

Truck Platoon Testing Allowed Under Assembly Bill 1671



Report to the Legislature

2023

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Executive Summary

This is the California Department of Transportation's (Caltrans) third report, as required by Assembly Bill 1671 (Berman, Chapter 322, Statutes of 2019), which covers the results of the development and testing of cooperative adaptive cruise control systems to perform truck platooning operations on the State Highway System (SHS). This bill extended an authorization for Caltrans, in coordination with the California Highway Patrol (CHP), to conduct testing of technologies that enable drivers to safely operate motor vehicles with less than 100 feet between each vehicle or combination of vehicles until January 1, 2024. The first report required by Senate Bill 719 (Hernandez, Chapter 163, Statutes of 2015) was submitted to the California State Legislature (Legislature) in June 2017 and covered the time period from January 2016 through March 2017. The second report required by Assembly Bill 669 (Berman, Chapter 472, Statutes of 2017), covers the time period from April 2017 through March 2019 and was submitted to the Legislature in November 2019. This report covers activities from April 2019 through January 2023.

The Truck Platooning program has significantly improved over the past few years after the successful completion of the Partial (longitudinal) Automation for Truck Platooning project in 2018, which focused on the development of a Cooperative Adaptive Cruise Control system to perform truck platooning operations and examined its potential benefits. The 2019 Truck Cooperative Adaptive Cruise Control Technical Performance Improvements project refined the cooperative adaptive cruise control system by revising the braking control strategy and addressed safety issues within the system by adding Coordinated Emergency Braking along with the service and engine brake. Limited tests of the improved system were conducted with different loads at low and high speeds which addressed a couple of key safety concerns. Technical gaps between the previously developed cooperative adaptive cruise control system and a cooperative adaptive cruise control system that is required for a field operational test for daily freight movement were filled.

These research, development, and testing activities have validated that the operation of vehicles at gaps shorter than the statutory 100 feet minimum normally prohibited for caravans of vehicles traveling together, confer benefits when under close coordination with vehicle-to-vehicle communication. These closely coordinated vehicles have been demonstrated to:

- Enhance safety through mature platooning technology due to:
 - improved connectivity and situational awareness; and

- improved coordination of maneuvers and behaviors among all the trucks in a platoon, between platoons and other connected road users.
- Improve air quality and reduce emissions by reducing fuel consumption by a range of 10 to 15 percent, depending on a variety of factors including aerodynamic drag reduction due to short following distance (see Reference 3 on Page 22).
- Improve traffic flow stability by increasing density without sacrificing traffic speed.
- Potentially reduce driver's effort through further iterative improvement of the Cooperative Adaptive Cruise Control system performance.

Authorization for carefully controlled testing at shorter gaps was provided by Senate Bill 719, which was extended to January 1, 2024, by Assembly Bills 669 and 1671. Continued research, development, and testing would require an extension of the January 1, 2024, sunset date to:

- Allow the development of Connected Driving Automation research and testing which includes cellular vehicle-to-everything (CV2X) connectivity, connected automated vehicle research, and integration of Connected Driving Automation in traffic management.
- Facilitate and encourage both government and private sector projects that are continuously working toward vehicle platooning development and deployment for both heavy-duty trucks and passenger cars.
- Facilitate industry players that are significantly invested in the development of autonomous trucks and cars and connected automated trucks and cars and performing tests in California.
- Accommodate recent change in Federal Communications Commission's policy of discontinuing Dedicated Short-Range Communication (DSRC) and moving toward vehicle-to-everything technology. This change would require significantly more field tests and improvements of the vehicle-to-vehicle communications technologies which were tested with DSRC before the new cellular vehicle-to-everything technology can be implemented and deployed. Usually, a new communication technology needs three to five years of iterative field testing and improvement before maturity for deployment. Several cellular vehicle-to-everything products are available in the market for testing and evaluation purposes. Few federal projects have started to test them.

Since the last Caltrans report, two-truck platoons and three-truck platoons have driven an additional 3,000 miles on the state highway system at 55 miles per hour without incident. The platoons drove a combined total of 23,500 incident-free miles since 2014 with cooperative adaptive cruise control assistance.

The primary objective of this project was to accelerate the deployment of Connected and Automated Vehicle technologies for freight movement through the development of a truck platooning pilot deployment that includes in-service freight hauling. This would be a critical step to advance research results toward field deployment. Moreover, connected and automated vehicle technology has the potential to significantly transform surface transportation with respect to the movement of people and goods.

Background

Program Background

The 2020 and 2023 California Freight Mobility Plan discusses and supports truck platooning under Multimodal Mobility and Connectivity and Accessibility. This plan supports pilot projects for automated truck platooning both on the open road and in transition zones and promotes the implementation of pilot projects. As the magnitude of future freight challenges continues to grow in California, traditional roadway projects will not be able to keep up with the demand. Caltrans, in partnership with the University of California at Berkeley, Volvo Group, Cambridge Systematics, Los Angeles County Metropolitan Transportation Authority, Gateway Cities Council of Governments, and Peloton Technologies, applied for and received a Federal Highway Administration grant in 2014 to fund research to develop and test a cooperative adaptive cruise control system for heavy trucks. This grant required testing in live traffic with short spacing between the trucks and was the basis for Senate Bill 719 (Hernandez, Chapter 163, Statutes of 2015), which created an exemption from the California Vehicle Code provisions that require a minimum of 100-foot spacing between vehicles in a platoon. Assembly Bill 669 (Berman, Chapter 472, Statutes of 2017) and Assembly Bill 1671 (Berman, Chapter 322, Statutes of 2019) extended the sunset date of the exemption to January 1, 2024.

