Cooperative Adaptive Cruise Control (CACC) For Partially Automated Truck Platooning: Final Report

Steven E. Shladover
Xiao-Yun Lu
Shiyan Yang
Hani Ramezani
John Spring
Christopher Nowakowski
David Nelson

California PATH Program
Institute of Transportation Studies
University of California, Berkeley

Deborah Thompson
Aravind Kailas

Volvo Group North America

Brian McAuliffe

National Research Council, Canada
(Sponsored by Transport Canada)

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ABSTRACT

Cooperative Adaptive Cruise Control (CACC) provides an intermediate step toward a longer-term vision of trucks operating in closely-coupled automated platoons on both long-haul and short-haul freight corridors. There are important distinctions between CACC and automated truck platooning. First, with CACC, only truck speed control will be automated, using V2V communication to supplement forward sensors. The drivers will still be responsible for actively steering the vehicle, lane keeping, and monitoring roadway and traffic conditions. Second, while truck platooning systems have relied on a Constant Distance Gap (CDG) control strategy, CACC has relied on a Constant-Time Gap (CTG) control strategy, where the distance between vehicles is proportional to the speed.

A CACC system has been implemented on three Volvo Class-8 truck tractors and has been tested under a variety of conditions to assess its potential impacts if introduced into public use. The vehicle-following control system performance has been tested to demonstrate its ability to maintain accurate spacing between the trucks with reasonably smooth ride quality, and to respond safely to cut-in maneuvers by drivers of other vehicles. The energy saving potential of the close formation driving of the trucks has been tested through an extensive set of test-track experiments under a range of speeds, with and without aerodynamic improvements to the trailers, showing that the closer separations and trailer aerodynamic improvements have a more than additive contribution to fuel economy. Truck driver responses to the CACC system have been assessed through an on-road experiment with nine test drivers, who provided their opinions about the system in questionnaire responses and demonstrated which gap settings they preferred to use while driving in mixed public traffic on California freeways.

The larger-scale impacts of truck CACC on traffic flow and energy consumption were assessed in a traffic microsimulation of a high-density urban freeway with heavy truck traffic. A baseline condition with all manual driving was compared with a scenario in which all the heavy trucks used CACC, showing how this could relieve traffic bottlenecks and improve the speed and smoothness of traffic for all vehicles on the freeway. The trucks saved time and energy in this scenario, and because the speeds were only moderate the energy savings were primarily from the reductions in speed variations rather than from aerodynamic drag reductions.

Key Words: Cooperative Adaptive Cruise Control, CACC, Adaptive Cruise Control, ACC, Intelligent Transportation Systems, ITS, Speed Control, Truck Platooning, V2V Communication, DSRC

EXECUTIVE SUMMARY

Project Overview

This report summarizes the findings from the Partially Automated Truck Platooning project led by the California PATH Program, funded through the Federal Highway Administration's (FHWA) Exploratory Advanced Research Program (EARP) and Caltrans. The project team includes PATH, Volvo Technology of America, LA Metro, the Gateway Cities COG, and Cambridge Systematics, Inc. The goals of the project include identifying the market needs for a CACC based truck platooning system; building, demonstrating, and testing a CACC system on commercial trucks; and evaluating the potential benefits of CACC along the I-710 corridor in California.

While the concept of closely-coupled truck platooning has been the focus of many research projects over the years, it has generally included the automation of both lateral and longitudinal control in the following trucks because of the very close following distances targeted by those projects. CACC provides an intermediate step toward a longer-term vision of trucks operating in closely-coupled automated platoons on both long-haul and short-haul freight corridors. There are important distinctions between CACC and automated truck platooning. First, with CACC, only truck speed control will be automated, using V2V communication to supplement forward sensors. The drivers will still be responsible for actively steering the vehicle, lane keeping, and monitoring roadway and traffic conditions. Second, while truck platooning systems have relied on a constant clearance distance gap control strategy, CACC has relied on a constant-time gap control strategy, by which the distance between vehicles is proportional to the speed. For these reasons, a series of trucks using CACC are referred to as a string, rather than a platoon.

This project has included substantial work on implementing the CACC capability on three Class-8 truck tractors and testing their control system responses, their energy saving potential and their usability by normal truck drivers. It has also included computer microsimulation modeling to estimate the traffic and energy consumption impacts that could be gained in an urban freeway corridor where large numbers of heavy trucks would be using CACC control. A third key element has been stakeholder outreach, including not only publications and presentations at meetings, but also demonstrations for the media, government officials and industry stakeholders. These demonstrations were conducted on California SR-87 in San Jose for the ITS America Annual Meeting (June 2016), in Blainville, Quebec for Canadian stakeholders, including the Transport Minister (October 2016), on I-110 near the Port of Los Angeles for southern California stakeholders (March 2017) and on I-66 in northern Virginia for Federal Government, State of Virginia and national association representatives (September 2017). These demonstrations helped to communicate the main findings of the project to non-technical audiences and provided opportunities for decision makers to directly experience the truck CACC system in public operation.

The results of the research on this project have largely confirmed the potential value of CACC on heavy trucks. The key findings include:

- The production ACC system could be modified to produce a high-performance CACC system with relatively minor additions of hardware, combined with suitable control software. This implies that a production CACC system should not be significantly more costly than a basic ACC system.

- The CACC system was able to improve the vehicle following performance of the trucks, enabling significantly closer following distances and more stable vehicle following dynamics. The prototype system was normally able to respond automatically to cut-in vehicles, increasing the gap to accommodate them safely.

- Truck drivers from the general fleet driver population were comfortable using the CACC system in mixed public traffic. They generally tended to prefer the intermediate gap settings over the longest and shortest settings, although there was a significant sub-group that preferred the shortest available setting (0.6 s time gap).

- When the heavy trucks are driven using CACC at the tested time gaps between 0.6 s and 1.5 s, a three-truck platoon pulling conventional well loaded dry goods van trailers can save a total of between about 6% and 5% respectively of its fuel consumption when cruising at 65 mph. The first truck does not experience any significant saving, while the second truck saves between 7% and 6% and the third truck saves between 11% and 9%.

- When the heavy trucks' trailers are equipped with side skirts and boat tails to reduce drag, the energy savings are more than the simple sum of the individual savings from the shorter CACC separations and the aerodynamic enhancements. CACC and aerodynamic trailer treatments are mutually reinforcing, and lead to a fuel saving premium of between 0.5% and 2.0% over the individual savings from these separate strategies.

- The use of truck CACC can produce noticeable congestion reductions when used on a moderately congested urban freeway corridor with a substantial percentage of heavy truck traffic. The relief of traffic bottlenecks saves significant time and fuel for the trucks, with modest congestion relief effects for the cars that share the freeway with the trucks. However, the aerodynamic drag effects do not make a large contribution to energy savings in the urban environment where full highway speeds cannot be achieved.

ACRONYMS

ACC	Adaptive Cruise Control
ANOVA	Analysis of variance
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
C/ACC	Cooperative and/or Adaptive Cruise Control
Caltrans	California Department of Transportation
CDG	Constant Distance Gap
CTG	Constant Time Gap
DSRC	Dedicated Short Range Communication
DVI	Driver-Vehicle Interface
EARP	Exploratory Advanced Research Program
FHWA	Federal Highway Administration
GPS	Global Positioning System
GVW	Gross vehicle weight
ITS	Intelligent Transportation Systems
I2V	Infrastructure to Vehicle (communication)
NHTSA	National Highway Transportation Safety Administration
O/D	Origin/Destination
PATH	Partners for Advanced Transportation tecHnology
PeMS	Performance Measurement System
SAE	Society of Automotive Engineers International
UDP	User Datagram Protocol
V2V	Vehicle to Vehicle (communication)

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1 INTRODUCTION – PROJECT BACKGROUND AND MOTIVATION

1.1 Project Overview

This report summarizes the results of recently concluded research on heavy truck Cooperative Adaptive Cruise Control (CACC) and truck platooning by the California PATH Program, funded through the Federal Highway Administration's (FHWA) Exploratory Advanced Research Program (EARP) and Caltrans. The project team includes PATH, Volvo Technology of America, LA Metro, the Gateway Cities COG, and Cambridge Systematics, Inc.

The project team assessed the market needs for partially automated truck platoon systems in the local drayage and long-haul trucking industries and explored how the truck platoons could contribute toward improving traffic flow and providing environmental mitigation for the I-710 corridor, with its very heavy truck traffic. PATH and Volvo developed a new generation CACC system for three Class-8 tractor-trailer trucks, building on the existing Adaptive Cruise Control (ACC) system that Volvo already has in production, and tested it to determine performance and driver acceptability. Systematic tests assessed driver preferences for truck-following gap, and the range of reasonable gap settings was tested to provide careful measurements of the energy savings that can be achieved from aerodynamic drafting of the trucks. Traffic microsimulations of I-710 were used to estimate the potential impacts on traffic congestion and energy consumption from widespread adoption of CACC for the heavy trucks driving along that corridor. The project concluded with public demonstrations of the truck platoon system in the Los Angeles-Long Beach port area and in the Washington DC area.

1.2 Motivation

Although several research projects by the PATH team and other researchers in the U.S. and other countries have investigated and demonstrated higher levels of truck platoon performance, these have not yet produced the convincing body of evidence needed to encourage the broader stakeholder community in both the public and private sectors that there is a compelling benefits case for near-term deployment of truck platooning functionality. This project was designed to provide more compelling evidence to support deployment in several ways:

- Direct involvement of the Volvo Group in the development and testing work to ensure that the technical approach is readily commercializable and to provide direct interactions with truck fleet customers;

- Surveying trucking industry stakeholders at the start of the project to ensure that the project team understood their concerns before implementing the system;

- Designing the system as a cooperative ACC to represent a relatively small modification from the production ACC that is already available on the Volvo heavy trucks;

- Designing the system to interact with other vehicles in public traffic, including responding to cut-ins by drivers of other vehicles, so that it does not require segregation in truck-only lanes;

- Testing the usage of the system by normal truck drivers, to obtain their feedback about the performance of the system, its driver interface, and the vehicle following gaps that they would prefer to use in public highway traffic;

- Conducting carefully-controlled tests of fuel consumption under different operating conditions to provide an authoritative set of test data that can be cited to show how much energy (and therefore money) could be saved with more widespread usage of the technology;

- Developing a simulation model of a congested freeway corridor with heavy truck traffic (I-710 from the Long Beach port toward downtown Los Angeles) and using it to predict how much traffic congestion and energy consumption could be reduced along that corridor with more widespread use of the tested CACC system on trucks;

- Conducting public demonstrations for government, industry and media visitors in southern California and the national capital region, to give them the opportunity to ride in the test vehicles themselves so that they could directly experience the responsiveness of the system and learn about its other benefits.

