timing is one parameter that will be explored to optimize the performance of traffic signals. MMITSS could evaluate traffic and environmental parameters at each intersection, in real-time, and optimize available green time to serve the actual traffic demands while minimizing the environmental impact. **Deliverable:** Final Report: MMITSS Long Term Potential for Traffic Management
CAV2 **CAV Development and Testing (SAE Levels 1-5)**	CAV2.1	AV Safety Verification; Traffic Management; Congestion and Emissions Reduction	**Large-Scale (Level 3 and Level 4) CAV Testing & Demonstrations:** Conduct field-testing (and Demonstrations) of CAVs, including but not limited to: Longitudinal Control Functions, Lateral Control Functions as well as advanced CAV applications – for highway (high speed and low speed [such as traffic jams]) urban and parking applications. Such field-testing should verify the performance of the CAVs system and development information (technical aspects, user acceptance, driving and travel behavior impacts) with a high level of confidence, for stakeholders and the public, alike. CAV solutions of interest include CACC, Eco-speed harmonization and variable

			speed limits that respond to V2I communication to enable on-board automation to set operational limits – to minimize congestion and emissions. **Deliverable:** Final Report: Field-testing and Analysis of AV Level 3 and AV Level 4 Systems
CAV2 **CAV Development and Testing (SAE Levels 1-5)**	CAV2.2	AV Safety Verification; Sensor Inspection and Maintenance; Workforce Development	**Sensor Maintenance Guidelines:** CAV and AV vehicles rely on the addition of sophisticated sensors (camera, radar, lidar, etc.) that will be supported by new control systems (on-board computers) which, in total, will relieve the driver of vehicle operational tasks (and thus will be responsible for the safe operation of the vehicle.). The performance of all systems deteriorates with time and new sensor systems will require monitoring and maintenance to perform acceptably over the useful life of a vehicle. Work under CAV 2.2 will be executed collaboratively with other field-testing programs, proposed herein, to document OEM maintenance recommendations, best practices and ADAS performance during field-testing. The objective is to identify failures and gaps in the proposed performance/maintenance strategies. In addition, automotive training programs in the California Community College system will be engaged to review the evaluate maintenance strategies and determine if such strategies can be performed by current automotive technicians. Finally, the California DMV will be involved in the evaluation program to consider: the implications of automation; the requirements of safety inspections, and the concept of self-certification of automated systems by vehicle manufacturers.

			Deliverable: Final Report: Inspection, Testing and Safety Verification of AV Sensor Maintenance Guidelines
CAV2 **CAV Development and Testing (SAE Levels 1-5)**	CAV 2.3	CAV Public Acceptance, CAV Performance Testing; Safety Validation; Experimental Methods For Validation	**Infrastructure for testing CAV performance and safety:** Define the requirements for a state-of -the-art, closed-course CAV testing facility (for passenger vehicles, transit bus, and heavy vehicle applications.) CAV 2.3 will be conducted using an analysis of CAV safety systems applications performance, public acceptance and experiment methods required to produce results with a high level of confidence. Results will be compared against existing facilities to determine where investments should be targeted for enhancements. **Deliverable:** Final Report: CAV Test Facility Needs Analysis
CAV2 **CAV Development and Testing (SAE Levels 1-5)**	CAV 2.4	CAV Test Beds; CAV Performance Testing; Safety Validation	**Expansion of California CAV Test Beds:** The Caltrans CAV Strategic Plan identified the need to expand CAV Test Beds in California, including both off-roadway and on-roadway, to include additional applications, state vehicles, and physical assets so that they can support broader CAV testing. **Deliverable**: Expanded CAV Test Beds and Assets
CAV2 **CAV Development and Testing (SAE Levels 1-5)**	CAV 2.5	Platooning; Traffic Management; Emissions Reduction; Congestion Mitigation	**Light Vehicle Platooning CACC-V2X:** Develop and test vehicle data collection techniques to support experiments on different CACC control and traffic management strategies that are to be facilitated by V2X communications. Strategies to be investigated include (but are not limited to): finding CACC equipped vehicles and equipped roadside units on the roads (in real time); accurately determining relative positions of similarly equipped vehicles; developing platoons by

			mixing vehicles with different performance capabilities; improving the performance of CACC at on-ramp, off-ramp, and signalized intersections, etc. **Deliverable:** Final Report: Platooning Traffic Management Strategies
CAV2 **CAV Development and Testing (SAE Levels 1-5)**	CAV 2.6	Low Speed Automated Shuttles; Safety Validation	**Low Speed Shuttles:** Validate the safety and reliability of slow speed automated shuttles in a variety of environments through field-testing. Collect data on the interactions between low-speed shuttles and other road users in ongoing field tests. Determine how well they are avoiding conflicts, whether they are being excessively cautious, how frequently they have false-positive braking events, etc. Expanded deployment of AV shuttles beyond field-testing is for public acceptance and rapid adoption. Data collection requires close cooperation with field test operators, as specific instrumentation is added to the vehicles. **Deliverable:** Final Report: Safety Validation of Automated, Low Speed Shuttles
CAV2 **CAV Development and Testing (SAE Levels 1-5)**	CAV 2.7	Work Zone Safety	**Enhancing Work Zone Safety with CAV:** The Caltrans CAV Strategic Plan identified an action to pilot the use of CAV technology to increase the safety of Caltrans staff working near incident scenes and work zones. CAV2.7 will investigate different strategies to enhance work zone safety that exploit new technologies (connected arrow board, connected work trucks, connected delineators, connected flaggers, worker beacons) as well as V2I communications being incorporated into vehicles and their ability to exchange data (enhanced by low and high fidelity maps and the reduced speed zone warning applications). These strategies will address

