A First Investigation of Truck Drivers' Preferences and Behaviors Using a Prototype Cooperative Adaptive Cruise Control System

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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 responses in following vehicles and shorter headways compared to Adaptive Cruise Control (ACC). This not only enhances road safety, but also offers fuel savings 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 driving preferences and behaviors when following in "CACC mode," an area that remains largely unexplored. While in CACC mode, the brake and throttle 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. "On-the-road" experiments were conducted by recruiting drivers from commercial fleets for the second and third trucks in a three-truck CACC string. The driving route spanned 160 miles on freeways in Northern California and 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 the drivers' opinions about use of CACC. The findings presented in this paper provide insights into the factors that will influence driver reactions to the deployment of CACC in their truck fleets.

Keywords: CACC, truck platooning, human factors, on-the-road experiment

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/throttle 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 mobility (*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 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 the ability of CACC to enable trucks to follow closely has been demonstrated (e.g., SARTRE, GCDC, European Truck Platooning Challenge), truck driver acceptance and preferences for CACC have not been investigated (*9*).

Understanding driver experiences from multiple perspectives, such as time gap preference, truck position preference, trust, and satisfaction, when operating CACC-equipped trucks on public roads in real traffic conditions is therefore extremely important. This paper presents a first investigation of driver experiences, preferences, and behaviors when driving trucks equipped with CACC. Several key aspects have been investigated –

1) Time-gap preferences;
2) Truck position in a CACC string;
3) Using CACC with cut-ins
4) Using CACC on road grades; and
5) Situations during which drivers reclaim full control of the trucks.

By having test drivers from commercial fleets operate CACC-equipped Class 8 Volvo tractors over 160 miles on public roads, we could document their experiences in a range of traffic conditions and road grades. While the drivers had the freedom to choose the time gap settings for automated 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. Although a wide range of data was collected, only the driver experience is reported in this paper. 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.

ON-THE-ROAD EXPERIMENTS

Participants

Nine professional fleet truck drivers from the U.S. (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*). Furthermore, fleet drivers only had very limited flexibility to participate in our study because their schedules were 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 with the assistance from our truck manufacturer partner and local trucking industry associations in California.

Trucks and CACC Control

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 DSRC.

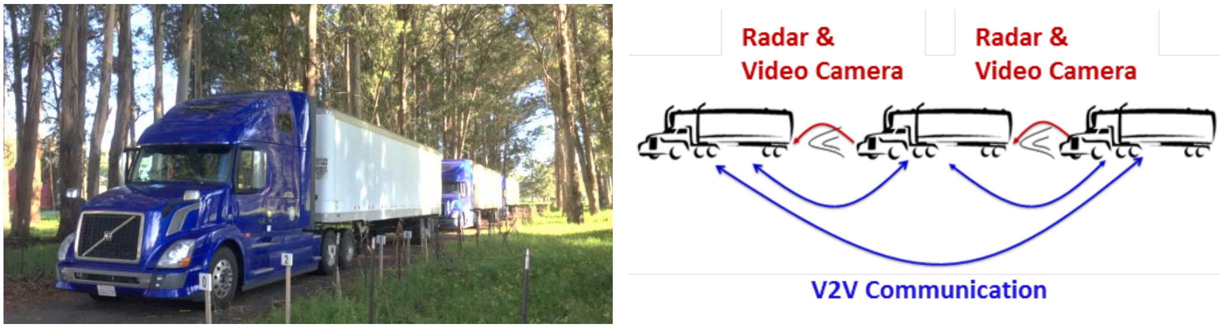


FIGURE 1 The Volvo Class 8 trucks (left) and the DSRC-based V2V communication system (right).

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 2 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 2 left). In addition to the control stalk, the brake pedal and the red safety button (see Figure 2 right) can be used to deactivate CACC.

FIGURE 2 The CACC control stalk (left) and truck cabin interior (right) with driver-vehicle interface (DVI) and safety disengage button.

