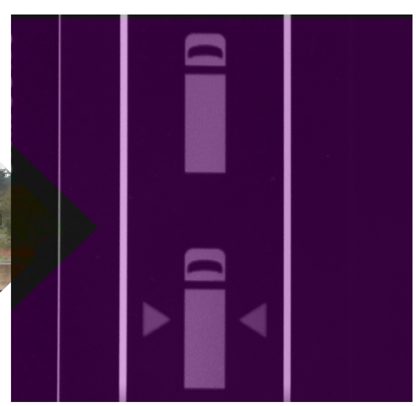
EXPLORATORY ADVANCED RESEARCH

The Exploratory Advanced Research Program

Partial Automation for Truck Platooning

RESEARCH SUMMARY REPORT



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16. Abstract Researchers at California Partners for Advanced Transportation Technology (PATH), a research and development program at the University of California-Berkeley, studied the potential benefits of cooperative adaptive cruise control (CACC) by deploying the technology in a platoon of three trucks. They built the CACC system and implemented it in three long-haul trucks, tested it on closed tracks and open highways, simulated its use in real traffic scenarios, and demonstrated its use to stakeholders and interested parties. CACC uses dedicated short-range communication and other technology components to enable vehicles to "talk" to each other. It has the potential to add stability to traffic flow, alleviate congestion, and reduce fuel use and vehicle emissions—all while improving safety on America's roads.		
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SI* (Modern Metric) Conversion Factors

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	654.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	meters	L
ft^3	cubic feet	0.028	meters	m^3
yd^3	cubic yards	0.765	kilometers	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9	Celsius	°C
		or (F-32)/1.8		
		ILLUMINATION		
fc	foot-candies	10.76	lux	lx
ft	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yard	yd^2
ha	hectares	2.47	acres	mi
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	mililiters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candies	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	ft
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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List of Abbreviations

ACC	adaptive cruise control
CACC	cooperative adaptive cruise control
Caltrans	California Department of Transportation
DSRC	dedicated short-range communication
DVI	driver vehicle interface
EAR	Exploratory Advanced Research
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
GPS	global positioning system
ITS	Intelligent Transportation Society
PATH	Partners for Advanced Transportation Technology
UC-Berkeley	University of California-Berkeley
V2V	vehicle-to-vehicle

Introduction

As the next generation of driver-assist technology for automating adjustments to vehicle speed, cooperative adaptive cruise control (CACC) offers many potential benefits for America's highway system. It can improve stability to traffic flow, alleviate congestion, and reduce fuel use and vehicle emissions.

The first step toward commercial availability of this partial automation likely will come in the form of long-haul heavy trucks that "talk" to each other while traveling together in platoons. The Exploratory Advanced Research (EAR) Program at the Federal Highway Administration (FHWA), working with the FHWA Office of Operations Research and Development, has been supporting research into such truck platoons. The University of California-Berkeley (UC-Berkeley) spearheaded one project through California Partners for Advanced Transportation Technology (PATH), a research and development program at the university. Along with UC-Berkeley, the U.S. Department of Energy, California Department of Transportation (Caltrans), Transport Canada, and Volvo Group North America were partners in the work.

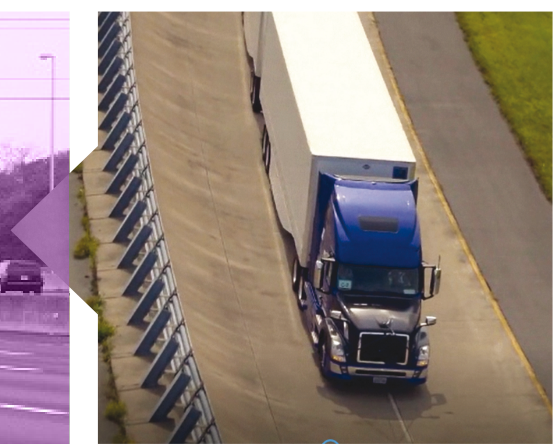
Three Class A trucks were equipped with adaptive cruise control (ACC), which uses sensors to maintain a specified time gap between the vehicle with the technology and the one in front of it. The researchers enhanced the ACC technology by adding communications and computing components that enabled longitudinal control among multiple vehicles. One improvement to the trucks was the addition of dedicated short-range communication (DSRC), the vehicle-to-vehicle wireless technology at the heart of CACC. It gave the trucks the ability to maintain set time gaps from each other while reducing the force of disturbances to ensure stable vehicle following.

