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Cooperative Adaptive Cruise Control:
Testing Drivers' Choices of Following Distances

PATH Research Report for
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Abstract

A Cooperative Adaptive Cruise Control (CACC) system has been developed by adding a wireless vehicle-vehicle communication system and new control logic to an existing commercially available adaptive cruise control (ACC) system. The CACC is intended to enhance the vehicle-following capabilities of ACC so that drivers will be comfortable using it at shorter vehicle-following gaps than ACC. This can offer a significant opportunity to increase traffic flow density and efficiency without compromising safety or expanding roadway infrastructure.

This report describes the design and implementation of the CACC system on two Infiniti FX-45 test vehicles, as well as the data acquisition system that has been installed to measure how drivers use the system, so that the impacts of such a system on highway traffic flow capacity and stability can be estimated. The results of quantitative performance testing of the CACC on a test track are presented, followed by the experimental protocol for on-road testing with human subjects. Finally, the results from the field testing by 16 naïve drivers are presented to show the user acceptance and quantitative measurements of how these drivers used the ACC and CACC systems, and how these systems affected their choice of car following gap.

Key Words: Adaptive Cruise Control, Cooperative Adaptive Cruise Control, Vehicle Following, Driver Behavior, Vehicle-Vehicle Communication

Executive Summary

This report provides documentation of the design and implementation of a Cooperative Adaptive Cruise Control (CACC) system on two Infiniti FX-45 vehicles that were provided to the project by Nissan Motor Company. The CACC system has been developed by adding a wireless vehicle-vehicle communication system and new control logic to an existing commercially available adaptive cruise control (ACC) system. The CACC is intended to enhance the vehicle-following capabilities of ACC so that drivers will be comfortable using it at shorter vehicle-following gaps than ACC, offering a significant opportunity to increase traffic flow density and efficiency without compromising safety or expanding roadway infrastructure.

The CACC concept is defined and described, and then the specific implementation for this project is described. The control logic of the CACC system is explained, and its implementation on the test vehicles is described. Quantitative measurements of the performance of the system in controlled tests at Nissan's Arizona proving ground are shown so that its advantages over conventional autonomous ACC can be understood. The enhanced performance makes it possible to operate the CACC at time gaps between 0.6 s and 1.1 s, compared to a range of 1.1 s to 2.2 s for the ACC. The shorter CACC gaps could enable significant highway capacity increases, while the longest CACC gap was set identical to the shortest ACC gap to provide a direct comparison.

Because the most important experiments involving these vehicles require measurements of the performance and behavior of drivers chosen from the general public, an important element of the project is a digital data acquisition system that records how the vehicles are driven. This system is used to record baseline driving data when the test drivers drive one of the vehicles as their regular personal car for two weeks, recording quantitative measurements of vehicle motions and driver actions, together with five channels of video data. When the same drivers drive the other vehicle using CACC during comparable test drives accompanied by a PATH researcher, the same measurements are recorded for comparison with the baseline driving. The design of the data acquisition system and the information that it records are described here for reference. The experimental protocol for the driver tests is explained and the questionnaires used to elicit the drivers' subjective reactions are presented.

The results of the field tests of 16 drivers drawn from the general public are presented. The demographic characteristics of this gender-balanced sample of drivers are explained, followed by the summaries of their subjective reactions and the objective measurements of how they used the ACC and CACC systems. The subjective reactions of the drivers were generally very positive, indicating a high likelihood of acceptance of the C/ACC systems, but without any indication of willingness to pay more for a vehicle equipped with one. The objective measurements showed that drivers of the CACC system selected vehicle-following gaps that were approximately half the length of the gaps they selected when driving the ACC system, and the latter gaps were comparable to today's vehicle-following gaps in congested highway driving. There was a significant gender difference in car-following gap selection, with the male drivers consistently choosing shorter gaps in both ACC and CACC (and to a lesser extent in baseline manual driving as well). The results indicate that drivers are likely to choose the shorter gaps enabled by CACC, thereby contributing to highway lane capacity increases.

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1 Introduction

This project is an element of PATH's research on methods for mitigating congestion via the application of Intelligent Transportation Systems. The first part of this research focused on the evaluation of the impact of Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) vehicles on traffic patterns via computer simulations [1, 2]. ACC systems are now commercially available on high-end vehicles. These systems enable the drivers to set a desired cruising speed as well as a desired following gap with respect to a lead vehicle. If no lead vehicle is present, then the system will regulate the vehicle speed, as any conventional cruise control does, but once a lead vehicle is detected, the system will adjust the vehicle's speed to maintain the gap set by the driver, with no intervention needed from the driver. The ACC functions with information it senses about the lead vehicle, and needs to sense a change in the lead vehicle's motion important enough to trigger a slowing down. Because of this delay in sensing a change in the vehicle following situation, there is a threshold for the minimum gap than can be technically achieved. On the other hand, a CACC benefits from the communication of information regarding the speed and brake actuation of the lead vehicle, which allows it to have faster responses, and therefore allows, from a technical point of view, a considerable reduction in the size of the gap that can be safely controlled by the system.

One of the primary questions raised during the simulation research relates to the size of car following gaps that drivers would be willing to use with comfort. This question led to the current research initiative, which includes three main thrusts: i) development, implementation and testing of the technical performance of a CACC; ii) data collection regarding its use by naïve drivers and analysis of those data; and iii) integration of the knowledge gained about driver use of the system into a traffic flow simulation. The CACC driver can choose a gap from 0.6 to 1.1 s, in contrast to the available ACC settings from 1.1 s to 2.2 s. The shorter CACC gaps could lead to a significant highway capacity increase, while the longest CACC gap provides a basis for direct comparison with the shortest available ACC gap.

This report describes the design and development of the Cooperative ACC system that was implemented by modifying the factory-installed ACC system on the (Nissan) Infiniti FX-45 vehicles and the data acquisition system that was added to the vehicles. It also includes the results of the testing of the technical performance of the system and the protocols for evaluation testing by naïve drivers. The report concludes with the results of the human factors experiments to learn about how drivers use the system and what they like or dislike about it.

2 Definitions of terms

Some of the important terms that will be used in the rest of this report include:

Adaptive cruise control (ACC) – 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) – an enhancement to ACC that enables more accurate gap control and operations at smaller gaps by adding communication of vehicle status information (primarily speed) from the preceding vehicle

DSRC – dedicated short-range communication, a wireless communication system that provides very reliable and low-latency communication of data between vehicles and the roadside or between vehicles and other vehicles (as it is used here)

ECM – electronic control module

Lidar – laser radar, a sensor that uses an infrared laser to measure the distance to the back of a preceding vehicle

Gap – the time between when the rear end of the lead vehicle and the front end of the following (ACC) vehicle pass the same location along the roadway. This is measured in terms of seconds. The distance corresponding to this gap is the clearance (the product of the time gap and the following vehicle speed).

This research focuses on the evaluation of drivers' comfort when following a lead vehicle at a short range controlled by an automation system. The vehicle that the observed drivers will be using is called the Subject Vehicle, or SV. As the prototype that is tested involves the presence of a specific vehicle as the predecessor of the SV, this vehicle is called the Lead Vehicle, or LV. Because the data collection protocol involves two distinct phases, we will further distinguish the names of the vehicles. In the first phase, the participant will be using a commercially available ACC in the silver-colored Infiniti FX45, while in the second phase the driver will be using a prototype CACC implemented in the copper-colored Infiniti FX45 (following the silver Infiniti, which will act as its lead vehicle, communicating data to it). The Principal Other Vehicle (POV) is the vehicle immediately ahead of the CACC lead vehicle during the CACC testing. The naming convention is illustrated in the two figures below.

ACC SV

ACC Lead

Figure 2.1: Vehicle naming convention for ACC system familiarization (Phase 1 testing)

Figure 2.2: Vehicle naming convention for CACC system testing (Phase 2 testing)

3 Cooperative Adaptive Cruise Control (CACC) System

The CACC prototype has been built on top of the commercially available ACC of the Infiniti FX 45. Only the CACC characteristics are presented in this report, as the commercially available ACC characteristics are the property of Nissan and were not developed under this project.

3.1 CACC concept

All production-level ACC systems are autonomous, which means that they can only obtain information about their distance and closing rate to the lead vehicle using their forward ranging sensors (typically radar or lidar). These sensors are subject to noise, interference and inaccuracies, which require that their outputs be filtered heavily before being used for control. That introduces response delays and limits the ability of the ACC to follow other vehicles accurately and respond quickly to speed changes of the other vehicles, which in turn limits the potential for ACC to contribute favorably to traffic flow capacity and stability. Augmenting the forward ranging sensor data with additional information communicated over a wireless data link from the preceding vehicle, (e.g., speed, acceleration, braking capability) makes it possible to overcome these limitations. Such a Cooperative ACC (CACC) system can be designed to follow the preceding vehicle with significantly higher accuracy and faster response to changes. This would in turn enable the regulation of shorter gaps than current systems can provide. From this perspective, CACC should be better able to dampen shock waves in the traffic stream.

However, the potential performance advantages cannot be realized in practice unless drivers are interested in acquiring and using the system. This is why the experiments with the drivers are important, to learn what they like and dislike about the cooperative ACC and which performance settings they prefer. If drivers like the shorter gap settings, CACC could produce significant improvements in lane capacity. However, if they do not find the shorter gaps acceptable these improvements will not be achievable.

3.2 System design

The primary elements of the CACC system, in addition to the underlying ACC system on which it is based, are the wireless system used for communication from the target vehicle to the subject vehicle, the CACC control system, which decides how to modify the driving commands issued to the vehicle's engine, transmission and brakes, and the driver interface, which is an expanded version of the ACC driver interface.

3.2.1 Communication System

Data are communicated from the CACC lead vehicle to the CACC subject vehicle using WAVE Radio Modules (WRMs) supplied by Denso (WAVE stands for Wireless Access in the Vehicular Environment). These use the IEEE 802.11p DSRC standard, but were developed and installed prior to the completion of the IEEE 1609 standards and therefore do not rely on those standards. The WRM radios are connected to antennas, which are temporarily mounted on the roofs of the test vehicles for the CACC testing.

3.2.2 CACC control system

3.2.2.1 CACC control implementation

Figure 3.1 shows the configuration of the ACC controller. The ACC sensor is a fixed five-beam LIDAR on the silver FX-45 and a scanning LIDAR on the copper FX-45, representing two different generations of the Nissan ACC product. The sensor provides measurements relative to the preceding vehicle such as distance and relative speed, which is sent to the ACC control unit through the CAN bus. Limited brake actuation (<0.3 g) is realized with a brake booster. A brake pressure sensor is installed to provide brake pressure information for fine brake control. The ACC control unit also sends CAN messages to actuate the engine through the engine ECM. The ACC controller is housed in the ACC control unit with a two-layer architecture. At low level, a speed servo controls the vehicle brake and engine so that vehicle speed will track the speed command V_{spc} generated by the upper level quickly and accurately. At the upper level, the ACC controller sends out appropriate speed commands based on the ACC sensor measurements so that a desired time gap to the preceding vehicle is maintained.

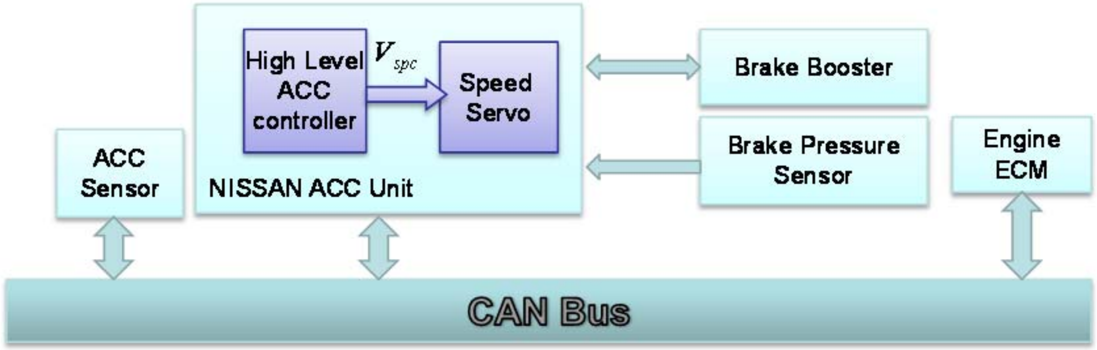


Figure 3.1: Configuration of Existing Nissan ACC Controller.

To develop a CACC control system, it is necessary for the prototype controller to have the capability to actuate the vehicle's brake and engine one way or another. Based on the existing ACC controller structure shown in Figure 3.1, this could potentially be accomplished in three different ways:

1. The prototype CACC controller directly actuates vehicle engine and brake (in this case, the brake booster). In this way, the prototype controller would have the full control authority for the vehicle longitudinal control purpose. However, actuating engine/brake directly would involve extensive modifications to the existing vehicle's hardware and software.

2. The prototype CACC controller sends out the same desired speed command as the higher level ACC controller. Although this would reduce the flexibility of the prototype controller design compared with the first option, the existing speed servo function could be utilized for the CACC controller design. Since the desired speed command is inside

the ACC control unit, substantial hardware/software modifications to the existing vehicle would still be required.

3. As shown in Figure 3.2, the ACC sensor sends the relative distance and speed of the preceding vehicle to the ACC control unit through the CAN bus. A simple way for implementing the cooperative vehicle longitudinal control is that the prototype CACC controller accepts the ACC sensor measurement information and sends out calculated virtual relative distance and speed to the ACC control unit instead. Although this includes the existing Nissan ACC controller in the loop and poses additional difficulties for the CACC controller design, it only requires minimum modifications to the existing Nissan software.

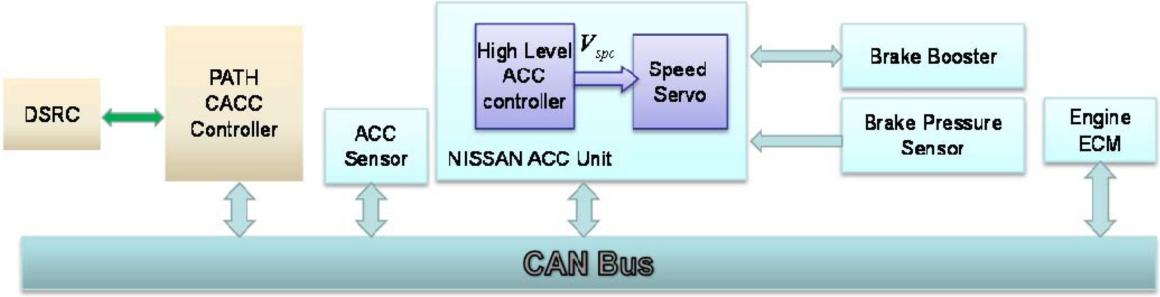


Figure 3.2: Add-on System Design for PATH CACC

Given the time frame of this project, the third option was chosen for the prototype CACC controller implementation. The configuration of the add-on system design for the prototype CACC is shown in Figure 3.2. With the CAN message definitions provided by Nissan, the prototype CACC controller can access the ACC sensor measurement and vehicle information such as wheel speed, gear position and engine RPM through the vehicle CAN bus. At the same time, the prototype CACC controller can also receive information about the preceding vehicle such as wheel speed, gear position, engine RPM, throttle pedal position and accelerator pedal position via DSRC wireless communication. A CACC control algorithm, which will be detailed in the following sections, calculates the virtual distance and relative speed command and sends it to the ACC control unit through the CAN bus.

3.2.2.2 CACC State Machine and CACC Vehicle Identification

Figure 3.3 illustrates the state machine for the prototype CACC controller. The nominal mode of CACC operation is gap regulation, but it is important to account for how this mode is initiated and terminated. The transition from conventional ACC operation to CACC gap regulation is accomplished through the target ID mode, which is needed to verify consistency between the ACC sensor data and the DSRC communication data. If the gap is larger than a suitable threshold for gap regulation, the gap closing mode is invoked.

Whenever there is a target change (e.g., a vehicle cuts in between the CACC and its lead vehicle), the prototype CACC controller retreats to the ACC mode by sending ACC sensor measurements directly to the ACC control unit. The following step is to identify if the preceding vehicle is the vehicle exchanging information through DSRC wireless communication. If the preceding vehicle is identified as one of the CACC vehicles, the gap between these two vehicles will be accessed. If the vehicle gap is too large, the PATH CACC controller will switch to gap closing mode until the vehicle gap is shortened below a predetermined threshold. The function of the gap regulation mode is to maintain the desired gap between the two vehicles.

