A First Investigation of Truck Drivers' On-the-Road Experience Using Cooperative Adaptive Cruise Control

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Task 2.5 – Driver Gap Acceptance Tests

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Abstract

Cooperative Adaptive Cruise Control (CACC) is a driver assist technology that uses vehicle-to-vehicle wireless communication to realize faster braking and acceleration responses in following vehicles and shorter headways compared to Adaptive Cruise Control (ACC). This technology not only enhances road safety, but also offers fuel saving benefits as a result of reduced aerodynamic drag. The amount of fuel savings is dictated by the following distances and the driving speeds. So, the overarching goal of this work is to explore truck drivers' preferences and behaviors when following in "CACC mode," an area that remains largely unexplored. While in CACC mode, the brake and engine control actions are automated. A human factors study was conducted to investigate truck drivers' experiences and performance using CACC at shorter-than-normal vehicle following time gaps. The "On-the-road" experiment required commercial fleets drivers to operate the second and third trucks in a three-truck string on the freeways for 160 miles in Northern California. The experiment was in mixed normal traffic without any on-site assistance of authorities, such as state police. All trucks were equipped with CACC systems and unloaded trailers. Five different time gaps between 0.6 and 1.8 seconds were tested. Factors such as cut-ins by other vehicles, road grades, and traffic conditions influenced drivers' experience using CACC. Other factors like time gap setting, individual differences, and route section affected drivers' usage of CACC. These findings reveal truck drivers' acceptance of the deployment of CACC in their truck fleets and provide useful information for decision making to promote CACC usage in the trucking industry.

Executive Summary

Cooperative Adaptive Cruise Control (CACC) systems leverage vehicle-to-vehicle (V2V) communication based on wireless technologies (e.g., DSRC) and provide coordinated longitudinal control in vehicles, thereby automating the control of a shorter following gap behind another CACC-equipped or V2V-capable vehicle. A reasonable market penetration rate of this technology is expected to produce operational benefits on transportation corridors, such as reducing fuel consumption/emissions and improving traffic flow.

These benefits of CACC on transportation corridors will be dictated not only by its market penetration rate, but also by the driver acceptance of the technology. However, there have only been limited studies of driver experience and behavior when using CACC and ACC in passenger cars, and none that we are aware of on trucks, the operation of which imposes rigorous requirements on driver perception. Although CACC systems on trucks have been successfully designed and the technical ability to follow closely demonstrated (e.g., SARTRE, GCDC, European Truck Platooning Challenge), truck driver acceptance and behavior have not been investigated. Therefore, it's extremely important to approach this topic from multiple perspectives on public roads in real traffic conditions.

This report presents a first human factors study on truck drivers' on-the-road experience and usage of CACC. Nine commercial fleet drivers were recruited to operate two following trucks in a three-Volvo-truck string. Drivers could engage and disengage the CACC system on the following trucks using the control stalk, brake pedal, and safety button. Also, they could select the CACC or ACC time gap via the driver-vehicle interface, which is a tablet display mounted on the instrument panel. The test route consisted of several public highway sections starting from the U.C. Richmond Field Station in Richmond and ending at Westley on I-5, with a round trip over 160 miles. Once past Walnut Creek, drivers had the freedom to select the CACC time gap they preferred for truck platooning, but under the monitoring of the experimenter next to them. Drivers were responsible for steering during the whole experiment. When arriving at Westley, drivers took a short break, switched to the other following truck, and then drove back to the Richmond Field Station via the same route (the 9^{th} driver was the only driver available that day so he could not make a switch). A background questionnaire and a post-experiment debriefing questionnaire were used before and after the on-the-road driving to document each driver's background information and experiences from multiple perspectives. The driver behavior data were recorded via the truck's CAN bus system at 50 Hz sample rate throughout the experiment.

Our findings provide important insights into drivers' subjective acceptance and actual usage of CACC and the correlation between them. The test drivers on average did not prefer using CACC to drive too close (< 0.9 s) or too far (1.8 s) behind the lead truck, and seemed to prefer using time gaps of 1.2 and 1.5 seconds. The shorter time gaps limited their forward driving view by following too closely behind the trailer of the preceding truck, while the largest time gap seemed to encourage more frequent vehicle cut-ins. However, the test drivers in fact spent on average 30% of their CACC driving time at the shortest time gap (0.6 s). It's not surprising to find that the "conservative" drivers (five drivers in Group 1) spent 48% of their CACC usage at time gap 1.2 s and 26% at time gap 1.8 s, which strongly correlates with their preferences for the moderate-to-long time gaps. But it's interesting to notice that the "aggressive" group (four drivers in Group 2) spent more than 60% of their CACC usage at the shortest time gap, which didn't reflect their relatively weak post-experiment preference for this time gap, showing a discrepancy between actual usage and subjective preference. Their concerns about road safety may have lowered the aggressive drivers' preference for the shortest time gap, which they experienced the most during the test.

The test drivers did not have a preference regarding the position of the following truck (second or third in the three-truck string), which should allow for flexibility in forming ad-hoc CACC strings "on the fly". But most drivers engaged CACC for more time in the second truck than in the third truck, which may be attributable to the more responsive braking control provided by the second truck rather than drivers' preference regarding truck position.

In addition, trust in the other drivers is a critical human factor in forming a connected truck string. They only want to partner with reliable drivers (who are not distracted from driving). This could work against the concept of completely ad-hoc formation of CACC strings, and might make it more important to have prior scheduling of truck departures coordinated with other drivers from the same fleet or from trusted partner fleets. However, information about the lead truck and lead driver actions provided on the DVI may enhance trust among unfamiliar drivers, such as notification of braking, following distance, transition from automation to manual, and road traffic ahead.

Overall, the drivers felt comfortable with the CACC system, but preferred the manual mode in cases of heavy traffic and merging on the highway. Despite the performance limitations of the prototype CACC system (e.g., the level of braking action was sometimes either too strong or too weak and countermeasures for limited road visibility were not provided), the drivers' positive feedback based on their on-the-road experience and their high usage of CACC in different traffic and road conditions inspire confidence for investing in such advanced technologies in the trucking industry.

1 Introduction

Cooperative Adaptive Cruise Control (CACC) systems leverage vehicle-to-vehicle (V2V) communication based on technologies such as Dedicated Short Range Communication (DSRC) to provide coordinated longitudinal control (i.e., brake/engine maneuvers) in vehicles, thereby enabling vehicles to automatically maintain a proper following gap behind another CACC-equipped or V2V-capable vehicle. Without V2V, CACC systems default to Adaptive Cruise Control (ACC). Cooperative automated longitudinal control reduces delays in human response, thereby enabling shorter following distances. Increasing market penetration rate of this technology is expected to provide macro-level benefits to transportation corridors such as reducing fuel consumption and emissions (*1*), and improving traffic flow (*2*, *3*, *4*).

However, the benefits of CACC in a transportation corridor will be dictated not only by the rate of adoption, but also the driver settings and other preferences for use of the technology. For example, commercial drivers may prefer to avoid following other trucks closely, despite the technical capabilities of CACC, thereby limiting the fuel savings and throughput benefits offered by CACC. With this in mind, our work explores driver acceptance and usage of CACC during routine driving operations, especially when time gaps are much shorter than normal.

A previous PATH-led research study established that drivers in passenger cars in general feel comfortable to accept a time gap less than one second while driving in a two-vehicle CACC string (*5*). Other studies involving ACC systems may provide insights into driver experiences when using CACC. For example, passenger car drivers in the Netherlands were favorable to using ACC on high speed roads and in low-density traffic, but were annoyed by the occasional clumsiness and dangerous events induced by ACC (*6*). The application of ACC has influenced driving behaviors such as an increased tendency to drive in the right lane (*7*) and forcing drivers to intermittently reclaim vehicle control (*8*). The work done to understand driving preferences and behaviors when using CACC systems is quite limited. Compared to passenger cars, the design and implementation of CACC systems on trucks is more involved, given the nature of operation of commercial fleets. Operating trucks imposes rigorous requirements on driver perception without distracting the vehicle operator. Although CACC systems have been successfully designed and the ability to follow closely demonstrated (e.g., SARTRE, GCDC, European Truck Platooning Challenge, to name a few), driver acceptance and behavior have not been investigated (*9*).

Therefore it’s extremely important to understand driver experience and behavior from multiple perspectives when operating CACC-equipped trucks on public roads in real traffic conditions. This report presents a first investigation of the factors that affect drivers’ experience and behavior using CACC in truck driving. The key factors influencing drivers’ experience and usage of CACC include:

- time gap setting
- truck position in a CACC string
- cut-ins by other vehicles
- road grades
- trust between drivers
- traffic/road situations (during which drivers reclaim full control of the trucks)
- route section (the first and second halves of the round trip)
- individual differences among drivers

The study recruited test drivers from commercial fleets to operate Class 8 Volvo tractors equipped with CACC and unloaded trailers over 160 miles on public roads. The drivers' experiences in a range of mixed traffic conditions and on different road grades were documented. Their usage of CACC during the test was also recorded by the CAN bus system on the trucks. While the drivers had the freedom to choose the time gap settings for automatic vehicle following, the real-time truck speeds were determined by the CACC control system on the trucks. The drivers were responsible for steering, while the braking and engine control actions were automated. A wide range of driver experience and usage data are reported in this report. These findings provide valuable insights into the design of better CACC systems, and also aid in setting reasonable expectations for the benefits offered by CACC.

2 Definition of Terms

These important terms will be used in the rest of this report, including:

Adaptive cruise control (ACC)
ACC is a system that automatically controls the gap between vehicles driving at highway speeds (by actuating engine and brake controls) based on measurements of the distance to the preceding vehicle.

Cooperative adaptive cruise control (CACC)
CACC is an enhancement to ACC that enables more accurate gap control and operations at smaller gaps by adding wireless communication of vehicle status information (primarily speed and acceleration/deceleration) from the preceding vehicle(s).

Dedicated short-range communication (DSRC)
DSRC is a wireless communication system that provides very reliable and low-latency communication of data between vehicles and infrastructure or between vehicles and other vehicles (as it is used here).

Time Gap
Time gap is the time interval between the moments when the rear end of the lead vehicle and the front end of the following vehicle pass the same location along the roadway. This is measured in terms of seconds. The clearance distance corresponding to this gap is calculated as the product of the time gap and the following vehicle speed.

Driver-Vehicle Interface (DVI)
DVI is an interface (a Samsung touch-screen tablet fastened on the top of the instrument panel inside the truck) that enables drivers to select the CACC/ACC time gap and monitor the status of the other trucks in the CACC string

Lead Vehicle and Following Vehicle
We used three Volvo Class 8 trucks with unloaded trailers on each truck in our study. The first vehicle in the truck CACC string is called the lead truck. The second vehicle and third vehicle are the following trucks, called truck 2 and truck 3 respectively.