The project succeeded in producing valuable data to demonstrate the benefits of truck CACC operations, and especially to show how the addition of direct vehicle-vehicle communication of vital data among the trucks could enhance performance. This was evident in the shorter and more stable vehicle following gaps that could be maintained continuously, enabling the trucks to occupy less road space and damp out traffic disturbances in the simulations of operations with high market penetration of CACC trucks on I-710. The traffic improvement benefits also accrued to the other traffic (passenger cars) sharing the freeway with the trucks in the simulation of the congested corridor, where some of the bottleneck jams were relieved.

These shorter gaps also produced measurable reductions in energy consumption for steady cruising of the trucks on the test track, based on aerodynamic drag reductions. These savings can provide the basis for the economic decisions that truck operators can make to invest in the CACC technology, with the potential for a good return on their investment.

The truck drivers found the CACC system easy to use and they liked using it, which should increase confidence that the system would actually be used by drivers when it becomes available commercially. Different populations of drivers had different preferences regarding the shortest and mid-range CACC gap settings, which is important for designers of commercial systems to understand.

The public demonstrations and their media coverage provided useful insights about how to communicate about the technology to the wider audience, especially emphasizing the driver assistance aspect of the system. The media people were tempted to apply the term “driverless” to this Level 1 automation system, which was misleading to the public and led to unnecessary anxieties about potential job losses among the truck driver interests. This highlights the importance of emphasizing the vital role of the driver in use of the system.

1.3 Report Overview

The overall goal of this project was to demonstrate that CACC will provide sufficient benefits to justify the investments of early adopters in the technology so that the technology can start to gain usage. Although the longer-term vision of full truck automation in dedicated lanes cannot be reached in a single leap, truck CACC should be an important first step in that direction.

The balance of this report summarizes the results of the project, representing an overview of information that has been provided in more detail in the informal reports on the individual tasks of the project and technical papers that have been published through professional journal and conference papers.

Chapter 2 describes the overall design of the CACC system and how it was implemented on the Volvo Class-8 truck tractors.

Chapter 3 summarizes the technical performance of the CACC system, including its vehicle following accuracy and responses to cut-ins by other vehicles' drivers.

The tests of the energy savings gained from use of the CACC system are described in Chapter 4, including the testing procedures and the results of those tests.

The tests of truck driver usage of the CACC system on public freeways are described in Chapter 5, including their preferences among the different available gap settings.

Chapter 6 reports on the estimates of the net impacts on traffic and energy consumption from use of the CACC system, using the detailed traffic simulation to synthesize the findings from the technical performance, fuel economy and driver acceptance experiments.

Finally, Chapter 7 describes the open issues that should be addressed in future work to advance the CACC technology into public use on heavy trucks.

2 CACC SYSTEM DESIGN

2.1 Design Approach

The CACC system was designed as an enhancement to the production adaptive cruise control (ACC) system that was already installed on the host trucks by Volvo, so that it would be as close to production-ready as could be expected from a research prototype. For this project, the trucks were equipped with an ACC system that is normally used on European Volvo trucks rather than the North American models because Volvo had better access to the intermediate data from the forward-looking radar, and could provide real-time data about range and range rate to the primary forward target vehicle for use in the CACC control logic (this would not have been possible with the ACC used on their North American trucks).

2.2 Implementation on Trucks

The physical implementation of the CACC system included the following main components that were retrofitted to the three Volvo VNL 440 model Class-8 truck tractors:

- PC-104 computer: mounted in a cabinet behind the driver's seat
- Emergency disengage switch: mounted on the right-hand-side of the driver's seat for convenience of driver access
- Supplementary DVI: touch-screen tablet computer mounted on the instrument panel to the right of the driver for convenience of access within constraints of the available space
- DSRC radio transceiver for vehicle-vehicle data communication
- Dual DSRC antennas: mounted on both side mirrors for robust line of sight communications
- 5 Hz GPS: antenna mounted inside the tractor cab roof

The production Volvo ACC system on the trucks included a video camera mounted near the top center of the front windshield (for target confirmation) and a Doppler radar mounted in the front bumper (for measuring range and range rate to target).

The default ACC built-in by Volvo was purposely deactivated so that the operation switch on the steering column could be used for CACC operation. The ACC control logic used for tests in this project was also PATH developed for easier integration with CACC and for easier switching between different driving modes: manual, cruise control, ACC and CACC. All the following functions for the original ACC operation were retained for driver's easy adaptation:

- ACC/CACC ON
- ACC/CACC OFF (switching to manual)
- Resume: going back to ACC/CAC mode if the control has been deactivated for any reason

Such implementation is feasible due to the real-time access of the operation switch signal information from J-1939 data bus.

The driver can deactivate the automatic speed control in any driving mode (CC, ACC and CACC) in any of the following three ways in case it becomes necessary:

- Switching off the operation switch on the steering column (turn off the CACC from the vehicle control system but CACC software is still running after deactivation)
- Pressing the service brake pedal (turn off the CACC from the control system but CACC software is still running after deactivation)
- Pressing down the emergency switch (physically cutting off the connection between the central control PC-104 computer and the J-1939 Bus; as a result, all the interface with J-1939 including data reading and command sending are deactivated; by default, it will return to manual mode.)

2.3 Supplementary Driver Interface

Because this was a prototype implementation by retrofit into an existing truck cockpit, it was not possible to implement a fully integrated driver interface for the CACC functions. In this case, although the primary steering wheel stalk input device for the production ACC was retained for activating and deactivating the CACC, a supplementary driver interface was added, using a touch-screen table computer.

Figures 1 and 2 on the next pages show screen shots of the supplementary Driver Vehicle Interface (DVI). Its main functions include: (a) for the driver to observe the current status of several critical items such as vehicle position in the platoon, driving mode (manual, CC ACC or CACC), DSRC health, service brake usage of all the vehicles in the platoon; and (b) for the driver to select driving mode between ACC or CACC (for the following trucks since the lead truck is always in CC or ACC) and Time-Gap selection for ACC and CACC driving modes. A more detailed DVI description is presented in the separate report on Task 2.2. User Datagram Protocol (UDP) messaging is used to send/receive messages from/to the control algorithm. The two sets of arrows on the DVI are used to send time gap requests, and the CACC/ACC radio buttons are used to request CACC or ACC control modes. The current status of the control system is contained in UDP messages received from the control computer.

Table 1. Available Time Gaps for Truck ACC and CACC

ACC Gap Setting	ACC Time Gap (s)		CACC Gap Setting	CACC Time Gap (s)
1	1.1		1	0.6
2	1.3		2	0.9
3	1.5		3	1.2
4	1.7		4	1.5
5	1.9		5	1.8

for ACC and CACC respectively. Those numbers have been selected based on previous work in this field and field tests that the PATH team has conducted with passenger car drivers. Note that the ACC gap values listed here are shorter than the ACC gaps provided in the production ACC system that is used on these trucks.

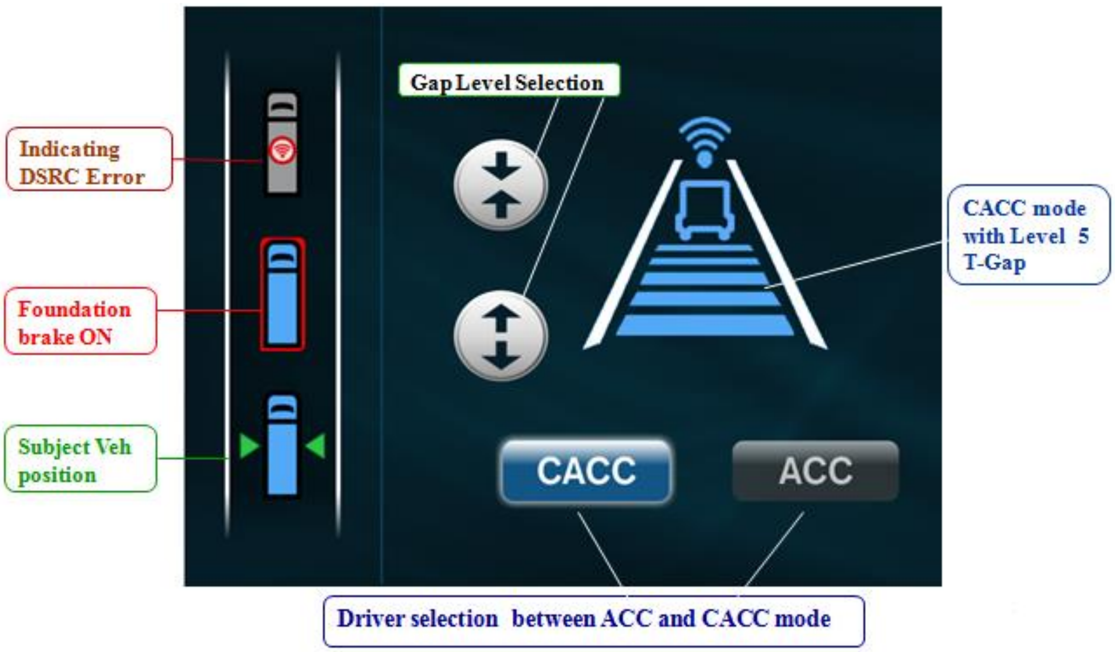

Figure 1 Driving Mode and Time Gap Selection: CACC

This figure shows the image of the supplementary display on the touch-screen table display. The left side of the screen shows icons representing three tractor-trailer trucks driving in tandem between solid white lines representing lane boundaries. The first truck, at the top of the screen, is shown in gray to indicate that it is in ACC control mode, while the other two trucks are in blue to indicate that they are in CACC control mode. A circular red icon superimposed on the first truck indicates that it has a DSRC communication error. A red boundary surrounding the second truck icon indicates that its foundation brakes are on. Green arrowheads pointing toward the third truck icon from both sides indicate that this is the position of the subject vehicle. The center of the image contains two circular buttons to provide the gap level selection for the driver. The upper button contains two arrows pointing toward each other to indicate that it is for shortening the gap and the lower button contains two arrows pointing away from each other to indicate that it is for extending the gap. The lower right portion of the image contains two rectangular buttons labeled CACC and ACC respectively. The button labeled CACC is blue and is illuminated to indicate that it is active, and the button labeled ACC is gray and dark to indicate that it is inactive. The upper right portion of the image contains an icon representing the rear view of a vehicle, with lane boundary markings spreading out below it. There are five horizontal bars displayed between the lane boundary markings to indicate that the longest of the five possible gap setting values has been selected, and these are in blue to correspond to the CACC mode of operation.