			CAVs, which can utilize communication (broadcasting V2I / V2X information) and AVs, which solely rely on on-board sensors (and thus would require the temporary installation of special markings). This project will include the conceptual development of the strategies, prototypes, their bench-scale testing, controlled on-road testing and finally large-scale, on-road demonstrations. **Deliverable:** Final Report: Improving Work Zone Safety through Connected Technologies
<u>CAV2</u> **CAV Development and Testing (SAE Levels 1-5)**	CAV2.8	Emissions Reduction; Congestion Mitigation; Safety Improvement	The **Connected Eco-Driving** application provides customized real-time advice to drivers so that they can adjust their driving behavior to save fuel and reduce emissions. Eco-driving advice includes recommended driving speeds, optimal acceleration, and optimal deceleration profiles based on prevailing traffic conditions, interactions with nearby vehicles, and upcoming road grades. The application also provides feedback to drivers on their driving behavior to encourage drivers to drive in a more environmentally efficient manner. Finally, the application may also include vehicle-assisted strategies (L1 automation) where the vehicle automatically implements the eco-driving strategy (e.g., changes gears, switches power sources, or reduces its speed in an eco-friendly manner). This task anticipates the development, small scale demonstration and large-scale demonstration of Connected Eco Driving. **Deliverable:** Final Report: Connected Eco-Driving
<u>CAV2</u>	CAV2.9	Emissions Reduction;	**Eco-Speed Harmonization**. Feasibility investigation, small- and large-scale

CAV Development and Testing (SAE Levels 1-5)		Congestion Mitigation; Safety Improvement	demonstration of The Eco-Speed Harmonization application. This application determines eco-speed limits based on traffic conditions, weather information, and emissions information. The purpose of speed harmonization is to change speed limits road links that approach areas of traffic congestion, bottlenecks, incidents, special events, and other conditions that affect flow. Speed harmonization assists in maintaining flow, reducing unnecessary stops and starts, and maintaining consistent speeds, thus reducing fuel consumption and emissions on the roadway. Finally, the application may also include vehicle-assisted strategies (L1 automation) where the vehicle automatically implements the eco-sped harmonization strategy (e.g., changes gears, switches power sources, or reduces its speed in an eco-friendly manner). **Deliverable:** Final Report: Connected Eco-Speed Harmonization
CAV2 **CAV Development and Testing (SAE Levels 1-5)**	CAV2.10		**CAV Pilots in Specific Operational Design Domains (ODDs):** The Caltrans CAV Strategic Plan identified an action to conduct pilots to study how safely and efficiently CAVs operate in specific ODDs. For example, a pilot could be conducted on a managed or dedicated lane facility in California to see how that type of environment impacts the safety and efficiency of CAV operations. Other potential ODDs to test include low speed urban environments, rural mountain areas, or inclement weather conditions. This action requires partnering with districts, local agencies and private sector AV providers and seeking out grant opportunities to conduct the pilots.

			Deliverable: Final Report: Operational Effectiveness of CAVs in Specific ODDs
CAV3 **Heavy Vehicle Platooning and Automation (SAE Levels 1-5)**	CAV3.1	Reduced Emissions and Fuel Consumption; Congestion Mitigation	**Truck Platooning – Mixed Fleets:** Enhance the performance of truck platooning systems, eliminating current limitations (which require platoons of homogeneous vehicles). Develop simulations and algorithms that facilitate the formation and control of truck platoons, composed of trucks with different performance characteristics and different manufacturers. This paves the way for the adoption of multi-brand truck platooning, which will improve fuel economy, CO2 emissions, traffic capacity and throughput for the goods movement sector. **Deliverable:** Final Report: Enhancing the Mixed Fleet Performance of Truck Platooning Systems
CAV3 **Heavy Vehicle Platooning and Automation (SAE Levels 1-5)**	CAV3.2	Reduced Emissions and Fuel Consumption; Congestion Mitigation	**Truck Platooning – Control:** Enhance the performance of current truck platooning systems, by developing platoon control algorithms to handle grade change situations when the different trucks in the platoon are on different grades at the same time. **Deliverable:** Final Report: Enhancing the Grade Change Performance of Truck Platooning Systems
CAV3 **Heavy Vehicle Platooning and Automation (SAE Levels 1-5)**	CAV 3.3	Reduced Emissions and Fuel Consumption; Congestion Mitigation	**Truck Platooning – Bridge:** Enhance performance of current truck platooning system; assess the implications of truck platooning for bridge structures. Examine periodic axle loadings that could stimulate resonant modes of the structures at certain speeds. Determine countermeasures for representative bridge designs such as avoiding certain speeds or