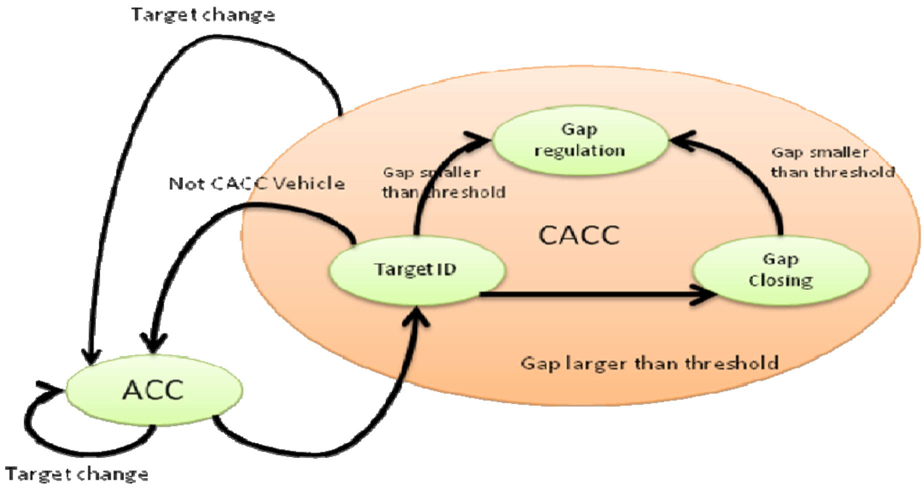


Figure 3.3: State Machine for PATH CACC Controller

Before using the information from DSRC wireless communication for CACC control purpose, we really need to identify if the ACC sensor target is the vehicle that is communicating through the DSRC wireless communication. This is the primary function of the target ID mode. This problem would be much more complicated if there were multiple vehicles with DSRC wireless communication around, but that is not being addressed in these experiments, which are focused on the human factors issues of driver use of the system. The complete target association problem will have to be addressed in future research before the CACC system can be commercialized. Since there will only be two DSRC equipped vehicles during our testing, a simple method is adopted for the target ID purpose. Figure 3.4 shows the comparison of relative speed output between the ACC sensor and DSRC when the ACC sensor target is the DSRC vehicle. The ACC sensor output follows the DSRC output with about 0.5 sec time delay. This characteristic is used to confirm the target ID.

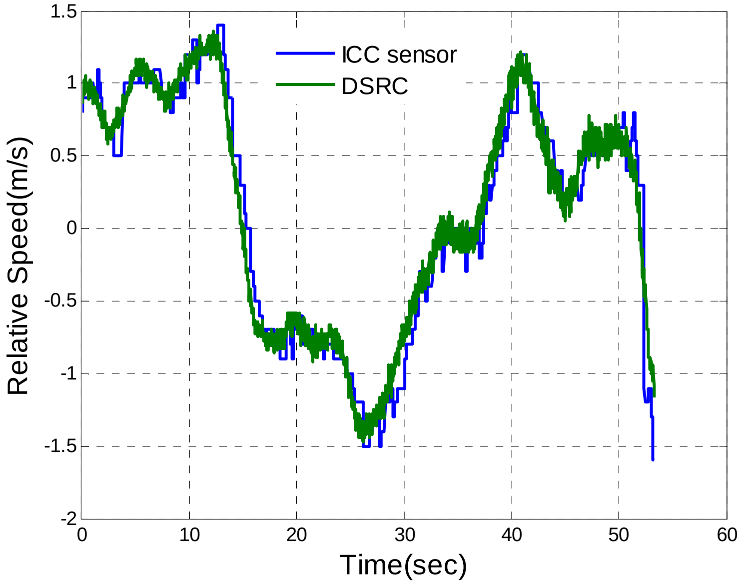


Figure 3.4: Comparison of relative speed output between ACC sensor and DSRC

3.2.2.3 CACC Controller Structures and Enhanced Speed Servo Loop

Figure 3.5 and Figure 3.6 show the controller structures for the CACC gap closing controller and CACC gap regulation controller. One of the important components of the prototype CACC controller is the enhanced speed servo. As mentioned in the previous section, the actuation of the existing engine/brake is implemented by sending virtual relative distance/speed commands to the ACC control unit through the CAN bus. To fully utilize the existing ACC controller and simplify CACC controller design, the enhanced speed servo is designed to maintain the vehicle speed according to the desired speed command from the higher level controllers (e.g., speed trajectory planning for the prototype CACC gap closing controller). In the implementation, the virtual relative distance command is always kept at the desired time gap and the virtual relative speed command is used as the control input. After extensive frequency response testing, the enhanced speed servo loop was designed using the loop shaping method. This controller structure is very similar to the successful existing ACC controller.

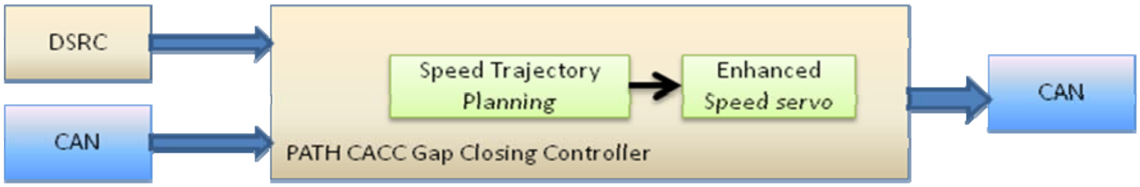


Figure 3.5: PATH CACC Gap Closing Controller

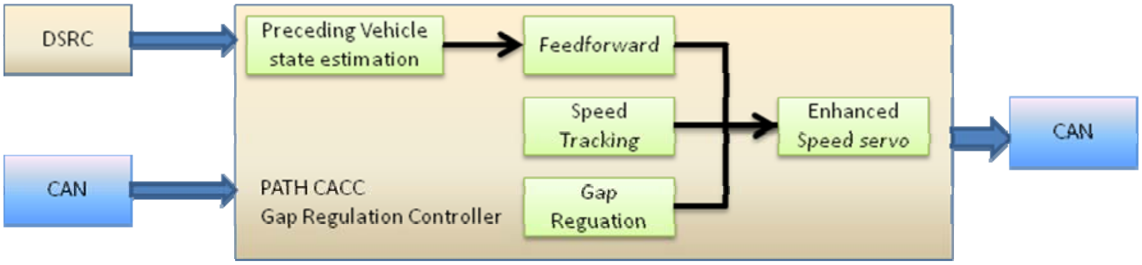


Figure 3.6: PATH CACC Gap Regulation Controller

3.2.2.4 CACC Gap Closing Controller Design

When the relative distance between two vehicles is much larger than the desired time gap, controller saturation will occur if the high-gain gap regulation controller is engaged immediately. Such controller saturation will generate an oscillating response and make the driver uncomfortable. One way to resolve this problem is to introduce controller switching. The CACC gap closing controller will be engaged before the relative distance reaches a predetermined threshold value. The CACC gap closing controller is a "semi" open loop controller. A trapezoidal relative speed trajectory is planned with respect to relative distance as shown in Figure 3.7. All the parameters (e.g. Δv) can be tuned to provide different driver comfort levels.

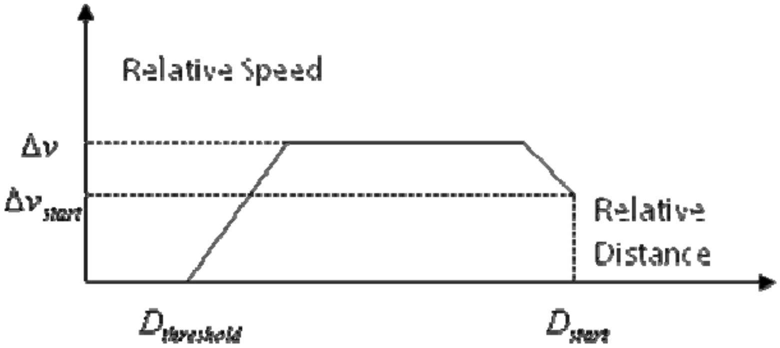


Figure 3.7: Trajectory Planning for CACC Gap Closing Controller

3.2.2.5 CACC Gap Regulation Controller Design

When the distance between two vehicles is reduced below a certain threshold by the CACC gap closing controller or when the distance between two vehicles is already below that threshold, the CACC gap regulation controller is engaged to maintain a desired time gap between two vehicles. As shown in Figure 3.6 the CACC gap regulation controller consists of preceding vehicle state estimation, speed tracking and gap regulation.

Lead Vehicle State Estimation and Feedforward

One of the advantages of CACC is that lead vehicle information such as throttle pedal position, brake pedal position, gear position and engine RPM can be transmitted to the following subject vehicle through DSRC wireless communication. Such information is related to the specific vehicle and cannot be used in the CACC controller design directly. The function of lead vehicle state estimation is to assess the lead vehicle motion states. In the prototype CACC controller design, lead vehicle acceleration is estimated and used in the feedforward control part.

Speed Tracking

The speed tracking module is designed to provide fast response to the speed changes of the lead vehicle. In the CACC controller, a bandpass filter is used for speed tracking. It has low gain at low frequency, high gain from 1 Hz to 5 Hz and 40 db roll-off above 5 Hz.

Gap Regulation

The gap regulation controller is a high gain linear controller designed with the loop shaping method.

3.2.2.6 Proving ground test results

To fine tune the control design and controller parameters, two testing trips were made to the Nissan Arizona vehicle proving ground. At the end of the second field trip, a series of scenarios was performed to test the performance of the final controller under a range of representative driving conditions:

- change of time gap setting while CACC car is approaching the leading car
- leading car brakes moderately while CACC car is approaching it and closing the gap
- leading car does repeated accelerate and decelerate maneuvers while CACC car follows it
- a manually-driven POV does repeated accelerate and decelerate maneuvers, followed by the ACC car acting as the leading car for the CACC car, following in sequence.

Figure 3.8 – Figure 3.10 show performance in the scenario when the CACC car is approaching the leading car, and the time gap setting is changed from 1.1 sec to 0.9 sec. Smooth action is taken by the CACC car to approach the leading car and the time gap is then well regulated at 0.9 sec.

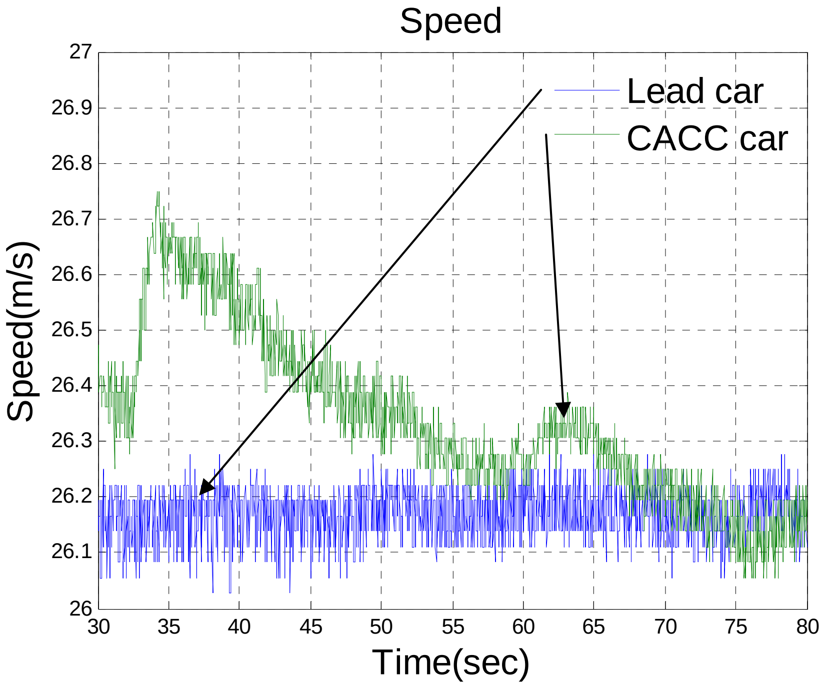


Figure 3.8: Proving ground test: steady state speed performance

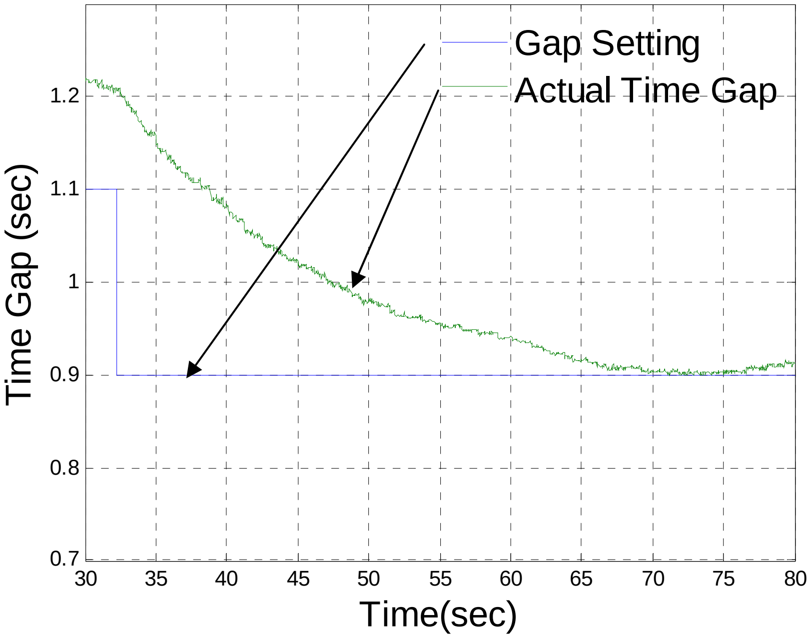


Figure 3.9: Proving Ground Test: steady state time gap performance

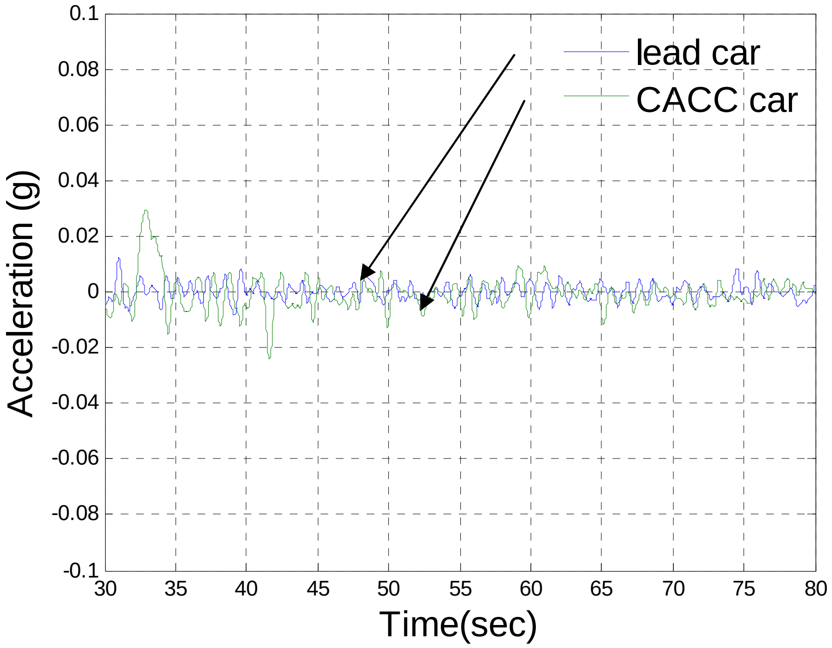


Figure 3.10: Proving Ground Test: steady state acceleration performance

Figure 3.11 – Figure 3.14 show the scenario when the leading car brakes at about 0.16 g while the CACC car approaches. With the feedforward information from the wireless communication, the CACC controller reacts very quickly, as can be seen in both Figure 3.13 and Figure 3.14. Therefore, the CACC car can always follow the speed of the leading car and regulate the time gap at the desired time gap setting at the end.