Modern smart infrastructure requires intelligent transportation systems improvements for efficient, effective, and sustainable people movement. Intelligent transportation systems improve transportation by integrating advanced information and communications-based technologies into transportation infrastructure and vehicles (see Reference 1 on page 22). Technology tools built using intelligent transportation systems elements increase efficiency for travelers across the nation and increase the value of existing transportation infrastructure. Emerging intelligent systems technologies include automated driving systems, data exchanges and cybersecurity support, and utilize spectrum and artificial intelligence to meet travelers' needs. Moreover, intelligent transportation systems technologies include sensors that can detect the locations and motions of vehicles and other road users (pedestrians, bicyclists, and even animals); wireless communication systems that enable the exchange of data among and between vehicles and the roadway infrastructure; computer systems that can analyze the data; and actuators that can automatically control vehicle motions (steering, acceleration, and braking).

A very significant aspect of intelligent transportation systems technologies is connected and automated vehicles. Connected Vehicle (CV) technologies combine leading-edge technologies which include advanced wireless communications, onboard computer processing, advanced vehicle sensors, Global Positioning System navigation, smart infrastructure, and other technologies that provide vehicles with capabilities to identify threats and hazards on the roadway. These technologies help communicate important safety information over wireless networks to give drivers alerts and warnings about upcoming road conditions.

At CV's core is a networked environment supporting very high-speed transactions among vehicles, and between vehicles and infrastructure components or handheld devices to enable numerous safety and mobility applications (see Reference 2 on page 22). CV technologies help identify, collect, process, exchange, and transmit real-time data and provide drivers with a greater situational awareness of planned and unplanned events, potential setbacks, delays, and imminent hazards around the vehicle at all times. Drivers make better, safer, and faster decisions while using technologies that intuitively and clearly present safety alerts, situational advice, and warnings. When combined with automated vehicle-safety applications, the CV has the ability to respond and react to a situation when the driver cannot or does not react in time; hence, significantly increasing the effectiveness of crash prevention and mitigation applications. An example of this is adaptive cruise control and cooperative adaptive cruise control systems. Some potential applications that are being researched and are in the production environment are described below:

- Vehicle-to-vehicle (V2V) applications – When a vehicle brakes suddenly, it sends a message to the vehicles behind it and those vehicles warn their drivers to stop or automatically apply brakes if a crash is imminent. Examples: Adaptive cruise control, Cooperative adaptive cruise control.
- Vehicle-to-Infrastructure (V2I) applications – A vehicle transmits and receives data from Roadside Units installed in certain corridors. The vehicle receives basic safety messages, intersection geometry map also known as MAP messages, green time or red time information, and other associated data. A vehicle in a crash could also transmit incident data which includes the time of the incident, type of crash, and severity to Roadside Units and CVs around it. This data can then be broadcasted as regional warnings for other drivers. Simultaneously, incident data could be transmitted directly to emergency dispatchers for emergency response.

- Vehicle-to-others applications – A car making a left or right turn can alert a bicyclist in the same intersection by sending safety alerts to a device on the bike to avoid a potential collision.

Automated vehicles (AV) are vehicles in which some aspect of a safety-critical control function (e.g., steering, throttle, or braking) occurs without drivers' direct input. The word "automated" is more general. Automated vehicles can be divided into two categories: (1) autonomous vehicle for which control relies on the onboard sensors only; and (2) connected and automated vehicles, for which control uses both onboard sensors and wireless communication information-sharing systems through cellular vehicle-to-everything (vehicle-to-vehicle, vehicle-to-infrastructure, and infrastructure-to-vehicle). Connected and automated vehicles have the potential to significantly impact driver safety, personal mobility, energy consumption, operating efficiency, environmental sustainability, and land use (see Reference 2 on page 22). Research into automated vehicles is rapidly expanding and more and more applications are being developed for production environment. Lower-level automated vehicles can include technology that assists, but does not replace, a human driver.

One important class of intelligent transportation systems and connected and automated vehicle applications is adaptive cruise control which is already available for use on many passenger cars and commercial vehicles. The adaptive cruise control feature automatically controls the acceleration and braking of a vehicle so that it maintains a set following distance behind the preceding vehicle in its lane. Adaptive cruise control systems use forward-looking sensors (for example: Radio Detection and Ranging (RADAR), Light Detection and Ranging (LIDAR), and/or video cameras) to measure the distance from the preceding vehicle and calculate the difference in speed between vehicles. This information is used by the adaptive cruise control system software to determine the acceleration or braking commands that should be implemented to maintain the desired spacing. Approximately two million adaptive cruise control-equipped heavy trucks are now on the road in the United States.

Currently, adaptive cruise control is a widely used driver assistance system as it automatically adjusts the vehicle speed to maintain a safe distance from preceding vehicles. Cooperative adaptive cruise control is created by integrating high-speed vehicle-to-vehicle communications into passenger cars and heavy trucks equipped with commercially available adaptive cruise control, thus allowing the vehicles to communicate with one another. Using cooperative adaptive cruise control, a truck's cruise control system maintains a proper following distance behind another truck by slowing down once it gets too close and allows vehicles to "cooperate" by communicating with each other. The result is that vehicles can follow more closely, accurately, and safely,

with braking and accelerating done cooperatively and synchronously.