An Episode of CACC Use
An episode of CACC use is the interval between an engagement and the following disengagement of CACC by a driver.

The usage of CACC
The usage of CACC indicates how long (in seconds) a driver engages CACC in driving.

The Fraction of CACC Usage

The fraction of CACC usage (%) indicates the percentage of a driver’s total CACC usage at each time gap setting.

3 Driver-CACC Interactions

3.1 CACC Control

The control stalk behind the left side of the steering wheel, originally implemented to activate the production ACC system, was modified to activate or deactivate CACC (See Figure 1 left). The drivers could engage or resume CACC by pushing the control button on the stalk to the left and disengage CACC by pushing it to right (see Figure 1 left). In addition to the control stalk, the brake pedal and the red safety button (see Figure 1 right) can be used to deactivate CACC. If the V2V wireless communication is lost for an extended time during CACC mode, CACC will switch to default ACC with larger time gaps (see Table 2).

Figure 1. The CACC control stalk (left) and truck cockpit interior (right) with driver-vehicle interface (DVI) and safety button.

3.2 Driver-Vehicle Interface

The CACC DVI screen (shown in Figure 2) was redesigned in multiple iterations using QT (qt-opensource-windows-x86-msvc2015_64-5.7.1) based on field observations and human factors design guidance. Some components of the DVI, such as buttons, were edited via the online photo editor Pixlr (https://pixlr.com/editor/). The final version was implemented on a Samsung tablet that served as the DVI for the experiments. The CACC DVI presented elementary status information about the other trucks in the CACC string and was used to control the time gap and driving mode (details in Table 1). It was fitted on top of the truck instrument panel (see Figure 1 right).

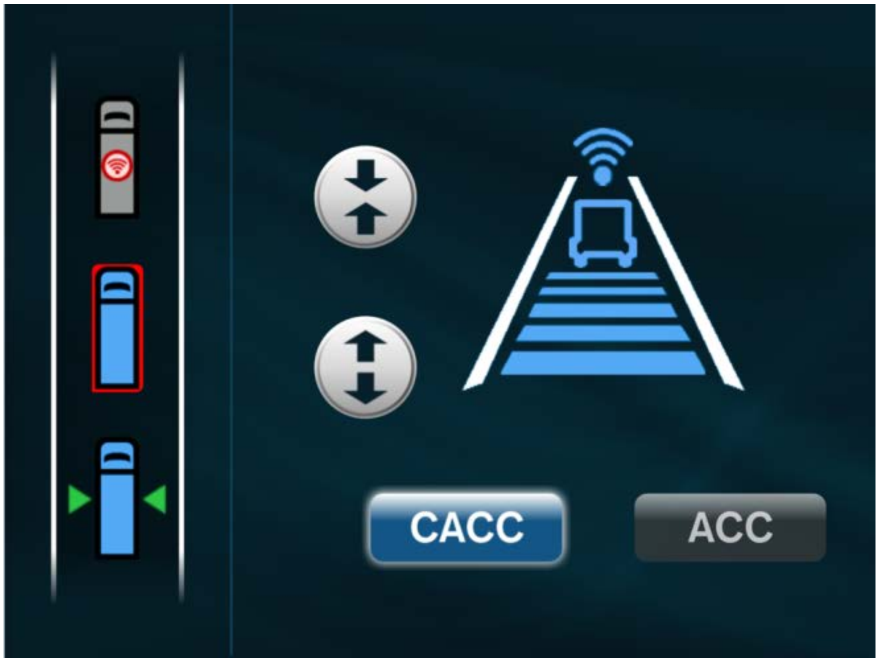
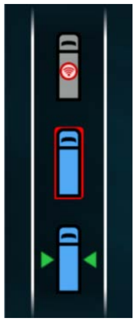


Figure 2. The display of driver-vehicle interface (DVI) inside the truck.

The function of each component is described in Table 1.

Table 1. The function of each component of the DVI.

Component	Description
	• The truck icons on the left side of the interface indicate the trucks that are part of a string. • The color of each truck icon indicates the operation mode of that truck - White – Manual mode; Gray – ACC mode; Blue – CACC mode.
	• Red icon indicates the occurrence of problems in the V2V communication system on that truck.
	• Red outline indicates that the driver has pressed the brake pedal or the foundation brakes have been applied automatically on that truck.
	• The pair of Green triangles indicates the position of the host vehicle.
	• The glow indicates mode activation. In this example, CACC mode is active. The driver may also choose to use ACC mode by touching the ACC button.
	• The five bars indicate the five CACC or ACC time gaps. Gap 1 (shortest gap) Gap 2 (medium-to-short gap) Gap 3 (medium gap) Gap 4 (long-to-medium gap) Gap 5 (longest gap) 
	• The round buttons with arrows inside are controls to increase (bottom button) or reduce (top button) the CACC or ACC time gap. When pressing the button on the bottom, the arrows inside move away from each other; when pressing the top button, the arrows move towards each other.

4 Time Gap

Time gaps for CACC and ACC modes are listed in Table 2. The time gaps for CACC are shorter than the corresponding ACC time gaps. The CACC time gaps were chosen to match some of the time gaps that were tested for CACC on passenger cars in prior PATH research projects (*5*), which found that drivers had a significant preference for the shorter gaps. It should be noted that some of these gaps could be shorter than 30 m, which is the minimum following distance permitted in a “caravan” as established by the California Vehicle Code. As a result, a special law was passed by the State Legislature to permit this testing to occur at distances shorter than 30 m. The lead truck only operated in the ACC mode but the two following trucks could be in CACC or ACC modes. They may switch from CACC to ACC when the wireless V2V communication signal is not available.

Table 2. The time gap settings and corresponding distances in CACC and ACC mode.

Setting	CACC Time Gap (s)	Clearance Distance (m) at 55 mph	ACC Time Gap (s)	Clearance Distance (m) at 55 mph
1	0.6	14.8	1.1	27.0
2	0.9	22.1	1.3	32.0
3	1.2	29.5	1.5	36.9
4	1.5	36.9	1.7	41.8
5	1.8	44.3	1.9	46.7

5 Experiment

5.1 Participants

Nine professional fleet truck drivers from the US (7) and Canada (2) participated in the on-the-road experiments. All test drivers were male, with an 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. Their driving records were verified by the UC Berkeley Fleet Services prior to commencing experiments.

The process of recruitment was hindered by the fact that the supply of truck drivers is in shortage in the US (*10*). Also, fleet drivers only have very limited flexibility to participate in our study because their schedules are arranged by their fleet companies according to business demands. Although a larger sample size would have been desirable, we only ended up with 9 male drivers for the day time test despite four months of intensive recruiting efforts.

5.2 Trucks

Three Volvo Class 8 trucks (see Figure 1 left) with an empty trailer behind each were used for the on-the-road experiment. All trucks were equipped with CACC, meaning that they can exchange the control-related messages with each other via Dedicated Short Range Communication (DSRC) (aka V2V communication in Figure 3 right).

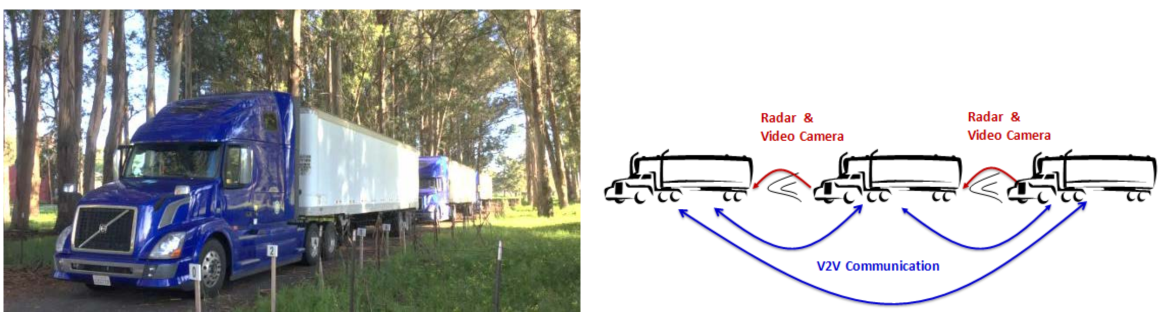


Figure 3. Volvo Class 8 trucks (left) and the V2V communication system (right).

5.3 Testing Schedule

The three trucks were labeled as 476, 475, and 474 and assigned to different positions in the string (see Table 3). In the test on 5-24-2017, only one driver was recruited so that he only drove the second truck (474) in a two-truck string, without the opportunity to experience driving in the third position.

Table 3. Truck ID on each position in test.

Date	Lead Truck ID	Truck 2 ID	Truck 3 ID
5-3-2017	476	475	474
5-15-2017	475	474	476
5-16-2017	475	474	476
5-17-2017	475	474	476
5-24-2017	475	474	N/A

5.4 Test Route

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 (see Figure 4). After arriving at Westley, we took a short break at a parking area near a truck stop and then returned to RFS via the same route. There is a weigh station near Livermore that drivers had to drive through when it was open.

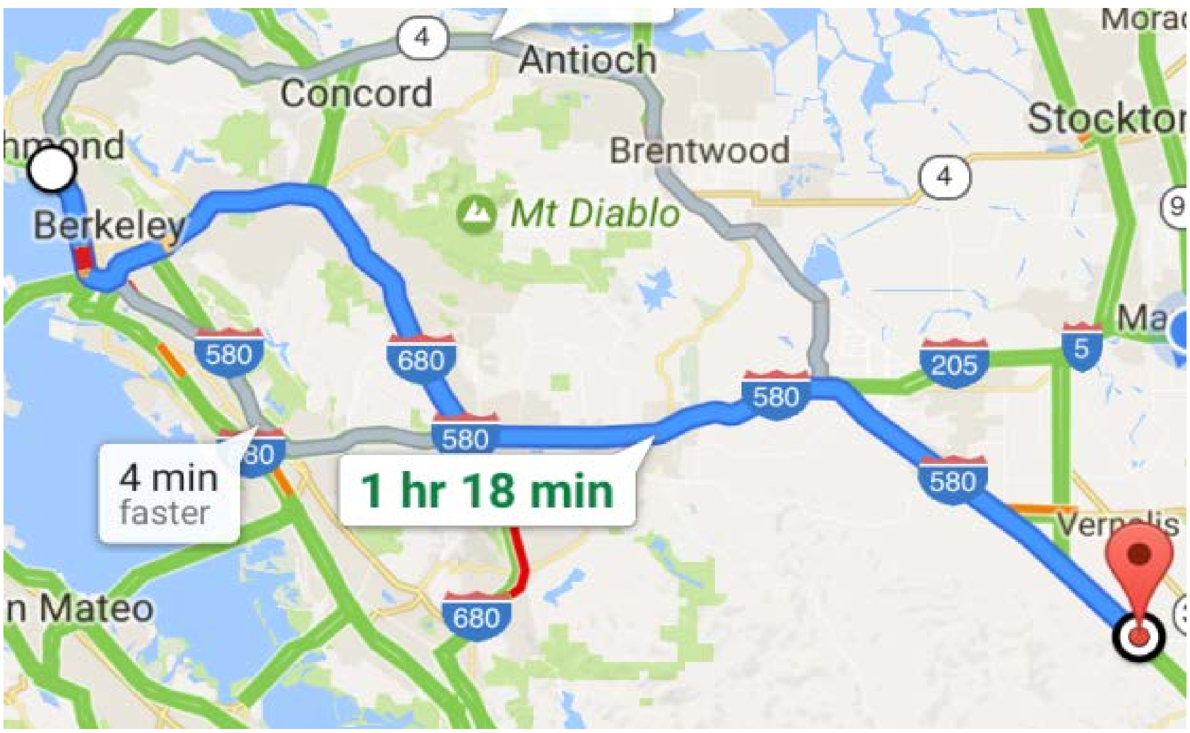


Figure 4. The test route from RFS in Richmond to Westley on I-5.