			using irregular separations between the trucks. **Deliverable:** Final Report: Enhancing the Performance of Truck Platooning Systems on Bridges
CAV3 **Heavy Vehicle Platooning and Automation (SAE Levels 1-5)**	CAV 3.4	Reduced Emissions and Fuel Consumption; Congestion Mitigation	**Trucking Platooning – Fuel Economy:** Determine minimum truck platoon gap that can be used for Level 1 automation through simulation, development and field-testing. Access the impact on the driver, identifying the minimum platoon gap below which steering will need to be automated in order to avoid excess stress on driver (through human factors experiments). **Deliverable:** Final Report: Enhancing the Fuel Economy Performance of Truck Platooning Systems
CAV3 **Heavy Vehicle Platooning and Automation (SAE Levels 1-5)**	CAV 3.5	Reduced Emissions and Fuel Consumption; Congestion Mitigation	**Truck Platooning – Demonstration:** Conduct large scale demonstrations of truck platooning to gain regulatory, driver, fleet operator, as well as public confidence in this emerging technology (that offers the benefits of improved safety, improved freight productivity, reduced fuel consumption and reduced emissions). **Deliverable:** Final Report: Enhancing the Public Acceptance of Truck Platooning Systems through Demonstration
CAV3 **Heavy Vehicle Platooning and Automation (SAE Levels 1-5)**	CAV 3.6	Reduced Emissions and Fuel Consumption; Congestion Mitigation	**Truck Platooning – Deployment Facilitation:** In addition to technical challenges, platooning faces additional barriers (legal, regulatory, public acceptance) before large-scale deployment can be initiated. These must be addressed in a collaborative manner (with industry, government, public) and include: system validation and legal challenges, impact assessment on infrastructure, traffic flow,

			road safety and perception by users and the public about the safety of platooning. **Deliverable:** Final Report: Facilitating the Deployment of Truck Platooning Systems
CAV 4 **Critical Enabling Technologies for Highly Automated Driving (SAE Levels 3-5)**	CAV 4.1	Highly Automated Vehicles; Safety Assurance	**Enabling Technologies for High Automation: Safety Validation of AI based Vision Systems** Evaluate the safety performance of high levels of driver automation that utilize vision systems, based on artificial intelligence and machine learning. This evaluation includes simulation, controlled testing and large-scale field-testing of its software, their safety assurance methodology including system fault detection. **Deliverable:** Final Report: Validation of AI Safety Assurance Methods, Through Simulation and Field-testing
CAV 4 **Critical Enabling Technologies for Highly Automated Driving (SAE Levels 3-5)**	CAV 4.2	Highly Automated Vehicles; Safety Assurance	**Critical Evaluation of Enabling Technologies for Automated Driving – Communications**: Evaluate the safety performance of high levels of driver automation that utilize multiple communication systems. This evaluation includes simulation, controlled testing and large-scale field-testing of DSRC and C-V2X/5G safety assurance methodology conformance, performance and interoperability. **Deliverable:** Final Report: Critical Evaluation of the Utilization of Multiple Communication Systems (DSRC and C-V2X/5G) for Automated Driving
CAV 4 **Critical Enabling Technologies for Highly Automated**	CAV 4.3	Highly Automated Vehicles; Safety Assurance	**Critical Evaluation of Enabling Technologies for Automated Driving – Sensor Fusion**: Evaluate the safety performance of high levels of driver automation that utilize the fusion of data

Driving (SAE Levels 3-5)			from multiple sensors. This evaluation includes simulation, controlled testing and large-scale field-testing of safety assurance methodology, conformance and performance. **Deliverable:** Final Report: Critical Evaluation of the Safety Performance of Sensor Fusion Systems for Automated Driving
<u>CAV 4</u> **Critical Enabling Technologies for Highly Automated Driving (SAE Levels 3-5)**	CAV 4.4	Highly Automated Vehicles; Safety Assurance	**Critical Evaluation of Enabling Technologies for Automated Driving – Vehicle Positioning**: Evaluate the safety performance of high levels of driver automation that positions vehicles within a lane. Such systems include (but are not limited to) vision, lidar and GPS. These are all interactive with infrastructure (e.g., lane striping). Testing will include simulation, controlled testing, and field-testing. Gaps in performance may identify proposed changes to the road infrastructure to improve CAV positioning. **Deliverable:** Final Report: Critical Evaluation of the Safety Performance of Vehicle Positioning Technologies as it relates to Infrastructure Modification, for Automated Driving
<u>CAV 4</u> **Critical Enabling Technologies for Highly Automated Driving (SAE Levels 3-5)**	CAV 4.5	Highly Automated Vehicles: Safety Assurance of Partial Automation	**Automation During the Transition Phase:** As automation is progressively deployed (at levels below full automation), it will operate in environments of non-automated vehicles, pedestrian and cyclists. During this period, there will be a need for automation to gracefully transfer control back to the driver. All other users of the road environment must be aware of the state and behavior of surrounding automated vehicles. Improvements in safety are anticipated but not assured. Road user behavior during the transition