Figure 2. Driving Mode and Time Gap Selection: ACC

This figure shows the image of the supplementary display on the touch-screen table display. The left side of the screen shows icons representing three tractor-trailer trucks driving in tandem between solid white lines representing lane boundaries. All three trucks are shown in gray to indicate that they are in ACC control mode. A circular red icon superimposed on the first truck at the top of the screen indicates that it has a DSRC communication error. A red boundary surrounding the second truck icon indicates that its foundation brakes are on. Green arrowheads pointing toward the third truck icon from both sides indicate that this is the position of the subject vehicle. The center of the image contains two circular buttons to provide the gap level selection for the driver. The upper button contains two arrows pointing toward each other to indicate that it is for shortening the gap and the lower button contains two arrows pointing away from each other to indicate that it is for extending the gap. The lower right portion of the image contains two rectangular buttons labeled CACC and ACC respectively. The button labeled CACC is blue and is dark to indicate that it is inactive, and the button labeled ACC is gray and illuminated to indicate that it is active. The upper right portion of the image contains an icon representing the rear view of a vehicle, with lane boundary markings spreading out below it. There are five horizontal bars displayed between the lane boundary markings to indicate that the longest of the five possible gap setting values has been selected, and these are in gray to correspond to the ACC mode of operation.

3 VEHICLE FOLLOWING CONTROL PERFORMANCE

3.1 Relevant Measures of Performance

An automated vehicle following system needs to be able to serve several purposes, which are closely linked to the relevant measures of performance for the system. These are:

- Accurately maintain the desired gap behind the preceding vehicle
- Minimize the speed difference relative to the preceding vehicle
- Minimize accelerations and jerks to ensure ride quality, subject to maintaining small gap and speed difference errors.
- Provide string stability so that disturbances to the motions of preceding vehicles are attenuated rather than amplified
- Respond safely to disturbances, including cut-in and cut-out maneuvers by drivers of other vehicles.

As with any complex system, there are trade-offs among the different performance goals, so compromises need to be sought to balance how well these are achieved. Other highly relevant measures of performance, such as driver comfort and satisfaction and energy saving, are ultimately derived from these more elementary measures of the control system performance, and those other measures will be addressed in later chapters.

3.2 Testing Environments

The initial tests of the CACC system were done at low speeds on a short, closed test course at the University of California's Richmond Field Station. After the basic functionality was verified under these conditions, the trucks were tested on freeways in the San Francisco Bay Area, generally during times of low to moderate traffic. These tests provided an opportunity to test performance with varying road grades and with interactions with drivers of other vehicles, who would frequently cut in between the trucks with little to no prior warning. Finally, the trucks were tested under carefully controlled conditions at Transport Canada's Motor Vehicle Test Centre in Blainville, Quebec, to make direct measurements of their fuel consumption under a variety of different scenarios. Those tests provided opportunities to collect steady-state data under consistent conditions, as well as repeatable data on responses to cut-in maneuvers.

3.3 Test Results

Field testing of 3-truck CACC in public traffic has been conducted in California on several freeway sections/corridors including: Interstate 580 (or I-580), I-80, I-880, I-205, I-680, I-505, I-205, and State Routes 24, 4, and 110 (LA). Those freeway sections/corridors have different types of road geometry – curves and road grades (ascending and descending). Tested scenarios for three truck CACC included:

- truck one following other vehicles in ACC mode
- following trucks responding to traffic-imposed speed changes of leader truck
- grading up/down as a CACC string
- cut-in and cut-out by other vehicles at different positions; the cut-in vehicles include those of public traffic and a confederate vehicle; the cut-ins included long distance, short distance, and medium distance from the following truck.

3.3.1 Cut-in and Cut-out maneuvers

Figure 3 shows the test results for a sequence cut-in and cut-out maneuvers that occurred during the truck demonstration on I-66 in northern Virginia, first between the first and second truck and then between the second and third trucks.

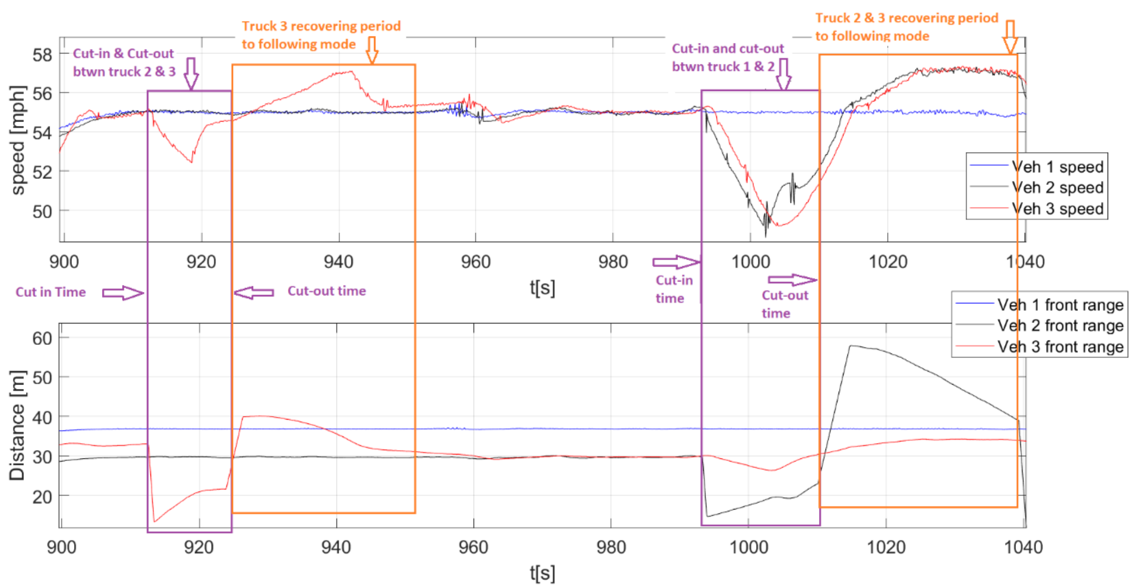

Figure 3 Three-truck CACC at 55 mph on I-66 with cut-in and cut-out maneuvers by a confederate vehicle

This is a graph depicting the vehicle speeds on the upper part of the figure and the distances between the vehicles on the lower part. The first part of the graph, on the left side shows that when a vehicle cuts into the gap between truck 2 and truck 3 the speed of truck 3 decreases by about 3 mph for several seconds to increase the separation behind that vehicle, but then as soon as that vehicle cuts out of the gap, truck 3 accelerates to about 2 mph above the speeds of the other trucks to reduce the gap. The distance plot shows the abrupt decrease in the gap ahead of truck 3, from 35 m to 15 m when the cut-in occurs, and then when the other vehicle cuts out the gap to truck 2 jumps up to about 40 m until the increased speed of truck 3 gradually reduces this to the nominal value of 30 m over a period of about 20 seconds. The right side of the graph shows the response to a cut-in between trucks 1 and 2, which involves both trucks 2 and 3 decelerating together by about 5 mph during the cut-in event. After the intruding vehicle cuts out, trucks 2 and 3 accelerate to about 3 mph above the speed of truck 1 to close the gap, and then gradually decelerate as the gap shortens. The lower (gap) plot shows the gap between trucks 1 and 2 reducing abruptly from 30 m to 15 m, and after the intruder cuts out that gap jumps to almost 60 m because this was a longer cut-in than the first one. The right side of the gap plot shows the gradual reduction of that 60 m gap back toward the original nominal gap.

In Figure 3, the purple rectangle marks the cut-in and cut-out maneuver time period. The orange rectangle marks the recovering period of the subject vehicle after cut-out to the CACC following mode with desired (driver selected) time gap. The first pair of purple and orange rectangles marks the cut-in between trucks 2 & 3, while the second pair of orange rectangles marks the cut-in between trucks 1 & 2. It is noted that, for the former, the cut-in vehicle would affect only truck 3, while for the latter, the cut-in vehicle would affect both truck 2 and truck 3. It can be observed that the cut-in between trucks 2 & 3 caused the front range measurement of truck 3 to significantly reduce from about 35 m to about 18 m. As a response, the CACC control of this truck reduced its speed and the front range starts to increase to about 23 m. Then the cut-in vehicle started to cut-out, which caused the front range of truck 3 to increase to about 40 m, which is larger than the desired D-gap (determined based on the selected T-Gap).

It can be observed that, after cut-out, the subject vehicle, and its follower, if applicable, will take about 30 s to recover, characterized by speed increasing and distance decreasing to the default CACC following mode at the driver selected T-Gap. This time is usually determined by two factors: (a) the cut-in vehicle speed and distance in front of the subject vehicle: the closer in distance and/or the lower speed relative to the subject vehicle, the more speed reduction will be incurred by the subject vehicle, leading to longer D-Gap to the preceding truck, and therefore it will take longer time to catch up (recover) with the preceding truck after cut-out; and (b) control design for smoothness for driver's comfort: it is intuitive that a smoother control response will take a longer time to recover after disturbance.

3.3.2 <u>Steady-state vehicle following on test track</u>

These tests were conducted during the fuel consumption experiments (to be discussed in the next chapter) on the four-mile closed loop test track at Transport Canada's Motor Vehicle Test Centre, which includes two one-mile straight sections connected by semicircular banked curves that are each one mile long.