A single trip by truck from Richmond to Westley usually takes around 1 hour 40 minutes without heavy traffic delay, so a round trip is more than 3 hours. The timing of 1 hour 18 minutes on Figure 4 was calculated according to the speed of passenger cars, but the trucks were limited to the state truck speed limit of 55 mph. The on-the-road driving test normally started after 10:00 am and ended before 2:30 pm to avoid the morning and afternoon peak congestion periods.

5.5 Driving Task

The lead truck was driven by an employee from 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 DVI. However, they were responsible for steering and other maneuvers (responding to actions of other drivers) during the experiments. An experimenter sat in the front passenger seat to monitor the CACC operations and press down the safety button (shown in Figure 1 right) immediately to stop 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 in some road and traffic conditions (e.g., heavy traffic and the steep downgrades of the Altamont Pass, exceeding 6% in some parts).

5.6 Experiment Procedure

First, the experimenters introduced the study to the fleet drivers using a PowerPoint presentation and video in a conference room. Also, the experimenters ensured that the drivers had enough service hours for truck driving in the study. After the introduction the drivers signed the consent form and completed the background questionnaire (see Appendix 1). Then they moved on to the training section in which they needed to get familiar with the control of CACC (e.g., engagement, disengagement, and time gap selection) and experience each time gap setting during the drive between Emeryville and Walnut Creek. Once past Walnut Creek, they had the freedom to use CACC in the way they preferred for truck platooning, but under the monitoring of the experimenter next to them. When arriving at Westley (the end of the testing route), the drivers took a short break, switched to the other following truck, and then drove back to RFS via the same route. After arriving at RFS, they finished the post-experiment debriefing questionnaire (see Appendix 2) and were compensated for their time at $30 per hour, including the pre- and post-drive periods for briefings and filling out questionnaires.

6 CACC-Supporting Components

The CACC supporting system consists of four components: PC-104 computer, Volvo computer, wireless access point, Ethernet, and DSRC radio.

6.1 PC-104 Computer

"PC-104" is a standard for PC-compatible modules (circuit boards) to stack together to create a complete computer system with 104 pins, which is often found in factories, laboratories, and machinery to provide a programmable control of complex systems. Thus, PC-104 computer (see Figure 5) is a special stackable bus connector, which is very similar to the standard desktop PC but with a different form factor. Although the size of PC-104 computer is about 10 cm x 10 cm, its boards are very powerful for their size.

PC-104 computer executes the ACC and CACC algorithms(s) to control the three Volvo Class 8 trucks. It reads around 100 types of driver behavior data (e.g., speed, steering angle, and CACC usage) from the CAN buses on the trucks at a sampling rate of 50 Hz and relies on these data to produce the torque command to control the acceleration and deceleration. It also stores these data for post-test analyses.

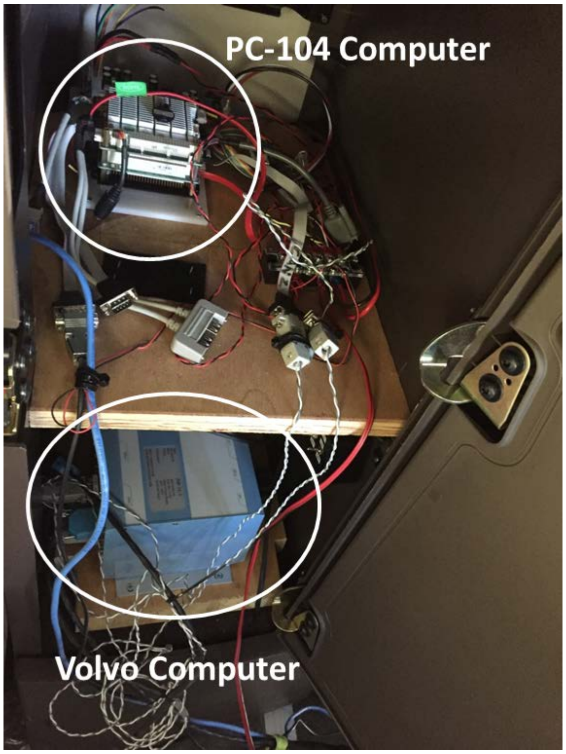


Figure 5. PC-104 and Volvo computers inside the truck cabinet.

6.2 Volvo Computer (XPC box)

The Volvo computer (see Figure 5) stores the data collected by the embedded radar and video camera to detect the target (e.g., cut-in or other truck) in front of the truck. The target detection is an important input for the CACC control that is implemented on the PC-104 computer, which also receives estimates of the distance, speed and acceleration of the primary forward target vehicle from the XPC.

6.3 Wireless Access Point

Wireless access point (TRENDnet TEW-654TR; see Figure 6) connects the Samsung tablet that serves as the driver-vehicle interface with the PC-104.

Figure 6. Wireless access point on top of the truck control panel.

6.4 DSRC Radio

The DSRC radio (GWP5121 V0.4; see Figure 7) provides low-latency communication of data among the three Volvo trucks vehicles with a 10 Hz update rate. The data received from the other trucks is provided to the PC-104 computer for use in implementing the CACC control.

Figure 7. The top view (left) and side view (right) of DSRC radio.

6.5 Ethernet Switch

Ethernet switch (Black Box LBS008A) supports the Local Area Network (LAN) that connects the above components inside the truck cab.

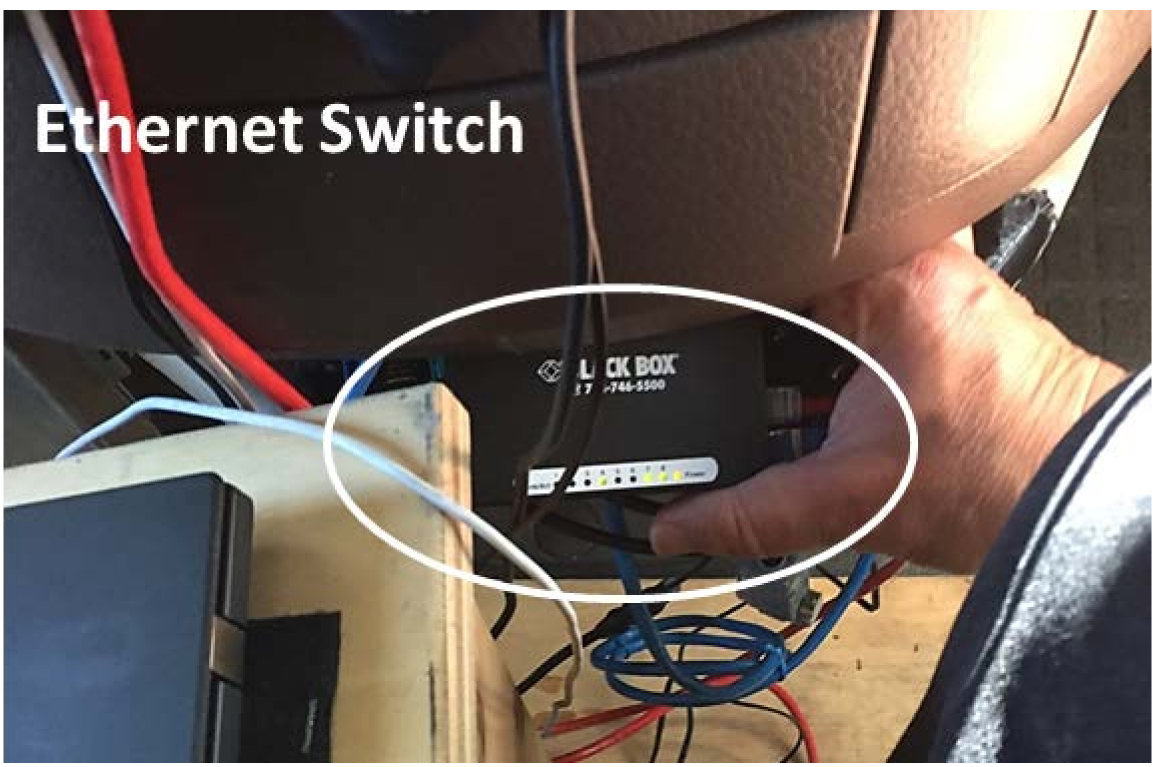


Figure 8. Ethernet switch beneath the truck instrument panel.

7 Data Collection, Processing, and Reduction

7.1 Data File and Directory

The data files were grouped into the same folder based on the date of the experiment and the truck ID. There were 5 dates of experiment:

5-3-2017
5-15-2017
5-16-2017
5-17-2017
5-24-2017

In the example below (see Figure 9), the top folder is named as the testing date “5-3-2017”. The sub-folder is named as “volvo474_17503_162423” in the format of “truckID_YYMMD_hhmmss”. The components of the sub-folder name are described as:

Truck ID = volvo474, or volvo475, or volvo476
YY = Year
(M)M = Month
DD = Day
hh = Hour
mm = Minute
ss= Second

The name format of a data file is "test_MMDDYYYY_hhmmss_DN#_MMDDSSS.dat". The timestamp in the file name is the start time of the file. The components of the file name are described as:

MM = Month of year, 1=January...12=December
DD = Day of month
YYYY = Year
hh = Hour
mm = Minute
ss = Second
DN# = Driver number
MM = Month
DD = Day of month
SSS = Sequence number, starting from 000

Thus, the MATLAB program can read the data files collected on Volvo 474 on May 3rd, 2017 via this directory in the example displayed in Figure 9.