Commercially available adaptive cruise control systems for passenger cars are typically designed with a minimum time gap of 0.8 to 1.0 seconds between vehicles, while adaptive cruise control systems for heavy trucks typically provide a minimum time gap of 1.6 or 2.0 seconds. Defining these gaps in terms of time means that the distance between the vehicles will vary with vehicle speed. For example, at a speed of 55 miles per hour, the 0.8-second gap represents a distance of 64.5 feet, and the gap of 1.6 seconds represents a distance of 129 feet. The gap gets shorter at lower speeds, but if the speed drops below a minimum safe threshold value (typically in the range of 20 to 30 miles per hour), the gap stops decreasing and remains at a fixed minimum distance for safety (see Reference 3 on page 22).

In recent years several adaptive cruise control systems that can operate in stop-and-go traffic or perform emergency braking have become available on many models of automobiles and trucks. Existing adaptive cruise control systems have some limitations that can be overcome with the addition of vehicle-to-vehicle wireless communications of key vehicle data. Existing adaptive cruise control systems only detect changes in the motion (or response) of the vehicle immediately in front of them, not the actions or intentions of vehicles further ahead. They are relatively slow to respond to changes in the motion of vehicles ahead, and their minimum gap settings are large enough that drivers of other vehicles can freely change lanes using these gaps, even in dense urban traffic settings. This weaving of vehicles causes some delay in the detection and response of the subject vehicle (car or truck). If there are more than two vehicles in tandem with the adaptive cruise control feature enabled, then, with respect to the action of the leader vehicle, the delays will cumulate from downstream to upstream. As an example, assuming five vehicles using adaptive cruise control are driving in tandem and the delay is 0.8 second, the reaction delay of the fifth vehicle with respect to the leader will have a delay of 3.2 seconds, which is similar to human drivers. This delay in reaction is the reason for multiple vehicle crash accidents, which still happen around the world, due to perception and recognition problems. Severe weather is one of the environmental conditions that can cause these delays in reaction.

With the addition of vehicle-to-vehicle communication of data, these systems become cooperative adaptive cruise control, which provides several performance improvements:

- Receive information from vehicles further ahead than their sensors can detect which allows vehicles to respond faster and more smoothly to changes in traffic speed.

- Operate safely at shorter time gap settings (0.6 seconds, corresponding to a clearance gap of 48 feet at 55 miles per hour) by enabling synchronized operation/control of the vehicles driving closer together in a platoon using vehicle-to-vehicle information.
- Respond more quickly and predictably to braking actions by preceding vehicles, hence increasing driver comfort and confidence in the systems.
- Smooth out traffic flow disturbances which improves the stability of freeway traffic flow (dampening stop-and-go behavior).
- Any vehicle in the platoon can immediately respond to the actions of any front vehicle(s) to avoid a crash by using vehicle-to-vehicle communication. In particular, if all the vehicles are connected and automated, multi-vehicle pileup accidents can be effectively and completely avoided. This role will be played by the Coordinated Emergency Braking initially implemented and tested under a Caltrans project in 2018-2019 on a test track.
- Prior safety analyses and experiments with passenger car drivers have indicated that time gaps in the range of 0.6 seconds (clearance distance of 48 feet at 55 miles per hour) should be considered, and assessment of platoon performance and acceptability by commercial drivers require testing at these shorter gaps on public roads.

Cooperative adaptive cruise control systems can increase safety by reducing reaction time as explained in the previous pages. The cooperative adaptive cruise control system in the middle and trailing truck in a three-truck platoon will begin responding within 0.2 seconds when the lead truck brakes or accelerates. Human reaction time is more complex, highly variable, and can range from half a second for an attentive experienced driver to the range of 1.4 to 2 seconds for the average driver (a driver that is fatigued, or not focused on the driving task will likely have more reaction delays [see Reference 3 on page 22]).

Cooperative adaptive cruise control systems currently exist only as research prototypes. The first commercially available cooperative adaptive cruise control systems are likely to be implemented on long-haul heavy trucks because of the opportunity to obtain a return on investment through the fuel savings associated with “drafting” heavy trucks in a coordinated platoon. However, additional refinement to system designs and technical standards to govern vehicle-to-vehicle data exchanges would assist with making such systems commercially viable. This was the purpose of the Federal Highway Administration - Caltrans Truck Platooning Early Deployment project.

Truck Platoon Testing Status

The promising results from the 2014 Partial Automation for Truck Platooning project, which was completed in 2018, prompted the Federal Highway Administration (FHWA) to come up with a follow-on grant in 2019. Caltrans teamed up with the FHWA, the University of California, Berkeley, Volvo Group, Westat, Cambridge Systematics, and Roly's Trucking to deploy Truck Platooning Early Deployment Assessment Phase 1 and Phase 2 projects. The overall objective of this project was to refine, operate, and test cooperative adaptive cruise control-equipped commercial trucks by utilizing close-spaced truck platooning operation to move freight along the Interstate 10 corridor from Los Angeles to the Dallas/Fort Worth metro area. The goal of this project was to implement cooperative adaptive cruise control on four new trucks, develop a research data collection system to collect data from the trucks, analyze the data collected from the operational test, demonstrate system readiness for the field operational test, and conduct the field operational test for 12 months by the professional truck drivers of Roly's Trucking with daily freight movement between California and Texas.