The following are the data analysis of three truck CACC test results on this track tabulated in Table 2, with D-Gap of 18 m (T-Gap = 0.6 s) and speed of 65 mph, after test runs of 16 laps of the track (64 miles).

Speed Error [m/s]; the speed tracking error of each truck in meters per second; it is defined as the difference between the reference speed and the measured truck speed, which is quantified as: mean value, maximum value and standard deviation;

Distance Error [m]; the distance tracking error of each truck in meters; it is defined as the difference between the reference distance and the measured front gap in meters, which is quantified as: mean value, maximum value and standard deviation;

Standard Deviation of Speed Error and Distance Error respectively, which is a statistical parameter.

Table 2 Root Mean Square (RMS) and Maximum Steady-State Tracking Errors at 0.6 s Time Gap

Mode	**Vehicle Position**	**Speed Error (m/s)**		**Distance Error (m)**	
		RMS	**Maximum**	**RMS**	**Maximum**
ACC	1	0.052	0.53	0.289	0.53
CACC	2	0.079	1.11	0.193	0.84
CACC	3	0.087	0.97	0.231	1.19

The first truck is in ACC mode with no cooperative vehicle ahead of it (so its distance error is measured relative to a virtual target vehicle rather than a real vehicle), while the two following trucks are using CACC control to help track the motions of the vehicle(s) ahead of them. It is important to note that the speed and distance errors do not vary significantly along the string of three vehicles, indicating that disturbances are not being amplified, although they are also not being significantly attenuated.

3.3.3 Responses to speed variations of first truck

Lead truck speed variation is the test case for *string stability* for any multi-vehicle following strategy including platooning and CACC from a control viewpoint. The reason is that the overall system delays and control responses will be reflected in the speed variation scenarios. Admittedly, the response also depends on the reference trajectory planning of each truck and the information that is used from the front truck, particularly, the maximum acceleration and deceleration. The effect of maximum deceleration on the feedback control would not heavily depend on the current speed of the truck since the total braking torque of the truck would not change significantly with speed. The acceleration capability of a fully loaded truck is rather limited as truck speed increases. From a control point of view, the reachable set of the torque control at high speeds is rather small. However, for commercial trucks with engine braking, higher vehicle speed would correspond to higher engine speed, which will lead to larger available braking torque, while engine braking capability is rather low at low speed due to low engine speed.

For the current trucks since service brake activation will deactivate the control of engine torque, engine braking torque and the service brake itself, we have deactivated the service brake control for most maneuvers except the coordinated braking control in emergency situation. Therefore, the deceleration needs to fully rely on the engine brake control since the truck does not have a transmission retarder. For those reasons, in the speed variation maneuver, the maximum deceleration is limited to 0.3 m/s^2 and the maximum acceleration is below 0.1 m/s^2. The speed switching logic between minimum 55 mph and maximum 65 mph is as follows: once it reaches minimum or maximum, the CACC string will stay at that speed to cruise for 1 minute, and then it starts to switch to the other.

Table 3 shows the maximum speed and distance tracking errors for 3-truck CACC speed variation maneuvers. It can be observed from the table that (a) the truck further behind has larger speed and distance tracking errors, which reflects the weak string stability characteristics; and (b) the maximum distance tracking error is nearly 2.5 m, which means that for highway maneuvers with the maximum acceleration and deceleration listed before, the following distance should not be closer than 10 m for safety. This is similar to the maximum distance tracking error for cut-in maneuver observed before. However, the performance should be improved when the service brake automatic control deactivation can be eliminated so that service brakes could be applied to provide a higher braking rate. Also, if the truck had a transmission retarder, the deceleration performance could be improved.

Table 3. Root Mean Square (RMS) and Maximum Tracking Errors During Truck Speed Variations at 1.2 s Time Gap

Mode	**Vehicle Position**	**Speed Error (m/s)**		**Distance Error (m)**	
		RMS	**Maximum**	**RMS**	**Maximum**
ACC	1	0.125	0.98	0.922	5.73
CACC	2	0.226	1.53	0.479	2.50
CACC	3	0.573	4.35	0.419	2.50

4 FUEL CONSUMPTION IN STEADY CRUISING

4.1 Test Conditions

These tests were conducted following a modified version of the SAE J1321 fuel consumption test procedure.

Four tractor-trailer combinations were used as part of the fuel-economy tests. The control tractor was a 2013 International ProStar aerodynamic sleeper-cab, which was driven individually for all of the test runs, far away from the Volvo test trucks, to provide a common baseline for referencing all the fuel consumption measurements to compensate for variations in environmental conditions (temperature, winds). The same model of 53 ft dry-van trailers, Utility model 4000D-X, was used for all four test vehicles. Each of the Volvo test trucks was tested driving individually (without using CACC) at a long distance from the other trucks (about one mile) to provide a baseline value for its fuel consumption before applying the CACC vehicle following control.

The use of different tractor models for the test and control vehicles does not strictly conform to the SAE J1321 requirements, which specify that identical vehicles are to be used, although both are aerodynamically-treated tractors with similar engine specifications that were expected to behave similarly in the controlled conditions of the tests. Investigation of the fuel-use data from the tests reveals that, for the non-platooning measurements, the test vehicles used approximately 3% more fuel than the control tractor for the drive cycles used in the test campaign.

Fuel levels in the main tanks of the control vehicle were adjusted to match the vehicle weight to those of the test vehicles. The trailers were ballasted using concrete blocks aligned evenly along the centerline of each trailer. For some of the tests, the trailers were outfitted with two aerodynamic technologies: side-skirts (Transtex Edge) and a boat-tail (Stemco TrailerTail Trident).

Auxiliary fuel tanks were installed on each tractor to allow measurement of the fuel used during each run. An LCCA-500 S-beam load cell (500 lb range) was used to weigh the fuel tanks before and after each run. The fuel weighing procedure was repeated on Truck 1, Truck 2, Truck 3 and the Control Truck before and after each test run.

A test program was devised to examine the influence of four parameters on the fuel-savings potential of the three-truck CACC-based platoon:

- Separation Distance/Time: 17 m (57 ft) to 43 m (142 ft), equivalent to 0.6 s to 1.5 s in 0.3 s increments at 105 km/h (65 mph)

- Truck configuration: standard trailer vs. aerodynamic trailer

- Vehicle speed: 89 km/h (55 mph) and 105 km/h (65 mph)

- Vehicle weight: 29,000 lbs (empty) and 65,000 lbs (loaded)

4.2 Effects of Aerodynamic Trailer Treatments

Even before assessing the effects of different truck separations achieved using CACC, it was interesting to learn about the effects that the aerodynamic trailer treatments had on energy consumption by comparing cases with and without the aerodynamic treatments. The results for the individual trucks varied from 6.3% to 7.6% fuel consumption savings when comparing the individual trucks driven with and without the aerodynamic trailer treatments. It was important to establish this baseline case before considering the interactions between the shorter platoon separations and the use of aerodynamic trailer treatments.

4.3 Effects of Truck Loading and Speed

The base conditions for most of the tests were trucks loaded to 65,000 pounds GVW (gross vehicle weight) (representing typical over-the-road loading rather than the legal limit) and driving at 65 mph. However, some runs were also done for empty trailers (29,000 pounds GVW) and driving at 55 mph (the truck speed limit in some states). These runs showed that the effect of speed was too small to be measurable, so the savings associated with the other factors (especially separation distance) were essentially the same regardless of speed. The empty trailer runs showed a saving of fuel about 1.6% greater than the saving for the loaded trailer runs, which is logical because the rolling resistance is lower for the empty trailers, so the aerodynamic component of the total energy consumption is larger.

4.4 Effects of Truck Separation Distance and Aerodynamic Trailer Treatments

It was important to understand the interactions between the changes in truck separation distance based on use of CACC and the aerodynamic trailer treatments to determine whether these are independent of each other or coupled (either favorably or unfavorably).

The effect of vehicle separation distance on fuel consumption was investigated for the two trailer configurations (standard and aerodynamic), for which the fuel-savings measurements for the individual vehicles are presented in Figure 4. For this vehicle speed of 105 km/h (65 mph), the corresponding time-gap is shown on the upper edge of the plot. The data in Figure 4 show that, for each respective trailer configuration, the middle and trailing vehicles experience fuel savings in excess of 6%, with a general trend of decreasing fuel savings with increasing separation distance. The trailing vehicle experiences the greatest fuel savings, while the lead vehicle for both trailer configurations is shown to experience little to no change in fuel use for the range of separation distances tested here. These results are consistent with results reported in other previous experiments in the U.S. and overseas.

The negligible change in fuel savings for the lead vehicle provides some evidence to explain the differences between the middle and trailing vehicles. If the lead vehicle does not experience a measurable fuel savings at the shortest separation distance, it would therefore not be expected that the middle vehicle experience any influence from the trailing vehicle. The middle vehicle fuel savings is therefore dominated by the low-speed air-wake of the lead vehicle. The trailing vehicle experiences a greater fuel saving than the middle vehicle likely due to a compounding effect of the low-speed air-wakes of the lead and middle vehicles, producing an air-wake with a greater wind-speed deficit (relative to the moving vehicles) than the air-wake of an individual vehicle.