Driver-Vehicle Interface (DVI)

The CACC DVI screen (shown in Figure 3) was redesigned in multiple iterations using QT (qt-opensource-windows-x86-msvc2015_64-5.7.1) based on field observation 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 other trucks in the CACC string and was used to control the time gap and driving mode (details in Table 1). The CACC interface was fitted on top of the truck instrument panel (see Figure 2 right).

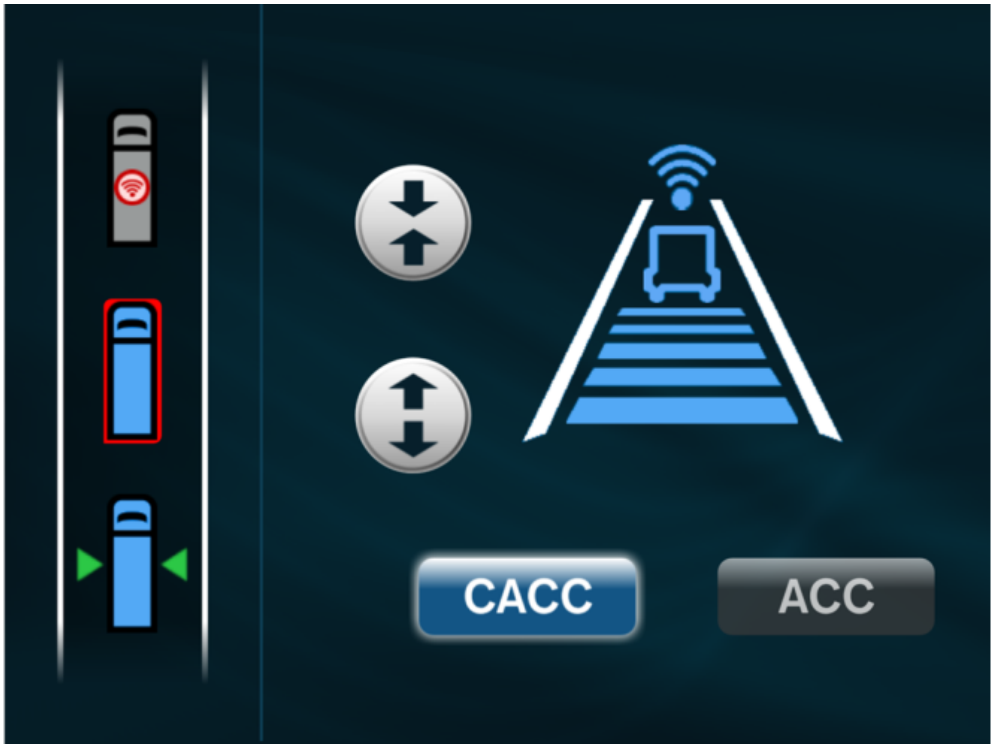
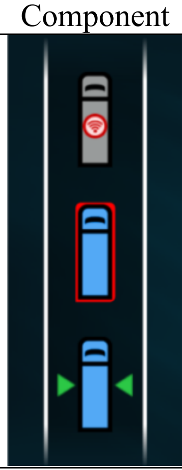
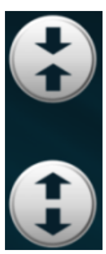


FIGURE 3 CACC driver-vehicle interface (DVI)

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 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.

Time Gap

Time gaps for CACC and ACC modes are listed in Table 2. The CACC time gaps are smaller than corresponding ACC time gaps because the vehicle-vehicle communication function included in the CACC enables the trucks to be driven safely and smoothly at significantly shorter following time gap (or clearance distance). 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 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 V2V communication signal is not available.

TABLE 2 Time Gaps and Corresponding Clearance Distances in CACC and ACC Modes

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

Driving Tasks

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 2 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 steep downgrades).

Testing 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.