			period will be simulated and tested to verify safety improvements are attained through the deployment of partial to full automation. **Deliverable:** Final Report: Safety Assessment of Vehicle Automation During the Transition Phase
CAV4 **Critical Enabling Technologies for Highly Automated Driving (SAE Levels 3-5)**	CAV4.6	CAV Safety Verification;	**Safety Assurance of CAV:** Scenario analysis is currently used as the basis for safety assurance. Scenarios are extracted from simulations, accident data and field-testing of vehicles. The objective of CAV4.6 is to evaluate existing scenarios currently used to quantify CAV safety, and create additional scenarios from California centric accident data, field test data or simulations – using common formats, analyses, processes and models. **Deliverable:** Final Report: Safety Assurance of CAV Use Cases
CAV 4 **Critical Enabling Technologies for Highly Automated Driving (SAE Levels 3-5)**	CAV 4.7	Cybersecurity; Safety Assurance;	**Infrastructure Resilience - CyberSecurity:** Analyze security issues associated with DSRC and 5G cellular; cooperate with automotive and communications industries (where appropriate). Develop, bench-scale test and conduct a field operational test of cybersecurity solutions that mitigate threats to automotive DSRC and 5G cellular communications. Implement a pilot on common cybersecurity infrastructures and processes needed for secure and trustworthy communication between vehicles and infrastructure for road safety and traffic management related messages according to published guidance on the certificate and security policy. **Deliverable:** Final Report: CAV Cybersecurity Risk and Risk Mitigation Strategies

CAV 5 **Analysis, Modelling and Simulation of CAV Impacts**	CAV 5.1	Reduced Emissions and Fuel Consumption; Congestion Mitigation	**Model and Simulation of California Corridors**: Model promising corridors for CAV field-testing and early deployment; estimate the impacts of CAV vehicle and highway performance at various levels of penetration, of CAV systems into private, commercial and publicly owned vehicles on the corridor. **Deliverable:** Final Report: Early Deployment of Automated Vehicles on California Corridors
CAV 5 **Analysis, Modelling and Simulation of CAV Impacts**	CAV 5.2	Reduced Emissions and Fuel Consumption; Congestion Mitigation	**Platoon Formation Testing:** Perform interactive, driving-simulator modeling of alternative approaches for informing CACC drivers about locations of other suitably equipped vehicles that can join into a platoon. Develop the most promising approaches for bench and field-testing. **Deliverable:** Final Report: Platoon Formation Simulation and Testing
CAV 5 **Analysis, Modelling and Simulation of CAV Impacts**	CAV 5.3	Reduced Emissions and Fuel Consumption; Congestion Mitigation	**Analysis and Modeling of CAVs Operating in Corridors:** Improve existing freeway analysis and modeling systems to predict realistic performance of CAV system on California's freeways. This includes the identification of gaps, model development, conceptual validation and field-testing. **Deliverable:** Final Report: Analysis and Modeling of CAVs and Their Impact Upon California's Corridors
CAV 5 **Analysis, Modelling and Simulation of CAV Impacts**	CAV 5.4	Reduced Emissions and Fuel Consumption; Congestion Mitigation; Safety improvement	**Benefits of Speed Harmonization:** Identify the potential benefits (safety, congestion mitigation, emissions and fuel economy reduction) for smoothing effects of CAV and AV technology, through simulation, emissions modeling, small and large-scale field-testing - particularly when

			implemented at a low percentage of vehicles on the freeway. **Deliverable:** Assessment and Demonstration of the Benefits of Speed Harmonization
CAV 5 **Analysis, Modelling and Simulation of CAV Impacts**	CAV 5.5	Reduced Emissions and Fuel Consumption; Congestion Mitigation; Safety Assurance	**Modeling CAV Use Cases on I-210**. The I-210 Aimsun model is one of the largest and most well calibrated micro simulation models in the world. It was developed by Caltrans for the I-210 Connected Corridors ICM pilot. The use of this model as a core component of CAV simulation studies. Conducted under CAV 5.5, would save funding, provide consistency in results and permit integration of results with the I-210 Decision Support system which could lead to real life testing as CAVs become a part of the vehicle mix. **Deliverable**: Final Report: A Plan for Integrating I-210 Aimsun Model with CAV Simulations
CAV 6 CAV Policy and Planning	CAV 6.1	CAV Strategic Planning; Infrastructure Needs; Safety Assurance	**CAV Deployment – Infrastructure Modification:** The CAV Industry is recommending different kinds of infrastructure modifications to enhance CAV performance. To set priorities for investments in infrastructure modifications, recommendations need to be transformed into best practices that are widely adopted by states. This transformation process will require an analysis of life cycle costs, simulation and then demonstration (first small and large scale) to prove the CAV performance and societal benefits. The results of these studies will be an important input into the SB1 infrastructure improvement projects. **Deliverable:** Final Report: CAV Infrastructure Modification Requirements

CAV 6 CAV Policy and Planning	CAV 6.2	V2I Deployment; Safety Improvement; Congestion Mitigation; Emissions Reduction	**CAV Deployment – V2I:** Develop a strategy to deploy V2I equipment across Caltrans' network, establishing a priority for deployment that minimizes risk and costs, yet maximizes benefit (improved safety and mobility). This effort will require simulation and modeling of road network performance as well as the development of appropriate resource allocation models to maximize benefits. **Deliverable:** Final Report: V2I Deployment Plan
CAV 6 CAV Policy and Planning	CAV 6.3	Traveler Behavior; Safety Improvement; Congestion Mitigation; Emissions Reduction	**Impact of Automation on User Behavior:** Define traveler's demand behavior and preferences to different levels of automation, up to and including "Mobility as a Service", through experimental, modeling, surveying and simulations. Specific questions that need to be answered include: traveler preferences for use of different automation concepts and increased annual daily traffic (ADT) if travel became significantly cheaper or easier due to vehicle automation. **Deliverable:** Final Report: Impact on Traveler Behavior from Automated Vehicles.
CAV 6 CAV Policy and Planning	CAV 6.4	Traveler Behavior; Safety Improvement; Congestion Mitigation; Emissions Reduction	**Impact of Automation on Freeway Capacity:** Automation was first evaluated as a tactic to mitigate congestion, but it has recently been viewed as another possible source of congestion. Plummeting costs for travel (driving an increase in VMT) and empty AVs repositioning for the next passenger have been identified as congestion causing concerns. Driver behavior changes, and their impacts on the transportation networks, will be assessed, through experimental, modeling, surveying and simulations.