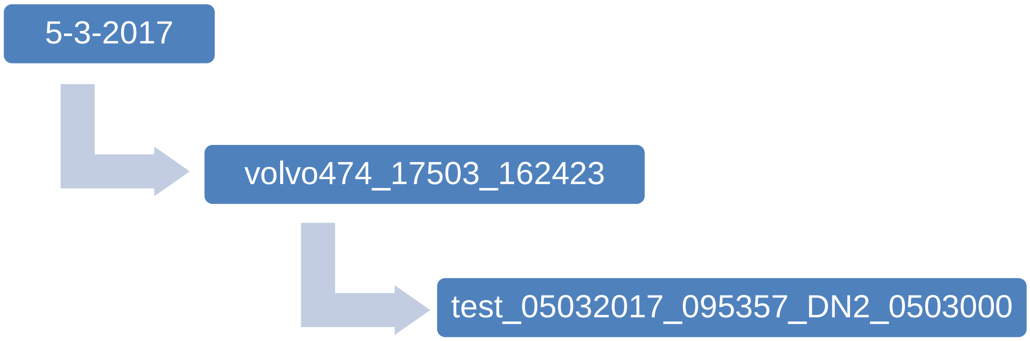


Figure 9. The example of a data file directory.

Each data file has around two hundred columns. Only 15 columns were selected for our data analysis of driver experience and CACC usage (see Table 4).

Table 4. The description of each variable selected.

Col No.	Variable	Description
1	Time	Timestamp of each row of data
5	Drive Mode	The status of the automatic or manual mode of each truck, including: 1 – Manual 2 – Cruise Control 3 – Adaptive Cruise Control 4 – Cooperative Adaptive Cruise Control
11	CC Switch	0 – off; 1 – on
12	Brake Switch	0 –brake off; 1– brake on
16	Vehicle Speed	>= 0, m/s
18	Acceleration	>= 0, m/s/s
62	Time Gap Level	1 – Gap 1; 2 – Gap 2; 3 – Gap 3; 4 – Gap 4; 5 – Gap 5
64	Foundation Brake	0– brake off >0 – brake pressure
74	Steering Angle	>0 – steering left; <0 –steering right
75	GPS Latitude	
76	GPS Longitude	
84	Brake Pressure	0 – brake off >0 – brake pressure
93	Road Grade	>0 – upgrade; <0 downgrade
97	ACC Time Gap	Actual measured time gap values
98	CACC Time Gap	Actual measured time gap values

7.2 MATLAB File

MATLAB programming files (see Table 5) were built to process and analyze the raw driver behavior data.

Table 5. The description of each MATLAB file.

MATLAB File	Description
columnSelection.m	• Select the columns listed in Table 4 and combine them into a new data file for further analysis • Convert the speed from m/s to MPH
getAutoEpisode.m	• Process data using Filter 1, 2 , and 3 (see Data Reduction section) • Generate a table that records the start time and end time of each episode of automatic speed control (when Drive Mode = 2, 3, and 4)
getCACCEpisode.m	• Process data using Filter 4, 5, and 6 (see Data Reduction section) • Generate a table that records the start time and end time of each episode of CACC driving (when Drive Mode = 4 only) • Generate a data file for each episode of CACC driving
getCACCStat.m	• Generate a table that records the length of each time gap use during each CACC episode
CACCAnalysis.m	• Analyze the overall usage of CACC (in seconds) at each time gap setting

7.3 Data Reduction

The driver behavior data collected during the route between Walnut Creek and Westley were used for analysis. The longitude and latitude of Walnut Creek (37.894269, -122.067663) and Westley (37.540387, -121.267263) were used to generate the first filter.

Filter 1

$$37.540387 < \text{GPS Latitude} < 37.894269$$

$$-122.067663 < \text{GPS Longitude} < -121.267263$$

A real CACC episode

The data in the column "Drive Mode" can be used to identify each episode of CACC use. Ideally, the value of Drive Mode should jump from 1 to 4 at the beginning of a CACC episode and stay at 4 until the end of this episode. The value should change back to 1 when CACC is disengaged. However, the pattern of Drive Mode does not always indicate the human control of CACC for several reasons:

1) CACC sometimes turned itself off when it activated the service brake of the truck;

2) CACC could automatically switch to ACC or CC mode (Drive Mode = 3 or 2) when a cut-in vehicle is ahead;
3) a wireless communication error could also turn off CACC.

Thus, the real pattern of Drive Mode during an episode of CACC use is much more complicated than the ideal pattern. Filters 2 -6 were applied to identify true episodes of CACC use from the human driver perspective.

Filter 2 – ignore short self-disengagements by control system

If a driver reengages the CACC within 15 seconds after its self-disengagement, this short period of disengagement is counted as an "accident" that disrupts the operation of CACC during one episode, which means that the driver doesn't intentionally start a new CACC episode. However, if a driver doesn't activate the CACC within the 15-second time window, we assume that he already noticed the self-disengagement of CACC but decided to activate it later. In this case, the driver starts a new episode of CACC use. The disengaged interval – 15 seconds – is determined by the experimenters based on their field observations and is used to determine whether an episode of CACC use should be broken into two.

Filter 3 – ignore the short intervals between automated episodes

The interval between the end of a previous CACC episode and the beginning of a new CACC episode should be more than 5 seconds. It's not likely for human drivers to intentionally disengage and then reengage CACC within a very short interval (we used 5 seconds here) in normal truck driving. Therefore, this short interval is treated as an interruption of a single CACC episode rather than the breaking point between two episodes.

Filter 4 – ignore short automated episodes

The length of each CACC episode should be more than 5 seconds. Shorter CACC episodes are assumed to not reflect a driver's conscious decision to use CACC.

Filter 5 – clean the data when Drive Mode is 0, 1, and 2

In each CACC episode, the data were cleaned when its Drive Mode was 0 (Stay), 1 (Manual), or 2 (CC).

Filter 6 – remove the data rows with NaN data

The "NaN" (Not a Number) indicated that the data elements were not numerical. They cannot be used for analysis so we had to ignore these data during the processing.

Filter 7 – ignore the CACC episodes in which more than 20% of the data was in ACC mode

There were a few CACC episodes in which more than 20% of the data were collected during the ACC engagement (CACC switching to ACC). We decided to remove these episodes to guarantee the “purity” of a CACC episode, which means at least 80% of the data in a CACC episode were collected during CACC engagement.

7.4 R Program

The file “DataAnalysis.R” was developed to perform ANOVAs (type III) on the fraction of CACC usage, analyzing whether the main effects of *Time Gap* and *Group* on the fraction of CACC usage are significant, as well as their interaction effects (see “10 Analysis of CACC Usage”). Following ANOVAs, the R program run a post hoc pairwise comparison between the fractions of CACC usage on different time gap settings and also compared the fractions of CACC usage between different driver groups on each time gap setting. Moreover, we analyzed the correlation between drivers’ preference for the CACC time gap setting and their actual usage of CACC on that time gap setting using R program. Additionally, the impacts of *Position* and *Section* on the CACC usage were analyzed in paired t-tests.

8 Participants' Demographics

The demographic statistics of the drivers were collected by the background questionnaire and reported in Table 6.

Table 6. The demographics of the recruited drivers.

Category	Background Question	Results Mean (Std. Dev.)
Demographic	Age	48 (13)
	Gender	9 male, 0 female
Truck Driving Experience	How many years have you driven tractor-trailer trucks?	21.1 (14.1)
	How many years of experience do you have as an owner/operator?	2.4 (3.7)
	How many years of experience do you have as a company or fleet driver?	18.9 (11.9)
	What fraction of your heavy truck driving is with manual versus automatic transmission?	75.9 (31.0) Manual 24.1 (31.0) Auto
	What fraction of your driving is short haul versus long haul?	66.1(34.4) Short 33.9 (34.4) Long
	What is the fraction of total mileage you spend driving on freeways, other highways, and urban streets in a typical month?	63.3 (20.0) Freeway 15.0 (14.6) Highway 21.7 (17.7) Urban
Experience Related to Technology and Platoon	How is your familiarity with Adaptive Cruise Control (ACC)?	1.4 (1.9) out of 7
	How is your familiarity with collision warning systems?	2.1 (2.0) out of 7
	How is your familiarity with driving in a truck platoon?	0.7 (2.0) out of 7
Route Scheduling	How many hours before departure do you usually schedule your routes?	7.1 (8.8)
	Who plans/schedules your routes?	4 yourself 6 local dispatcher 1 central dispatcher (multiple selections)
	How is your flexibility on adjusting departure or arrival time?	5.6 (2.5) out of 7
	How is your flexibility on the specific route that you take?	5.4 (2.6) out of 7

In the questions “who plans/schedules your routes”, 4 chose “yourself”, 6 chose “local dispatcher”, and 1 chose “central dispatcher”. The total number is more than 9 because this is a multiple-section question.

On average, the tested drivers are relatively senior in the trucking business, with an average of 21.1 years of driving experience; most were for a company or fleet versus driving as an owner or operator. The drivers have more experience in manual transmission driving than automatic transmission driving and they drive more in short haul compared with long haul. Their driving mileages are largely on freeway and partially on highway or urban. However, they only have very limited experience with ACC, collision warning systems, and driving in truck platoons, in their relatively long careers as commercial vehicle operators.

9 Analysis of Driving Experience

The results reported in this section were obtained from the final debriefing questionnaire that all the drivers filled out. The drivers' written answers in the tables in this section were processed by the experimenter to ensure their grammatical correctness and readability. The acronym such as "P1" in the table means Participant 1, so as other acronyms P2 - P9.

9.1 Driver-Vehicle Interface

Table 7 shows that drivers well understood the information on the table display (6.7 out of 7). Although one participant (P7) mentioned that the communication error symbol on the tablet display was unnecessary in the test, on average drivers found that the information about other trucks on the tablet display was very useful (5.9 out of 7). Moreover, they mentioned that additional display information, such as alarms on CACC self-stop (P6, P7) and road view ahead of the lead truck (P7), could help drivers to use the CACC system more safely and effectively.

Table 7. Drivers' feedback on DVI.

Question about DVI	Results Mean (Std. Dev.)
How much do you understand the information on the tablet display?	6.7 (0.7) /7
How useful was the information about the other trucks on the tablet display?	5.9 (1.7) /7
Which information on the tablet display do you consider to be unnecessary?	• Communication error symbol is unnecessary (P7)
What additional information do you think the tablet should provide for you to use the CACC system safely and effectively?	• Alarms when CACC self-stops (P6, P7) • Road view ahead of lead truck (P7)

Note. 7 is the maximum possible score.

9.2 Time Gap Preference

The drivers ranked the five time gaps from 1 to 5 to indicate their preference for each time gap from high to low. The Friedman test showed that the average preference rankings of the time gaps were significantly different from each other (χ^2 = 10.1, df = 4, p = .040; see Figure 5). Post hoc test showed that the preference ranking of Gap 3 (1.8) was significantly higher than that of Gap 1 (4.0, p<.001), Gap 2 (3.8, p<.001), and Gap 5 (2.9, p=.027), but not significantly different from Gap 4 (2.6). Similarly, the preference ranking of Gap 4 was significantly higher than that of Gap 1 (p=.016) and Gap 2 (p=.045).