Since 2019, under the Federal Highway Administration - Caltrans Truck Platooning Early Development Phase 2 project, the cooperative adaptive cruise control system was implemented on four new Volvo VNL 760 trucks; the system performance was refined for operation under a wide range of scenarios including various tractor-trailer load varieties; the safety measures were improved; and data collection and a real-time monitoring system were developed. The newly instrumented two-truck and three-truck platoons have driven an additional 3,000 miles on the state highway system at 55 miles per hour without incident. The platoons drove a combined total of 23,500 incident-free miles since 2014 with cooperative adaptive cruise control assistance. The Field Operational Testing planned to take place on the Interstate 10 corridor was not completed because of difficulties arising between the research team and the trucking industry. More information is provided on the pages below.

Previous Report

Pursuant to Senate Bill 719, Caltrans provided the Legislature with a report titled "Truck Platooning Testing Allowed Under Senate Bill 719" in June 2017. The report covered testing and project activities from 2015 through March 2017, and included the testing required to develop the prototype cooperative adaptive cruise control system, fuel consumption experiments performed on a test track, and two public demonstrations in California.

Pursuant to Assemble Bill 669, Caltrans submitted a report to the Legislature titled "Truck Platoon Testing Allowed Under Assembly Bill 669". The report covered additional testing activities that were conducted between April 2017 and March 2019. The report summarized continued cooperative adaptive cruise control development testing on San Francisco Bay Area highways, an experiment of truck drivers' experiences and preferences, a second round of fuel consumption experiments at Canada's Department of Transportation test track near Montreal, Canada, and a public demonstration for federal decision-makers on Interstate 66 in Virginia.

Since that report, the following additional activities were conducted between April 2019 and January 2023:

1. Coordinated brake project funded by Caltrans:
 - Coordinated emergency braking algorithm was implemented on three Volvo VNL670 trucks for two scenarios: (a) the driver manually activating the truck's service brakes; and (b) the braking system activating automatically based on sensor detection of hazardous scenarios.
 - The coordinated emergency braking was intended to decelerate all the trucks in a platoon, in a synchronized way, in case a hazard appeared in any of the front truck(s); the algorithm was devised to avoid multi-vehicle pileup crashes by using vehicle-to-vehicle communication.
 - The system was tested on a test track at the Crows Landing airfield for different acceleration levels and: (a) for tractor only; (b) tractor and empty trailer; and (c) tractor and fully loaded trailer combinations.
2. Updated cooperative adaptive cruise control system under the Federal Highway Administration-Caltrans Truck Platooning Early Deployment project:
 - Updated instrumentation of the overall cooperative adaptive cruise control system as shown in Figure 1 on page 14.

- Executed system implementation on new Volvo VNL 760 trucks.
- Initially tested one-truck, two-truck and three-truck platooning on California highways near Berkeley, California.
- Refined cooperative adaptive cruise control system for better performance.
- Developed safety consideration and hazards analysis for field operational test.

Program Status/Program Accomplishments

System Refinement

The cooperative adaptive cruise control system was refined and updated to fill the technical gaps between the cooperative adaptive cruise control system that was developed under the previous 2014 project and the cooperative adaptive cruise control system that is required for a Field Operational Test for daily freight movement by the fleet operator. The system was improved in these aspects: the feedback control was updated; functional safety and reliability were improved by using the control and data collection computers and better analyzing the perception/prediction of the front targets in more hazardous scenarios such as other vehicle cut-in and merging from onramps; vehicle-to-vehicle communication was enhanced through the middle truck relay; coordinated emergency braking was added, supplementing Volvo's built-in Collision Mitigation System; new functions were added to the Driver-Vehicle-Interface to allow the driver to activate/deactivate voice recordings to report any observed incidents, accidents and/or abnormal situations; and the Global Positioning System-based overall system time-synchronization and subject truck position estimation in the platoon was updated. These system improvements were conducted in the following aspects:

- Front Traffic Scene Perception: A fixed beam lidar with a 180-degree field of view was added at the front bumper to enhance target detection and tracking and to handle short-distance cut-ins and onramp merge scenarios.
- Global Positioning System-based Platoon Position Estimation: Global Positioning System signals of all the trucks in the platoon (passed by wireless communication) were used to determine the relative position of the subject truck in the platoon.
- Safety: Besides inheriting the Volvo truck's built-in safety measures, coordinated emergency braking was added for safety improvement which is intended to keep a nearly constant distance (at the time instant of braking) by using feedback control to modulate the braking torques of all the trucks involved. The coordinated emergency braking can be activated by the driver by manually stepping on the service brake pedal or it can be activated automatically by the control system based on remote sensor perception and safety-related decision-making logic. This is an addition to the commercially built-in Collision Mitigation System for each truck which is activated based on the relative speed/distance with respect to the forward target vehicle.
- Reliability Improvement of vehicle-to-vehicle communication by adding a relay through the second truck.

- Improvement on Driver-Vehicle-Interface: The improvement was in two aspects: (a) driver's voice recording so that the driver could report any incident, accident, and/or abnormal situation observed; and (b) allowing the driver to input an anonymous Identification and truck position in the platoon at the start of the platoon in case the Global Positioning System did not work correctly.
- Added Data Collection System: This system was intended to collect all the engineering data, additional sensor data, and driver behavior data to capture the traffic surrounding the truck.
- Added Real-time Monitoring System: This system was intended to provide a real-time link through a cellular modem between the trucks in the field and a computer so that the status of the cooperative adaptive cruise control system and the data collection system could be monitored in real-time. Furthermore, if some of the systems or subsystems had any errors, staff could correct them remotely. However, this does not mean that all the problems in the Field Operational Test could be handled remotely.