			Deliverable: Final Report: Impact of Automation on Freeway Capacity
CAV 6 CAV Policy and Planning	CAV 6.5	Congestion Mitigation; Emissions Reduction	**Impact of Automation on Criteria Pollutants and CO2 Emissions:** Quantify the emissions reduction potential of vehicle and highway automation, so that California Metropolitan Planning Organizations (MPO's) can include these tactics in their strategy to comply with SB 375. Efforts to quantify emissions benefits include controlled testing, simulations, modeling as well as the modification of regional transportation/emissions models. **Deliverable:** Final Report: Impact of Automated Vehicles on the Production of Criteria Pollutants and CO2 Emissions
CAV 6 CAV Policy and Planning	CAV 6.6	Safety Improvement; Congestion Mitigation; Emissions Reduction	**Impact of Automation on CAV Costs and Benefits in California:** Estimates the economic impact of statewide CAV deployment activities costs and benefits. **Deliverable:** Final Report; CAV Costs and Benefits in California.
CAV 6 CAV Policy and Planning	CAV 6.7	CAV Testbeds; CAV Assets; Inventory	**California CAV Test Bed Inventory:** The recently completed Caltrans CAV Strategic Plan identified the need to publish a complete list of California CAV test beds and their assets. This involves creating a detailed inventory of the existing California CAV testbeds and their assets and then publishing that list on the Caltrans website. It also involves publicizing the list to CAV stakeholders throughout the state to attract additional users and partnerships.
CAV 6 CAV Policy and Planning	CAV 6.8	Data Exchange; Cybersecurity; Safety Improvement;	**Data Exchange for Public Benefit**: CAV data ownership and data sharing issues need to be addressed by California Public policy. First, the free flow of non-personal data is required to facilitate fair and undistorted competition between service

			providers. Secondly, some of the data generated by vehicles is of public interest – for traffic management, infrastructure maintenance, CO2 and criteria emission reduction from light duty vehicles. **Deliverable:** Final Report: CAV Data Exchange for Public Benefit
CAV 6 CAV Policy and Planning	CAV 6.9	Safety Improvement; Congestion Mitigation; Emissions Reduction; CAV Benefit Analysis	**Impact of Automation – Societal Impacts:** The long-term effects of driverless mobility on the transport system, the economy, the environment and on existing jobs are still largely unknown. The impact of CAV on congestion & emissions needs to be quantified. Will it cause urban sprawl? Another concern is that little is known about the interaction between automated vehicles and other road users in mixed traffic conditions. The economic impacts from automated and connected mobility will bring benefits far beyond the automotive industry and could possibly negatively affect some sectors like insurance, maintenance and repair. Aspects related to social inclusiveness and ways to address the needs of vulnerable users will play a role in making sure that such gains benefit society as a whole. All of these concerns need to be illuminated and efforts to mitigate impacts should be identified. **Deliverable:** Final Report: Vehicle Automation – Societal Impacts Risks, Benefits and Risk Mitigation Strategies
CAV 6 CAV Policy and Planning	CAV 6.10	Goods Movement; Congestion Mitigation; Emissions Reduction; CAV Benefit Analysis	**Title: Goods Movement Automation:** Capturing the maximum benefit (as in congestion mitigation) from the automation of delivery of goods and services will require the reconfiguration of the current delivery process.

			Deliverable: Final Report: Impact of Automation on the Goods Delivery Process: Recommendations for Reconfiguration to Maximize Benefits
<u>CAV 6</u> CAV Policy and Planning	CAV 6.11	Good Movement; Congestion mitigation; Emissions Reduction	**Title: Collaborative Transportation Networks:** Quantify the role and benefits of CAV enabled collaboration, in local package delivery. Specifically quantify how collaboration could reduce both highway and urban congestion as well as emissions and fuel consumption. Identify industry trends, new designs in transportation hubs and goods transfer on urban streets. Finally, quantify the impact on the transportation infrastructure that collaborative transportation would require to be successful. **Deliverable:** Final Report: Collaboration in Package Delivery, CAV Enablement Strategies Risks and Benefits
<u>CAV 6</u> CAV Policy and Planning	CAV 6.12	Good Movement; Congestion Mitigation; Emissions Reduction	**Automation in the Last Mile of Package Delivery:** Quantify the impact of last mile automation in package delivery on the transportation network on both highway and urban networks. Last mile automation includes both automated vehicles and drones. These new delivery tactics will be applied in high cost labor regions, such as California, and offer both beneficial and deleterious impacts to the transportation network. **Deliverable:** Final Report: Risks and Benefits of Automated Package Delivery in the Last Mile
<u>CAV 6</u> CAV Policy and Planning	CAV 6.13	Congestion Mitigation; Emissions Reduction; Demand Management	**Demand Management Utilizing CAVs** – Research, develop and demonstrate demand strategies that reduce congestion by routing AVs off of the highway. It is envisioned that CAVS will either drive without an occupant or an occupant that