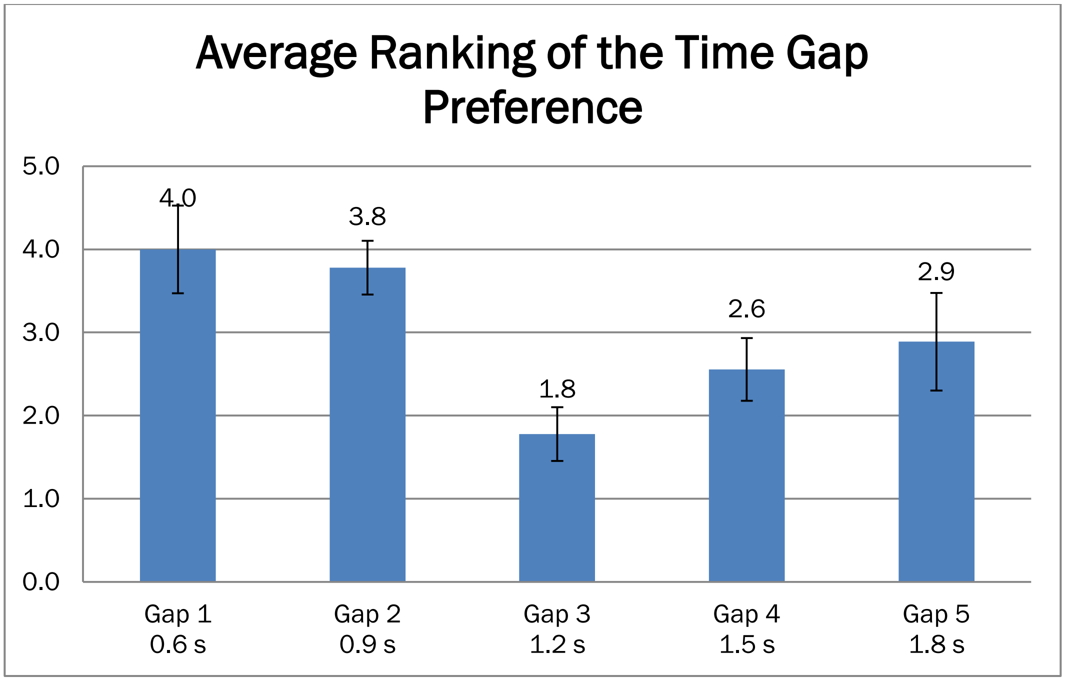


Figure 10. The average ranking of the time gap preference at each setting. Smaller value indicates higher preference.

Participants preferred the Gap 3 (1.2 s) and Gap 4 (1.5 s) settings of CACC the most. When the time gap was very small, their view of the road ahead was obstructed by the trailer of the preceding truck. This was reflected in the debriefing questionnaire, where eight out of nine drivers chose the two shortest CACC time gaps (0.6 s and 0.9 s) as the gaps where they felt it was most difficult to see enough of the road ahead for comfortable driving. The drivers also did not prefer Gap 5, the largest CACC time gap. They mentioned that the large gap tended to encourage cut-ins by other vehicles on the road, mainly light duty vehicles. Therefore, the two medium gap settings (Gaps 3 and p 4) were preferred by the drivers as a compromise between their perceived driving safety/comfort and for deterring cut-ins by other vehicles.

9.3 Truck Position in String

Drivers' experience of driving the truck 2 and 3 is described in Table 8, with regard to their preferences between the second and third positions.

The position of a truck in the CACC string was not a key factor limiting or enhancing drivers' ability to see ahead. Only one participant reported that driving in the third truck provided a better view of the highway and more anticipation of the events ahead. He thus preferred driving the last truck. Two other drivers noticed the difference in the braking performance rather than the road visibility between the following trucks. They found that CACC in the third truck did not generate sufficient braking to slow down the vehicle and maintain the predefined time gap compared to the second truck (because of the unavailability of the service braking), so they preferred the second truck. The majority of the drivers (five out of eight) didn't notice any difference between driving in the second and third trucks and had no preference for either position.

Table 8. Driving experience in different positions.

Question about the Truck Position	Results
Did you notice a difference between driving in the 2nd or 3rd position?	5 No 3 Yes
If you notice a difference between driving in the 2nd and 3rd position, what's the difference?	• The 3rd truck provided clearer view of the highway to anticipate events (P1) • The 3rd truck's brake control was not as effective as the 2nd truck's (P3, P4)
Did you have a preference for being in the 2nd or 3rd position?	2 preferred 2nd position, 1 preferred 3rd position 5 no preference
If you prefer 2nd position or 3rd position, please explain why you have such a preference.	• Preferred 3rd position because it enabled better vantage point and more anticipation of the on-road events because of the view of both other trucks (P1) • Preferred the 2nd truck because of its better control reaction to the lead truck (P3, P4)

Note. Participant 9 was not able to answer these questions because he only drove the second truck in a two-truck string without experiencing the third truck.

9.4 CACC Response to Cut-ins and Road Grade

During the experiments, the CACC system responded to a vehicle cut-in by detecting it and then slowing the truck to leave a larger distance between itself and the cut-in vehicle. Once the vehicle cut out, the truck increased its speed automatically to reduce its distance to the preceding truck until it reached the time gap (or corresponding following distance) set by CACC. When driving uphill or downhill the CACC system needed to manipulate engine and braking controls to offset the acceleration and deceleration caused by the road grades and maintain the proper following time gap. The drivers' opinions about the CACC response to cut-ins and road grade are reported in Table 5.

Table 9.The experience of using CACC in different driving conditions.

Category	Debriefing Question	Results Mean (Std. Dev.)
Cut-in	When a vehicle cut in between you and the truck ahead of you, how comfortable did you feel with the CACC system response?	5.2 (2.1) / 7
	How much did you trust the CACC system to ensure safety when a cut-in occurred ahead of you?	5.0 (1.8) / 7
Road Grade	How reliably do you think the CACC worked when you drove on upgrades?	4.6 (2.0) / 7
	How reliably do you think the CACC worked when you drove on downgrades?	3.1 (1.8) / 7

On average the participants felt comfortable with CACC response to cut-in vehicles. Also, they seemed to be convinced of the safety benefits offered by CACC, especially during vehicle cut-ins.

However, participants were less confident with the reliability of the prototype CACC when it was operating on steep road grades, especially on downgrades. This was partially attributable to the pre-test instructions and partially attributable to their direct experience. In particular, the prototype CACC control relies primarily on engine braking for deceleration, which cannot generate sufficient deceleration to slow the truck on steeper downgrades. When the foundation brakes were activated to provide stronger deceleration, that disengaged the CACC control based on some of the internal logic of the Volvo ACC system that could not be circumvented. On upgrades, CACC sometimes could not trigger enough acceleration for the following truck to stay close to the preceding trucks. During the pre-test briefing, experimenters explained these limitations to the participants and asked them to disengage CACC whenever they were not comfortable with its performance, including on steep grades.

9.5 Switching from Automated Driving to Manual Driving

During the experiments, the drivers were allowed to turn off the CACC mode and take complete control of the truck as necessary. Conditions in which a transition from automation to manual happened are summarized in Table 10.

Table 10. The situations in which drivers took control of the truck.

Debriefing Question	Results
Under what conditions do you prefer to turn off the CACC and take over full control of the truck?	• Heavy traffic (P1, P2, P3, P4, P5 , P6, P7, P8) • Road grades (P1, P2, P5, P9) • Highway merging (P4) • Slow speed (S2)

Heavy traffic was the primary reason to trigger the transition from CACC to manual mode. Heavy traffic increases the likelihood of vehicle cut-ins, and frequent cut-ins can disrupt driving in CACC strings. Furthermore, the trucks may be slowed down by heavy traffic, which results in shorter following distances based on the unchanged time gap setting, which could be uncomfortable for the drivers. On the other hand, the drivers demonstrated greater willingness to use CACC when traffic was light and predicable, such as driving on the rural highway I-5.

Road grade was the second most frequently-mentioned factor that contributed to the transition to manual driving because of the performance limitations of the current CACC prototype implementation that was not able to provide sufficiently strong and smooth control to counteract the accelerations and decelerations caused by the road grades.

Highway merging was also a situation in which drivers preferred operating in manual mode. The automated truck string may "block" other vehicles when they had to merge into the highway after passing the limited length of on-ramp. Since the sensors in the current CACC prototype were not able to detect the merging vehicles approaching alongside the trucks, drivers had to switch to the manual mode to let them cut in, or change lane to provide enough space for other vehicles to merge into highway, or speed up to pass the merging vehicles.

9.6 Trust

Drivers' evaluations of the trust and communication among drivers are described in Table 11.

Table 11. Trust and communication among drivers.

Debriefing Question	Results
How much do you need to trust the other drivers in the platoon?	6.9 (0.3) out of 7
What kind of information would you like to obtain from the lead truck and lead driver?	• Better notification of braking (P2, P4) • Distance between lead truck and vehicle ahead (P4) • Switch from automation to manual (P5) • Traffic and Road visibility (e.g., detecting obstructions) (P3, P7, P8)

Trust in the other drivers is a critical human factor to form a connected truck string. Almost all drivers agreed that the level of trust in the other drivers should be very high when they drive in a CACC string. They only want to partner with reliable drivers (who are not distracted from driving). This could work against the concept of completely ad-hoc formation of CACC strings, and might make it more important to have prior scheduling of truck departures coordinated with other drivers from the same fleet or from trusted partner fleets.

The DVI is a critical tool to improve the trust among drivers. The information needed from the lead truck and lead driver were reported to be in four categories: notification of braking, following distance, switch from automation to manual, and traffic ahead of the lead truck. Although the DV displays the braking of the trucks using a red outline on the truck icons, it may not be easy for truck drivers to notice the appearance of the red outline because they have to pay attention to the brake pedal control when the lead truck is braking. Also, it's important to foresee the traffic ahead. There was an instance in which the following truck had to quickly change to the left lane to avoid a flat tire in the road that was skipped by the lead truck (the lead truck changed to the left lane to avoid the flat tire).