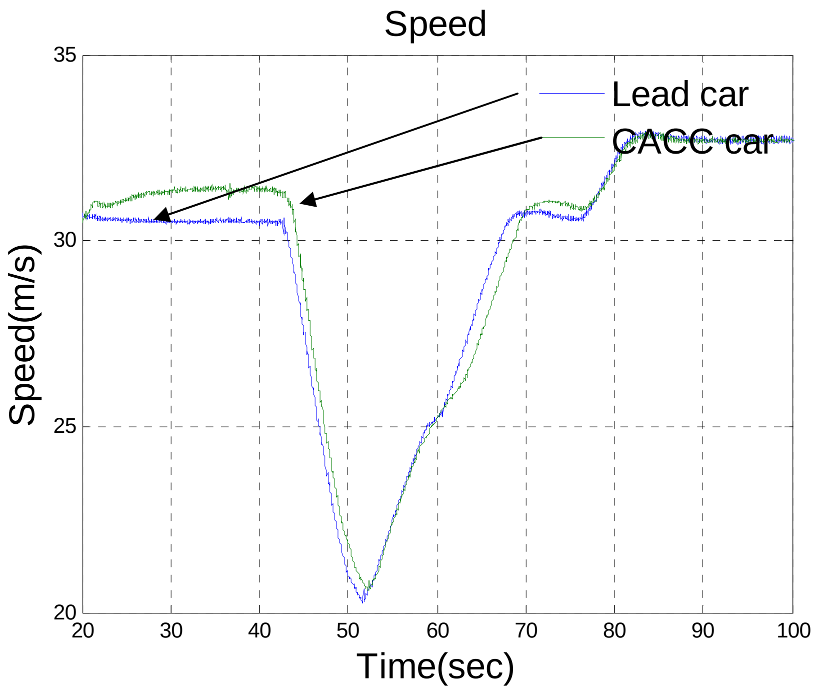


Figure 3.11: Speed response when leading car brakes while CACC car is approaching

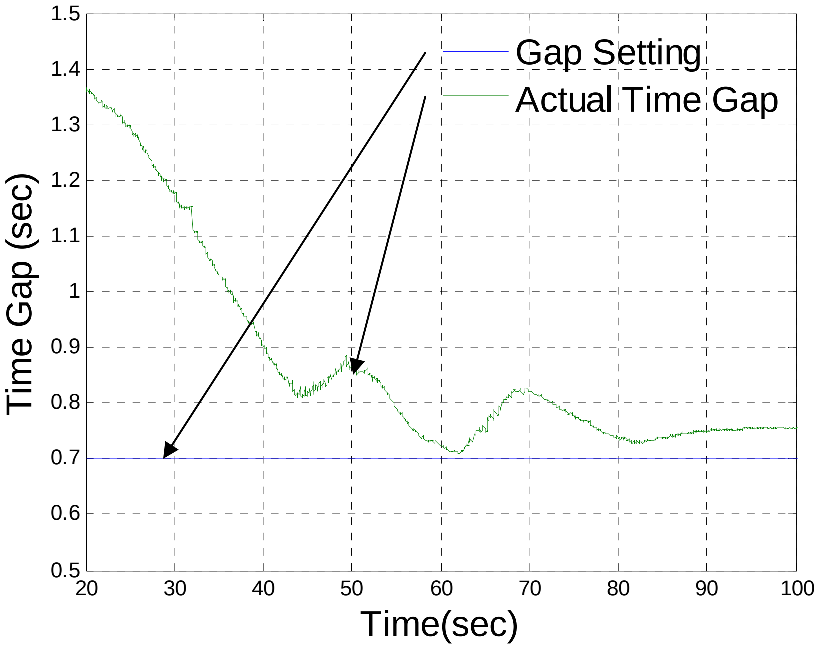


Figure 3.12: Time gap response when leading car brakes while CACC car is approaching

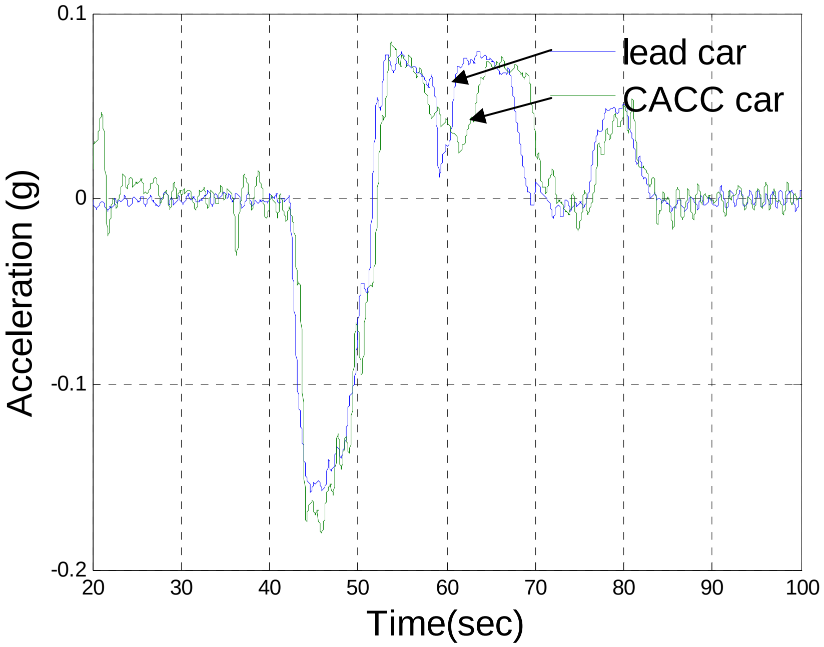


Figure 3.13: Acceleration response when leading car brakes while CACC car is approaching

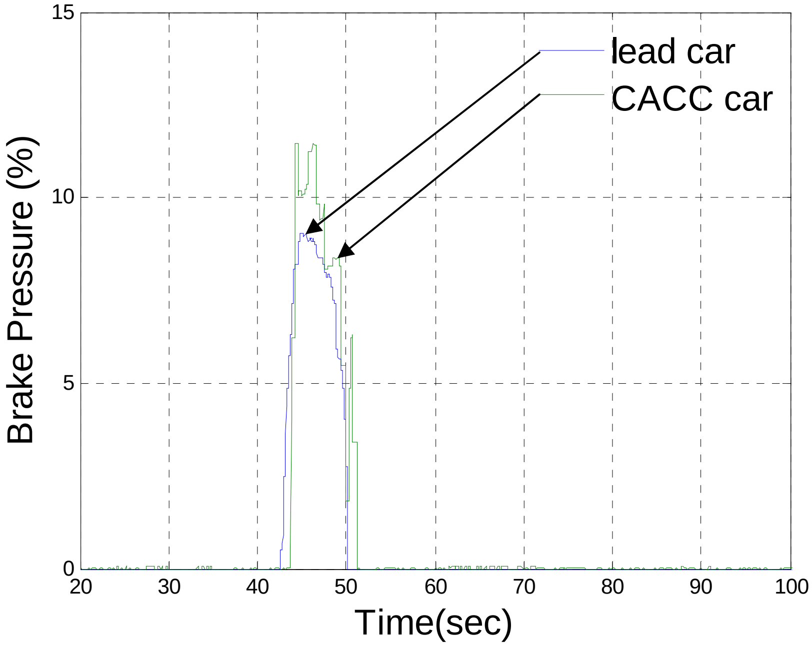


Figure 3.14: Brake pressure response when leading car brakes while CACC car is approaching

To further illustrate the advantages of the feedforward information from wireless communication, Figure 3.15 – Figure 3.18 show the scenario that the leading car makes repeated braking and acceleration transients. The largest magnitude of braking is around 0.25 g, which is close to the maximum capability of the brake actuator. As shown in Figure 3.15, the CACC car is always able to track the leading car's velocity, even with this aggressive braking. Figure 3.17 and Figure 3.18 also show that the CACC car brakes almost immediately following the lead car's braking.

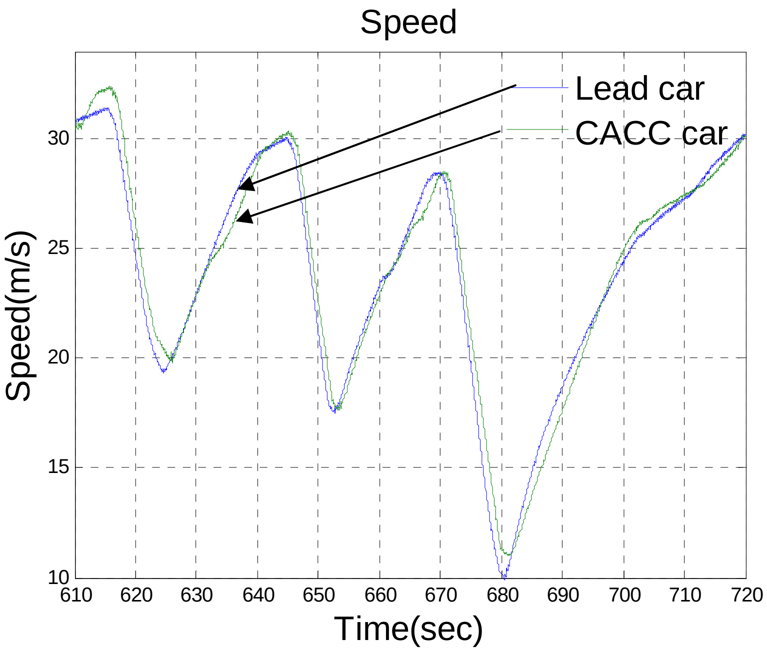


Figure 3.15: Speed profiles when leading car brakes and accelerates repeatedly

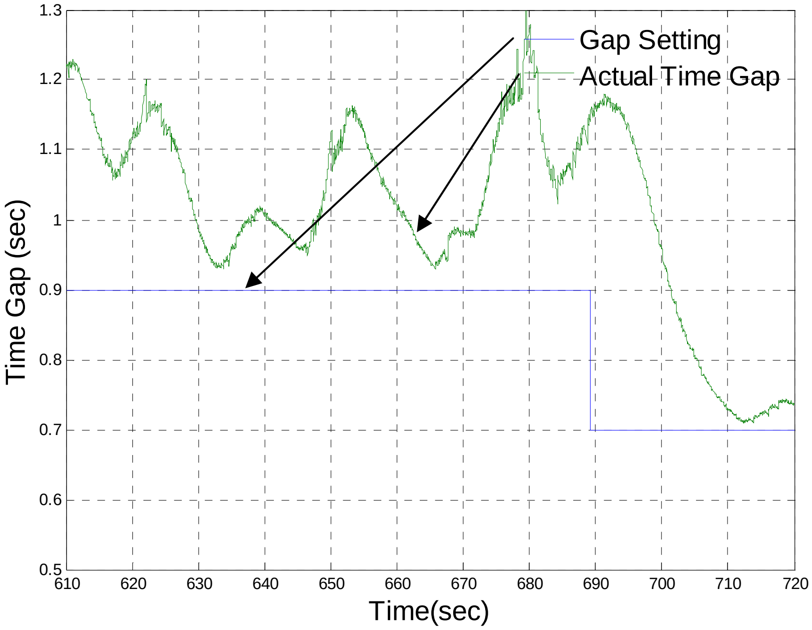


Figure 3.16: Time gap profiles when leading car brakes and accelerates repeatedly

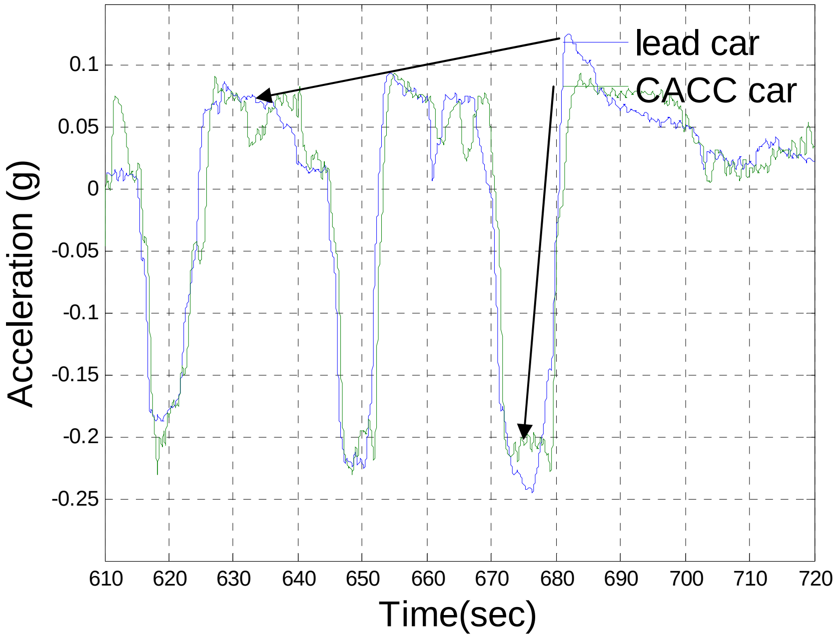


Figure 3.17: Acceleration profiles when leading car brakes and accelerates repeatedly

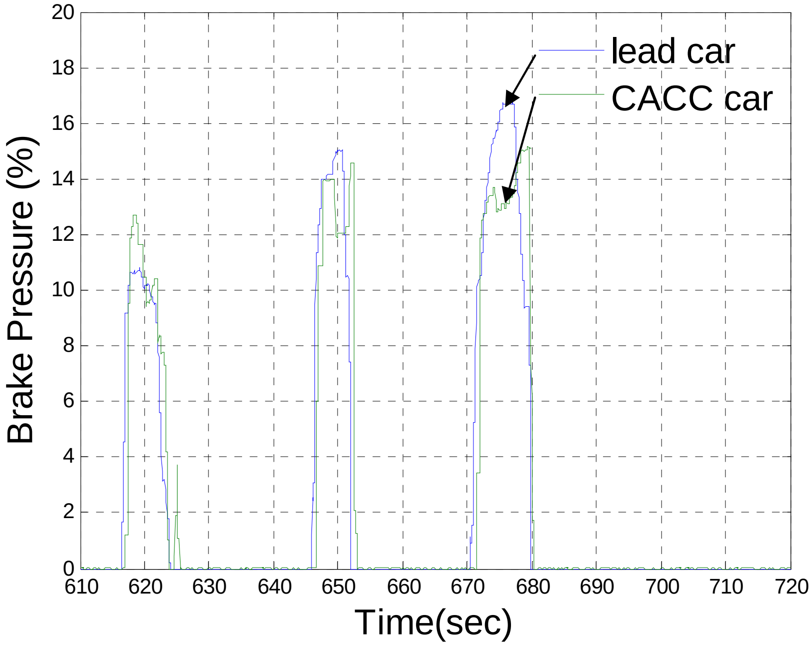


Figure 3.18: Brake pressure profiles when leading car brakes and accelerates repeatedly

At the end of the performance testing, a three car platoon scenario was conducted to test the string stability effect and compare the performance between the conventional autonomous ACC controller and the CACC controller. A manually driven Infiniti G35 led the platoon and the silver Infiniti FX45 followed it with the factory ACC controller turned on. The copper Infiniti FX45 followed the silver one with the PATH CACC controller turned on. The G35 made repeated aggressive braking and acceleration maneuvers. As shown in Figure 3.19, the autonomous ACC equipped silver FX45 tracked the leading car's speed with a much larger time lag compared with the CACC equipped copper FX45's tracking of the silver FX45. Therefore, a large variation of time gap regulation is shown in Figure 3.20 for the autonomous ACC equipped silver FX45. More importantly, the amplification of the time gap variations for the autonomous ACC shows a potential loss of string stability, which is compensated successfully by the cooperative ACC's enhanced vehicle following capability.

Figure 3.21 shows how the acceleration transients of the lead car are attenuated by the ACC car following it, while the CACC car is able to keep the acceleration transients at a similarly attenuated level, smoothing the ride for the vehicle occupants. Similarly, Figure 3.22 shows how the brake pressure transient for the CACC car is attenuated from that for the preceding ACC car. This attenuation is only possible because of the use of the vehicle-vehicle communication of the CACC system; in its absence these transients would have been amplified.