			may be involved in other activities (studying, working, etc). This may permit the use of demand management strategies where CAVs are asked to park for a while, take a longer route, or can be used for carpooling. If a driver is working in a car, he/she may not mind taking a longer route. At times a small change in the amount of traffic can have a large impact on congestion. **Deliverable**: Final Report: A Study of How CAVs May be Used with Demand Management
CAV 6 CAV Policy and Planning	CAV 6.14	CAV Design Standards; physical infrastructure	**CAV Design Standards for California's Physical Infrastructure:** The recently completed Caltrans CAV Strategic Plan identified the need to assess the state of CAV design standards in California. This involves greater leveraging of federal standards and guidelines to investigate if statewide standards are needed for physical infrastructure that supports CAVs including striping, signage, traffic control devices and roadside communications devices. **Deliverable**: Assessment of CAV Design Standards for California's Physical Infrastructure
CAV 6 CAV Policy and Planning	CAV 6.15	CAV Design Standards; digital infrastructure	**CAV Design Standards for California's Digital Infrastructure:** The recently completed Caltrans CAV Strategic Plan identified the need to assess the state of CAV design standards in California. This involves greater leveraging of federal standards and guidelines to investigate if statewide standards are needed for digital CAV infrastructure including digital mapping, data message sets, traffic management center (TMC) software and cybersecurity. **Deliverable**: Assessment of CAV Design Standards for California's Digital Infrastructure

CAV 7 CAV Public Awareness and Education	CAV 7.1	Public Awareness; Safety Improvement	**How Safe is Safe Enough:** Identify the public's concerns about the level of safety achieved with vehicle automation. Depending upon public response, develop a safety evaluation program (for CAV) to specifically develop the information to address these concerns. Develop and deliver an outreach program and continually monitor the impact that it has on the public's perception of CAV safety. Revise and re-deliver the safety outreach information should previous efforts not attain the desired level of public acceptance. **Deliverable:** Final Report: Attaining the Public's Expectation for CAV Safety – Analysis and Outreach
CAV 7 CAV Public Awareness and Education	CAV 7.2	Public Awareness; Safety Improvement	**Enhance the Public's Awareness of CAV and its Benefits:** Develop public outreach materials to provide accurate, realistic and readily understandable portrayals of the different CAV concepts, up to high levels of automation. These would be used for public education and a general assessment of public understanding (through surveys and focus groups, etc.) to gauge public attitudes toward these systems, to ensure California maintains a leadership role in the adoption of CAV technologies. **Deliverable:** Final Report: Assessment of Public Concerns with Automated Vehicles
CAV 7 CAV Public Awareness and Education	CAV 7.3	Public Awareness; Safety improvement Congestion Mitigation and Emissions Reduction	**Stakeholder Outreach – Regional Demonstrations:** Develop reusable demonstration platforms to educate CAV stakeholders regarding opportunities, functionality, and the need for select investment in CAV areas with substantial societal benefit.

			Deliverable: Final Report: CAV Demonstration, Public Feedback and Concerns
CAV 7 CAV Public Awareness and Education	CAV 7.4	Management and Outreach	**Annual Update to Caltrans and State Officials on the State of CAV Technology:** Annually inform Caltrans leadership and related state officials on the latest developments in CAV technology. The updates will cover international, national and statewide developments in CAV technology, including deployments. **Deliverable:** Annual Report and Webinar: State of CAV Technology.
CAV 7 CAV Public Awareness and Education	CAV 7.5	Management and Outreach	**Develop a CAV Communications and Outreach Plan for Caltrans:** The recently completed Caltrans CAV Strategic Plan identified the need for Caltrans to develop a Communications and Outreach Plan to communicate CAV progress and activities to various external audiences. A proactive approach to communicating CAV efforts through websites, factsheets, or other material would pave the way for eliminating confusion and improve the standing of the department as a leader in emerging transportation technology. This plan should prepare Caltrans to respond to requests for information and questions from media, the public and legal entities. **Deliverable:** CAV Communications and Outreach Plan
CAV 8 Automated Electric Vehicles (AEVs)	CAV 8.1	AEVs, Energy Management; Emissions Reduction;	**AEV Energy Consumption Concerns, Risks and Mitigation Strategies:** Develop AEV fleet management strategies to be implemented by state fleets that include dispatch and charging infrastructure optimization to mitigate risks and costs. This should include: the design of smart grid communication architecture for AEV to collect and analyze real-time power