9.7 Limitations of Prototype CACC

Keeping in mind that that CACC implementation was an advanced research prototype, there were limitations to the performance of the CACC system on the trucks. The drivers reported a variety of concerns based on their experience operating the system on public highways, including unreliability and jerkiness in the speed control (P2, P7), wireless communication errors (P3), CACC reliability concerns (P5), limited road visibility from the following truck (P7), and the position of the tablet display being outside peripheral vision (P8). For example, the brake control by CACC using engine braking was not strong enough, so that the second truck could get too close to the lead truck on downhill sections (P2). Sometimes the truck failed to release brakes in time so that its following distance to the preceding truck became much larger than what it should be (P2). Furthermore, they mentioned a few potential issues for CACC that should be explored in the future, including the impact of mechanical breakdown or tire blowout on the preceding truck to the following truck (P1), highway infrastructure to assist truck platoon (P8), and CACC-induced complacency (P4).

9.8 Overall Experience with CACC

Drivers' overall experience using CACC is measured in Table 12. These results show that the drivers were satisfied with their truck driving experience with the driver assist capabilities of CACC. However, CACC did not have a large enough effect to make the commercial vehicle operation job more attractive to them. Perhaps other factors, beyond automation technology, will have change to increase job satisfaction, which need further investigation.

Table 12. Drivers' Overall Experience using CACC.

Debriefing Question	Results Mean (Std. Dev.)
Overall, what was your satisfaction with driving in a platoon using CACC?	5.6 (0.9) out of 7
If you were regularly driving a truck with CACC, would that make the truck driver job more attractive to you?	0.6 (1.6), close to 0
After you got familiar with the CACC system, did you find that you were paying more or less attention to the driving task than your normal truck driving?	0.1 (1.6), close to 0

10 Analysis of CACC Usage

The usage of CACC (in seconds) and the usage fraction (%) at each time gap are described in two separate tables -Table 13 and Table 14 - because the drivers were divided into two groups based on our post-experimental analysis of their CACC gap selections. Group 2 (including P3, P7, P8, and P9) primarily used the short CACC time gaps, while Group 1 (including P1, P2, P4, P5, and P6) primarily used the longer CACC time gaps. Several factors that may affect CACC usage are also listed in Table 13 and Table 14, including:

- ***Date* –** the testing date, including 3, 15, 16, 17, 24 in May 2017
- ***Truck ID* –** the labels of the trucks, which are 474, 475, and 476
- ***Subject* –** the ID of each participant (P), which ranges from P1 to P9
- ***Position* –** the truck position, either the 2nd (truck 2) or the 3rd (truck 3) position
- ***Section* –** the first half (RFS to Westley) and second half (Westley to RFS) of the test round trip

Table 13. The fraction of CACC usage (%) at each time gap setting by Group 1 drivers.

Date	Truck ID	Subject	Position	Section	Gap 1	Gap 2	Gap 3	Gap 4	Gap 5	Usage (seconds)
3	475	P1	2nd	1st	0.0%	33.0%	41.9%	22.2%	3.0%	1786.8
3	475	P2	2nd	2nd	3.0%	1.8%	43.7%	48.5%	3.1%	2064.3
3	474	P2	3rd	1st	1.6%	4.2%	50.4%	0.1%	43.7%	1795.7
3	474	P1	3rd	2nd	0.8%	1.3%	26.9%	24.5%	46.5%	1598.3
15	474	P4	2nd	2nd	8.7%	8.9%	78.3%	4.0%	0.0%	3642.4
15	476	P4	3rd	1st	1.9%	37.4%	52.1%	1.0%	7.6%	3090.5
16	474	P5	2nd	1st	7.8%	15.4%	10.2%	0.0%	66.7%	3398.1
16	474	P6	2nd	2nd	0.0%	0.9%	99.1%	0.0%	0.0%	3569.4
16	476	P6	3rd	1st	2.9%	13.2%	60.6%	14.5%	8.8%	3074.4
16	476	P5	3rd	2nd	0.9%	1.9%	16.8%	0.1%	80.2%	2992.0
Mean					2.8%	11.8%	48.0%	11.5%	26.0%	
Standard Deviation					3.1%	13.4%	27.1%	16.2%	30.5%	

Table 14. The fraction of CACC usage (%) at each time gap setting by Group 2 drivers.

Date	Truck ID	Subject	Position	Section	Gap 1	Gap 2	Gap 3	Gap 4	Gap 5	Usage (seconds)
15	474	P3	2nd	1st	69.0%	18.6%	12.4%	0.0%	0.0%	2801.2
15	476	P3	3rd	2nd	29.5%	38.4%	32.1%	0.0%	0.0%	3631.4
17	474	P7	2nd	1st	69.8%	13.9%	13.0%	0.9%	2.5%	2992.2
17	474	P8	2nd	2nd	76.0%	5.0%	17.7%	0.9%	0.4%	3344.5
17	476	P8	3rd	1st	48.2%	15.6%	16.8%	14.9%	4.5%	2108.7
17	476	P7	3rd	2nd	73.5%	1.5%	23.8%	1.2%	0.0%	2994.1
24	474	P9	2nd	1st	78.7%	3.2%	15.7%	2.4%	0.0%	2626.1
24	474	P9	2nd	2nd	62.7%	1.0%	36.3%	0.0%	0.0%	3171.5
Mean					63.4%	12.2%	21.0%	2.5%	0.9%	
Standard Deviation					16.7%	12.6%	9.0%	5.1%	1.7%	

10.1 Overall CACC Usage

The total usage of CACC during the test on May 3rd was less than 4000 s per person, much lower than those on other testing dates, which were between 5400 s and 6800 s. The reason for this is that the braking control in the first day test on May 3rd did not perform as well as we expected. Moreover, on May 3rd, participants in truck 2 spent almost 50% of their time at Gap 3. But when they drove truck 3, they switched to the longer time gap Gap 5 for 50% of their CACC usage.

10.2 The fraction of CACC Usage at each Time Gap Setting

ANOVAs showed that the fraction of CACC usage (%) at different time gap settings was significantly different from each other ($F(4, 50)=9.66$, $p<.001$). 'p' in the data analysis represents p value, which means 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 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.

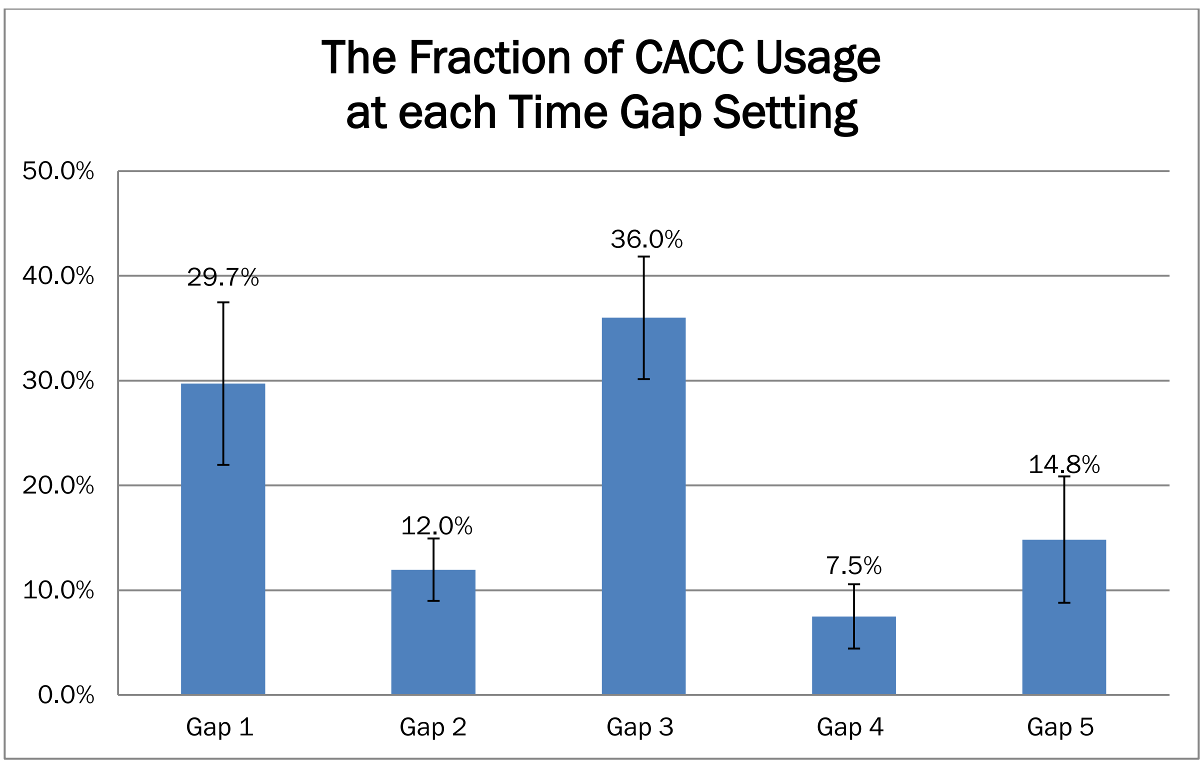


Figure 11. The faction of CACC usage (%) at each time gap setting.

Post hoc test showed that the fraction of CACC usage at Gap 1 (29.7%) was significantly higher than Gap 2 (12.0%, $p=.012$), Gap 4 (7.5%, $p<.001$), and Gap 5 (14.8%, $p=.048$). Similarly, the fraction of Gap-3 CACC usage (36.0%) was significantly higher than that at Gap 2 ($p<.001$), Gap 4 (p<.001), and Gap 5 (p=.002). These findings showed that drivers spent a larger fraction of their time at Gap 1 and Gap 3 than the other three time gaps.

10.3 The Fraction of CACC Usage between Groups

The interaction effect between *Gap* and *Group* on the fraction of CACC usage was significant ($F(4,50)=21.8$, $p<0.001$).