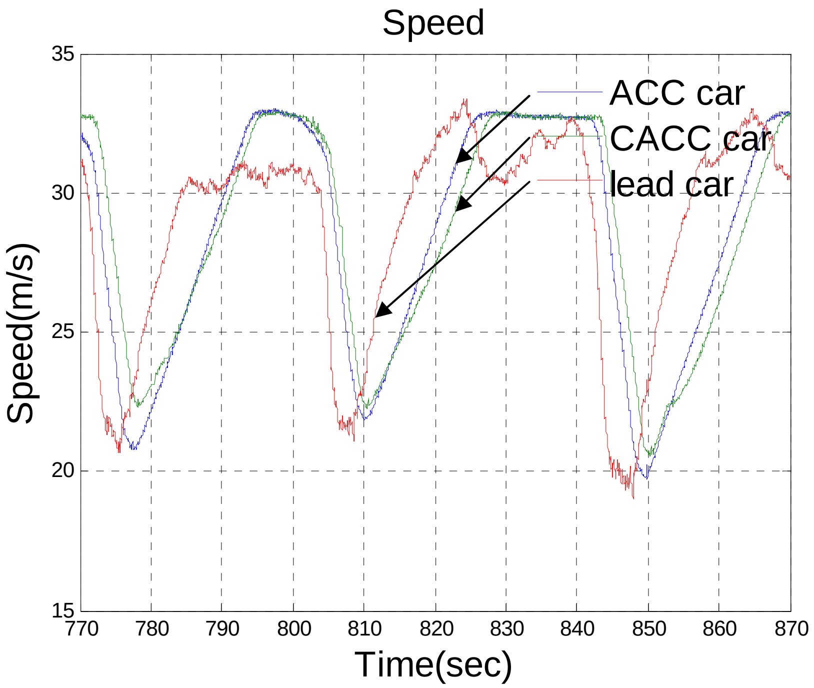


Figure 3.19: Three car platoon test – speed profiles

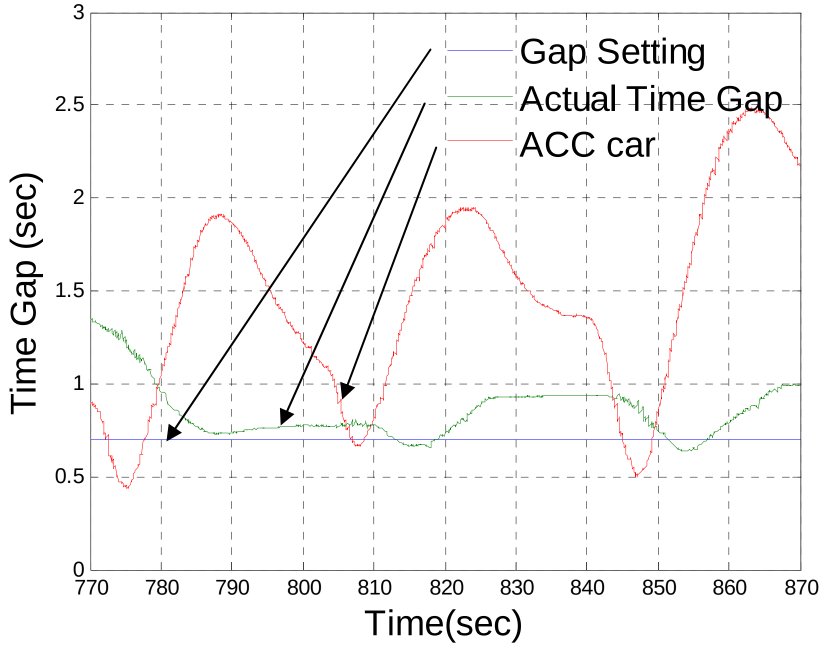


Figure 3.20: Three car platoon test – time gaps

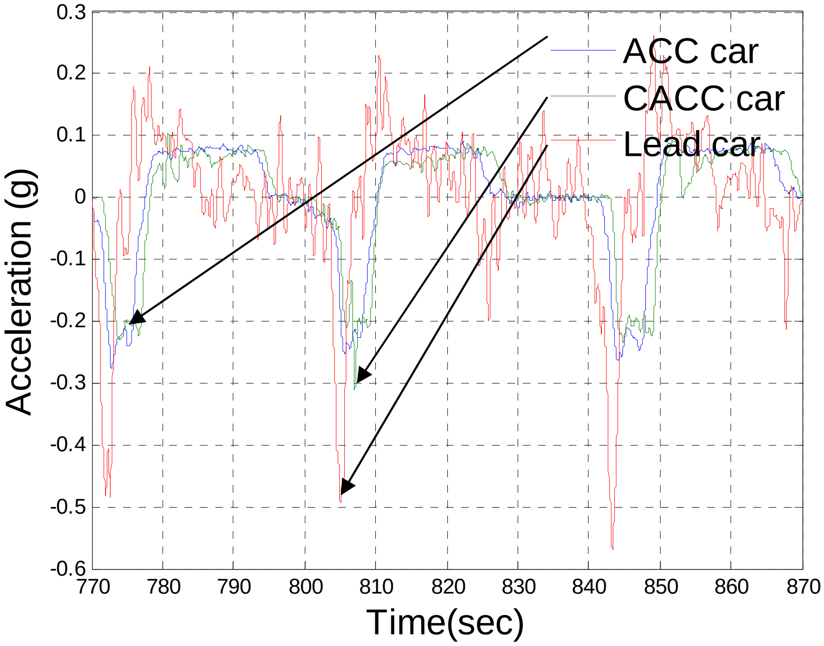


Figure 3.21: Three car platoon test - accelerations

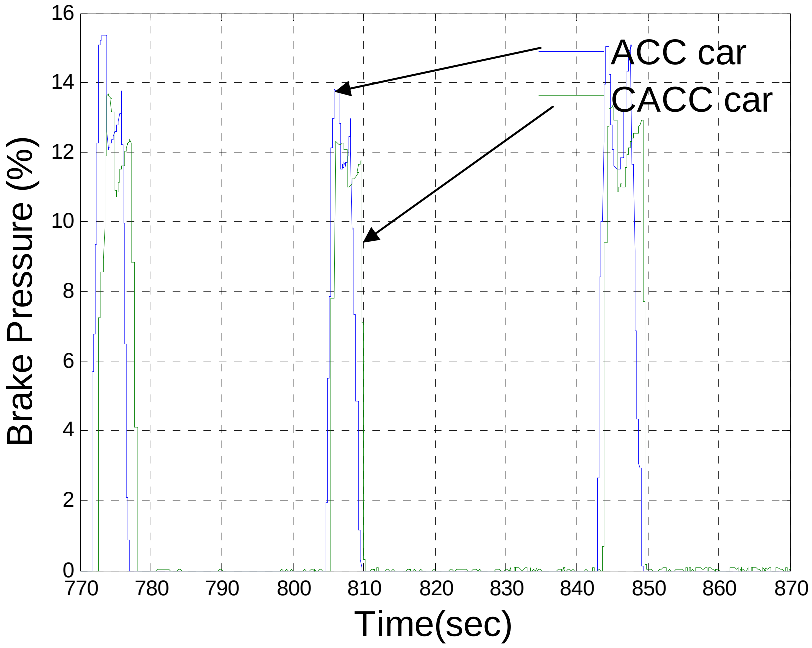


Figure 3.22: Three car platoon test – brake pressure

3.2.3 Driver Vehicle Interface

The Driver-Vehicle Interface (DVI) for the CACC was based on the original DVI for the Infiniti ACC. Ideally, there should have been no change in the CACC DVI; however, the standard dashboard display provided in the Infiniti vehicles could not be modified to support displaying all of the gap settings that would be available during the CACC testing. This necessitated that an additional LCD display be mounted in the CACC test vehicle to show the correct current gap setting. Both the ACC and CACC DVIs are explained in the subsequent sections.

3.2.3.1 ACC Driver-Vehicle Interface

The ACC DVI consists of a set of 4 buttons located on the right side of the steering wheel and two visual displays located on the dashboard. Figure 3.23 and Figure 3.24 depict the dashboard displays and the steering wheel controls. The main ACC display is located at the bottom of the tachometer dial on the instrument panel, adjacent to the transmission gear indicator, as shown in Figure 3.24. This picture shows how the display looks when the ACC has first been activated, but the set speed has not yet been selected. Additionally, the vehicle is not moving fast enough for a lead vehicle to be detected and indicated.

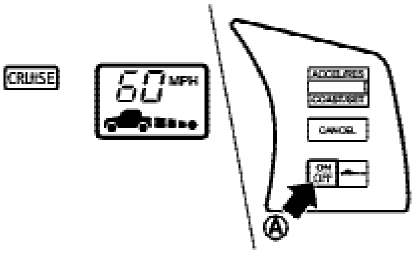


Figure 3.23: ACC display and controls as illustrated in vehicle owner's manual

Figure 3.24: ACC displays (left) and controls (right)

The first visual display is the "CRUISE" indicator light, located along the left side of the instrument cluster, which is activated with a green background when the on/off switch is pushed down. In case of system malfunction, this display background turns to orange. This light only indicates that the cruise control system has been turned on, and not that it is currently active and controlling the vehicle speed.

The second, and main, ACC display is located within the tachometer to the left of the current gear indication ("P" in Figure 3.24). This display shows the current ACC set speed (for example, 60 mph in Figure 3.23). The display also shows the current gap setting. Each square between the vehicle and dot represents an increasing gap setting. If all squares are visible, the longest gap has been selected. When the shortest gap has been selected, only the square closest to the dot is present. Finally, this display indicates whether or not a lead vehicle has been detected by the system. If no lead vehicle has been detected, there is no car icon to the left of the current gap setting (as shown in Figure 3.24). If a lead vehicle has been detected, there is a car icon to the left of the current gap setting (as shown in Figure 3.23).

The driver controls the ACC with four buttons. The ACC is activated by the driver pushing the "on/off" button (the left side of the middle button on the steering wheel), as shown in Figure 3.23 and Figure 3.24. The set speed is selected by toggling the top button down, and then toggling it up or down to increase or decrease the set speed. Short toggles produce changes of 1 mph in set speed, while holding the button in the up or down position for about one second produces a change of 5 mph in the corresponding direction. The bottom button ("Cancel") is used to interrupt the ACC action at any time the user chooses, analogous to hitting the brake pedal, but retaining the set speed value for the next time the system action is resumed by toggling the top button up.

3.2.3.2 CACC Driver-Vehicle Interface

From a driver's perspective, the CACC operation is identical to that of the original factory-installed ACC. Therefore, the existing ACC driver interface (described above) has been adapted for the CACC with minor changes on the display. The primary differences between the two systems lie in the number of available gap settings and the location of the display. On the copper-colored FX-45, which is used for the CACC driving experiments, this display is located on an additional larger LCD screen, mounted to the right of the steering wheel as shown in Figure 3.25. This display was provided for experimental convenience and will not be a topic for evaluation in the experiments.

This display allows both the driver and the experimenter to see the CACC system status and current gap settings during the experiment. One additional icon was added to the CACC display, resembling a radio transmitter icon. The presence or absence of this icon indicates whether or not the vehicle-vehicle communication is operational.

Figure 3.25: CACC display (right of steering wheel)

Note that in Figure 3.25 there is also a small video camera mounted by this display, pointed at the driver's face. This camera is used to verify that the correct person is driving the vehicle, and that it has not been driven by an unauthorized driver who is not part of the experiment. (See the DAS section of this report for more details on data collection setup.)

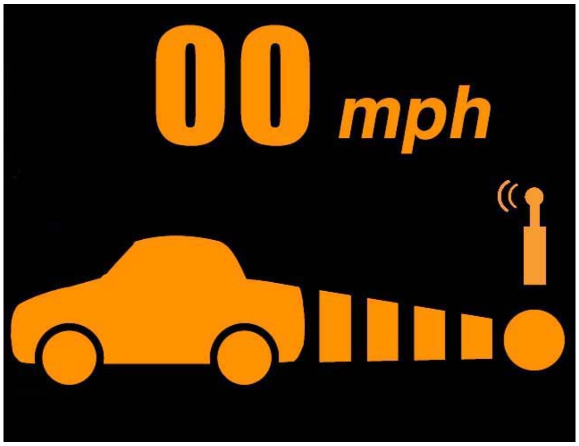


Figure 3.26: CACC Driver Vehicle Interface

Figure 3.26 shows a close-up of the CACC display with the set speed indication and lead vehicle icon (indicating that the system has identified the lead vehicle for possible following). The four bars behind the lead vehicle icon indicate that the driver has selected the largest following gap setting. As the driver toggles the gap setting switch (the right side of the middle button shown in Figure 3.24), this cycles through the three shorter gap settings in sequence, until only one bar remains. If the driver toggles it again, the system switches back to the longest gap setting. The CACC time gap settings are 1.1, 0.9, 0.7 and 0.6 seconds (compared to 2.2, 1.6 and 1.1 seconds for the ACC on these vehicles).

4 Data Acquisition System (DAS)

An identical data acquisition system is installed on both vehicles. The silver ACC vehicle will be used for establishing a baseline; i.e., observing the driver's following behavior without the use of any system, and also to collect data during the ACC familiarization. The test of CACC driving will be conducted with the participant driving the copper vehicle. The data collected on each vehicle will provide the opportunity to compute the parameters classically used for describing driver behavior, such as time gap or time to collision, describe the participant's control of the vehicle with either system, and characterize some of the driving environment conditions, making it possible to compare the driver behavior with the systems and the use of each system.

The data acquisition system records a variety of engineering variables to characterize the motions of the vehicles, the driver actions, and the functioning of the ACC and CACC systems. In addition, it records two channels of video data to provide additional information about the driving environment (forward and rear driving scenes, especially for cut-in and cut-out maneuvers that may be difficult to interpret from the lidar data) and three to record the driver's actions (four views are grouped on a four to one video splitter: use of pedals, hand motions for adjustment of speed and gap settings, driver's face for ensuring that the driver is indeed the experiment participant, and rear view of the traffic).

4.1 DAS Hardware

For each of the vehicles, the DAS package contains the following equipment:

- Video computer (PC 104 –Linux)
  - 5 video cameras
  - One "four-to-one" video splitter
  - 2 titlers (Horita)
- Engineering data computer (PC 104), connected to the C/ACC system computers to provide data about the vehicle controls use (e.g. steering wheel, pedals), system uses (C/ACC on/off, gap selected) and dynamics (speed, yaw rate)
- Accelerometer: longitudinal and lateral acceleration
- DGPS: latitude, longitude and UTC

The DAS is shown in Figure 4.1, which illustrates the connection between the ACC and CACC computers with the engineering computer already interfaced with the CAN bus. (See Figure 3.2.)

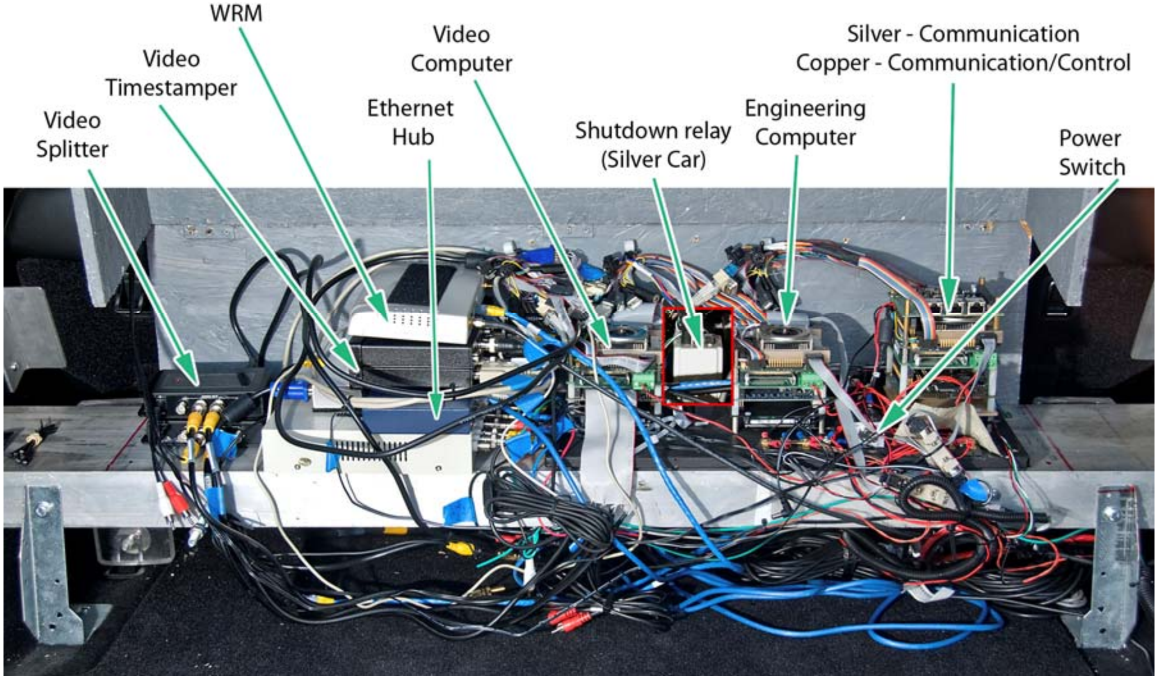


Figure 4.1: C/ACC DAS and Engineering Computer

Figure 4.2 shows the computer installation with the cover closed, as it will be seen by the test participants. The closed cover protects the equipment and leaves the participants with trunk space behind it for storing goods that they need to transport.

Figure 4.2: Computer enclosure in luggage compartment behind rear seat of vehicle, with cover closed.

The DGPS system is used to provide continuous information about the location of the vehicle and the accurate time reference. It receives satellite signals from an antenna mounted on the roof of the vehicle, adjacent to the additional antenna used to receive the vehicle-vehicle DSRC communications, as shown in Figure 4.3.

Figure 4.3: DGPS Antenna (left) and DSRC Communication Antenna (right)

The locations of the video cameras in the front portion of the vehicle interior are shown in Figure 4.4. An additional video camera is mounted in the rear window of the vehicle, facing back, to capture images of the traffic scene behind the vehicle.

Figure 4.4: Vehicle Interior, Showing Locations of Video Cameras

4.2 DAS Software

The software architecture on the vehicles consists of a set of processes running on PC-104 computers and communicating through the *Publish/Subscribe database*. The software is written in C or C++ and runs either on the QNX 6.2 (engineering computer) or 6.3 (Communication and control computer) real-time operating system and Linux (video computer). Specific details of the software architecture, such a listing of processes and diagrams of how they interact, can be found in Appendix A, while a higher level description of the data flows can be found in Figure 4.5 and Figure 4.6. Figure 4.5 describes the data flow in the Silver Infiniti FX45 which only has the factory ACC enabled for vehicle control, but also serves as the lead vehicle for CACC testing. Figure 4.6 describes the data flow in the Copper Infiniti FX45 which has the CACC system enabled.