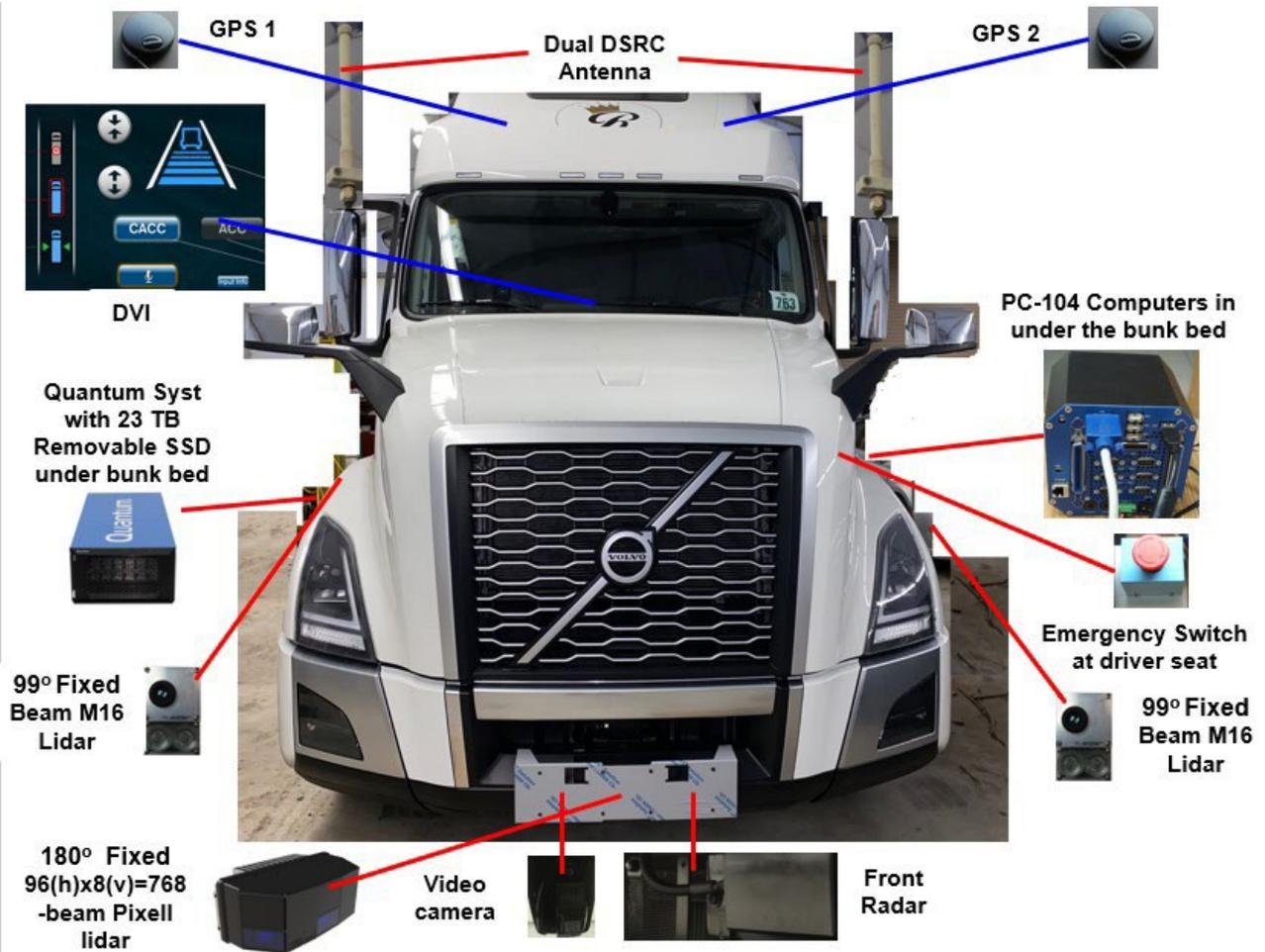


Figure 1: Overall Cooperative Adaptive Cruise Control (CACC) System Components

Safety Considerations and Hazard Analysis

Safety can only be progressively and iteratively improved through different levels of field operational tests. Safety was improved in four major aspects, including:

- a) System functional safety and reliability improvements – This covers the hazards (or safety issues) caused by system functionality and reliability. This is determined by the system design and implementation.
- b) Maintaining the manufacturer's built-in safety measures such as warning, crash mitigation, and avoidance systems – This covers Front Collision Warning; Side Collision Warning; Lane Departure Warning; Frontal Collision Mitigation System by emergency braking.

- c) Limiting the driver's operating conditions to remain within the system's Operational Design Domain – Specific operating conditions have been defined under which the system can be safely operated during field testing based on the known performance boundaries of the cooperative adaptive cruise control.
- d) Driver training and qualification testing – This enhanced the overall safety and reduced hazards, particularly by ensuring the driver's understanding of the system limitations and of the limited operating conditions in which they are permitted to use the cooperative adaptive cruise control system.