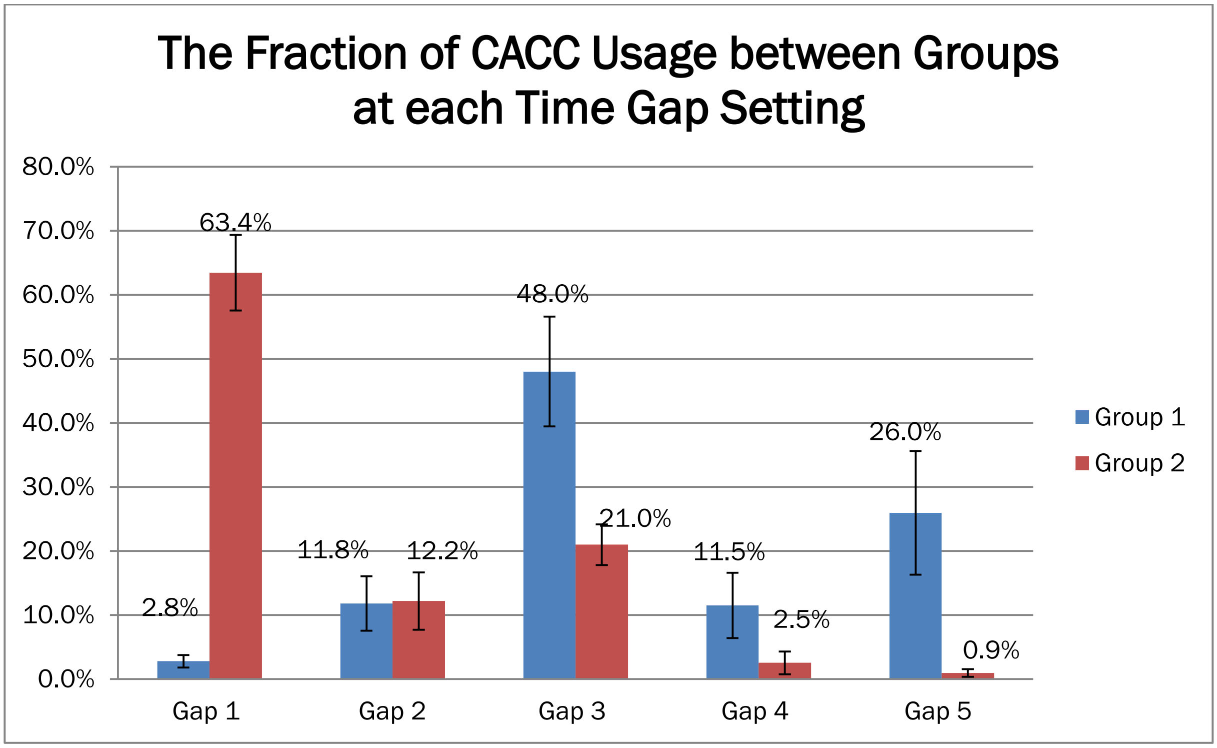


Figure 12. The fraction of CACC usage (%) between the two groups at each time gap setting.

Post hoc test showed that Group 2 spent more than half of their CACC usage time at Gap 1 (63.4%), which was significantly higher than Group 1 (2.8%, p<.001). 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 times for Group 1 (fraction of CACC usage: Gap 3=21.0%, p=.003; Gap 5=0.9%, p<.001). The fraction of CACC usage between the two groups was not significantly different when the time gap settings were selected as 2, 3, and 4. The finding showed that the five drivers in Group 1 primarily used Gap 3 and Gap 5 in the test while the other four drivers in Group 2 primarily used Gap 1.

The demographic differences between the two groups may contribute to the group 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. Group 2 also had more experience with ACC and collision warning systems than Group 1. Although t-tests didn't show statistical differences in the four comparisons in Table 15, it's still likely that the drivers with more professional experience and higher familiarity with driver assistance system are more confident with shorter following time gaps to the preceding truck.

Table 15. The demographic differences between the two groups.

Demographics	Group 1	Group 2
Average years driving tractor-trailer trucks	15.8	27.8
Average years as a company or fleet driver	13.4	25.8
Familiarity with Adaptive Cruise Control (ACC)	0.4 / 7	2.8 / 7
Familiarity with collision warning systems	0.5 / 7	3.5 / 7

10.4 Correlation between Preference and CACC Usage Fraction

This correlation analysis aims to understand the relationship between drivers' expressed preferences for the CACC time gaps and their actual usage of the CACC time gaps. In Group 1, the preference ranking of the CACC time gaps significantly correlated with their fraction of CACC usage ($p=.004$), with the correlation coefficient -0.53 (see Figure 13). This means the drivers in Group 1 tended to use the CACC time gaps which they preferred. It's worth noting that P6 intentionally ranked the "5, 5, 1, 1, 2" for Gaps 1 -5, which meant some time gaps were equally important to him. Therefore, the scatter dots in Figure 13 are not equally distributed among the five rankings.

In Figure 13, several scatter dots in the black dashed circles indicate an obvious discrepancy between preference and usage, which happened when the time gaps were selected as Gap 4 and Gap 5. The reason for this is that P4, P5, and P6 spent 81.3%, 73.0%, and 66.3% of their usage, respectively, at their most preferred time gaps. Therefore, they can't spend large fractions of their time at their second preference time gaps (P6 selected both Gap 3 and Gap 4 as his most preferred time gaps, but spent most of his time at Gap 3). P1 and P2 preferred Gap 5 the most but they only spent a moderate percentage of their time at Gap 5 (23.5% and 22.0%, respectively). Perhaps, they would like to spend a reasonable amount of time to experience Gaps 3, 4, and 5 during the test and reported which time gap they liked the most in the post-experiment debriefing questionnaire.

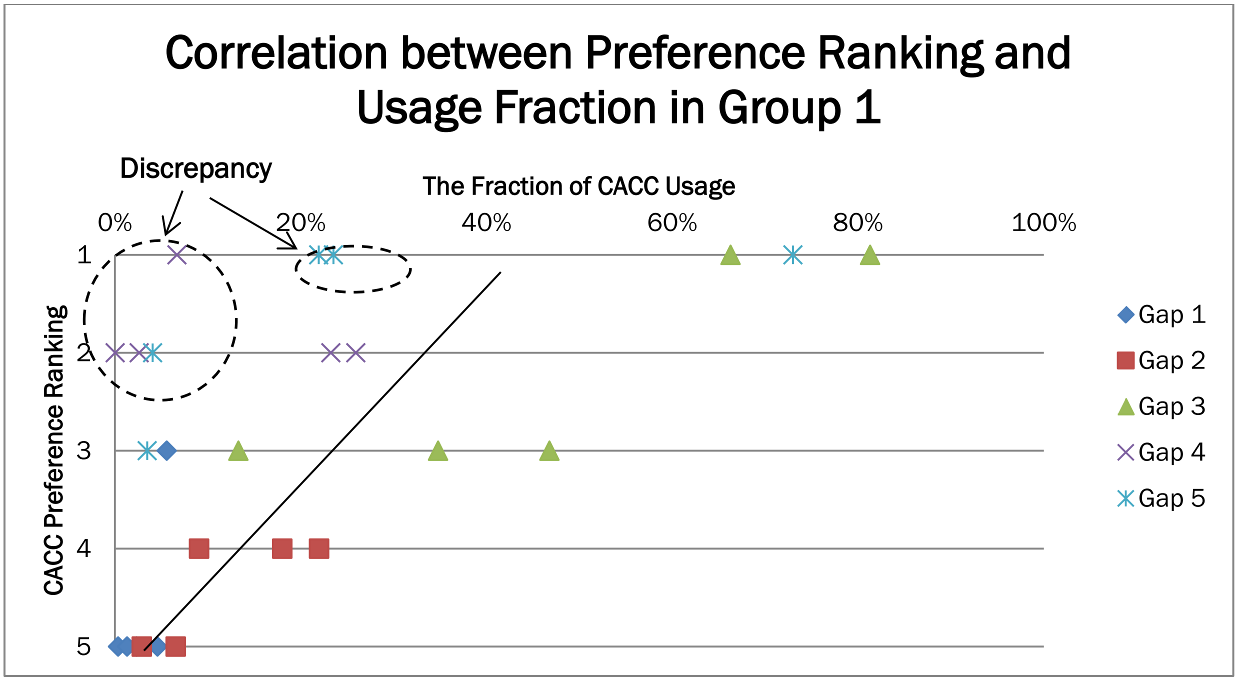


Figure 13. The correlation between the preference ranking of CACC and the fraction of actual CACC usage at each time gap setting in Group 1. The value on Y axis is in a reverse order to naturally map the high-to-low preference for time gap to top-to-down position

In Group 2, the correlation between the preference ranking and the fraction of CACC usage was insignificant (p=.110), with the correlation coefficient -0.36. However, we found an outlier in Figure 14, which indicated a driver who did not prefer Gap 1 but spent more than 60% of his CACC usage at Gap 1. If we remove the outlier, the correlation coefficient increases to -0.59, becoming statistically significant (p=.007).

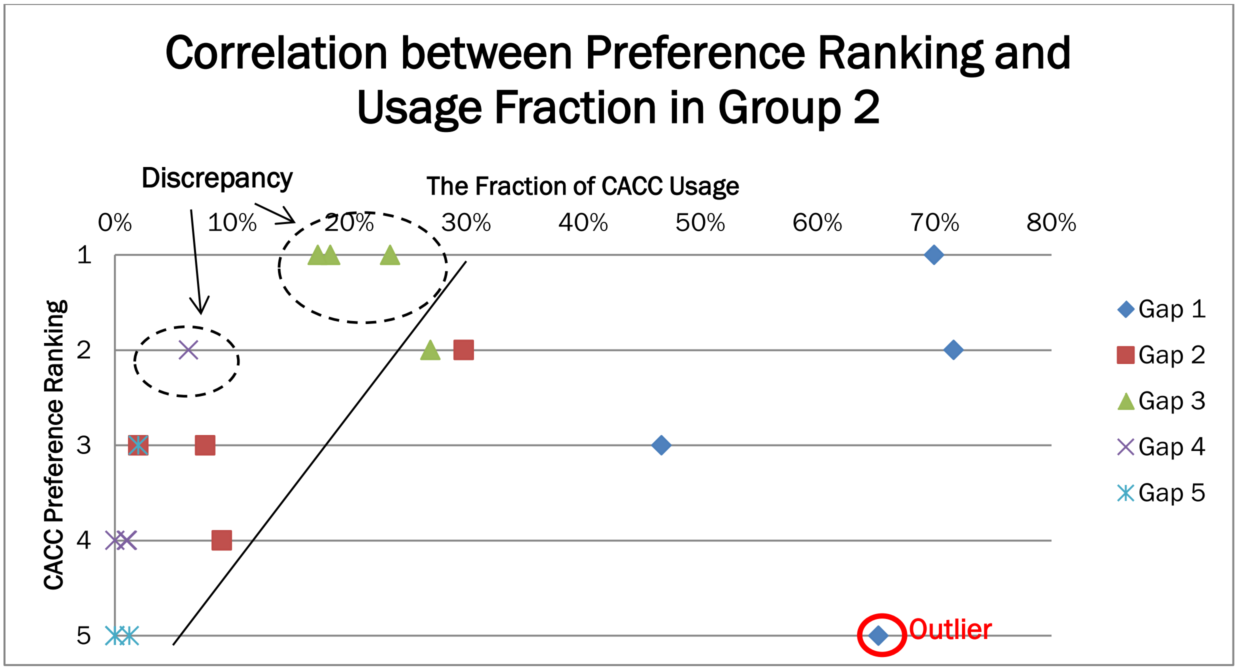


Figure 14. The correlation between the preference ranking of CACC and the fraction of CACC actual usage at each time gap setting in Group 2. The value on the Y axis is in a reverse order to naturally map the high-to-low preference of time gap to top-to-down position of the axis.

At first glance, the drivers in Group 2 did not appear to use the time gaps that they said they preferred. However, once the outlier was removed, the correlation analysis showed a consistent preference-usage pattern to that in Group 1.