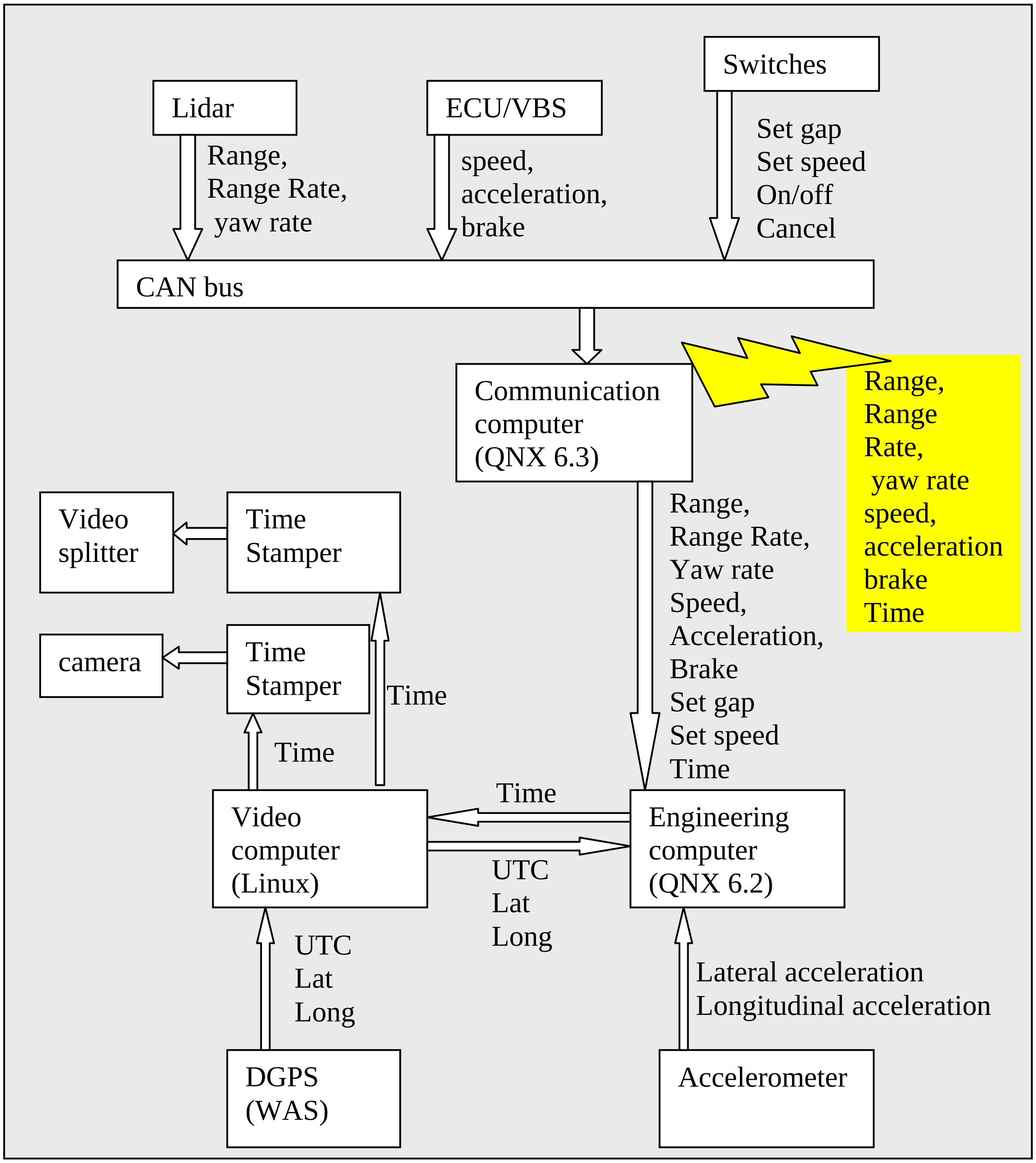


Figure 4.5: DAS Data Flow for Silver FX45 (ACC or lead vehicle for CACC)

The yellow boxes in Figure 4.5 and Figure 4.6 contain the information that is sent from the silver ACC vehicle to the copper CACC vehicle from the Communication Computers. The silver lead vehicle logs the information that it sends to the copper CACC equipped vehicle while the copper CACC vehicle logs the information that it receives from the silver lead vehicle.

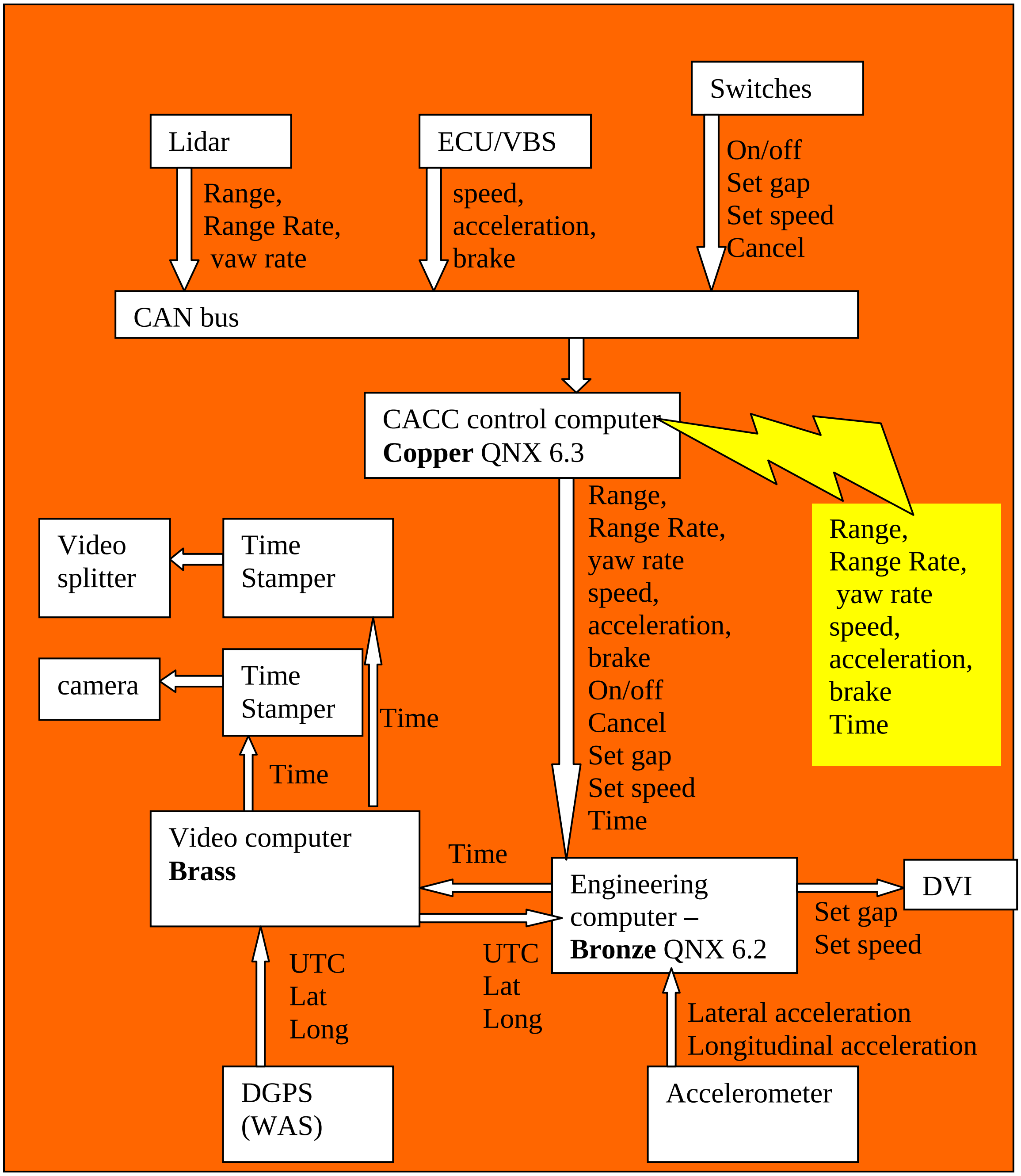


Figure 4.6: DAS Data flow for Copper (CACC) Vehicle

5 Data Collection, Processing, and Reduction

Two types of data files were generated by the ACC and CACC vehicle Data Acquisition Systems (DAS). First, the vehicles generated engineering files, collected and stored on the engineering computer installed each vehicle. Second, the vehicles generated two digital video files from the five onboard cameras, which were stored on a separate video collection computer. Additionally, two paper questionnaires were also administered during the experiment regarding driving practice and ACC/CACC usage.

5.1 Engineering and Video Files Created by the DAS

5.1.1 Engineering files

The engineering files are essentially text files containing rows and columns of numeric vehicle data such as speed, distance, latitude, longitude, etc. Data were recorded every 50 ms (20 Hz sampling rate) and the files were saved every two minutes. Three types of engineering files were recorded by the DAS and their contents are described in Table 5.1 to Table 5.3. Although it may seem trivial, much effort was put into creating a file naming method that would insure that each file contained a unique name, thus avoiding any potential to accidentally overwrite data when they are copied or moved. The engineering filenames were constructed using the following convention:

[V][F][MMDD][TTTT][SSS].dat

Where:

- [V] is a single character representing the vehicle on which the data are collected:
    'c' is used for data from the copper car, equipped with the CACC prototype
    's' is used for data from the silver car, with the commercial ACC
- [F] is a single character representing the type of data that will be contained within the file:
    'a' is used for C/ACC data
    'c' is used for communication from the lead vehicle data
    'd' is used for driver behavior and target data
- [MMDD] is the date with 2 characters for month and 2 characters for the day of the month
- [TTTT] is a 4-digit Trip ID number which is incremented each time the vehicle is started
- [SSS] is a 3-digit sequence number which starts at 000 and increments every 2 minutes

When the engineering files are downloaded from the vehicle, they are grouped into the concept of a trip, where a trip corresponds to each time the vehicle ignition was switched on. The files are copied into a single trip directory which is named using the following convention:

e[YYMMDD][TTTT]

where:

- 'e' is the indication that the directory contains engineering (instead of video) data
- [YYMMDD] is the trip date with 2 digits representing year, month, and day
- [TTTT] is a 4-digit Trip ID which matches the trip ID number of the enclosed files

Table 5.1: Contents of the 'a' File (CACC Data)

Column		Description	Unit/Range
1	A	Time of day this entry was recorded	hh:mm:ss.sss
2	B	Number of seconds since start of process	sec
3	C	Virtual pedal position (from driver, ACC or CACC)	percent
4	D	Engine RPM	rpm
5	E	Mean effective torque	Nm
6	F	During shift (no/yes)	0/1
7	G	Current gear	0-7
8	H	Front right wheel speed	rpm
9	I	Brake pressure	bar
10	J	Change counter	0-7
11	K	Output Shaft revolution rate	rpm
12	L	Turbine revolution rate	rpm
13	M	Target engine torque	Nm
14	N	Target lock	0/1
15	O	Virtual distance (CACC output command)	m
16	P	Virtual speed (CACC output command)	m/s

Table 5.2: Contents of the 'c' File (Communication Data)

Column		Parameter	Units
1	A	Time of day this entry was recorded	hh:mm:ss.sss
2	B	Number of seconds since start of process	sec
3	C	Time wireless comm message sent	sec
4	D	Time wireless comm message received	sec
5	E	Time engineering message sent	sec
6	F	Time engineering message received	sec
7	G	Message count	0-255
8	H	My time	msec
9	I	Accelerator pedal position (from driver)	percent
10	J	Virtual pedal position (from driver, ACC or CACC)	percent
11	K	Engine RPM	rpm
12	L	Mean effective torque	Nm
13	M	During shift (no/yes)	0/1
14	N	Current gear	0-7
15	O	Front right wheel speed	rpm
16	P	Driver braking (no/yes)	1/0
17	Q	Target lock	0/1
18	R	Car space (ACC gap selection)	1-3
19	S	Set speed	km/h
20	T	Brake pressure	bar
21	U	Distance from silver Nissan to target vehicle	m
22	V	Relative speed (between silver Nissan and its ACC target vehicle)	m/s
23	W	Yaw rate	deg/s
24	X	Vehicle Speed	km/h

Table 5.3: Contents of the 'd' File (Driver Behavior Data)

Column		Parameter	Units
1	A	Timestamp of file write	hh:mm:ss.sss
2	B	Number of seconds since start of process	sec
3	C	Time wireless comm message was sent	sec
4	D	Time wireless comm message was received	sec
5	E	Time engineering message was sent	sec
6	F	Time engineering message was received	sec
7	G	Yaw rate	deg/s
8	H	X-Acceleration	g
9	I	Y -Acceleration	g
10	J	ACC Active (off/on)	0/1
11	K	Car Space (ACC or CACC Gap Setting)	2-3-4-5 for copper 1-2-3 for silver
12	L	Target Approach Warning (false/true)	0/1
13	M	MainSW – ACC powered on (off/on)	0/1
14	N	ACC Buzzer - Master Alarm (off/on)	0/127
15	O	ACCBuzzer2nd - Target Approach Warning (off/on)	0/1
16	P	ACCBuzzer3rd	0/1
17	Q	ACC/CACC Set speed	km/h
18	R	Accel. PedalPosition (from driver)	percent
19	S	VirtualPedalPosition (from driver, ACC or CACC)	percent
20	T	Driver Braking (off/on)	1/0
21	U	ACCMainSW – ACC powered on (off/on)	0/1
22	V	Brake pressure	bar
23	W	Vehicle Speed	km/h
24	X	UTC Time	HHMMSS:ss
25	Y	Longitude	degrees & minutes
26	Z	Latitude	degrees & minutes
27	AA	Altitude	m
28	AB	GPS Speed Over Ground	km/h
29	AC	Numsats (number of GPS satellites available)	-
30	AD	Date	ddmmyy
31	AE	Change Counter	-
32	AF	Distance to Lead Vehicle	m
33	AG	Relative Speed Compared to Lead Vehicle (+ if closing gap / - if opening gap)	m/s

5.1.2 Video Files

Video data were recorded continuously from five cameras into two divx digital video files at a rate of 500 kbps. The files were roughly two minutes long such that the ends of the video files were synchronized with the ends of the corresponding engineering files. Unfortunately, due to technical constraints and some level of randomness with the time it takes to open a new video file in real time, the beginnings of the video files are not necessarily synchronized with the beginnings of the engineering files. The video files typically contain an additional 1 to 2 seconds of video at the beginning to avoid the possibility of a loss of video.

Figure 5.1 illustrates the views provided by each of the two video file types. The image on the left is the front scene from a single forward looking camera. At the bottom of the image is the time, in hours, minutes, seconds and milliseconds and the date. The image on the right is a composite of 4 cameras using a video quad splitter. In the top left corner is the rear view. In the top right corner is a view of the steering wheel. In the bottom left corner is a view of the driver's right foot above the accelerator and brake pedals, and finally, in the bottom right corner is a view of the driver's face.

Figure 5.1: Example of video file content (left is front view, right is quad view)

As with the engineering filenames, care was taken to ensure unique video filenames which followed the following naming convention:

[V][F][MMDD][TTTT][SSS].avi

where:

- [V] is a single character representing the vehicle on which the data are collected.
    's' is used for the silver car.
    'c' is used for the copper car.
- [F] is a single character representing the video file type or channel
    'f' represents the file containing the single video looking out of the front window
    'q' represents the file containing the four (quad) video images
- [TTTT] is a 4-digit Trip ID number which is incremented each time the vehicle is started
- [SSS] is a 3-digit sequence number which starts at 000 and increments every 2 minutes

Similar to the engineering files, the video data files were organized and copied into video trip directories. The video trip directories were named using the following convention:

v[YYMMDD][TTTT]

where:

- 'v' is the indication that the directory contains video data.
- [YYMMDD] is the trip date with 2 digits representing year, month, and day
- [TTTT] is a 4-digit Trip ID which matches the trip ID number of the enclosed files

5.1.3 DAS System Failures

There were typically between one to three DAS system failures per participant, which resulted in the loss of all or partial data for an individual trip. Three modes of failure were common during the experiment. The first mode of failure happened only during the first six participants, after which the problem was identified and repaired. For the first six participants, there were a number of trips of both the copper and silver vehicles that were simply not recorded. This mode of failure was eventually traced to a routine in the DAS startup that was relying on updates from the GPS receiver before starting to record data. If the GPS did not start receiving current information shortly after the DAS was started (often due to clear sky issues, such as the vehicle being parked in an underground garage), then there was the potential for the DAS to become hung and to not record the subsequent trip. Failures of this type were discovered during the data download and validation stage by comparing the list of trips imported from the DAS to the hand-written driver log sheets.

A second mode of failure involved a communication failure between two of the DAS system computers. In this mode of failure, the serial communication connection failed between the data recording computer and the computer that interfaces with both the vehicle’s CAN data and the DSRC antenna. Although the DAS system still recorded some parameters for the entire trip, such as GPS and accelerometer, most vehicle data parameters, such as vehicle speed and cruise control settings, became frozen at the last value received just prior to the communication failure. This mode of failure generally occurred fairly early in the trip, so these trips were not included in subsequent analyses. Failures of this type were discovered by manually reviewing graphs of the data parameters during the initial data processing step, the manual coding step, or even sometimes upon the examination of outliers in a particular analysis.

A third common mode of failure was characterized as a result of a DAS system reboot occurring during the middle of a trip. While the cause of the DAS system reboots is unknown, this mode of failure did not result in a total loss of trip data. This mode of failure typically resulted in the loss of 2 to 3 minutes of data while the DAS rebooted, but once the system finished rebooting, the recording of the data (.dat) files resumed. Unfortunately, after the reboot, the DAS system generally did not record video files. Failures of this type were generally discovered by manually reviewing the graphs of the data parameters during the initial data processing and coding step. Trips with system reboots were generally included in data analyses.