The project followed the principles of Safety of the Intended Functionality and included the following considerations:

1. The cooperative adaptive cruise control system is designed and used as a Level 1 driving assistance system applying longitudinal control only.
2. The driver continuously maintains responsibility for truck control and must remain fully engaged because of the continuous requirement to steer the truck.
3. A convenient Driver-Vehicle-Interface allows the driver to take over manual control at any time by several alternative means.
4. Only properly trained drivers, as described below, are authorized to operate the system.
5. The truck cooperative adaptive cruise control/platooning can only be operated within a limited Operational Design Domain.

The truck platooning project is a research project, so the trucks that were to be used for the tests were not pre-production prototype products and their cooperative adaptive cruise control system could only be used within the scope of the field test project which has limited Operation Design Domain.

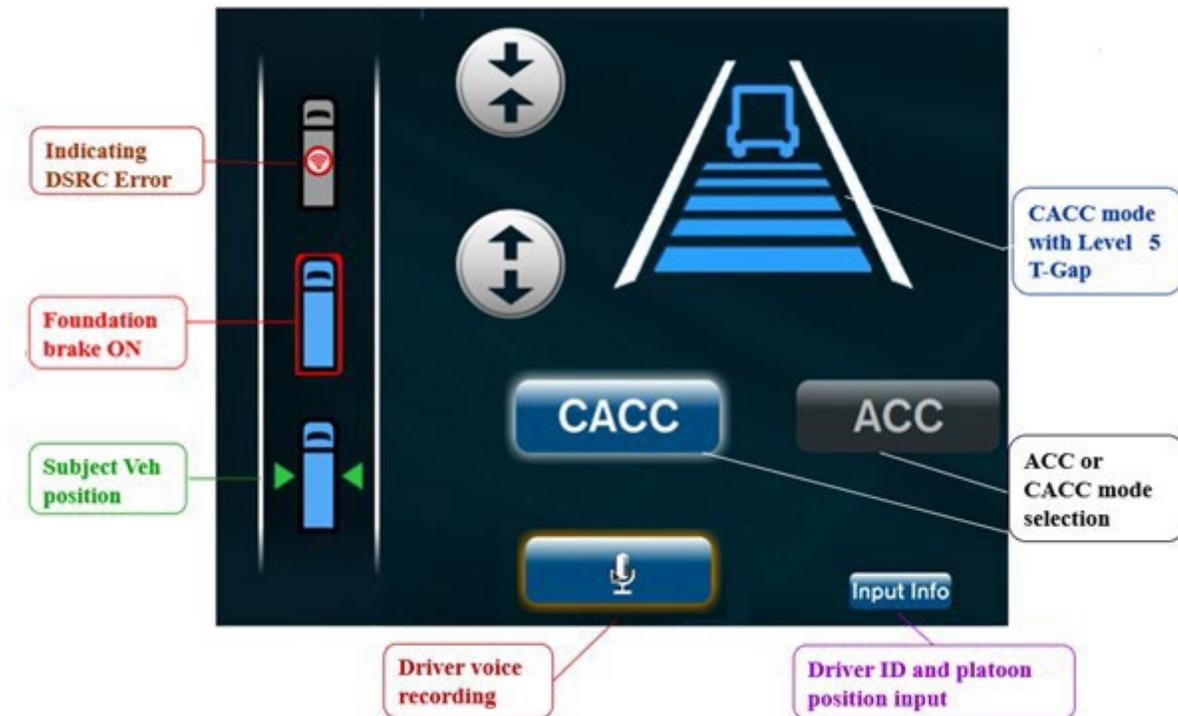


Figure 2: Improved Driver Vehicle Interface

Data System Development

A data management system was developed that streamlined data transferring, missing data imputation, and performance metrics computation. The goal of data management was to ensure that future researchers or users may benefit from an intact and easy-to-use dataset that faithfully records the truck platooning operation status and the surrounding environment. The data management system included a data transferring tool that moved raw data to the data storage locations in a secure, reliable, and efficient manner. The system also used an automated data imputation algorithm to address missing or incorrect data points.

Driver Monitoring

The effects of platooning on fatigue and distraction were studied. Two state-of-the-art systems were selected to capture the data and measure the impact of platooning situations on the level of engagement and fatigue of the respective drivers. For capturing fatigue, an Australian-made “dry electroencephalogram” system called the SmartCap LifeBand™ was chosen. Used successfully for over a decade in Australian mines, it has recently been introduced in U.S. mining and trucking operations for this application and were intended to provide a simple and reliable measure of fatigue with automatic processing and reporting of

each driver's status. For capturing distraction situations, an Israeli-made system called the Jungo VuDrive™ system was chosen. This Artificial Intelligence-enabled dash camera is capable of recognizing eye movements, torso orientation, and facial pose context to identify distraction events as well as fatigue and other measures of driver engagement.

Relevant aspects of training and data processing (retrieval, data processing, and memory management) applications for the systems were developed. Most of the functionality required to retrieve data, differentiate drivers, and automatically clear storage space on media, so that no data would be lost, was developed and locally tested but the final demonstration and use of those capabilities within the actual study vehicle environment never occurred.

Real-Time Monitoring System Development

A real-time monitoring system was developed to preserve the integrity and validity of the truck platooning datasets during the platooning field operational test. The main function of the real-time monitoring system was to automatically check the operation status of key subsystems of each test truck by examining their real-time data streams and saved data files. The checking functions generate notification messages when the monitoring system identifies abnormal conditions. Normal operation of the subsystem can be restored after receiving the notification. The application of the real-time monitoring system was essential for the project to collect high-quality data sets.