Other factors rather than preference may contribute to the outlier's (P8) motivation for using the 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 short gap for CACC in the controlled study in which the experimenter monitored the driving conditions to ensure safety. A further interview may be needed to understand the reasons behind this preference-usage inconsistency.

Several data points indicating discrepancy (related to P3, P7, and P8,) were also found in Figure 14. Since P8 spent 65.2% of his time at Gap 1 which he liked the least, he could not spend much time at Gap 3 and 4, which earned his higher preference. Although P3 and P7 spent most of their time using CACC Gap 1 during the test, they reported Gap 3 as their favorite time gap setting later on the post-experiment debriefing questionnaire. Their final decision was probably influenced by the concern of other safety-related factors, such as braking control performance and road visibility.

Taking into account the findings from both groups, we concluded that in general the drivers in both groups used the CACC at the time gap settings that they preferred, although the two groups showed different preferences for the time gaps.

10.5 CACC Usage between Trucks

Since the sum of the fraction of CACC usage across the five time gaps per participant always equals 1, it's meaningless to compare the fraction of CACC usage between truck positions and between sections. Thus, we compared total CACC usage (in seconds) rather than the usage fraction using t-test.

We excluded the data of P9 in the comparison of CACC usage between trucks since he didn't drive truck 3, but only drove in a two-truck string. T-test showed that the usage of CACC (p=.405) was not significantly different between truck 2 and truck 3. During the test the drivers' usage of CACC in truck 2 (mean=2939.7 s) was not different from that in truck 3 (mean=2660.6 s).

However, if we remove the data of P3 (P3 CACC usage: truck 2=2801.2 s, truck 3=3631.4 s), who engaged CACC much longer on truck 3 than on truck 2, the t-test showed that the CACC usage for the other seven participants was significantly longer on truck 2 (2971.1 s) than truck 3 (2522.0 s. p=.024).

10.6 CACC Usage between Sections

ANOVAs showed that the main effect of *Section* was also significant to the usage of CACC (p=.180). In other words, the usage of CACC in the second half of the round trip (mean=3000.9 s) was significantly higher than that in the first half (mean=2630.4 s). The higher usage of CACC on the second half of the route is not likely attributable to lighter traffic since traffic was denser in the second half of the round trip based on PeMS traffic data. So it's likely that drivers' higher familiarity with CACC as the test continued contributed to the higher CACC usage in the later route section.

11 Conclusion

This report has presented a first human factors study of truck drivers' on-the-road experience using CACC. Our findings provide important insights into drivers' subjective acceptance of CACC from multiple perspectives, as well as revealing their actual usage of this advanced technology in the test. It was evident that on average the test drivers did not prefer to drive too close (< 0.9 s) or far (1.8 s) behind the lead truck, and seemed to prefer time gaps of 1.2 and 1.5 seconds. While the shorter time gaps limited their driving view from following too closely, the largest time gap seemed to encourage more frequent vehicle cut-ins.

However, the test drivers in fact spent 30% of their CACC usage time at the shortest time gap on average. It's not surprised to find that the "conservative" drivers (five drivers in Group 1) primarily engaged the medium-to-long CACC time gaps in driving, which was consistent with their time gap preferences. But it's interesting to notice that the "aggressive" group (four drivers in Group 2) spent more than 60% of their CACC period at the shortest time gap, which didn't necessarily reflect their post-experiment preference ranking for this time gap, showing a discrepancy between actual usage and subjective preference to some extent. Their realistic concerns about road safety may lower the aggressive drivers' preference for the shortest time gap which they experienced the most in the test.

The test drivers did not have a preference for the position of the following truck (second or third in the three-truck string) regarding their driving visibility, which should allow for flexibility in forming ad-hoc CACC strings "on the fly". But most drivers in the second truck engaged CACC for longer periods than in the third truck, which may be attributable to the more responsive braking control of the second truck rather than the time gap preference.

Overall, the drivers felt comfortable with the CACC system, but preferred the manual mode in cases of heavy traffic and merging on the highway. Despite the performance limitations of the prototype CACC system, drivers' positive feedback based on their on-the-road experience and their high usage of CACC in different traffic and road conditions inspire confidence for investing in such advanced technologies in the trucking industry.

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Appendix 1

Subject Number______

Subject Background Questions

What's your age? _________

What's your gender?   M   F

How many years have you driven tractor-trailer trucks? _________

How many years of experience do you have as an owner/operator? ______ years

How many years of experience do you have as a company or fleet driver? ______ years

What fraction of your heavy truck driving is with manual versus automatic transmission?

a.   manual   _____%   b. automatic _____%

What fraction of your driving is short haul versus long haul?

a.   short haul _____%   b. long haul _____%

What is the fraction of total mileage you spend driving on freeways, other highways, and urban streets in a typical month?

Freeways：______%   Other Highways：______%   Urban Streets ______ %

How is your familiarity with Adaptive Cruise Control (ACC)?

Not familiar at all   0   1   2   3   4   5   6   7   Very familiar

How is your familiarity with collision warning systems?

Not familiar at all 0 1 2 3 4 5 6 7 Very familiar

How is your familiarity with driving in a truck platoon?

Not familiar at all 0 1 2 3 4 5 6 7 Very familiar

If you have previous experience of driving in a platoon, what was your satisfaction with this type of experience?

Not satisfied at all 0 1 2 3 4 5 6 7 Very satisfied

How many hours before departure do you usually schedule your routes? ______

Who plans/schedules your routes?

a. you b. local dispatcher c. central dispatcher

How is your flexibility on adjusting departure or arrival time?

Not flexible at all 0 1 2 3 4 5 6 7 Very flexible

How is your flexibility on the specific route that you take?

Not flexible at all 0 1 2 3 4 5 6 7 Very flexible

Appendix 2

Subject Number______

Post-Experiment Debriefing Questions

Display

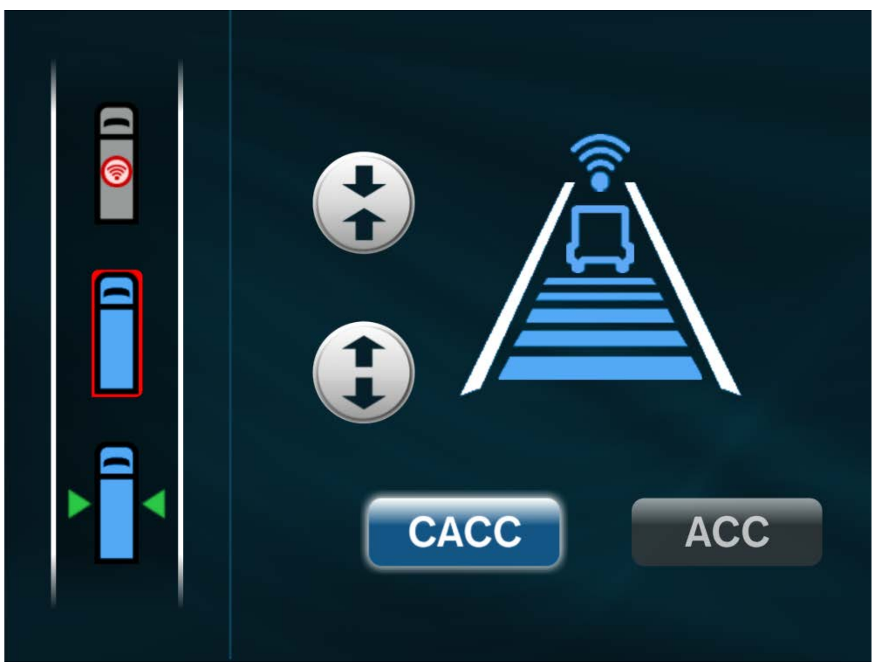
How much did you understand the information on the tablet display?

Not at all 0 1 2 3 4 5 6 7 All of the information

How useful was the information about the other trucks on the tablet display?

Not useful at all 0 1 2 3 4 5 6 7 Extremely useful

Which information on the tablet display do you consider to be unnecessary? You can draw arrows pointing to the pieces of information (multiple choices) and explain why.



What additional information do you think the tablet should provide for you to use the CACC system safely and effectively?

Gap Setting

Please rank the different gap settings based on your preference (1 – most liked to 5 – least liked).

a. longest gap  _____

b. long-to-medium gap  _____

c. medium gap  _____

d. medium-to-short gap _____

e. shortest gap _____

Why did you most prefer the gap setting which you ranked No.1 above?

In which gap setting(s) did you notice any difficulty in seeing enough of the road ahead to drive comfortably? You can select multiple choices for this question.

a. longest gap  _____

b. long-to-medium gap  _____

c. medium gap _____

d. medium-to-short gap _____

e. shortest gap _____

f. none _____

Position in Truck Platoon

Did you notice a difference between driving in the 2nd or 3rd position?

Yes No

If yes, what's the difference?

Did you have a preference for being in the 2nd or 3rd position?

a. Prefer 2nd position b. Prefer 3rd position c. No preference

If you choose a or b, please explain why you have such a preference.

What kind of information would you like to obtain from the lead truck and lead driver?

How do you like the lead truck to communicate information?

a. By audible voice communication from the driver b. By visual display

Under what conditions do you prefer to turn off the CACC and take over full control of the truck?

How effective was the display at informing you when CACC turned itself off?

Not at all 0 1 2 3 4 5 6 7 Very well

Response to Cut-in Vehicle

When a vehicle cut in between you and the truck ahead of you, how comfortable did you feel with the CACC system response?

Not comfortable at all 0 1 2 3 4 5 6 7 Very comfortable

How much did you trust the CACC system to ensure safety when a cut-in occurred ahead of you?

No trust at all 0 1 2 3 4 5 6 7 Completely trusted it

Driving on Upgrades and Downgrades

How reliably do you think the CACC worked when you drove on upgrades?

Not reliable at all 0 1 2 3 4 5 6 7 Extremely reliable

How reliably do you think the CACC worked when you drove on downgrades?

Not reliable at all 0 1 2 3 4 5 6 7 Extremely reliable

Overall Preference and Concern

Overall, what was your satisfaction with driving in a platoon using CACC?

Not satisfied at all 0 1 2 3 4 5 6 7 Extremely satisfied

How much do you need to trust other drivers in the platoon?

Very low trust 0 1 2 3 4 5 6 7 Very high trust

If you were regularly driving a truck with CACC, would that make the truck driver job more attractive to you? Please rate the change of job attractiveness.

Much less attractive -3 -2 -1 0 1 2 3 Much more attractive

After you got familiar with the CACC system, did you find that you were paying more or less attention to the driving task than your normal truck driving?

Much less attention -3 -2 -1 0 1 2 3 Much more attention

Do you have other potential concerns about using a CACC system on the highway? If so, please write them down.