Other DAS failures occurred less frequently and were usually the result of isolated incidents in which data or video files for a particular trip were either missing or corrupted. As an example, video file corruption occurred on several trips taken by participant 10 which were later diagnosed as having occurred as a result of running low on disk drive space. Overall, the number of missing commute trips per driver was generally no more than one or two, and the impact of the data collection failures on the subsequent analyses should be minimal. All drivers had at least 10 ACC and 3 CACC commute trips that could be analyzed.

5.2 Questionnaires

5.2.1 Drivers' characteristics files

Information that might allow a subject to be identified is always kept confidential; however, there are some attributes that get coded for each participant. This information is entered manually by an experimenter in either Excel or SPSS, and then coded to a random participant number assigned to each participant.

The driver characteristics that are typically coded for each participant include the following:

- Age
- Gender
- Typical Annual Mileage Driven
- Daily Commute Miles Driven One Way & Round Trip

5.2.2 ACC and CACC comfort assessment questionnaire

Two questionnaires were administered during this experiment, and copies of them can be found in Appendix C. The first questionnaire was administered after the participant had about a week's worth of experience with the ACC system, but before the participant had a chance to experience the CACC system. Thus, the first questionnaire focused on comparing the ACC system to both conventional cruise control and manual driving. The second questionnaire was administered at the end of the study, after the participant had experienced both the ACC and CACC systems, and more or less repeated many of the questions found on the first questionnaire. This allowed for a more direct comparison of the ACC and CACC systems. The questionnaires were administered on paper, and later, they were manually transcribed to electronic data files.

The questionnaires covered four basic topics:

1. Comfort and Convenience
2. Safety
3. Driving with the System
4. Road and Traffic Conditions

5.3 Data Analysis Plan

The main question posed by this study is whether or not drivers will be comfortable with the shorter gaps provided by the CACC system. In order to do so, both opinions and more "objective" data were gathered to observe:

- Their use of the systems
- The influence of the system on their driving

The part of their driving of primary interest is:

- Gap regulation with a lead vehicle
- Lane changes, in terms of number and location, along the commute trip.

The data analysis activities proceeded in roughly six steps or phases:

1. Each section of each trip is described in terms of the time when the driver is following a vehicle versus the times when the driver is driving “alone”, i.e. no targets are sensed. Each trip may have a number of vehicle following episodes or epochs of varying duration. Furthermore, this description is examined from two perspectives:

   - First, from the chronological time perspective,
   - Second, from the location or distance perspective as there may be certain locations where the ACC/CACC is systematically used/not used

2. Each following epoch is then characterized along the following dimensions:

   - Duration
   - Initiation condition (e.g. SV catches up with slower POV, SV changes lane, POV changes lane)
   - Time gap at ACC initiation
   - Average time gap
   - Number of braking events
   - Max braking level
   - SV speed
   - End condition (SV changes lane, POV changes lane, POV distances SV)

3. For each following epoch, a number of graphs and metrics are examined including, but not limited to, the following:

   - Lead vehicle speed and speed variability over the duration of the epoch
   - ACC vehicle speed and speed variability
   - Time gap to lead vehicle
   - Time To Collision (TTC)

4. Lane changes are identified, and the causes for each lane change are identified and categorized as best as possible. This must be done to distinguish between lane changes for overtaking and lane change for following a route.

5. ACC/CACC system use is characterized along the following dimensions:

   - For each trip using one of the ACC/CACC systems
     - Number of episodes when the system is used
     - Length of each of these episodes
     - Sections when the system is engaged/disengaged.
   - For each system use episode within a trip

  - Initial set speed
  - Conditions of disengagement of the system (brake pedal vs. button on steering wheel)
  - Elapsed time between disengagement and next engagement
  - Setting used, for speed and gap, and conditions for changes

6. ACC/CACC comparison

  - Comparison of system engagement and use, e.g., is the ACC or CACC typically disabled by the driver under conditions when the other variant would normally be used?
  - How and when is each of the systems disengaged by the driver and is there a difference for these disengagements for which the system type might account, e.g., does the closer gap maintained by the CACC system cause the driver to brake (thereby disengaging the system) more often?
  - Comparison of typical system gap settings used.

5.4 Initial Data Processing

5.4.1 Data Transfer Process

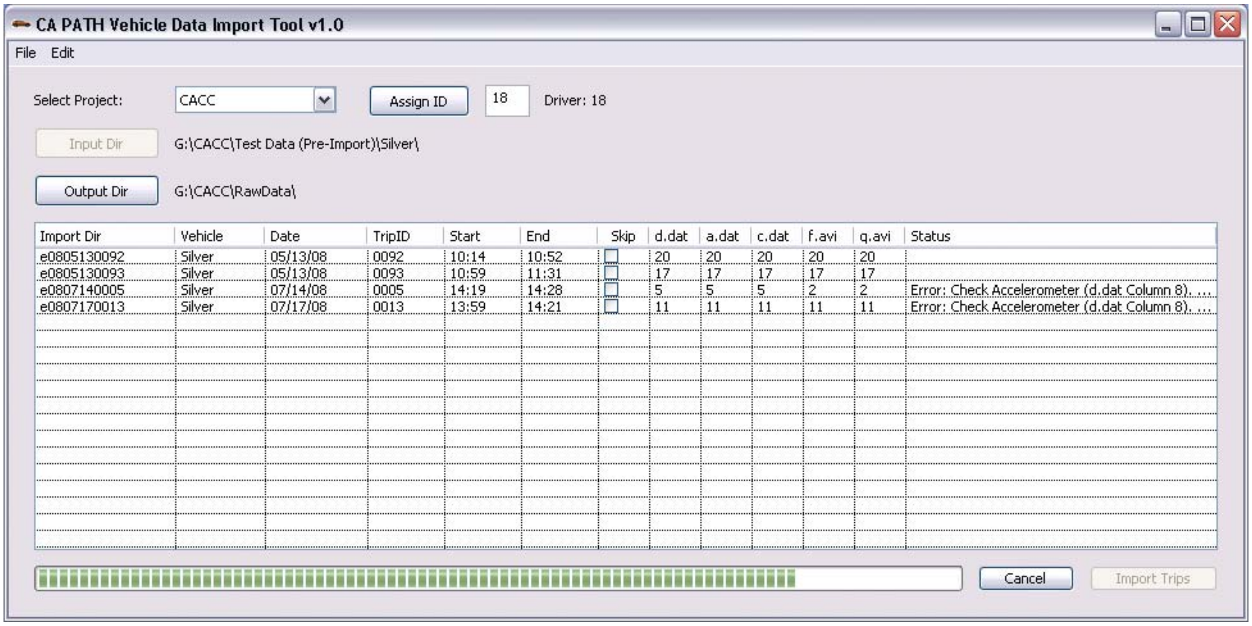
For each test participant, somewhere between 8 and 11 GB worth of data were collected across the two, in-vehicle, DAS computers. A number of automatic and manual steps or procedures are required to retrieve the data, verify its integrity, and move it to a server where it could be archived and analyzed. On the vehicle DAS computers themselves, when a new trip is generated (each time the vehicle is started), the files for the last completed trip are automatically copied to a directory on the DAS video computer and put into a queue to be downloaded. The data remained stored on the vehicles until the vehicles were brought back to California PATH to be readied for another participant. The transfer of data from the vehicles to the storage server was done manually using external disk drives. When an external drive is attached to the video DAS computer via USB, a script could be activated that would copy all of the data in the download queue to the external drive. After the download, a copy of the data remained on the vehicle until it was manually deleted, a process that was done after every few participants.

The data were transferred from the vehicles to a data repository server for storage and analysis. The data repository server was attached to a secured computer in a secured room at California PATH. To assist in uploading the vehicle data from the USB drive to the repository, a data importing tool was written in the RealBasic programming language. The data import tool served six functions (listed below) and a screenshot is provided in Figure 5.2:

1. The tool displays the list of trips recorded by the DAS in a table that can be easily read by an analyst. The analyst can then cross-reference the trips that were downloaded from the vehicles with the paper trip logs kept by the test participants to determine whether or not data for any of the trips made by the participant were missing.
2. The tool allows the analyst to filter out or skip the importing of inconsequential trips, such as short trips when the vehicle is simply moved, or trips when there was no opportunity for freeway travel and ACC use.

3. The tool allows the analyst to assign a Driver ID number to the trips.
4. The tool imports (copies) the files from the USB drive to the storage server, while both restructuring and renaming the files to make subsequent data processing easier.
5. The tool provided the first step in the verification of the integrity of the data being copied by reporting any expected, but missing files, and by checking for potential sensor failures on the vehicles.
6. The tool created an import log file of all operations performed and errors encountered.

After the data were imported to the repository, several backups were made of the data after various steps in the subsequent data processing. First, the data repository storage server used Raid5 technology for fault tolerance against any one disk drive failing. Second, periodic backups were made of all of the project data on the storage server to an external hard disk to guard against more catastrophic failures. The backups contained on the external hard disk were kept in a locked file cabinet with the subject paper records in order to limit access and protect the confidentiality of the records. Third and finally, the original data for each subject were backed up to a series of DVDs, stored in a locked media vault off-site.



Select Project: CACC

18 Driver: 18

G:\CACC\Test Data (Pre-Import)\Silver\

G:\CACC\RawData\

Import Dir	Vehicle	Date	TripID	Start	End	Skip	d.dat	a.dat	c.dat	f.avi	q.avi	Status
e0805130092	Silver	05/13/08	0092	10:14	10:52	☐	20	20	20	20	20	
e0805130093	Silver	05/13/08	0093	10:59	11:31	☐	17	17	17	17	17	
e0807140005	Silver	07/14/08	0005	14:19	14:28	☐	5	5	5	2	2	Error: Check Accelerometer (d.dat Column 8). ...
e0807170013	Silver	07/17/08	0013	13:59	14:21	☐	11	11	11	11	11	Error: Check Accelerometer (d.dat Column 8). ...

Figure 5.2: Sample screenshot of the CACC data import and validation tool

5.4.2 Data Repository Organization

While the file naming conventions used on the vehicles were optimized to prevent the possibility of overwriting files due to duplicate file names, the resulting file-naming structure was a bit unwieldy for a person or analyst to visually parse and comprehend. As the files were imported to the data repository, the directory structure and files names were changed to match the following conventions:

- Driver[XX]
  - [Vehicle]
    - Date[YYMMDD]
      - Trip[TTTT]
        - [SSS]
          - [V][F][TTTT][SSS].[EXT]

Where:

- [XX] is a two-digit test participant ID number
- [Vehicle] is the name of the vehicle from which the data were collected
  - 'Silver’ is used for the silver ACC-enabled car
  - 'Copper’ is used for the copper CACC-enabled car
- [YYMMDD] is the trip date with 2 digits representing year, month, and day
- [TTTT] is a 4-digit Trip ID number which incremented each time the vehicle was started
- [SSS] is a 3-digit sequence number which started at 000 and incremented every 2 minutes
- [V] is a single character representing the vehicle on which the data is collected.
  - 's' is used for the silver car.
  - 'c' is used for the copper car.
- [F] is a single character representing the data file type
  - 'a' is used for C/ACC data
  - 'c' is used for communication from the lead vehicle data
  - 'd' is used for driver behavior and target data
  - 'f' represents the file containing the single video looking out of the front window
  - 'q' represents the file containing the four (quad) video images
- [EXT] is a 3-letter file extension, either .dat or .avi for data or video files, respectively.

The resulting file and directory naming conventions allowed analysts to more easily navigate the data and find a particular driver, trip, or video segment. The resulting directory structure also aided in keeping any additional data, generated during post-processing, organized. As examples, a summary file generated to detail each trip taken by a particular driver would be stored in the driver directory; whereas graphs that were generated to summarize a particular trip were stored in each trip directory.

5.4.3 Initial Data Processing

After a participant’s data were downloaded from the vehicle, validated, and uploaded to a data repository, a number of initial data processing steps needed to be performed. The initial data processing was done using a script written for MatLab. This script basically ran through the data for each trip in order to summarize key parameters on both a trip-by-trip basis and on a participant-by-participant basis. On a trip-by-trip basis, the initial data processing script generated the following:

1. a best estimate synchronization between the DAS system clock and time as obtained by the GPS receiver on the vehicle. This synchronization was required in order to compare events that occurred in the lead vehicle with events that occurred in the following vehicle.
2. a number of indices, tables, and sensor calibration files which could be used in later processing steps.

3. graphs of key system and vehicle parameters versus time (shown in UTC time corrected for the US Pacific Time Zone), as shown in Figure 5.3.
4. a KML file from the GPS points collected by the vehicle, which could be loaded into Google Earth allowing an analyst to visualize the trip's starting and ending points along with the route taken by the vehicle during the trip. (See Figure 5.4.)

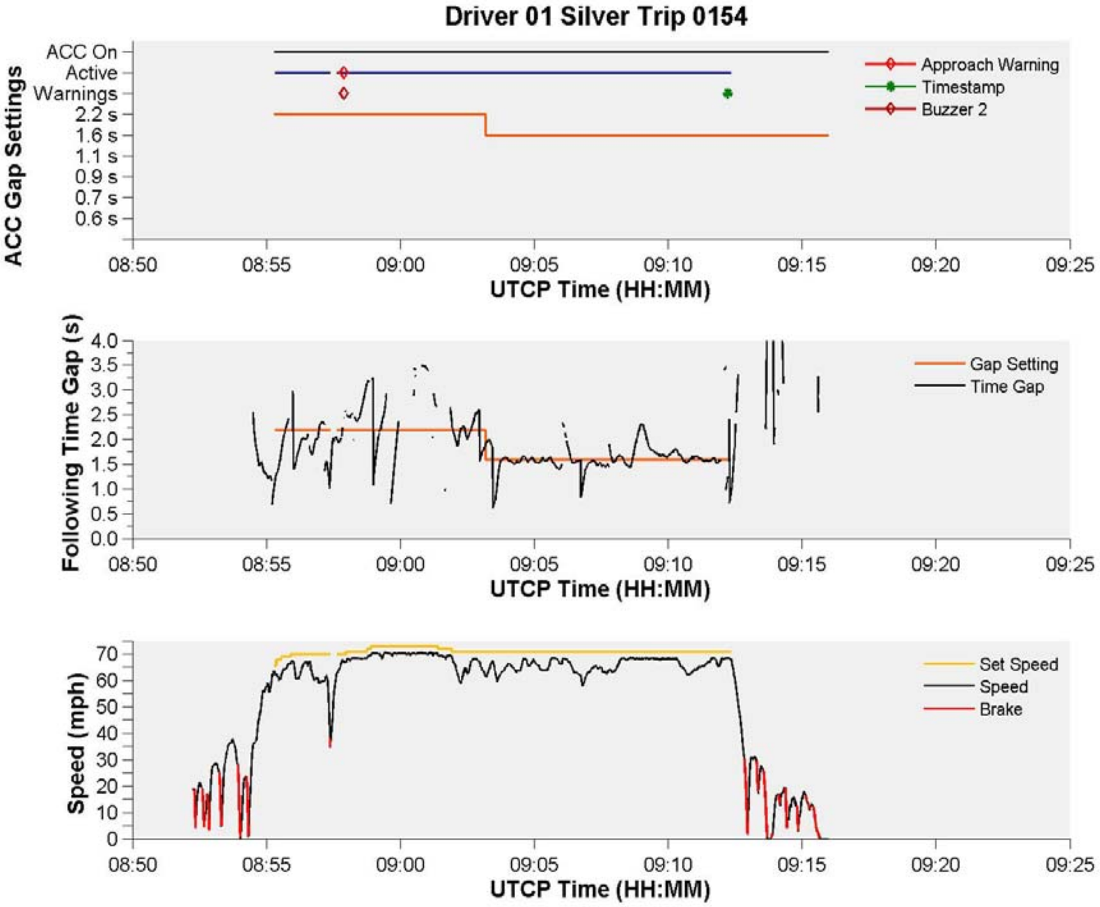


Figure 5.3: Plot of key vehicle and cruise control parameters for a trip

On a participant-by-participant basis, the initial data processing script generated a trip summary dataset which listed all of the trips taken by a driver during the experiment. See Table 5.4 for a description of the metrics that were generated for the initial trip summary data set. Although this data set was used to perform subsequent analyses, its immediate use was as a tool to help an analyst perform the manual trip coding task.