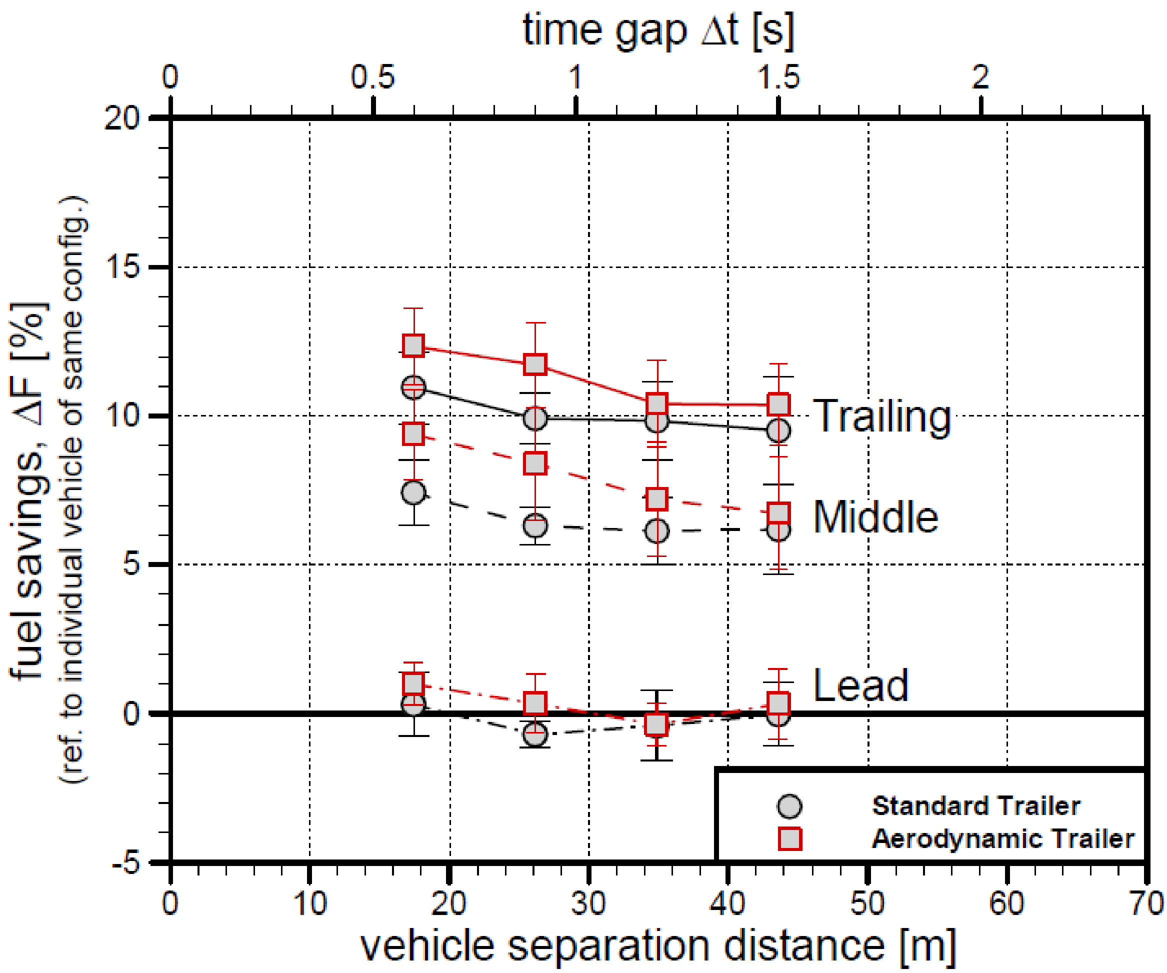

Figure 4. Variation in fuel saving measurements with separation distance for each vehicle in CACC string, fully loaded, 65 mph, (measurements referenced to the *same vehicle configurations* driven individually, without CACC)

This graph shows data points for the percentage of fuel savings for each of the three trucks in two configurations, with standard trailers (black circles) and with aerodynamic trailers (red squares) at the four tested separation distances, compared to the fuel consumption for the same trailer configuration when the truck is driven solo. These results show that the lead truck only achieves savings of about 0.5% with the standard trailer and 1% with the aerodynamic trailer at the shortest of the tested gaps (18 m), but almost no perceptible savings at the other gaps. The middle truck showed savings ranging from about 6% at the 44 m gap to about 7.5% at the 18 m gap, with a smooth trend for the intermediate gaps, with the standard trailer. These values increased to about 7% at the 44 m gap and 9.5% at the 18 m gap, with a similarly smooth trend, for the aerodynamic trailer. The trailing truck showed savings ranging from 9.5% at the 44 m gap to 11% at the 18 m gap with the standard trailer and from 10% at 44 m to 12.5% at 18 m with the aerodynamic trailer, with similarly smooth trends in both cases.

The data in Figure 4 show that, for the middle and trailing vehicles specifically, a greater fuel saving was measured for the aerodynamic-trailer tests, compared to the standard trailer. The aerodynamic-trailer configuration shows a fuel saving higher by 0.5% to 2%, with the largest differences at shorter separation distances. Part of this difference is due to the fact that the aerodynamic-trailer configuration has a lower starting drag, and hence lower road load, than the standard trailer. If the reduction in absolute aerodynamic drag associated with platooning were the same for each configuration, the aerodynamic-trailer configuration will demonstrate a larger percentage-based fuel savings as a result of its lower starting value. However, this effect is estimated to provide a difference on the order of 0.5%. Therefore, the results here provide a strong indication that a greater fuel savings, from an absolute sense (mpg), will be experienced by platoons outfitted with aerodynamic trailers.

At the shortest separation distance examined (17.4 m), the standard-trailer configuration experiences a 7.4% and 11.0% fuel savings for the middle and trailing vehicles, respectively, whereas the aerodynamic-trailer configuration experiences 9.4% and 12.3% fuel savings, respectively.

At the longest separation distance of 43.6 m, the middle and trailing vehicles for the standard trailers experience 6.2% and 9.5%, with the aerodynamic-trailer configurations experiencing 6.7% and 10.4% fuel savings. The results of Figure 4 also show that no significant difference is observed in the fuel savings of the standard-trailer configuration with separation gaps beyond 22 m. These results provide an indication that fuel savings are achieved for vehicles in moderately-close proximity, and do not necessarily require small separation distances to achieve measurable fuel savings. These results do not provide an indication of the distance at which the effect of vehicle platooning no longer yields a beneficial influence. It is, therefore, important to understand the true potential of vehicle platooning on fuel savings compared to what is already being experienced in general traffic conditions on the road.

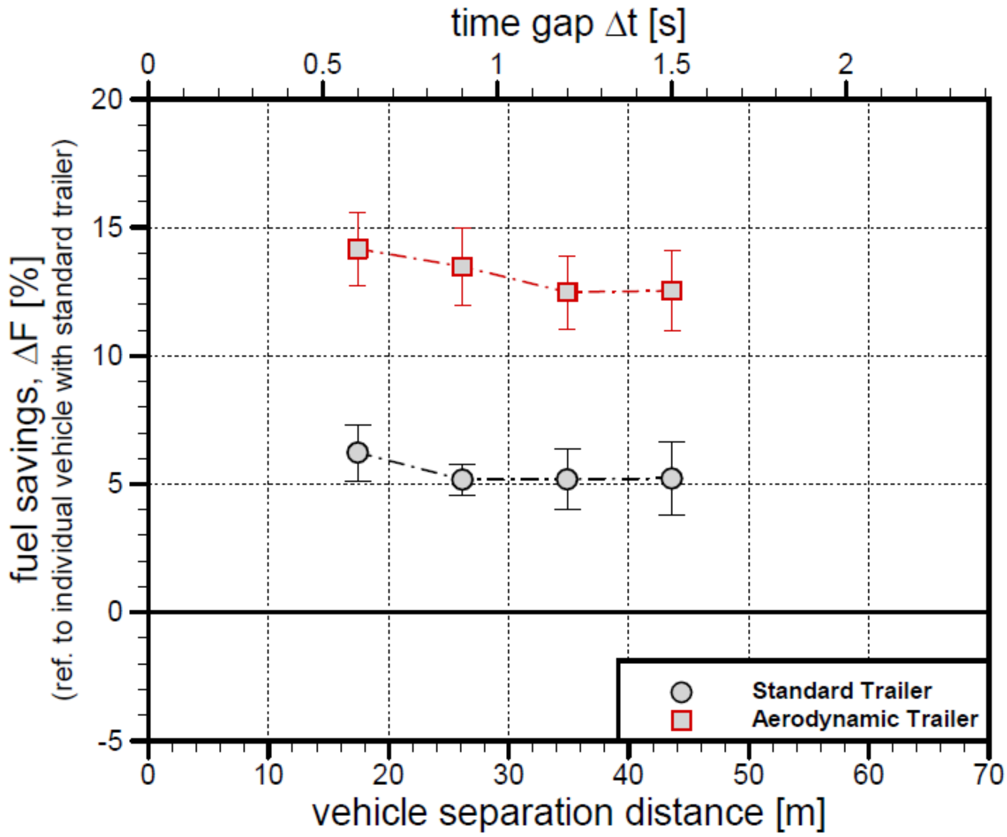

Figure 5. Variation in average fuel-savings measurements with separation distance for the complete three-truck platoon, speed of 65 mph, loaded trailer (measurements referenced to *standard-trailer configuration* in non-platooned arrangement).

This graph shows the average fuel savings for the three-truck platoons at the four tested separation distances, plotted separately for the standard trailers (black circles) and aerodynamic trailers (red circles). For the standard trailers, the average savings were 5% at the gaps from 44 m to 26 m and 6% at the 18 m gap. For the aerodynamic trailers, these savings were 12.5% at the 44 m and 35 m gaps, 13.5% at 26 m and 14% at 18 m.

The average full-platoon fuel-savings measurements for both trailer configurations, referenced to the non-platooned standard-trailer, are presented in Figure 5. These data show that the full platoon experiences a fuel saving associated with the CACC system and the aerodynamic trailer technologies, up to 14.2% at the shortest separation distance and 12.5% at the longest distance tested. Note that the fuel savings shown here for the aerodynamic trailer cases appear much larger than here than in Figure 4 because these results are all referenced to the standard trailer driven individually, while the aerodynamic trailer CACC cases in Figure 4 were referenced to the aerodynamic trailer driven individually. Figure 5 shows the combined savings from both the aerodynamic trailer treatments and the closer CACC separation distances.

Following the completion of the testing work that was sponsored under this project, another round of test track experiments was conducted by the same project team using the same test vehicles under the sponsorship of the U.S. Department of Energy, again in collaboration with Transport Canada and their partners at the National Research Council of Canada. Those experiments covered a significantly wider range of separation gaps and included the effects on energy consumption of cut-in maneuvers by other vehicles, of the trucks following behind a sport-utility vehicle, and comparisons with two-truck platoons and long combination vehicles. Those experiments provided additional insights into the gradual diminution in the energy savings as the gaps extended as long as 87 m between the trucks and into the significant changes in the fuel savings gained by the trucks in each position within the CACC string as the gaps became as close as 4 m. Those results will be published in separate reports and technical papers.