			consumption, status and demand; the optimization of energy management in real-time path planning and event-based control; as well as battery life estimation and trip planning to ensure safety. **Deliverable:** Final Report: California State Fleet AEV Energy Management and Optimization
CAV 8 Automated Electric Vehicles (AEVs)	CAV 8.2	AEVs, Energy Management; Emissions Reduction	**Shared AEV's Energy Consumption:** Quantify (through simulation and field-testing) the Impact of AEVs used for shared transportation on energy consumption. Shared use vehicles' utilization will vary and include trips with zero passengers. **Deliverable:** Final Report: Shared AEV Energy Consumption
CAV 8 Automated Electric Vehicles (AEVs)	CAV 8.3	AEVs, Energy Management; Emissions Reduction	**AEVs: Grid Specific Energy Consumption, Emissions and Health:** Evaluate the energy consumption, emissions and health implications of AEVs across the different power grids of California. This study should quantify the current state and the intended future state for generation (accounting for renewable generation proliferation). The study should include the full cycle of emissions and losses in electric generation, transmission and distribution. In addition, the study should account for energy losses in AC inversion to DC, DC charging and DC discharging from battery storage. **Deliverable:** Final Report: AEV's Energy Consumption, Emissions and Health – Grid Specific impacts
CAV 9 Highway Automation and Control	CAV 9.1	Highway Automation; Ramp Meters; Congestion and Emissions Reduction	**Dynamic Control of Highways in a Mature CAV Environment – Ramp Meters:** Develop through modeling, simulation and field-testing, strategies for the dynamic management of ramp meters from Traffic

			Management Centers (based on CAV data). Control strategies subject to development would focus on mobility improvement, congestion reduction and emissions reduction. **Deliverable:** Final Report: Dynamic, CAV enabled Ramp Metering from Traffic Management Centers
CAV 9 Highway Automation and Control	CAV 9.2	Highway Automation; Dynamic Control; Congestion and Emissions Reduction	**Dynamic Control of Highways in a Mature CAV Environment – Flow Control:** Define, model, simulate and test traffic control strategies for use with CAVs, especially for highway and arterial applications. Control strategies subject to development would focus on mobility improvement, congestion reduction and emissions reduction. **Deliverable:** Final Report: Dynamic Control of Highways in a Mature CAV Environment
CAV 9 Highway Automation and Control	CAV 9.3	Highway Automation; Dynamic Control; Data Storage	**Dynamic Control of Highways in a Mature CAV Environment – Data and Data Management Needs:** Evaluate, research and develop data collection, storage and processing requirements for dynamic control of highways. Define storage and processing strategies (cloud-based CAV data collection, data quality assurance, data sharing, edge computing) for transportation management. **Deliverable:** Final Report: Data and Data Management Needs for Dynamic Control of Highways
CAV 9 Highway Automation and Control	CAV 9.4	Highway Automation; Dynamic Control; Congestion and Emissions Reduction	**Dynamic Control of Highways in a Mature CAV Environment:** Define, simulate and field test highway management strategies that mitigate congestion and GHG Emissions through highway automation. Control strategies subject to development

			would focus on congestion reduction and emissions reduction. **Deliverable:** Final Report: CAV Control Strategies for GHG and Congestion Mitigation
CAV 9 Highway Automation and Control	CAV 9.5	Highway Automation; Dynamic Control; Congestion and Emissions Reduction	**Dynamic Control of Highways in a Mature CAV Environment – Messaging:** Define, develop, simulate, field test and validate in-vehicle messaging addressing human factor research – for mobility applications (speed harmonization and VSL, etc.) testing and validation, human centered design. These mobility applications would focus on congestion reduction and emissions reduction. **Deliverable:** Final Report: In-Vehicle Messaging for CAV Control Strategies
CAV 9 Highway Automation and Control	CAV 9.6	Highway Automation; DSS; Congestion and Emissions Reduction	**Integrating CAVs into Decision Support Systems**. Research and develop the role of DSS in Urban corridors to exploit vehicle intelligence for emissions reduction and congestion mitigation. Decision Support Systems (DSS) are designed to help manage traffic in congested urban corridors. As vehicles become more automated and intelligent, we need to understand how this intelligence can be incorporated into the rules and response plans generated by the DSS. During an incident we need to ensure that the intelligence of the CAVs works to help with overall congestion and emissions reduction. **Deliverable**: Final Report: Integration of CAVs into Traffic Management Decision Support Systems
CAV 9 Highway Automation and Control	CAV 9.7	Highway Automation; DSS; Communications Standards; Congestion	**Communication Standards Between CAVs and Centralized Decision Support Systems**. Research, develop and demonstrate two-way communication strategies between vehicles and DSS.

		and Emissions Reduction	Currently there is no standard on how to communicate between transportation management decision support systems (DSS) and CAVs. This communication would be used to provide information to CAVs (route guidance, demand and active traffic management strategies) and receive information from CAVs (location, destination, urgency, openness to demand management strategies). **Deliverable**: Final Report: Recommendations for Modifications to Communication Standards between CAVs and DSS
CAV 10 Multimodal CAV	CAV 10.1	Intersection Safety Improvement; Transit Safety; Pedestrian Safety	**Intersection Safety Improvement using CAV:** Research, develop and demonstrate pedestrian crossing warning applications (including vehicle and infrastructure based sensors). These applications should leverage CAV technology to warn bus operators of pedestrian (including bicyclists and other Micro-Mobility users) presence in a crosswalk – at intersections and mid-block – as well as pedestrians in harm's way of bus movements at bus stops. **Deliverable**: Final Report: Intersection Safety Improvement for Pedestrians and Transit Vehicles
CAV 10 Multimodal CAV	CAV 10.2	Transit Safety Improvement; Collision Warning	**Transit Safety Improvement:** Research, develop and demonstrate applications that warn transit drivers of imminent collisions. Potential use cases include lane change warnings, rear-end collision avoidance, as well as applications that provide warnings to drivers of imminent angle or T-bone collisions at intersections. **Deliverable:** Final Report: **Transit Vehicle Collision Warning**