Figure 1. University of California-Berkeley researchers built a cooperative adaptive cruise control system into a platoon of three long-haul trucks to test the technology's potential to improve traffic flow, save fuel, and curtail emissions.
© Transport Canada

The researchers evaluated the technology in simulation scenarios and tested it on closed tracks and public roads. The research team recruited long-haul truck drivers for some of the road tests to gauge their comfort with various time gaps between the trucks and their overall confidence in the technology. The driver of the lead truck set the pace for the platoon, and the CACC determined the distance for the following trucks based on pre-set time gaps. The technology maintained constant time gaps proportional to vehicle speed, as opposed to the constant distance gaps in previous truck-platooning research. The available gap settings provided enough time for the truck drivers to see lane markings for steering and for the trucks to react when other vehicles interrupted the platoons. The drivers could take control of braking and acceleration in their trucks at any time, and they steered at all times.

The project was designed to gauge the potential for CACC to improve heavy truck operations in the short term, the willingness of drivers to participate in CACC-enabled platoons with short time gaps between trucks, and the achievable energy savings at the preferred time gaps. It also created an opportunity to illustrate the benefits of CACC to industry and public officials.

The results of the research showed that CACC in trucks could be an important step toward developing even more advanced platooning technology. The upgrade from ACC to CACC was relatively inexpensive; the trucks could travel together more closely and react quickly to cut-in traffic; and the drivers were comfortable using the technology. When paired with aerodynamic features on the truck trailers, CACC achieved noteworthy fuel savings. The research also suggested that CACC in truck platoons can ease congestion in certain conditions.



Project Overview

California PATH has been a leader in truck platooning research, funded in part by FHWA. This California PATH project focused on CACC for truck platoons. (California PATH, 2019) The research encompassed building the CACC system, testing it on closed tracks and open highways, simulating its use in real traffic scenarios, and demonstrating it to stakeholders and interested parties.

First, the researchers identified the trucking industry needs and opportunities, and defined operational concepts for the research. Then they designed the CACC system and built it into three trucks for multiple road tests and demonstration projects. The researchers initially developed and tuned the platoon performance at low speed at UC-Berkeley's short test track at its Richmond Field Station and then expanded it to higher-speed testing on nearby freeways. Then they showcased the CACC technology on a freeway in San Jose as part of the 2016 Intelligent Transportation Society (ITS) of America Annual Meeting.

Platooning experiments were performed on a closed test track in Quebec, Canada, to determine potential fuel savings from using CACC. The researchers conducted another public demonstration on an interstate near the Port of Los Angeles before conducting a comprehensive test of driver usage and acceptance of CACC in the San Francisco Bay Area and Central Valley of California. The tests of driver acceptance covered 168 miles on multiple interstates per round trip, with nine commercial truck drivers taking turns behind the wheels of the big rigs. The commercial truck drivers of the platooned trucks completed questionnaires about their comfort levels with the CACC technology. Finally, the researchers held a demonstration on Interstate 66 in Northern Virginia.

The research also included simulations based on traffic microsimulation software. Based on heavy truck traffic along I-710 in Southern California, the simulations explored how much CACC in multi-truck platoons could reduce traffic congestion and save fuel.

System Development

Although the trucks in this project were built for the North American market, the researchers equipped them with the ACC system available on European trucks. This version of the technology provided better real-time data from the trucks. Each truck's ACC system included a video camera behind the windshield and Doppler radar in the front bumper.

To build out the system for CACC, the researchers retrofitted each truck with additional communications and computer components. The researchers installed a PC-104 computer, a format that is smaller and uses less energy than office computers, in a closet behind the driver's seat to connect to the truck's internal communications network, a DSRC radio transceiver and two DSRC antennas to the side mirrors to connect the trucks wirelessly, a 5-Hertz updated global positioning system (GPS) to enhance the positioning and provide an accurate time reference, a touch-screen tablet on the instrument panel to serve as a supplemental driver vehicle interface (DVI), and an emergency switch to make it easy for the driver to disengage the system.

The researchers at California PATH developed control logic to integrate the ACC and CACC. Their solution enabled drivers to easily switch among manual driving mode, traditional cruise control, ACC, and CACC. Capable of gauging speed, steering angle, and other vehicle data elements, the PC-104 executed algorithms to control the trucks. It also stored the data for post-trip analyses. Acting similar to a Wi-Fi system that networks devices in a building (but with less delay and data loss), the DSRC gathered and shared information among the trucks at a rate of 10 times per second.