5 DRIVER ACCEPTANCE AND GAP SELECTION

5.1 Purpose of driver acceptance experiment

The potential benefits of CACC on heavy trucks can only be gained if the truck drivers are interested in using the CACC system. Therefore, it was important to understand how the general population of truck drivers would respond to the opportunity to use the CACC system. The survey of trucking industry people that was conducted at the start of the project revealed a low level of awareness of the reality of commercially available adaptive cruise control systems for trucks today, coupled with a low level of interest in the topic. The truck driver acceptance experiment was designed to be an important element of this project to ensure that the final project findings reflect a realistic view of how truck drivers are likely to make use of the CACC capability.

The benefits of CACC to the transportation system will be dictated not only by the rate of market adoption, but also by drivers' experience of using this technology. Although CACC is designed to assist driver speed control performance and reduce their workload, it could also lead to negative impacts on driver experience, such as lower acceptance, performance degradations, overreliance, and distraction, which would limit the usage of CACC and constrain the fuel savings and throughput benefits offered by CACC. For example, commercial drivers may reject using shorter-than-normal time gaps when following other trucks, despite the technical capabilities of CACC, so the theoretical benefits of CACC could remain unrealized. Therefore, it is critical to understand driver experience and usage of CACC, especially when time gaps are shorter than normal, to help guide the development of this technology.

5.2 Description of driver on-road experiment

Nine professional fleet truck drivers from the U.S. (7) and Canada (2) participated in the on-the-road experiment. All test drivers were male, with average age 48 years old, and everybody possessed a valid Class A driver license with a clean driving record and no moving violations over the past three years.

The process of driver recruitment as test subjects was hindered by the fact that the supply of truck drivers is in shortage in North America. Furthermore, fleet drivers only had very limited flexibility to participate in our study because their schedules were arranged by their companies according to business demands. Although a larger sample size would have been desirable, we only ended up with nine drivers for the test despite four months of intensive recruiting efforts with assistance from local trucking industry associations in California, and we were only able to schedule the tests under daylight conditions.

The lead truck was driven by an employee of UC Berkeley with a valid Class A driver license. The test drivers drove the second and third trucks in CACC mode. They had the freedom to engage and disengage CACC and select their preferred time gap using the supplementary DVI. However, they were responsible for steering and other maneuvers (e.g., responding to actions of other drivers) during the experiments. An experimenter sat in the front passenger seat to monitor the operations of CACC and to be available to press the safety disengage button immediately to deactivate the CACC if it performed abnormally. But this never happened during the tests. The experimenter also needed to remind the drivers to take control of the truck under some road and traffic conditions (e.g., heavy traffic and steep downgrades on I-580).

The test route started from the UC Berkeley Richmond Field Station (RFS) in Richmond, via I-580 (to Emeryville), SR 24 (to Walnut Creek), I-680 (to Pleasanton), I-580 (to Livermore), and ended around Westley on I-5, a distance of 84 miles. After arriving at Westley, the drivers took a short break at a parking area near a truck stop and then returned to RFS via the same route, for a total traveling time of more than 3 hours (about 1 hour 40 minutes each way unless the traffic was exceptionally heavy). At the midpoint of the test drive, the drivers switched positions in the two trailing trucks so that each driver was able to experience driving in the second and third position in the CACC string. The test runs were conducted during the mid-day period between the morning and evening traffic peaks, generally between 10 am and 2:30 pm, but the portions of the route within the urbanized Bay Area between Richmond and Livermore still involved a significant density of traffic and cut-ins by drivers of other vehicles.

The experiment included a combination of objective and subjective data collection. A PC-104 computer stored in a cabinet inside the truck cab was used to record the objective vehicle performance and driver behavior data (around 100 channels) at a sampling rate of 50 Hz. Only vehicle and driver behavior data collected during the part of the route between Walnut Creek and Westly were processed for analysis, to leave out the data from the training and familiarization stage of the experiment. A single episode of CACC usage was defined as the period between an engagement and following disengagement of CACC by conscious human control, therefore the short unexpected self-disengagements by the CACC system were ignored. Analyses of variance (ANOVAs (Type III)) were used to find the most-used time gap setting and the factors that impacted the usage of CACC. The subjective driver experience data were collected through questionnaires before and after the on-the-road testing. Friedman test and post hoc pairwise were used to find the time gap with the highest preference rankings. In addition, the correlation between the stated preference and actual usage of CACC time gaps was also analyzed.

5.3 Driver opinions about CACC usage (based on questionnaire responses)

The questionnaire results showed that the drivers generally did not prefer the two shortest gaps because their view of the road ahead was obstructed by the trailer of the preceding truck when using these two time gap settings. The drivers also did not prefer the longest gap because it tended to encourage cut-ins by other vehicles on the road. Therefore, the two intermediate gap settings – 1.2 s and 1.5 s - were preferred the most by the drivers as a compromise between their perceived driving safety/comfort and their intention of deterring cut-ins.

The post-experiment survey also documented drivers' experience in using CACC at different truck positions, under the situations of cut-in, and on different road grades. It was found that the majority of the drivers did not notice any difference between driving in the second and third trucks and had no preference for either position. Moreover, they felt comfortable and confident with the response of CACC to cut-in vehicles. However, they were less confident with the reliability of the prototype CACC when it was operating on steep road grades, because the prototype CACC on the following truck cannot generate sufficient deceleration/acceleration to maintain the predefined time gap to the preceding truck on downgrades. Additionally, most drivers reported that they deactivated the CACC system in the situations of high traffic density, large road grade, and highway merging.

Since the CACC implementation was an advanced research prototype, there were limitations in operating the CACC system on public highways, such as unreliability and jerkiness in the speed control, occasional wireless communication errors, limited road visibility from the following truck, and the position of the tablet display being outside peripheral vision (requiring head movement to the side). Furthermore, there were a few potential concerns for future commercial usage of CACC, including worries about the impact that a preceding truck's mechanical breakdown could potentially have on the following truck, doubts about the possible construction of highway infrastructure to assist truck platoons, and CACC-induced complacency. In general, the drivers were satisfied with their driving experience with the assist capabilities of the prototype CACC.

5.4 Measured driver usage of CACC

The analysis of the objective data recorded on the trucks during the experiment focused on the episodes of CACC usage, especially to try to understand which fractions of the drivers' usage of CACC were spent at each of the available time gap settings. The patterns of time gap selection were noticeably different for two subsets of the population of nine drivers, with five of them clustered in Group 1 and the other four clustered in Group 2. Group 1 mainly used the intermediate to longer time gap settings, while Group 2 gravitated toward the shortest setting. The differences between the two groups' time gap usage are illustrated in Figure 6.

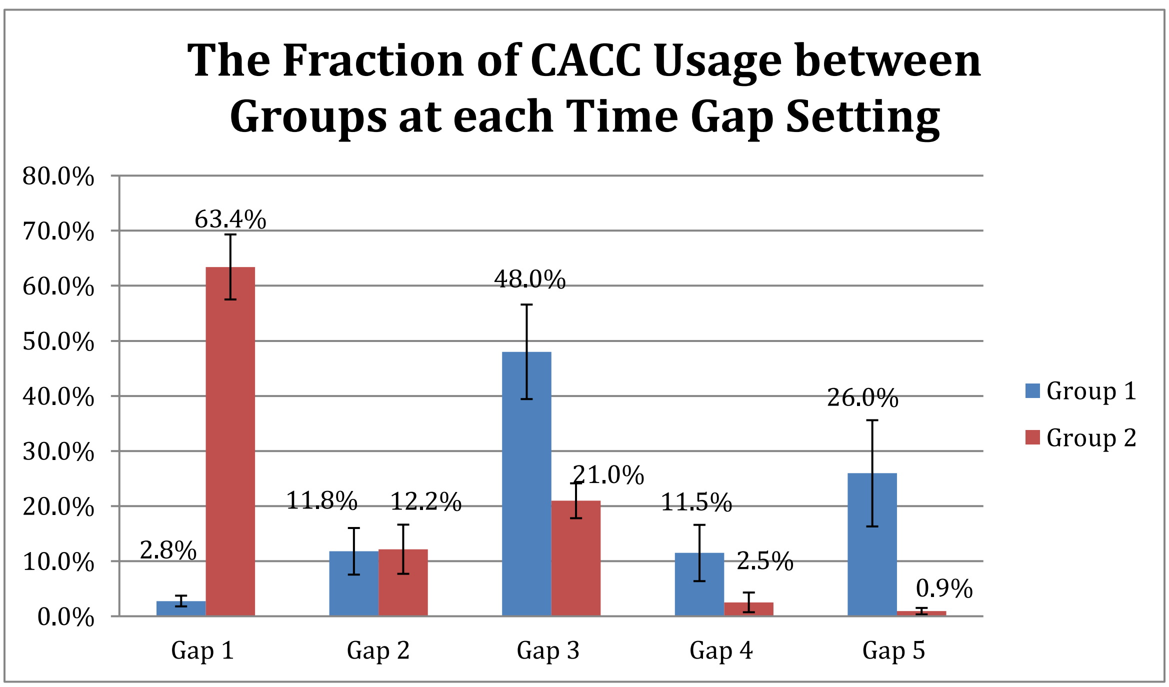

Figure 6. The fraction of CACC usage (%) for the two driver groups at each time gap setting

This histogram shows the average percentages of CACC usage time that the truck drivers in the two groups spent at each of the five CACC gap settings (numbered from 1 to 5). The values for the Group 1 drivers at each of the gap settings were 2.8%, 11.8%, 48.0%, 11.5% and 26.0% respectively. For the Group 2 drivers, the corresponding values were 63.4%, 12.2%, 21.0%, 2.5% and 0.9%.