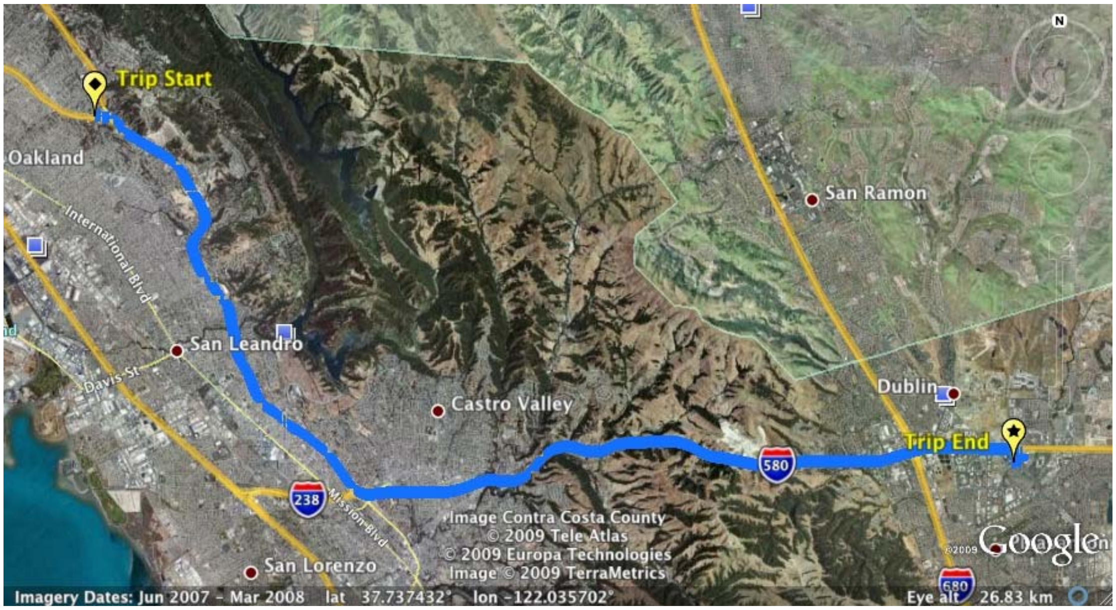


Figure 5.4: Google Earth Plot of a trip taken by a participant

Table 5.4: Initial trip summary data set

Parameter	Description
Driver ID Number	A random ID number assigned to each test participant
Vehicle Description	Silver (ACC Vehicle) or Copper (CACC Vehicle)
Trip ID Number	A vehicle-specific sequential trip number
Day/Month/Year	Trip Date
Clock Start/End	Original System Clock Times
UTC-P Start/End	Clock synchronized to UTC Pacific Time
Trip Length	Duration of Trip
ACC On Events	Number of times the ACC/CACC system was turned on
ACC On Time	Total length of time that the ACC/CACC system was on
ACC On Set Speed	Mean set speed when ACC system was on
ACC On Mean Speed	Mean vehicle speed when ACC system was on
ACC Active Events	Number of times that the ACC/CACC system was activated
ACC Active Time	Total length of time that the ACC/CACC system was active
ACC Active Set Speed	Mean ACC/CACC set speed when the system was active
ACC Active Mean Speed	Mean vehicle speed when the ACC/CACC system was active
Gap Setting Events	For each available gap setting, the number of times that the driver selected that gap setting
Gap Setting Times	For each available gap setting, the amount of time that the driver spent using that gap setting
Gap Setting Set Speeds	For each available gap setting, the mean set speed that the driver had set while using that gap setting
Gap Setting Mean Speeds	For each available gap setting, the mean vehicle speed that the driver was travelling while using that gap setting

5.4.4 *Manual Data Coding*

Once the initial automated data processing step was completed, an analyst was required to manually sort through each trip. The analyst was first looking for common DAS system failures, and second, coding trip characteristics. The end result of the manual coding step was to create a list of trips and their characteristics which could then be used during the data reduction step as means to filter certain types of trips to be included or excluded from the subsequent analyses. Trips were coded along five dimensions:

1. Day of Week (e.g., Monday, Tuesday, etc.)
2. Day of Study (i.e., number of days since receiving the ACC vehicle)
3. Trip Purpose (Morning Commute, Evening Commute, or Other)
4. Trip Mode (Baseline, ACC, CACC, or Urban Driving)
5. Full or Partial Trip

The coding for the trip purpose separated out morning and evening commutes from other casual trips. This coding was done using both the time of the trip and the GPS traces recorded during the trip. Morning commute designated a trip from home to work, and evening commute designated a return trip from work to home. Since participants did not always go directly between home and work, there was some subjectivity regarding the coding of which trips were actually commutes, and occasionally, a commute may span multiple trips. However, the guiding principle for calling a trip a commute was whether or not the trip was made on roads that the participant frequently travelled between their home and their work. Thus, for all trips that were labeled as commutes, it can be assumed that the participant was highly familiar with the route.

Most of the analyses performed for this report focused only on commuting trips, and this focus can be justified by the desire to limit the variability that comes from extraneous sources. Drivers are generally very familiar with their commuting route and the traffic patterns that they will likely encounter. By limiting the initial analysis to commuting trips, there is a good chance that most of the variations in ACC and CACC usage will be due to driver preference and local traffic conditions.

The coding for trip mode allowed for four possibilities: baseline, ACC, CACC, or urban driving. Baseline trips were trips taken on designated baseline days where the participant was instructed not to use the ACC system. However, since the participants did not always follow the baseline day instructions, baseline day trips were manually verified to ensure that the participants did not use the ACC system during the trip before the trip was officially coded as a baseline trip. Trips coded as ACC indicated that the participant was free to use the ACC system during that trip, regardless of whether or not the participant actually chose to use the system. Trips coded as CACC trips indicated that the participant was driving the copper CACC-equipped vehicle, and finally, trips coded as urban driving indicated that due to the trip’s length and the roads being travelled during the trip, there was no opportunity for the participant to use either the ACC or CACC system.

Finally, trips were coded as to whether or not they were full trips or partial trips. This coding was of particular concern for commutes. A partial trip could occur either from a data acquisition system error or from the driver breaking up a longer trip into smaller ones. As an example, a driver may have decided to stop at a mall or grocery store on the way home. If the store was near their work or home, then this was not of particular concern; however, sometimes, the store may have been half-way between work and home. Thus, instead of having a typical 45-minute trip home on the freeway, the evening commute was split between a 15 minute trip and a 30 minute trip. The coding of partial trips was accomplished using both the participant's trip logs and the GPS traces recorded during the trip.

5.5 Data Reduction

The final step of the data processing before the analysis phase is commonly referred to as the data reduction phase. The goal of the data reduction phase is to filter, combine, and process the DAS system data and any other required observations into meaningful metrics that can be coded into a data set and subsequently analyzed. As an example, if one wanted to analyze the conditions when drivers activated the ACC system, the data reduction step would consist of the following steps:

1. Define the criteria that would constitute an ACC activation event. In this case, the criterion that defines an ACC activation event is already recorded in a single value in one of the DAS data files. However, for more complicated analyses, the criteria that would constitute an event of interest might include filtering a number of different parameters.
2. Define a set of metrics of interest that would describe the event or the conditions around the event. In this case, the metrics may include vehicle speed and following distance at the time of the ACC system activation.
3. Locate all ACC activation events for all trips.
4. Process each ACC activation event, calculating and recording the selected metrics of interest for each event.

The amount of data collected during this study was quite large and unwieldy to process and analyze. For each driver there is approximately 10 GB of data and video files. That equates to roughly 15 to 18 hours of video and millions of lines of data. The sheer amount of data that needed to be processed required a number of tools to be created to both efficiently access, search, processes, and view the data.

Several architectures and data processing tools for storing and accessing the data were evaluated, and the decision came down to two leading candidates. The first candidate was to create a database with data. While this method holds some promise for the future, the issues in building and maintaining this type of system provided too challenging for the resources of this project. The second candidate architecture was to store the data in flat files using the standardized conventions previously discussed in Section 5.4.2. While this architecture was simple to implement, it necessitates the use of a number of tools to efficiently locate and access the data, as well as a trip key that was manually created (described in Section 5.4.4).

The majority of the data reduction was done using scripts written in MatLab, an interactive programming environment. For each analysis discussed in the results sections, one or more scripts were written to process the raw system and vehicle data in order to create the appropriate metrics that were required for analysis. Manual checking of the video data was used to clarify or code additional parameters or metrics as needed.

At the lowest level of the data processing architecture, functions were written to open and merge all of the original 2-minute data files for a single trip. At this level, each time the data for a trip was loaded into memory, unit conversions were applied, new parameters were generated, and filters were applied to smooth the data before any data processing commenced. As examples, all speed data were converted to m/s, acceleration was calculated and filtered based on vehicle speed, and new parameters such as time-to-collision and required deceleration were computed. Additionally, at this level of the architecture a number of general functions and utilities were written to support data format conversions, to support the creation and manipulation of graphs, and to support file operations, such as reading and saving the various data files generated during the analysis.

At the middle level of the automated data processing architecture, several analysis templates were written to facilitate running an automated analysis on either the entire set of data or on a subset of the data. The primary purpose of the analysis template was to cycle through each trip in the master list of trips for the project, load a trip into memory, process that trip, and compile and save the resulting data set in a format that could be easily imported into SPSS for statistical analysis or Excel for producing graphs.

The top level of the automated data processing architecture consisted of trip filter plug-in scripts and analysis plug-in scripts which could be referenced by an analysis template. Trip filter plug-in scripts allowed an analysis to examine a subset of the trips contained in the master list of trips. As an example, the list of trips to be processed by the analysis template could be filtered by driver, time of day, day of the week, whether or not the trip was a commute, etc. Most of the analyses in this report examined only commuting trips. Some of the analyses in this report examined only Baseline trips, while others examined ACC or CACC trips only.

The analysis plug-in scripts provided the instructions on how to process a trip once it was loaded into memory and what data parameters to calculate and save. The data files that come from the vehicles are all time-coded lists of when certain things happened in the data, such as the speed at any given time or when the driver activated the ACC/CACC system. An analysis plug-in script might, for example, search a trip for every instance when the vehicle is traveling greater than 35 mph and following a lead vehicle with a following time gap of less than 3 second. Each of those following events might then be summarized in terms of length, average speed, peak deceleration rates, etc. Thus, the analysis plug-in script defines the meaning of each row and column that goes into the data set that will be output by the analysis template.

This data analysis architecture provided advantages in data processing speed and efficiency. In order to generate a new analysis, one only needed to write an appropriate trip filter and an analysis script to analyze a single trip. Once these were written, the lower levels of the architecture took care of scaling the analysis up from being applied to a single trip to being applied to all of the relevant trips contained in the entire experiment data set.

6 Experiment Protocol

6.1 Overview

The experiment protocol was designed to evaluate the perceived acceptability of the shorter gap settings offered by the CACC system using an on-the-road, in-real-traffic, study. Although the goal of the experiment was to test the shorter gaps provided by the CACC system, most drivers in the U.S. are unfamiliar even with the already available ACC systems that are currently on the market. At the time of this study, ACC systems were generally only available on high-end, luxury cars, and often as a fairly expensive option, resulting in a very small market penetration. Thus, the experimental protocol that was developed needed to first allow the test participants enough time to get acquainted with a standard ACC system before the testing of a CACC system could begin.

The experiment protocol was split into two phases. (See Table 6.1.) In the first phase, the test participants were given the silver Infiniti FX45 with the factory installed ACC system to drive as their own (without an experimenter present) for a period of about 11 days. During that period, there were roughly 7 week days when the test participant would be commuting to and from work with the vehicle and 4 weekend days when the test participant was free to use the vehicle wherever they were going. Additionally, there were minor variations between participants. As an example, some participants had the car delivered on Thursday morning, making Friday the baseline day.

The second phase of the experiment lasted for two days, immediately following the last day of the first phase. In this phase, the test participant drove the copper Infiniti FX45 with the CACC system for their morning and evening commutes. During these four trips an experimenter was present in the vehicle with the test participant, and the silver Infiniti FX45 was driven by a confederate to play the role of the lead vehicle during the commute. Additionally, sometimes the CACC testing days ended up falling on Tuesday/Wednesday instead of Monday/Tuesday due to the holidays, rain, or other variations in the participant's work schedule.

Table 6.1: Summary of testing condition per day.

	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday
Week 1	Vehicle delivered	Day 1 No ACC	Day 2 ACC	Day 3 ACC	Day 4 ACC	Day 5 ACC	Day 6 ACC
Week 2	Day 7 ACC	Day 8 No ACC	Day 9 ACC	Day 10 ACC	Day 11 ACC	Day 12 CACC	Day 13 CACC

After the fourth participant, there was a slight change to the second phase protocol to add a short CACC practice session before conducting the CACC testing during the participant's morning and evening commutes. The half-hour CACC practice session was conducted at the participant's convenience between days 8 and 11. The purpose of this practice session was simply to familiarize the participant with the CACC system. This additional practice session was added because it subjectively seemed that it took the participants about a half hour to get comfortable with the CACC system, and this learning effect might have been influencing the first CACC testing day.

The CACC driving sessions took place on public highways on the routes designated by the participants. Thus, the CACC testing was all done on routes with which the participants were already familiar. The test participants were informed that they could stop at any moment or choose any route that they desired, but they were asked to drive in accordance with all state and local driving laws.

6.2 Participant Recruitment

To be eligible to participate in the study, potential candidates needed to meet the following criteria:

- Have a valid California driver's license
- Have a clean driving record with no moving violations within in the last 3 years and no DUIs
- Commute daily with 25 or more minutes spent traveling at freeway speeds each way
- Have relatively secure parking at both home and work
- Be between the ages of 25 and 55 years of age

The initial test participants were recruiting using the U.C. Berkeley and U.C. San Francisco Research Subject Volunteer Program, which is a basically a website bulletin board where potential participants can browse studies which are currently seeking volunteers. After an experimenter validated a candidate participant's eligibility, either through a phone call or email, a participant packet was mailed to the participant. (See Appendix B.) The packet contained a cover letter, study consent forms, and a DMV records release form (to verify the candidate's eligibility to participate). A potential participant's DMV records were checked either by having the participant mail the DMV directly and obtain a copy of their records or by consenting to have California PATH check their DMV records electronically using the Volunteer Select Plus service available from LexusNexis Risk & Information Analytics Group, Inc.

As part of the consent form package, three documents had to be signed by the participants. The first document provided participants with informed consent regarding their participation in the study. This document detailed the study, providing the participants with enough information to make an informed decision about whether or not they still wanted to participate in the study. The second document was a video and photographic image release form which allowed participants to designate appropriate uses for any images collected during the study. Finally, there was a fuel card user agreement, which was only required if the participant wished to use a University provided fuel card to purchase gas for the vehicle. It was not required if the participant wished to purchase fuel on his or her own and submit receipts for reimbursement at the end of the study. The participants generally had several weeks to review the consent materials and ask questions, as the forms were not signed until the day that the vehicle was delivered to the participant.

6.3 Test Procedures

6.3.1 Phase 1: Gaining Experience with ACC Systems

The goal of the first phase of the experiment was to allow the driver to acclimate to the test vehicle and to gain experience with a typical ACC system, since it was assumed that most drivers in the US would be unfamiliar with such a system. The first phase also allowed for the collection of baseline driver behavior data during two days when the test participant was asked to drive the vehicle without using the ACC system. This phase of the protocol could further be broken into five steps over 11 days.

6.3.1.1 Step 1: Vehicle Delivery

After a potential participant's eligibility to participate in the experiment was verified, a testing date was scheduled, and the vehicle was delivered to the participant's place of residence or work by an experimenter on either a Wednesday or a Thursday. At the time of delivery, the experimenter completed a vehicle checkout checklist, and trained the test participant in the features of the vehicle and the use of the ACC system.

The first part of the training took place when the vehicle was parked. The experimenter explained the ACC functions, how to activate them, and how to turn them off. The test participant was invited to ask questions throughout this step.

The second part of the training involved taking the vehicle on a highway for a short trip with the experimenter in the passenger seat. The participant was then instructed to turn the ACC system on whenever he or she felt comfortable to do so. The experimenter then talked the participant through the features of the system and answered any additional questions that the driver had about the system. The experimenter also stressed the following important parts of the experimental protocol to the test participant.

- The participant was the only person allowed to drive or ride in the vehicle.
- The participant was to try to use this vehicle as he/she would use their personal vehicle.
- The participant should try to use the ACC when conditions allowed (highway driving with relatively free flow traffic) as much as possible on the non-baseline days of the protocol.
- The participant was encouraged to try the different gap settings until finding one with which they were comfortable.
- The participant was reminded to fill out a logbook entry for each trip taken in the vehicle.

6.3.1.2 Step 2: One Baseline (Non-ACC) Driving Day

On Day 1, the first full day with the ACC equipped vehicle (which was typically a Thursday), the test participant was instructed to drive the vehicle without using the ACC system. Although the participant was not actively using the ACC system, the DAS was still recording all of the data that would normally be collected when the ACC system was active. The data collected from this day was then used as a baseline to characterize the test participant's normal driving behavior.

6.3.1.3 Step 3: Six ACC Driving Days

After the baseline driving day, the participant was allowed to drive the vehicle for the next six days while freely using the ACC system. This would include four days of commutes and two weekend days of experience with the ACC system. Data from the vehicle's DAS were typically downloaded on day 6 while the test participant was at work.

6.3.1.4 Step 4: Second Baseline (Non-ACC) Driving Day

At this point, the test participant has had the ACC equipped vehicle for about a week. On Day 7, the second Thursday, the participant was again instructed to drive the vehicle without using the ACC system. This day served as a second baseline to allow for comparisons to be made between the participant's behavior before using the system and the participant's behavior after using the system to see whether or not the system had an influence on the participant's typical behavior.

6.3.1.5 Step 5: Three More ACC Driving Days

On Days 8 through 11, the test participant was again allowed to drive the vehicle using the ACC system. This would include one commute day and two weekend days. During this period of time, the participants were instructed to fill out the first survey on their experiences with the ACC system (see Appendix C).