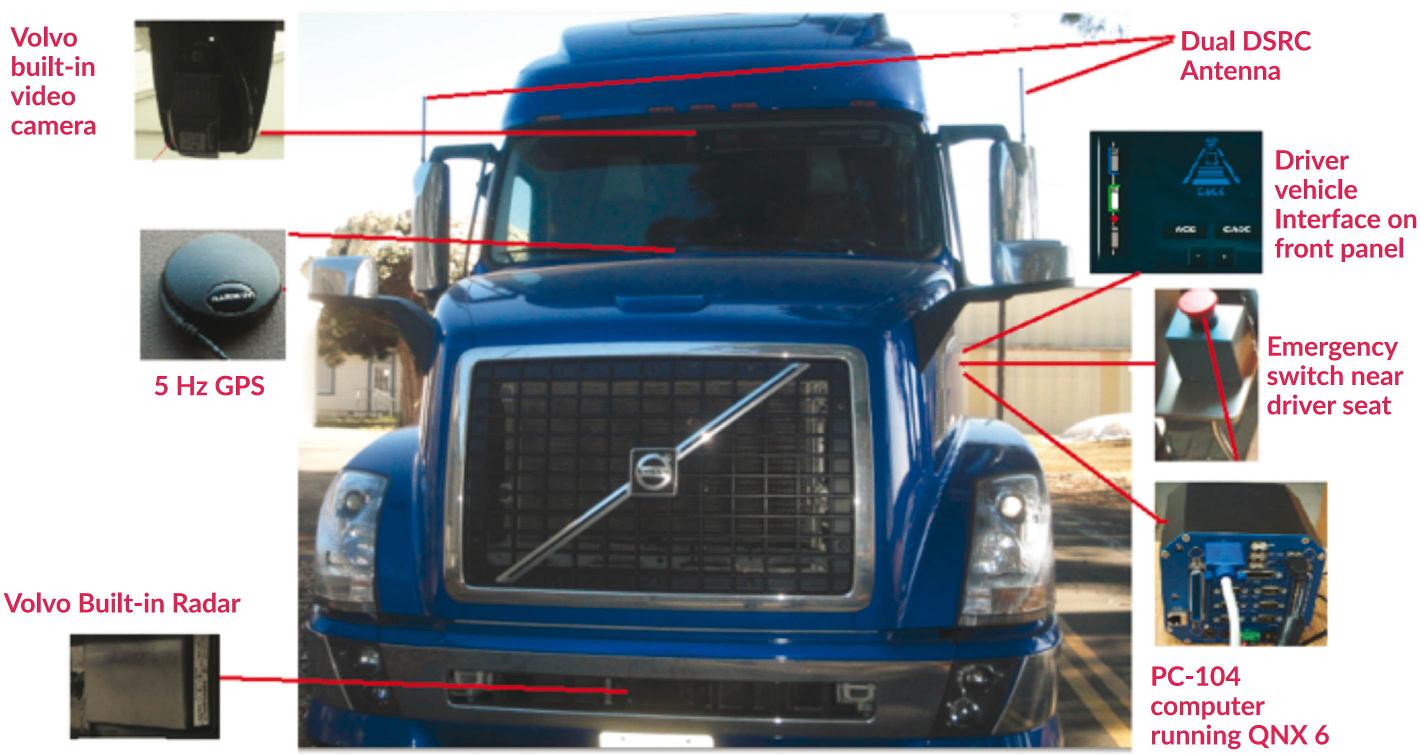


Figure 2. The components of the CACC system that researchers built included features such as digital short-range communications, a PC-104 computer, and a digital display. © California PATH.