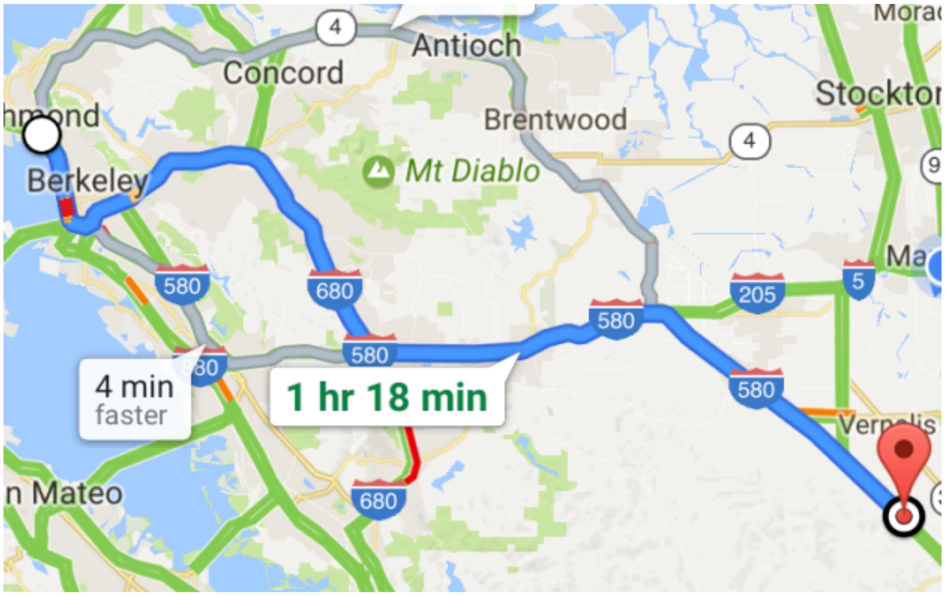


FIGURE 4 The testing route from RFS in Richmond to Westley.

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 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 (local time) to avoid the morning and afternoon peak congestion periods.

Experimental 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. 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. After the break, the driver of the second truck switched to the third truck and the driver of the third truck switched to the second truck, and then they drove back to RFS via the same route. After arriving at RFS, they finished the post-experiment debriefing questionnaire and were compensated for their time at $30 per hour, including the pre- and post-drive periods for briefings and filling out questionnaires.

Data Recording and Analysis

A PC-104 computer stored in a cabinet inside the truck cab was used to record the driver behavior data (around 100 columns) at a sampling rate of 50 Hz. However, those data are not reported in this paper because of the length limit. This paper only reports the driver experience data collected through the questionnaires. Friedman test and post hoc pairwise comparison on the time gap preference rankings were conducted using the software package R to find the most preferred time gap settings.

RESULTS AND DISCUSSION

The results reported in this section were obtained from the final debriefing questionnaire that all the drivers filled out. The participants are designated by labels P1 to P9 in which the letter "P" represents "Participant". The drivers' written answers in the tables in this section were processed by the experimenter to ensure their grammatical correctness and readability. In the questionnaires, a 7-point scale was used to quantify drivers' subjective reactions (e.g., familiarity, comfort, trust, and reliability) to each item, with 1 representing "not familiar/comfortable/trustable/reliable at all" and 7 representing "very familiar/comfortable/trustable/reliable", and with the other 5 levels evenly distributed between the two extremes.

Drivers' Demographics

The demographics of the drivers was collected by the background questionnaire and reported in Table 3.

TABLE 3 Demographics of the Recruited Drivers

Background Question	Mean (Std. Dev.)
Age	48 (13)
Gender	9 male, 0 female
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) Automatic
What fraction of your driving is short haul versus long haul?	66.1 (34.4) Short haul 33.9 (34.4) Long haul
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
How is your familiarity with Adaptive Cruise Control (ACC)?	1.4 (1.9) / 7
How is your familiarity with collision warning systems?	2.1 (2.0) / 7
How is your familiarity with driving in a truck platoon?	0.7 (2.0) / 7

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.

Time Gap Preference Ranking

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 ($\chi^2 = 10.1$, 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).