Driver Recruitment and Training Plan

Drivers are key to understanding and evaluating the performance of the cooperative adaptive cruise control technology. A complete approach to driver recruitment was developed including driver qualifications, the maximum number of drivers to recruit, the hiring and screening process, driver compensation, and anticipated challenges of driver recruitment. The driver training plan with a discussion of key safety considerations, the proposed training process for each stage of testing, training logistics, and training materials and policies for test drivers were developed.

Stakeholder Engagement

An Interstate 10 Corridor Coalition was created which including Caltrans, the Arizona Department of Transportation, the New Mexico Department of Transportation, and the Texas Department of Transportation. Collectively, these transportation departments have been examining long-haul truck vehicle-to-everything applications, truck-connected and automated vehicle infrastructure support, and truck-connected and automated vehicle operations and regulatory needs on the Interstate 10 corridor. Initial information on the

regulations and processes for exceptions to “following too closely” codes in each of the three states was obtained. Additionally, information on other specific rules and requirements in each state was gathered. A major focus of these efforts involved working with each state to develop the necessary agreements or commitments to support operational testing of the platooning system.

Issues

Four Volvo VNL 760 trucks were initially equipped with the cooperative adaptive cruise control system, which was developed and refined under these consecutive truck platooning projects. The Driver Vehicle Interface, real-time monitoring system, and data collection system were also developed. Under previous projects, the lower-level control actuation was done through direct engine torque control. However, for this Field Operational Testing with normal truck drivers, Volvo insisted that the engine control should go through their manufacturer’s original adaptive cruise control system instead of bypassing it (through the direct engine torque control) for safety reasons. Difficulties arose with the default adaptive cruise control setup. Once the service brake was applied, whether automatically or manually, the engine torque control (for adaptive cruise control) would be disabled so the driver would have to reactivate the adaptive cruise control or cooperative adaptive cruise control. To resolve this problem, it would be necessary for Volvo and Bendix (the provider of the service brake control Electronic Control Unit) to work closely with the research team to change the hardware and/or software installed in their commercial trucks so that the cooperative adaptive cruise control can be activated correctly. This difficulty was not recognized by Volvo and Bendix until many cycles of low-level Control Area Network data collection had passed and one truck was shipped to Volvo in Greensboro, North Carolina in July 2022 for direct diagnostics. This process took about a year and spent a significant amount of resources causing a significant delay in the project so it could not be accomplished within the proposed timeline and resources. It is unknown when Volvo USA and Bendix could resolve the problem. This issue blocked the project from moving forward with the planned tests. Hence, these tests were not completed: System Acceptance Test, Driver Acceptance Test, Operational Readiness Test, and Field Operational Test.

For these issues to be resolved, industry support is required. We recommend manufacturers to both be part of the project team instead of being external partners.

Related Projects and Activities

Caltrans and the U.S. Department of Energy have projects for the development of Cooperative Driving Automation which includes cellular-vehicle-to-everything connectivity, connected and automated vehicles (mainly cooperative adaptive cruise control or platooning which will typically drive with much shorter following-distance due to the connectivity and situation awareness), and integration of Cooperative Driving Automation in traffic management.

University of California, Berkeley is continuously working on vehicle platooning development and deployment. University of California, Berkeley is also working with the Department of Energy on a research project focused on Cooperative Driving Automation and its applications. Several automakers' research institutes and start-ups in the San Francisco Bay Area are currently working on truck platooning technologies toward deployment.

Several companies including Uber, Tesla, Waymo, CreateAI, Intel, and other automakers are investing significantly in the development of autonomous and connected automated trucks/cars, which will require testing. The Interstate 10 corridor coalition charter specifically mentions truck platooning as one of its goals to improve freight movement, safety, and efficiency along the corridor. One priority area is the development of policy and regulations, and infrastructure modifications needed to support connected automated vehicles including cooperative adaptive cruise control truck platooning.

In an independent effort, Peloton developed its two-truck platooning technology and worked with Caltrans and CHP for approval to test their technology on California highways. They began testing their system in California under the authority of Senate Bill 719 and continued it under Assembly Bill 669. Peloton refers to its cooperative adaptive cruise control system as PlatoonPro. PlatoonPro testing is similar to the testing conducted by Caltrans, the CHP, Volvo, and the University of California, Berkeley.

Conclusion

The development and testing of the heavy truck cooperative adaptive cruise control system were performed under the authority of Senate Bill 719, which covered the time period from January 2016 through March 2017; Assembly Bill 669 which covered the time period from April 2017 through March 2019; and Assembly Bill 1671 which covered activities from April 2019 through January 2023. These types of technologies offer the potential to lead transformational changes and advance freight and highway operations. The potential benefits include increased safety and capacity and reductions in fuel use and emissions, all without the need to build new and expensive infrastructure. Continuous refinement and testing (both in a controlled local environment and field environment) have validated that the operation of vehicles at gaps shorter than the California statutory 100 feet minimum, normally prohibited for caravans of vehicles traveling together, confer many benefits when the vehicles are under close coordination. These closely coordinated vehicles have been demonstrated to:

- Enhance safety through mature platooning technology due to:
 - Improved connectivity and situational awareness.
 - Improved coordination of maneuvers and behaviors among all the trucks in the platoon and between platoons and other connected road users.
- Improve air quality and reduce emissions by reducing fuel consumption in a range of 10 to 15 percent, depending on the following distance (see reference 3 on page 23).
- Improve traffic flow stability by increasing density without sacrificing traffic speed.