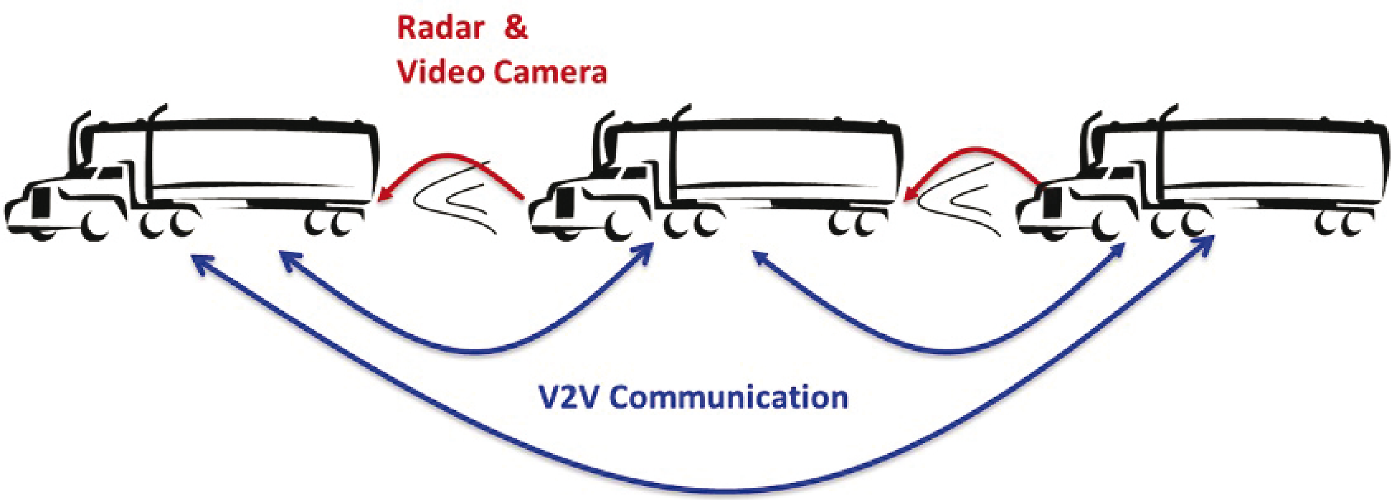


Figure 3. Trucks with CACC systems use radar and video cameras to "see" and vehicle-to-vehicle communication to "talk" to each other so they can maintain designated time gaps. © California PATH.

Among other purposes, the supplemental DVI allowed each following truck driver to pick between ACC and CACC and to set the constant time gap for his or her truck. The available time gaps ranged from 1.1 s to 1.9 s for ACC and from 0.6 s to 1.8 s for CACC, with five settings for each mode. When in CACC mode, the distance between trucks for each time gap changed in proportion to the platoon's speed. With the platoon traveling at 55 mi/h, for example, the time gap of 1.8 s kept the trucks 145 ft apart and the time gap of 0.6 s kept them 48 ft apart. The CACC was built to maintain the selected time gaps at speeds above 20 mi/h and to react to vehicles entering or leaving the platoon. Cut-ins prompted the CACC to switch to ACC in the truck behind the cut-in, with a larger gap because the interrupting vehicle, which lacks DSRC, could not provide data using the platoon communications system.

Drivers activated the CACC via an operation switch built into a steering-column stalk. They had three options to disengage from any cruise-control mode: turn off the switch, apply the truck's brakes, or press the emergency switch.

Driving Demonstrations and Road Tests

With the CACC system in place, researchers turned their attention toward testing it in various ways: on closed tracks, in actual traffic, and in computer-simulated heavy truck traffic. The first tests occurred on UC-Berkeley's closed track at its Richmond Field Station. The trial runs there verified the system's basic functionality at low speeds, and then more extensive trial runs on local freeways near Richmond were conducted to refine and assess performance at full speed, up to the legal speed limit for trucks. Over the next several months, researchers took the three-truck platoon from Richmond to Los Angeles in California, to Quebec, Canada, and finally to the Washington, DC, area.

San Jose, California

The public debut of the CACC-equipped truck platoon took place at the ITS America Annual Meeting in June 2016. Over 3 days, a demonstration team offered 25 rides on State Route 87, with up to 6 passengers along for each ride in the second and third trucks of the platoon. The passengers gained a firsthand look at how CACC coordinated the trucks' forward progress based on specified time gaps and how the system reacted when another vehicle moved into the lane between two trucks.

Figure 4. Drivers in a truck platoon used a vehicle interface like the one in this illustration. © California PATH.