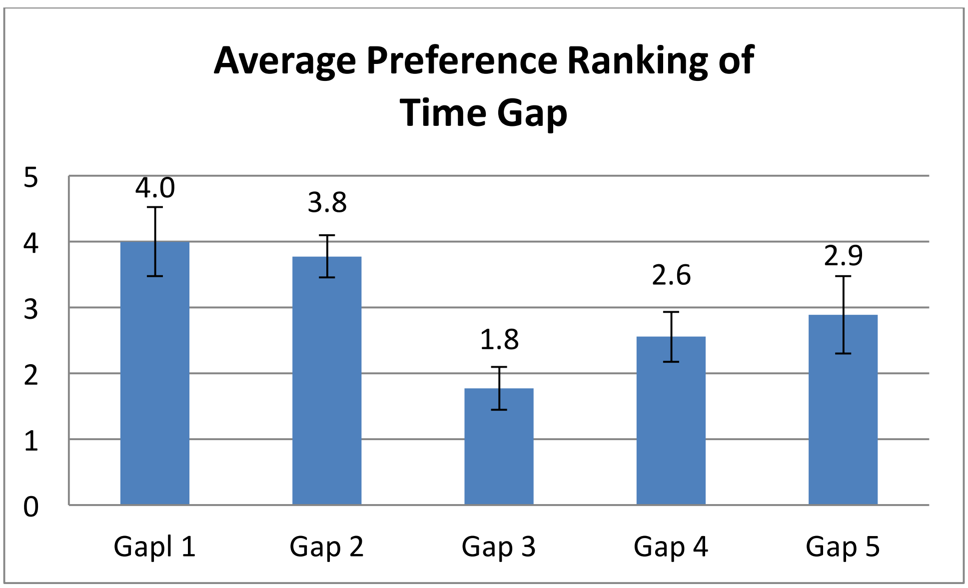


FIGURE 5 Average preference rankings of time gap at each setting. Smaller value indicates higher preference ranking.

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 compromise between their perceived driving safety/comfort and for deterring cut-ins by other vehicles.

Truck Position in the CACC String

Preference of drivers about their position in the string is described in Table 4. 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 the second truck had better braking performance than the third truck so that 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 4 Driving Experiences in Different Positions in the String

Question*	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 good 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)

*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.

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 cuts 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.

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.

TABLE 5 Experience of Using CACC in Different Driving Conditions

Category	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

Switching from Automation 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. Eight of the drivers reported deactivating the CACC system because of heavy (high density) traffic, which was by far the most significant cause of driver interventions. 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 (mentioned by four drivers) 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, and one driver reported deactivating the CACC for a highway merge. 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.

Limitations of Prototype CACC System

Keeping in mind that that CACC implementation was an advanced research prototype, there were limitations of the performance of the CACC system on the trucks. From driver experience of operating the system on public highways, a variety of concerns were reported. They are 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).

Overall Experience with CACC

On the 7-point scale used in the post-experiment questionnaire, the drivers reported their overall satisfaction with the CACC system (mean value of 5.6, with a standard deviation of 0.9). These results show that the drivers were satisfied with their truck driving experience with the driver assist capabilities of CACC. However, CACC failed to make the commercial vehicle operation job more attractive to them (rating for increasing attractiveness of truck driving job at a mean value of only 0.6 on the 7-point scale), which indicates that other factors, beyond automation technology, will have to change to increase job satisfaction. They also reported that it did not change their attention to the driving task in any significant way (mean value of 0.1 on the 7-point scale).

CONCLUSION

This paper presented a first human factors study on truck drivers' on-the-road experience of using CACC. Although the sample size was not ideally large, the findings of this study still illustrated important issues for drivers when they interacted with CACC and demonstrated the diversity of driver preference for CACC. A large sample size would provide higher statistical confidence in the results but would not be likely to change the findings in fundamental ways.

Our findings provide important insights into the acceptance of the technology at a higher level, as well as revealing preferences with respect to its usage (for example, gap settings, usage on road grades, etc.). It was evident that the test drivers did not prefer to drive too close (< 0.9 s) or far (1.8 s) behind the lead trucks, 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.

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". 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, the positive feedback from the drivers based on their experience driving on public roads in different traffic and road conditions inspire confidence for such advanced technologies in the trucking industry.

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