CAV 10 Multimodal CAV	CAV 10.3	Transit mobility Improvement; Automated Docking	**Precision docking at bus stops** – Research, develop and demonstrate CAV technology that supports precision docking for transit. Utilize sensors on buses and in roadside infrastructure to indicate the exact place where the bus should stop. Bus doors opening at the same location each time make it possible for passengers to be in position for immediate boarding once a bus has stopped, shortening dwell time. **Deliverable:** Final Report – Transit Vehicle Assistant and Automation
CAV 10 Multimodal CAV	CAV 10.4	Transit mobility Improvement; Automated Guidance in Terminals	**Transit Automation in Terminals:** Research, develop and demonstrate sensors systems to assist and ultimately automate maneuvering in terminals with limited space. This type of system can help minimize the amount of space needed for bus terminal operations, as well as reduce the overall amount of time a bus spends at terminals **Deliverable:** Final Report: Transit Automated Guidance in Terminals
CAV 10 Multimodal CAV	CAV 10.5	Connected and On-Demand Transit; Transit Dynamic Operation;	**Dynamic Transit Operation:** Research, develop and demonstrate operational system using CV technology to connect travelers' real-time demand and transit operators to provide flexible service for improving transit service quality and attracting more ridership. This system leverages CV technology, real-time transit data feed, operator interface, traveler app, and backend engine, which will be tested in a real operational scenario. **Deliverable:** Final Report: Dynamic and On-Demand Transit Operation
CAV 10 Multimodal CAV	CAV 10.6	Active Transportation; Connected Vehicles;	**CV Strategies for Active Transportation:** Research, develop and demonstrate CV strategies to improve safety and mobility

		Bicycle Collision Avoidance	of bicycle transportation. FHWA separated all collisions into three categories. Collisions on parallel-path events (36%) and crossing-path events (57%) can both be mitigated with CV technology. Further, CV technology can enable cyclist mobility improvements – with signal prioritization and actuated bicycle detection devices. This category of research will evaluate barriers in California policies and cyclist user behavior to connectivity, and the potential for it to mitigate accidents and improve mobility. **Deliverable:** Final Report: CV Strategies for Active Transportation
CAV 10 Multimodal CAV	CAV 10.7	Active Transportation; Bicycle V2X and C-V2X Integration	**CV Integration with Active Transportation:** Feasibility analysis, development and demonstrations of the integration of bicycles into the V2X (and C-V2X) communication environment. This includes direct two-way communications between bicycles, between bicycles and vehicles (B2V) and between bicycles and infrastructure (B2I). Sensors that create situational awareness can be integrated into roadside infrastructure, incorporated in vehicles or on bicycles. **Deliverable:** Bicycle V2X and C-V2X Integration
CAV 10 Multimodal CAV	CAV 10.8	Pedestrian Safety Improvement; Speed Management	**CAV Applications for Pedestrian Safety**: Research, develop and demonstrate CAV applications that will improve pedestrian safety through speed management. Nationally, the proportion of pedestrian deaths compared to all highway deaths is rising. Majorities of pedestrian fatalities occur at non-intersections, on urban arterials.

			Deliverable: Pedestrian Safety Improvement through Speed Management of Connected and Automated Vehicles.
CAV 10 Multimodal CAV	CAV 10.9	Pedestrian Safety Improvement; Automated Vehicles	**AV integration with Active Transportation**: Research, develop and demonstrate technologies that help automated vehicles navigate intersections with blind spots (that some intersection geometries create). Infrastructure sensors coupled with communication technologies mitigate blind spot risks for AVs and pedestrians. **Deliverable:** Final Report: Pedestrian Collision Risk Mitigation in an AV Environment
CAV 10 Multimodal CAV	CAV 10.10	Emissions reduction; Congestion Reduction	**Micro-Mobility Sandbox:** Research, develop and demonstrate different technical (connectivity and automation), organizational and regulatory solutions to overcome barriers and mitigate societal costs to Micro-Mobility deployment. One focus of the sandbox is to document how Micro-Mobility helps cities achieve their transportation goals (such as congestion mitigation, first-mile and last-mile challenges, public transit ridership, and access to under-served communities **Deliverable:** Final report: Micro-Mobility Sandbox
CAV 10 Multimodal CAV	CAV 10.11	Emissions reduction; Congestion Reduction; Collision Avoidance	**Connected Micro-Mobility:** Research, develop and demonstrate CAV strategies to improve safety and mobility for Micro-Mobility customers. FHWA separated all collisions into three categories. CV technology can enable Micro-Mobility improvements – with signal prioritization and actuated detection devices. This category of research will evaluate barriers in California policies and micro-mobility user behavior to connectivity, and the

			potential for it to mitigate accidents and improve mobility. **Deliverable:** Final Report: Micro-Mobility Collision Avoidance and Mobility Improvements