A report by UC-Berkeley's Institute of Transportation Studies noted that the acting Administrator of the Federal Motor Carrier Safety Administration was among the Federal, State, and local dignitaries who observed CACC in action. According to the Chief Operations Officer of California PATH, most of the demo rides were full and resulted in lines of alternates hoping to replace no-show passengers. (Institute of Transportation Studies, 2016)

Blainville, Quebec, Canada

The next truck-platooning test was at the 4-mile oval track of Transport Canada's Motor Vehicle Test Centre in October 2016. There, the researchers focused the road tests on the fuel efficiency that could be achieved by deploying both CACC and trailer aerodynamic enhancements to reduce drag. Drag is the opposing force created by wind against a vehicle as it travels. Reducing drag reduces the amount of energy—and thus the amount of fuel—it takes to move the vehicle. The researchers studied the impact of four factors on potential fuel savings: the time gaps and related distances among the trucks, and the configuration, speed, and weight of the trucks.

To establish a baseline for the experiment, the drivers stayed 1 mi apart on the track while pulling 53-ft trailers loaded at 65,000 lb, a typical setup for long-haul trucks. Next, the researchers ran two full sets of tests with the trucks in platoon formation, one with standard trailers and the other with panels known as side skirts and boat tails attached to the trailers to try to reduce drag even more than merely using CACC. Side skirts are attached to the underside of a trailer and run its full length, while boat tails fold out in a tapered shape from the rear of the trailer. Within each test set, the drivers traveled at 65 mi/h using four of the five CACC gap settings—0.6 s (57 ft), 0.9 s (86 ft), 1.2 s (114 ft), and 1.5 s (143 ft). Some test runs occurred at 55 mi/h, which meant the two trailing trucks moved together more closely behind the lead truck. The researchers repeated each test condition at least three times so the results of the three runs could be averaged to obtain higher statistical confidence in the data.

The results of the experiment were promising for the two following trucks in the platoon. The data showed that a trio of trucks using CACC and pulling standard trailers could cut their energy use by 5 percent on average. The number jumped as high as 14 percent when aerodynamic enhancements were added to the truck trailers.

Los Angeles, California

The platoon was demonstrated on I-110 near the Port of Los Angeles in March 2017. Then-Caltrans Director Malcolm Dougherty noted in a video that about 11,000 cargo trucks a day move in and out of the ports in that area, making it an ideal location for the demonstration. (Caltrans, 2017) According to news coverage of the event, the three trucks in the platoon kept their CACC systems active for the freeway portion of the 12-mi round trip at 55 mi/h. They were 48 ft apart for the journey. Other vehicles cut into the platoon to demonstrate the CACC's reaction to traffic interruptions. (ZumMallen, 2017)

Figure 5. Caltrans' director Malcolm rode in a CACC-equipped truck as part of a demo in Southern California.

Figure 6. Footage shows trucks in a platoon responding to a cut-in by another vehicle. Source: FHWA.

Richmond, California

For the most extensive freeway testing of CACC, the researchers returned to the project's starting point. The team recruited 9 licensed commercial truck drivers—7 from the United States and 2 from Canada—to rotate through the second and third positions in the platoon. Each driver logged 168 mi over more than 3 h. A properly licensed UC-Berkeley employee drove the lead truck for the tests, which occurred over 5 days in May 2017. The trucks operated within the State speed limit of 55 mi/h.

Beginning at the Richmond Field Station and ending near Westley, the itinerary took the drivers onto three interstates (I-5, I-580, and I-680) and State Route 24, usually between 10 a.m. and 2:30 p.m. Traffic was heavy enough between Richmond and Livermore for the drivers to see the CACC system react to numerous cut-ins. They could select different time gaps to test the CACC and could engage and disengage the system at will. A project team member accompanied each test driver to observe the CACC and disengage it if necessary, but none of them had to disengage the CACC system during the tests. The project team members did coach the drivers to take control in some highway and traffic conditions. The participating drivers switched trucks at the halfway point of each round trip. One of the tests had only one recruit, who drove the second truck in a two-truck platoon.

The PC-104 computer in each truck collected data about vehicle performance and driver behavior. The drivers also completed a questionnaire after their experiments to help researchers gauge their comfort levels with the technology. The majority of them neither stated a preference for nor noticed any differences between driving the second or third truck. They felt mostly comfortable and confident with CACC but less so when the platoon hit steep grades, causing the back two trucks to struggle to maintain the selected time gap. The drivers tended to deactivate CACC in such situations, as well as in heavier traffic and where highways merged.

Centreville, Virginia

Researchers conducted a final roadway demonstration on an 8-mi segment of I-66 in the Nation's capital region. (Institute of Transportation Studies, 2018) FHWA and FMCSA participated in that September 2017 run, which was supported by the Virginia State Police and Virginia Department of Transportation. The truck drivers set the time gap for the CACC system at 0.6 s, which kept the trucks about 50 ft apart at 55 mi/h. The demonstration included a passenger vehicle cutting into the platoon.