Post hoc test showed that Group 2 spent more than half of their total CACC usage at Gap 1 (63.4%), which was much higher than that of Group 1 (2.8%, $p<0.001$). 'p' in the data analysis represents the probability of finding the observed results when the null hypothesis (usually a hypothesis of no difference between experimental groups) of the research question is true. When the p value is smaller than the significance level (conventionally 0.05), we reject the null hypothesis and accept the alternative hypothesis that the variable is different between the experimental groups. Group 1 spent a large fraction of their CACC usage at Gap 3 (48.0%) and Gap 5 (26.0%), which were significantly larger than the corresponding usage fractions of Group 2 (fraction of CACC usage: Gap 3=21.0%, $p=0.003$; Gap 5=0.9%, $p<0.001$). The findings demonstrated that the five drivers in Group 1 mainly used Gap 3 and Gap 5 in the test while the other four drivers in Group 2 mainly used Gap 1.

The demographic differences between the two groups may contribute to their differences in CACC usage. Compared with Group 1, Group 2 on average had more experience in driving tractor-trailer trucks and working as company or fleet drivers. Moreover, Group 2 had more experience with ACC and collision warning systems than Group 1. It's likely that drivers with more professional experience and higher familiarity with driver assistance system are more confident with shorter following time gaps to the preceding truck.

5.5 Relationship between stated preferences and actual CACC usage

The correlation analysis aims to understand the correlation between drivers' expressed preference for CACC and their actual usage of CACC. In Group 1, the preference ranking of the CACC time gaps significantly correlated with their fraction of CACC usage ($p=0.004$), with the correlation coefficient -0.53. This means that the drivers in Group 1 tended to use the CACC time gaps that they preferred.

In Group 2, the correlation between the preference ranking and the fraction of CACC usage was insignificant ($p=0.110$), with the correlation coefficient -0.36. However, we found an outlier in the data, which indicated a driver who had the least preference for Gap 1 but spent more than 60% of his CACC usage on it. If we remove the outlier, the correlation coefficient increases to -0.59, becoming statistically significant ($p=0.007$). Other factors rather than preference may contribute to the outlier's motivation for using the shortest CACC time gap. Perhaps, as a first timer, he was curious about using the abnormally short time gap 0.6 s (Gap 1) in driving so that he tried to explore this time gap as much as he could, although he felt uncomfortable with the shortest time gap. Another reason could be that he felt safe to use the shortest time gap in the controlled study in which the experimenter monitored the driving conditions to ensure safety. A further interview would be needed to understand the reasons behind this preference-usage inconsistency.

6 OVERALL TRAFFIC AND ENERGY IMPACTS OF TRUCK CACC

6.1 Technical Approach

Since the project could only afford to do experiments on three trucks, it was not possible to conduct a large-scale real-world experiment to measure aggregate traffic or energy consumption impacts of widespread usage of CACC on trucks. Rather, it was necessary to rely on a computer simulation of a real-world freeway corridor, where scenarios could be evaluated based on widespread usage of CACC on heavy trucks. The I-710 corridor from the Port of Long Beach to downtown Los Angeles was chosen for this study because of its very high volume of heavy truck traffic in a highly congested urban setting.

The I-710 corridor was simulated using a traffic microsimulation tool that was developed in a parallel FHWA EAR project, "Using Cooperative ACC to Form High-Performance Vehicle Streams', but with some important modifications. The simulation model had to be augmented with modules to represent the performance of heavy trucks driven under manual control and under CACC control, since those were not included in the original simulation model. These additional modules represented the dynamic responses and car-following performance of the heavy trucks, calibrated based on the experiments on the full-scale trucks reported in the earlier sections of this report. In later research supported by the U.S. Department of Energy, the speed profiles for the individual vehicles produced by the traffic microsimulation model were used as inputs to an additional model to estimate the energy that had to be consumed to create those motions, accounting for both the vehicle dynamics and aerodynamic drag effects.

6.2 Micro-Simulation Model of Truck CACC

The micro-simulation model of truck CACC performance follows the same general logic as the previously developed model for CACC systems for passenger cars, but with some differences in terms of:

- Different parameters to represent dynamic responses to changes in desired speed
- Shorter maximum allowable length of CACC string

The model represents "ad hoc" joining of consecutive trucks into a CACC string, without getting into the more complicated protocols that would be required for active coordination among trucks to help them find potential partners to form a new CACC string. This ad hoc coupling determines which trucks are leaders or followers based on their time gap, arrival sequence, and not exceeding the maximum allowable string length. There is also logic to determine whether a specific truck is traveling using conventional cruise control (simple speed regulation) or using ACC or CACC (depending on whether its preceding vehicle can communicate with it). An automated truck travels in CACC when it is in the gap regulation mode and V2V communication is possible with the preceding truck. It travels in ACC when it is in the gap regulation mode, but V2V communication is not possible (the preceding vehicle is not an equipped truck within communication range). Usually this happens when it follows a passenger car or a truck that lacks V2V communication capability. An automated truck travels in CC (which only has the speed regulation mode) when there is no forward vehicle within its sensor range.

Separate vehicle-following dynamic models were derived for each of the modes of operation. Part of the model logic defines the conditions for switching among the different modes, including a collision avoidance mode based on providing a warning to the driver, who intervenes to apply the brakes, since this mode is outside the scope of the ACC or CACC controller.

Lane changing logic is very similar to that for the predecessor model of light-duty vehicle driving. Additionally, this study considered a new type of mandatory lane change to make sure trucks are not traveling in the faster lanes. California restricts trucks to avoid using the left two lanes. In real traffic conditions, truck drivers may not restrict themselves to the lanes designated above. This may happen, for instance, when a truck passes a slower moving vehicle. In the current version of the simulation model, lane restriction criteria have been strictly applied so trucks never use the faster lanes, even to pass a slow moving vehicle.

Manual cars or trucks may reduce their speeds and create a longer gap to cooperate with vehicles merging from on-ramps. An automated truck may cooperate with merging vehicles if it is a CACC string leader, or it has previously disengaged the automated mode and is traveling in the manual mode. This implies that truck followers traveling in CACC mode do not deactivate the automated mode and do not disturb platoon stability to cooperate with merging vehicles. Even with this setting, some passenger cars may cut-in between following trucks and interrupt a CACC string. A truck traveling behind a cut-in passenger car can travel in ACC mode, but if its deceleration rate is beyond the comfortable deceleration rate of 1.6 m/s^2, it will switch to the manual mode for the driver to perform collision avoidance.

All the driving behavior models described above have been implemented in Aimsun using its Micro-SDK (software development kit).

6.3 Simulation of I-710 Corridor

Effects of truck CACC on traffic operations were studied for an interstate highway in Southern California (I-710 northbound). This corridor connects the Port of Long Beach to the Interstate highway system and includes a large truck volume. The truck traffic percentage varies between 10% to 19%. In this study, only the northbound direction of this corridor was analyzed since trucks leaving the port are more likely to be heavily loaded than those traveling southbound, so this is the more severe condition.

This case study included about 15 miles of the corridor modeled in Aimsun, starting from Milepost (MP) 1. There are 21 on-ramps and 20 off-ramps along this corridor. Between Mileposts 2 and 3, geometric characteristics are more restricted than other parts of the corridor. In particular, the mainline has three lanes and there are off-ramps and on-ramps that are closely spaced; under a high traffic volume and frequent lane change maneuvers, congestion is likely to occur in this part of the corridor. After MP 3, the number of mainline lanes varies between 4 and 7 and overall geometric design is less restricted; however, there are major on-ramps and major off-ramps connecting I-710 to crossing Interstate highways. These major ramps can carry large traffic volumes and cause congestion on I-710.

The analysis period is from 10 AM to 11 AM for a typical weekday, when congestion is expected to be less severe and truck volume is larger than in the peak hours. There are 11 mainline loop detectors which were healthy and did not malfunction, but these were not sufficient to accurately estimate ramp volumes. The data from these detectors were collected on Tuesday 7-30-2017 and were downloaded from the Caltrans PeMS (Performance Measurement System) online database. The initial origin/destination (O/D) matrix was fine-tuned as part of the calibration process to replicate loop detector volumes and the speeds were calibrated using the PeMS archived data. Speeds at the MP2 and MP3 detectors are lower than those for the other detectors, which indicate the presence of congestion within MP2 and MP3 where geometric design is restricted.

The maximum acceleration and deceleration rates for the trucks were represented based on the best available information in the literature, and the time gaps used by the CACC trucks were derived from the driver acceptance experiment reported in the previous chapter (assuming 60% used 1.2 s and 40% used 1.5 s). For trucks using ACC, a gap of 2.0 s was modeled, in the middle range of commercially available truck ACC systems.

6.4 Energy Consumption Model and Calibration

One of the main potential benefits of truck platooning is fuel saving. The underlying idea is that followers would experience less aerodynamic drag and as a result consume less fuel. During past experimental studies, truck speed and time gap were constant and platoon characteristics did not practically vary; however in the real world they do vary. For instance, a platoon speed may vary due to presence of a slow moving vehicle in front of the lead truck, or intra-platoon gaps may not stay the same when a cut-in maneuver occurs. These traffic dynamics can influence fuel consumption, and their effects need to be represented. A method to estimate fuel consumption was developed and integrated with the traffic micro simulation model.

The method is a modified version of the Motor Vehicle Emission Simulator (MOVES) model. MOVES is a computer program which is used within the Environmental Protection Agency (EPA) to estimate fuel consumption and resulting emission impacts for different types of vehicles including cars and trucks. MOVES does not directly consider the effect of truck platooning on aerodynamic drag reduction and fuel saving; thus modifications had to be implemented to incorporate the effect of truck platooning.

The decrease in aerodynamic drag associated with close following in a platoon can be reflected in the MOVES computations by choosing a smaller value for one of its key coefficients, which incorporates the drag coefficient. The data to support this re-calibration were measured during the experiment reported in Section 4, and shown in Figure 4, using standard dry goods box trailers, which are not dissimilar to the containers on chassis that predominate along I-710.

Based on these data, the first truck is not considerably influenced by platooning. Both middle and trailing trucks significantly save fuel, but the benefit is larger for the trailing truck than the middle truck.

The experiment results on fuel savings are projected for the comparable conditions, which may happen in the simulation, as shown in Table 4. The results are extrapolated up to a gap of 2 seconds. Beyond this gap platooning may or may not result in measurable fuel saving, and this should be tested in experiments. Data in Table 4 were used to re-calibrate MOVES such that it returns the same fuel savings as were measured in the experimental conditions.