The 2017 demonstration showed that the closely coordinated cooperative adaptive cruise control heavy trucks were able to interact safely and smoothly with drivers of other vehicles. During the course of this demonstration, other drivers did not hesitate to change lanes into the gaps between trucks that were driving under cooperative adaptive cruise control coordination (see Reference 3 on page 23). This persistence of lane changing demonstrated that closely spaced cooperative adaptive cruise control trucks did not create an impediment to traffic movement and lane choice.

Continuing the efforts in 2019, the cooperative adaptive cruise control was refined; safety was improved; a data management system was developed; and a driver monitoring system was developed, along with developing a real-time monitoring system and driver recruitment and training plan. Even though the system was developed completely, and several local tests were performed to

test the individual parts of the system, field testing could not take place. Limited testing in the local environment did take place using trucks with empty trailers, trucks with fully loaded trailers, and a combination of the two. Difficulties arose due to the cooperative adaptive cruise control system, which could not be deployed on the Volvo VNL 760 truck. Additional testing is still necessary to accomplish the goals for the early deployment of truck platooning, which would include a System Acceptance Test, Driver Acceptance Test, Operational Readiness Test, and Field Operational Test. Volvo and Bendix, the provider of the trucks and the service brake control Electronic Control Unit, were loose partners and were under no obligation to research and help find a way to correct the hardware-software bug in their adaptive cruise control system and the service brake control. This may be resolved if manufacturers are made contractual partners in future projects.

The following items listed as the next steps in the previous reports were accomplished:

- Additional testing required to refine cooperative adaptive cruise control technology was completed.
- Collection and analysis of enough data for assurance that adequate safety, operations, and environmental testing have been performed.
- Understanding lane-changing behavior and how other vehicles interact with platooning trucks was completed.
- Implications of cut-ins at various gap settings were determined.
- Input from commercial vehicle drivers and fleets into the cooperative adaptive cruise control design was Incorporated.

Connected and automated vehicle technologies have the potential of increasing efficiency of existing highway infrastructure. Increasing safety while improving efficiency is the unique opportunity offered by modern connected and automated vehicle technologies. Several companies are investing significantly in the development of autonomous trucks and cars and connected automated trucks and cars and are preparing for testing in California. This research, development, and deployment of more and more connected and automated vehicle technologies and platooning will help California counter congestion and safety issues and improve the reliability and sustainability of its already strained freeway system.

The authorization for carefully controlled testing at shorter gaps was provided by Senate Bill 719. Assembly Bill 1671 extended the sunset date to January 1, 2024. Continued development and testing of connected and automated technologies would require an extension of the sunset date in law. Additional testing would be needed to further refine the overall connected and automated vehicle technology, specifically to:

- develop and implement various connected and automated vehicle applications to improve safety, operations, and sustainability;
- understand human and driver behavior around connected and automated vehicles;
- determine the implications of cut-ins at various gap settings for various types of vehicles and platoon sizes; and
- incorporate input from commercial vehicle drivers and fleets into connected and automated vehicle design, implementation, and field tests.

References

1. Sharon Chan-Edmiston, Stephanie Fischer, Suzanne Sloan, Melissa Wong. Intelligent Transportation Systems (ITS) Joint Program Office: Strategic Plan 2020–2025. March 2020.
https://www.its.dot.gov/stratplan2020/ITSJPO_StrategicPlan_2020-2025.pdf
2. Institute of Transportation Engineers (ITE) resources.
<https://www.ite.org/technical-resources/topics/connected-automated-vehicles/>
3. Report findings of the testing to the Legislature on or before July 1, 2019.

Appendix A. Statutory Reporting Reference

CALIFORNIA GOVERNMENT CODE DIVISION 3. EXECUTIVE DEPARTMENT PART 5. DEPARTMENT OF TRANSPORTATION CHAPTER 2. Powers and Duties

ARTICLE 1. General

14107. (a) The department, in coordination with the Department of the California Highway Patrol, may conduct testing of technologies that enable drivers to safely operate motor vehicles with less than 100 feet between each vehicle or combination of vehicles.

(b) Notwithstanding Section 21705 of the Vehicle Code or any other law, motor vehicles participating in testing of those technologies pursuant to subdivision (a) may be operated with less than 100 feet between each vehicle or combination of those vehicles.

(c) The department may only use motor vehicles and streets and highways in testing conducted pursuant to subdivision (a) that the Department of the California Highway Patrol authorizes for those uses.

(d) A person may not operate a motor vehicle participating in testing conducted pursuant to subdivision (a) unless the person holds a valid driver's license of the appropriate class for the participating vehicle.

(e) (1) The department shall report its findings from the testing conducted pursuant to subdivision (a) to the Legislature on or before July 1, 2017, and shall submit updated reports to the Legislature on or before July 1, 2019, and on or before April 1, 2023. The reports required by this subdivision shall be submitted in compliance with Section 9795.

(2) In addition to reporting its findings from the testing conducted pursuant to subdivision (a), the department shall also include in the updated report to be submitted on or before April 1, 2023, any recommendations of subsequent actions that should be taken with regard to the technologies tested pursuant to this section.

(f) This section shall remain in effect only until January 1, 2024, and as of that date is repealed.