Figure 7. Researchers demonstrated the truck-platooning system on Interstate 66 in Northern Virginia. Source: FHWA.

Modeling and Simulation

To test the potential for system-level benefits from CACC truck platooning, the researchers simulated real-world traffic in Southern California. They modified the simulation tool that California PATH developed as part of a different FHWA-sponsored research project into cars with CACC by adding modules for heavy trucks driven with CACC and manually. (California PATH, 2019)

The different parameters in the truck-platooning model represented the trucks' dynamic responses to changes in the desired speed. The new module also allowed a shorter maximum number of vehicles for the CACC string. These features enabled ad hoc coupling of trucks into CACC strings, with the lead and following trucks determined based on their time gap and arrival sequence within the length limitations for the string. Other aspects of the programming logic determined the mode of cruise control (conventional, ACC, or CACC) in specific trucks, defined vehicle-following models for those different modes, defined rules for lane changes based on California law, and accommodated merging vehicles from on-ramps. To gauge potential fuel savings in the simulation, researchers modified and integrated the Environmental Protection Agency's Motor Vehicle Emission Simulator computer program.

Figure 8. A view of the cab inside one of the three trucks used in the truck-platooning project. © California PATH.

The setting for the simulation was a northbound section of I-710 from the Port of Long Beach toward Los Angeles. The volume of trucks on that 15-mi, high-traffic stretch of road at any given time ranges from 10 to 19 percent of the total traffic, and several of the entrance and exit ramps are spaced closely together. Combine those realities with frequent lane changes among as few as three lanes in some spots and congestion is common. Researchers set the simulation period for a typical weekday between 10 a.m. and 11 a.m., when overall traffic volume is lower and truck volume is higher. The simulation used time-gap settings of 1.2 s and 1.5 s, the two most preferred in the CACC experiment with commercial truck drivers.

The study included a baseline case where all trucks in the scenario were driven manually and a test case where all of them were equipped with CACC. The addition of CACC to the traffic mix resulted in more throughput in bottleneck sections and higher speeds not only for the CACC-equipped trucks but for all vehicle traffic. The truck throughput rose nearly 6 percent, and the average truck speed jumped 19.3 percent, from 33.3 mi/h to 39.7 mi/h. Although car traffic experienced smaller increases, the use of CACC in trucks had residual benefits for cars, especially at the beginning of the simulated corridor and in the uncongested sections. The fuel savings for the trucks averaged 3 percent over five replications, while the fuel savings for cars was negligible.

Observations and Lessons Learned

California PATH's research demonstrated that adding CACC to trucks so they can travel in stable platoons could yield multiple benefits. The emerging technology has the potential to increase highway throughput, improve traffic flow, save fuel, and reduce emissions.

The addition of CACC in truck platoons enabled the trucks to follow each other more closely, and the system responded well to cut-in vehicles by widening the gap to maintain safety. The greatest improvement in traffic flow from CACC likely would be on moderately congested urban highways with heavy truck traffic. The researchers also found that complementing CACC with side skirts and boat tails on trailers could further reduce drag and save fuel.

System development for the project showed that a high-performance CACC system can be created by making relatively minor enhancements to commercially available ACC. Thus, the progression to partially automated truck platoons should not be too costly. Giving experienced truck drivers firsthand experience with CACC was beneficial, too. They were comfortable using it in mixed traffic, particularly at the intermediate time gaps between trucks and in less-congested traffic.

FHWA and FMCSA have plans to continue this research. FHWA and the ITS Joint Program Office are developing a truck platooning early deployment assessment which will address system-wide operational and safety impacts on truck drivers, light duty vehicle drivers, and other stakeholders. The agencies want to build upon previous research and conduct a multi-state, long-haul field test of platooning operations with similar trucks (e.g. same fleet, size, and make/model).

Through these research efforts, FHWA and FMSCA seek to assess the impacts and benefits of long-haul truck platooning to various stakeholders, including truck drivers, other road users, and fleet owners. The agencies hope to assess these impacts and benefits under a variety of operational conditions, and they want to determine how long-haul truck platooning will benefit traffic operations, safety, and policy.

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EXPLORATORY ADVANCED RESEARCH

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