Table 4 - Projecting Experiment Results for Different Gaps

Position in platoon	Gap category	Definition of gap	Fuel saving
Leader	_	_	0%
Follower 1	Long	$0.75\ sec < Gap \leq$ 2 sec	6.23%
Follower 1	Short	$Gap \leq$ 0.75 sec	7.41%
Follower >1	Long	$0.75\ sec < Gap \leq$ 2 sec	9.78%
Follower >1	Short	$Gap \leq$ 0.75 sec	10.96%

These values were used to re-calibrate the road load coefficient C in the MOVES model, producing the values shown in Table 5 below.

Table 5. Re-calibrated Values for Road Load Coefficient C

Position in platoon	Gap category	Fuel saving	Re-calibrated road load coefficient	Estimated drag coefficients
Leader	_	0%	0.0049	0.57
Follower 1	Long	6.23%	0.004375	0.488
Follower 1	Short	7.41%	0.004272	0.472
Follower >1	Long	9.78%	0.004073	0.441
Follower >1	Short	10.96%	0.00397	0.425

6.5 Traffic Congestion and Energy Consumption Estimates for I-710 Corridor

The initial scoping study that was conducted here contrasted two scenarios, a base case with all manually driven vehicles and a case in which all of the heavy trucks on the corridor were equipped for CACC driving. Even with all of the heavy trucks equipped for CACC, they can still only take advantage of its enhanced performance when they are traveling behind another similarly equipped truck, so that limits the fraction of their operations that can actually be driven at the shorter CACC gaps.

Traffic Congestion Changes

Truck CACC increased Vehicle Miles Traveled (VMT) and average speed for both trucks and passenger cars. For trucks, average VMT increased by 5.8% and average speed increased from 33.3 mph to 39.7 mph, a 19.3% increase. Average speed was computed as VMT divided by Vehicle Time Traveled (VTT). For cars driving along this corridor, VMT and average speed increased by 0.7% and 6.2%, respectively.

The main reason for these improvements is that truck CACC reduced congestion near the beginning of the corridor, which improved mobility of passenger cars as well. In addition, truck CACC increased truck speeds in the uncongested conditions; thus passenger cars which get stuck behind trucks or follow them could travel faster than in the Base condition.

All eleven detector stations showed speed increases ranging from 1.84 mph to 9.26 mph. The speed increase values were noticeably larger for the two detectors that had average speeds below 30 mph and that had persistent flow breakdowns in the Base condition. The speed increase values are larger because truck CACC reduced congestion severity by postponing the onset of congestion, and this resulted in much larger speed increases. Truck flow rates at these detector stations increased between 2.1% and 8.3%. This could be because of the speed increases discussed above as well as shorter following gaps in CACC.

For the passenger cars sharing the corridor with the trucks, there was no drawback and at some detector locations truck CACC considerably improved passenger car mobility. In particular, flow rate increased by 0.04% to 1.8%, and average speed increased between 0.11 mph and 3.85 mph. These statistics represent the effects of truck CACC on cars' mobility averaged over five simulation replications, with considerable variability across replications.

Energy Consumption Changes

For each vehicle type, total consumed energy was normalized by the corresponding Vehicle-Miles Traveled (VMT). Results showed that truck CACC reduced normalized fuel consumption for the trucks driving along the corridor by 2.57% to 3.60%, with the average of 3.05% over five replications. This corresponds to a fuel economy increase of 3.14% in miles per gallon. The average fuel consumption for cars was slightly increased, by 0.26%, which can be considered as negligible fuel sensitivity, attributable to their increased speed.

The effect of truck CACC on fuel consumption can be associated with two sources: 1) Aerodynamic effect 2) Speed change effect. The speed change is associated with an average fuel reduction of 2.57%, varying between 2.09% and 3.11% over the five different runs. The aerodynamic effect is associated with an average fuel reduction of 0.48%, which does not considerably vary over the different runs. For this specific corridor and traffic condition, the benefit from speed change is larger than the benefit from aerodynamic drag reduction by a factor of 5.35, since the speeds were generally not high enough to show a large aerodynamic drag saving. The results would be expected to be quite different in a lower density corridor where the trucks would be able to drive faster.

Table 6 shows the percentage of truck-time-traveled under different platooning conditions for one simulation replication. Two categories do not experience fuel reduction due to platooning. They are 1) leaders and 2) followers braking or stopped. For these two operating modes aerodynamic drag reduction was not considered since engine power is not used. These categories together represent 84.28% of truck-time-traveled. The rest (i.e. 15.72%) was used in computations to determine the effect of platooning on aerodynamic drag reduction. This fraction is called the degree of Aerodynamically Efficient Platooning (AEP), to represent the fraction of the platoon operations that can achieve aerodynamic drag reductions.

Based on Table 6, most of AEP belongs to followers with long gaps, which is expected as the desired gap was set to be 1.2 sec or 1.5 sec. Also, the percentage of AEP for follower1 is larger than that for follower >1 by a factor of larger than 2, which implies that most of the AEP comes from 2-truck platoons (including the leader). If additional logic was applied to assist trucks in finding other trucks with which they could join using CACC, it should be possible to increase this low percentage of AEP.

Table 6. Platooning Pattern in One Simulation Run

Platooning category	**Short gap**	**Long gap**
Leader	76.24%	
Followers braking or stopped	8.04%	
Follower 1	0.07%	11.76%
Follower >1	0.02%	3.86%

7 CONCLUSIONS AND FUTURE WORK

The results of the research on this project have largely confirmed the potential value of CACC on heavy trucks. The key findings include:

- The production ACC system could be modified to produce a high-performance CACC system with relatively minor additions of hardware, combined with suitable control software. This implies that a production CACC system should not be significantly more costly than a basic ACC system.

- The CACC system was able to improve the vehicle following performance of the trucks, enabling significantly closer following distances and more stable vehicle following dynamics. The prototype system was normally able to respond automatically to cut-in vehicles, increasing the gap to accommodate them safely.

- Truck drivers from the general fleet driver population were comfortable using the CACC system in mixed public traffic. They generally tended to prefer the intermediate gap settings over the longest and shortest settings, although there was a significant sub-group that preferred the shortest available setting (0.6 s time gap).

- When the heavy trucks are driven using CACC at the tested time gaps between 0.6 s and 1.5 s, a three-truck platoon pulling conventional well loaded dry goods van trailers can save a total of between about 6% and 5% respectively of its fuel consumption when cruising at 65 mph. The first truck does not experience any significant saving, while the second truck saves between 7% and 6% and the third truck saves between 11% and 9%.

- When the heavy trucks' trailers are equipped with side skirts and boat tails to reduce drag, the energy savings are more than the simple sum of the individual savings from the shorter CACC separations and the aerodynamic enhancements. CACC and aerodynamic trailer treatments are mutually reinforcing, and lead to a fuel saving premium of between 0.5% and 2.0% over the individual savings from these separate strategies.

- The use of truck CACC can produce noticeable congestion reductions when used on a moderately congested urban freeway corridor with a substantial percentage of heavy truck traffic. The relief of traffic bottlenecks saves significant time and fuel for the trucks, with modest congestion relief effects for the cars that share the freeway with the trucks. However, the aerodynamic drag effects do not make a large contribution to energy savings in the urban environment where full highway speeds cannot be achieved.

Future work is still needed to deal with several of the issues that remain unresolved at the conclusion of this project:

  - Fuel economy tests need to be performed for a wider range of conditions to capture the full range of fuel economy effects of CACC. This includes significantly longer and shorter CACC following gaps, the effects of cut-in maneuvers causing separations of the CACC strings, the effects of interactions with other classes of vehicles and comparisons with other fuel saving strategies such as use of long combination vehicles (LCVs). These tests were performed in the summer of 2017 under a successor project with funding support from the U.S. Department of Energy and the results are in the process of being documented.

- The effects of very close separations between the trucks on engine cooling need to be better understood, to learn whether the engines can be adequately cooled using the basic flow of air through the radiator or whether the cooling fan needs to be activated more frequently (at a significant energy cost). These tests were also done in the same summer 2017 series of experiments. Another potential approach to reducing cooling fan energy consumption could be proportional control of fan speed.

- The lower-level vehicle control software needs to be modified to distinguish between activations of the foundation brakes by the computer seeking to maintain proper separation between the trucks and brake pedal applications by the driver that indicate the desire to override the ACC system. This is necessary so that the foundation brakes can be made available to improve gap regulation in CACC, especially on down grades.

- Data need to be acquired to understand the driving patterns of heavy trucks on highways today, in particular with regard to the distances they are driving behind other vehicles (both heavy trucks and light-duty vehicles), so that the energy savings they are gaining from these aerodynamic interactions can be understood as part of the definition of the baseline condition. The Volpe Center conducted an initial study of this topic based on data from two field tests of instrumented trucks, the Safety Pilot Model Deployment project and the Integrated Vehicle-Based Safety System (IVBSS). They analyzed these data to identify the distances at which the drivers in these tests chose to follow cars and other trucks in highway driving, indicating an average time gap of 1.8 s for drivers of tractor-trailer trucks (although it was misleadingly called "headway" in the report).

- The computer simulations of traffic and energy consumption impacts need to be extended to long-haul rural freeway environments where there should be more high-speed driving, with a greater potential for energy savings. These simulations should also include strategies for actively facilitating the grouping of trucks into CACC strings so that more of the truck VMT can take advantage of the CACC capabilities, as well as models of diverse trucks with different performance capabilities to better understand their dynamic interactions.

- A substantial-scale field test needs to be done, with instrumented CACC trucks operated in regular fleet service. These trucks need to be instrumented to recorded comprehensive data about their usage in real traffic so the real-world effects of truck CACC can be measured, identifying the fraction of the truck usage that can be realistically achieved in CACC mode and also identifying a more realistic baseline condition to capture the drafting benefits that trucks are already achieving even without using CACC.

- A Level 2 driving automation system combining CACC with automatic lateral control needs to be developed and tested (initially on a closed track, and then on public highways) for use on heavy trucks at shorter gaps than the gaps that were tested in this project, to determine drivers' level of comfort and acceptance with this higher level of automation that could potentially enable significantly larger energy savings at the shortest gaps.