6.3.2 Phase 2: Using the CACC system

For most of the participants (excluding the first four), the second phase of the experimental protocol generally began with a half-hour practice CACC test drive. The experimenter and a confederate lead-vehicle driver generally met the test participant at his or her residence or place of work with the CACC equipped vehicle. The test participant then drove the CACC-equipped, copper-colored, FX45 with the experimenter present in the passenger seat, while the silver-colored FX45 was driven by the confederate driver to serve as the lead vehicle. The purpose of the practice session was to familiarize the participants with the CACC system. After a brief introduction to the differences between the ACC and CACC system while the vehicle was parked, a 15 to 30-minute practice drive was conducted on a nearby road selected by the participant. During the practice drive the participant was asked to try each of the new gap settings for a few minutes, just to get an idea of what the settings were like.

After the practice session, the protocol provided for two days (four commute trips) using the CACC system. For each CACC test trip, the experimenter and confederate lead-vehicle driver met the participant at their home or workplace with the CACC-enabled, copper-colored, FX45. Although an experimenter was present during this phase of testing, the participant still scheduled the times of departures, routes taken, and even the lane of travel. All of this was communicated to the lead vehicle driver via two-way radio. The experimenter also served as a safety observer since the CACC system was a prototype, and was only reliably capable of following the communication-enabled, silver-colored FX45. If the CACC system misbehaved or other vehicles cut in between the two test vehicles, the experimenter was able to turn the system off with a kill switch which, in effect, mimicked the functionality of the CACC on/off switch.

At the end of the last day of CACC testing, the participant was asked their general impressions of the CACC system and given a survey on their experiences with both the ACC and CACC system to be completed and mailed back (see Appendix C). The participants were then thanked and paid $100 for their participation in the experiment. They were also reimbursed for any fuel expenses incurred while in possession of the ACC equipped vehicle. The vehicles were then inspected and readied for the next participant.

It should be noted that the reimbursement of fuel expenses served partially as an additional incentive for participation. However, since the research vehicles required premium fuel and the EPA rated fuel economy was less than most vehicles, the fuel reimbursement also served as a means to make sure that participants did not have to pay a monetary penalty to participate in the experiment, especially if the participant typically drove a more fuel efficient car on their daily commute.

7 Overview of Participants and Trips

7.1 Test Participants

The sample was composed of 16 participants, 8 females and 8 males with ages ranging from 25 to 46 (mean 35, std dev 6.2). All of the participants had a clean driving record for at least 3 years, and none of the participants had a DUI on record. Table 7.1 below details some of the participants' characteristics. The self-estimated annual average mileage of the participants ranged from 10,000 to 26,000 miles per year with a mean of 17,500 mi and a standard deviation of 5600 mi. The daily commutes of the participants in the study ranged from 24 to 44 miles (each way), with a mean of 30 (±7) miles (where ± is used to denote the standard deviation), and the commutes ranged from 27 to 72 minutes with a mean of 45 (±19) minutes. All participants were familiar with conventional cruise control, but none had experienced driving an ACC equipped vehicle before participating in this study.

Table 7.1: Test Participant Characteristics

#	Gender	Age	Est. Annual Mileage	Commute (miles)	Mean Commute Time (minutes)	Month of Participation
1	Female	32	10,000	24	27.0	October 2008
2	Male	36	15,500	28	44.8	October 2008
3	Female	40	15,000	37	63.7	November 2008
4	Female	38	12,000	23	35.2	December 2008
5	Female	45	24,000	33	53.9	January 2009
6	Male	33	18,000	44	64.8	February 2009
7	Male	35	25,000	43	58.7	April 2009
8	Male	32	15,000	24	30.5	April 2009
9	Male	29	15,000	29	41.7	May 2009
10	Male	30	10,000	23	33.4	June 2009
11	Female	27	18,000	30	57.8	June 2009
12	Male	38	22,000	25	45.4	July 2009
13	Female	25	10,000	25	23.7	July 2009
14	Male	46	20,000	34	43.4	August 2009
15	Female	43	25,000	24	50.4	September 2009
16	Female	38	26,000	37	72.7	November 2009

7.2 Data Set of Participant Trips

The results presented and discussed in this report primarily focus on the participants' commutes, defined as a trip or series of trips taken by the participant between their home and work. A single commute may be broken into a series of trips because, in the context of this study, a trip is defined as the data gathered from the time when the vehicle was turned on until the time when the vehicle was turned off. Thus, if a participant drove from work to a store, parked the vehicle, and then later drove from the store to home, then the commute would span two trips. Table 7.2 summarizes the data set of commutes and individual trips that have been analyzed in this report.

Table 7.2: Overview of Commuting Trips in the Data Set

	Baseline Driving	ACC Driving	CACC Driving
Commutes	51	173	62
Individual Trips	58	180	62
Events of Interest	412 following events	689 system activations	352 system activations

Based on the experimental plan, it was expected that there would be approximately 64 baseline commutes (4 per participant); 160 ACC commutes (10 per participant); and 64 CACC commutes (4 per participant). However, there were a number of reasons for the differences between the expected and actual number of commutes collected during the experiment. Some trips that were taken were lost to DAS system failures, and others may have been lost to normal variations in the participant's schedule, such as having an engagement after work. Furthermore, a number of baseline trips were missing due to participants forgetting to follow the protocol on baseline days, which partly accounts for the increase in the number of ACC commutes collected. Additionally, variations between participants regarding on which day the ACC vehicle was handed out resulted in a few extra ACC trips for some of the participants. As shown in Table 7.3, even with minor data losses, all of the participants had at least 1 baseline driving trip, 7 ACC commuting trips, and 3 CACC commuting trips to analyze.

Table 7.3: Summary of Trips in the Data Set by Participant

Participant		Baseline			ACC			CACC		
		Morning	Evening	Other	Morning	Evening	Other	Training	Morning	Evening
1	Female	2	2	0	6	6	4	-[1]	1	2
2	Male	0	1	0	10	7	9	-	2	1
3	Female	1	1	0	6	6	10	-	2	2
4	Female	2	3	1	5	5	0	-	2	2
5	Female	1	1	0	5	6	4	1	2	2
6	Male	1	0	0	6	5	0	1	2	1
7	Male	2	2	0	6	4	5	1	2	2
8	Male	4	2	0	6	5	15	1	2	2
9	Male	3	3	0	5	5	11	1	2	2
10	Male	0	1	0	9	6	21	1	2	2
11	Female	2	1	2	5	6	0	1	2	3
12	Male	0	2	0	6	7	18	0[2]	2	2
13	Female	2	3	0	5	4	4	1	2	2
14	Male	1	2	0	5	7	6	1	2	2
15	Female	3	4	0	5	4	19	1	2	2
16	Female	1	2	0	4	3	2	1	2	2
Totals		25	30	3	94	86	128	123	31	31

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[1] No pre-commute CACC training was provided for participants 1 through 4.

[2] Pre-commute CACC Training was provided for participant 12, but the data was lost.

The data set also contained 128 trips that were recorded when the ACC was used even though the trip was not part of a commute, and 123 trips were recorded when the driving was primarily low speed without a chance to use the ACC system. Neither of these sets of trips was analyzed in this report.

7.3 Participant Commute Characteristics

7.3.1 *Overview*

There were 265 commuting trips recorded that were comprised of a single trip that was, more or less, directly between the participant's home and work. The overall mean commuting distance was 30.2 miles, and the mean commuting time was 45.5 min (±19 min std. dev.), with individual commutes ranging from as little as 15.5 min to 105.3 min. Table 7.1 previously detailed the mean length of each participant's commute both in terms of distance and time, and Figure 7.1 depicts the general freeway routes of the study participants. The shortest commutes were approximately 24 miles, taking an average of 27 minutes; and the longest commutes were on the order of 37 to 44 miles taking, on average, 58 to 73 minutes. However, commuting distance was not always a very good predictor of commuting time due to variations in traffic patterns.

Figure 7.1: Bay Area Freeways Covered During the Study

As shown in Figure 7.1, most of the freeways in the San Francisco Bay Area were covered as part of this study. Each color overlaid on the map represents a different driver's commute during the study. However, what is not depicted in the figure is the fact that most of the participants had what would commonly be considered partial reverse commutes. Given the congested nature of Bay Area freeways during commuting hours, this bias was both by design and necessary since the ACC and CACC systems only worked when the vehicles were travelling more than 35 mph. Participants who had highly congested commutes were simply not selected for the study.

7.3.2 Commute Length

As previously stated, the overall mean commuting trip length was 45 (±19) min, but the commutes varied greatly by participant. Thus, the lengths of the commuting trips in the data set were examined using a repeated measures, generalized linear model to understand whether or not there were any inherent biases in the data set that might lead participants or groups of participants to favor one mode of driving over another. The model included a full factorial of gender (a between-subjects effect), cruise control system (baseline, ACC, and CACC), and commute time-of-day (both within-subjects effects). Two other factors, day-of-the-week and day-of-the-study, were included in the model as within-subjects covariates since there would have been missing cell problems if they were included as factors. In essence both of these covariates are confounded with the main effect of cruise control system since baseline and CACC testing occurred only on specific days of the week and CACC testing always occurred at the end of the study. Gender was not significant, but the cruise control system factor was statistically significant, Wald χ^2_2=6.49, p=.039. As shown in Figure 7.2, commutes when the CACC system was used tended to be about 6 to 7 minutes longer than the commutes on baseline days or ACC days.

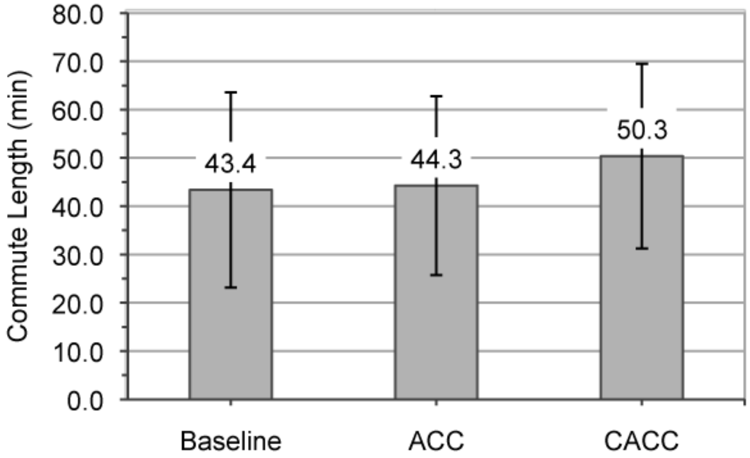

Figure 7.2: Relationship Between Commute Length and Study Phase.

The roughly 6-minute difference in commuting times between CACC trips and other trips was most likely an artifact of the experimental protocol. The instrumented vehicles typically take several minutes for the DAS to fully start up and start recording data. Thus, on Baseline and ACC trips, this would mean that the first few minutes of the trip, typically urban driving, were not recorded. However, during CACC testing, the experimenters and participants typically waited for both the ACC and CACC vehicles to complete their startup sequence before beginning a commute in order to make sure that the CACC communication was working properly. Thus, the apparent additional commuting time for CACC trips is most likely explained by the pre-trip coordination between the ACC and CACC vehicles.

Additionally, as one might expect, both time of day (Wald χ^2_1=4.23, p=.04) and the interaction between time of day and day of the week (Wald χ^2_1=12.58, p<.001) were found to have a significant impact on the length of the commute. As shown in Figure 7.3, evening commutes were generally longer than morning commutes, and Thursday and Friday evening commutes were typically the longest during the week. However, there are some biases in this figure because, as described earlier, CACC trips were generally longer than Baseline or ACC trips, and CACC trips usually only took place on Mondays or Tuesdays. As such, Figure 7.4 removes the confounding CACC trips, showing only Baseline and ACC trips as a function of day of the week. This graph is probably a better representation of the effects of time of day and day of the week on the length of the commute during the study. While the general trends are similar between the two figures, the removal of the CACC trips lowered the mean commute lengths on Monday, Tuesday, and Wednesday.

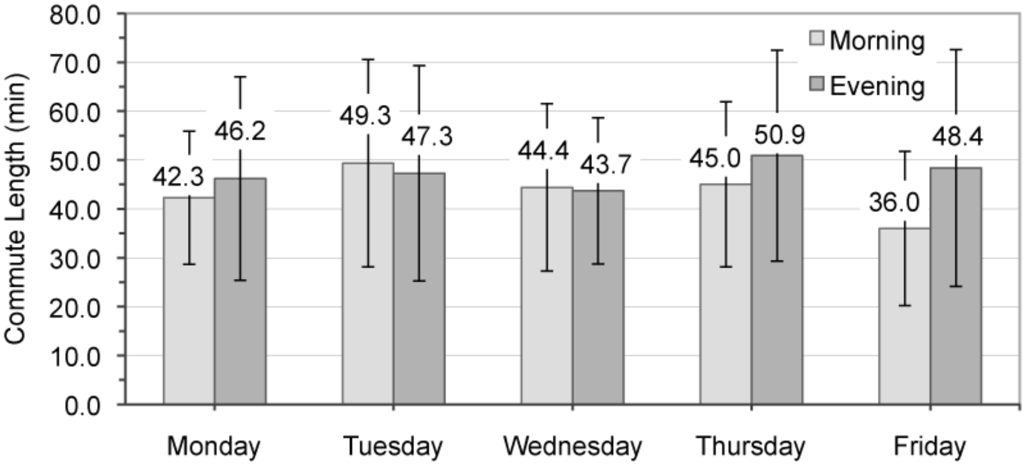

Figure 7.3: Relationship Between Commute Length, Day of the Week, Time of Day.

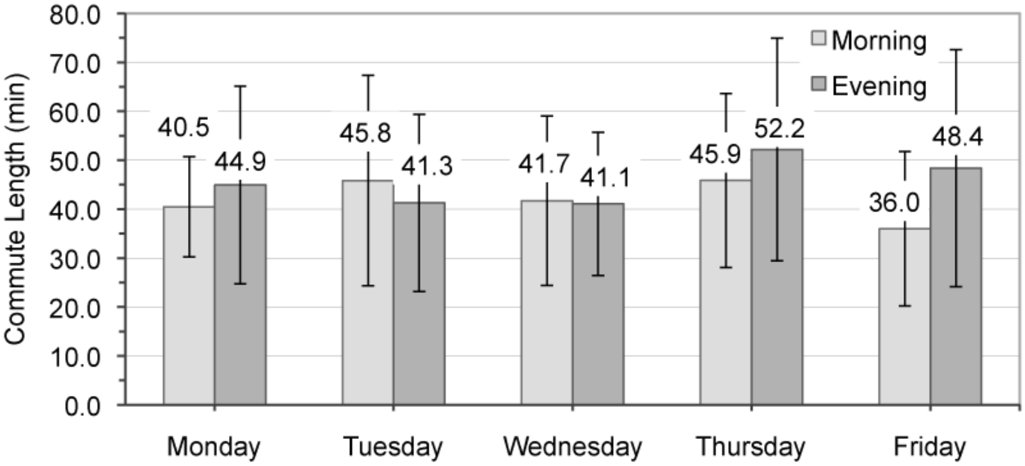

Figure 7.4: Relationship Between Commute Length, Day of the Week, Time of Day, Excluding CACC Testing Days.

7.3.3 *Opportunity to Use the ACC-CACC Systems During Commutes*

The overall length of the commuting trips, which was examined in the previous section of this report, provided some confidence that there were no inherent biases in the data set; however, the overall commute length may not necessarily equate to equal opportunity for ACC or CACC system use. Since the ACC and CACC system generally only functioned (or at least could be engaged) when the vehicle was travelling faster than 35 mph, the analyses detailed in this section examined both the number of times and the total length of time that the participant's vehicle was travelling faster than 35 mph during each commuting trip.

Overall, there was a median of 12 and a mean of 14.8 (±10.3) events when the vehicle was travelling greater than 35 mph, with a minimum of 1 and a maximum of 50 events per trip. The number of events was modeled using a repeated measures, generalized linear model. In the model, gender was considered a between-subjects factor, and cruise control system and commute time of day were considered within-subjects factors. Day of the week (excluding weekends), was again modeled as a within-subjects covariate, even though it was confounded with the cruise control system factor. None of the model factors had a statistically significant impact on the number of over 35 mph events per trip, but there was a slight trend for fewer events during the morning commutes, median of 11 and mean of 13.6 (±9.3), than there were during the evening commutes, median of 12 and mean of 16.0 (±11.1).

Examining the total time spent travelling faster than 35 mph, the overall mean was 24.9 (±8.3) minutes. Using the same analysis and model as described above, several factors were found to be significant. First, the cruise control system main effect was significant, Wald χ^2_2=6.19, p=.045. As shown in Figure 7.5, trips that were designated as baseline driving (without the aid of ACC or CACC) resulted in a shorter time spent travelling faster than 35 mph. This bias was probably due to the fact that baseline driving days were usually designated for Thursdays or Fridays, which as discussed in Figure 7.4, tended to be days with longer commutes due to increased traffic.

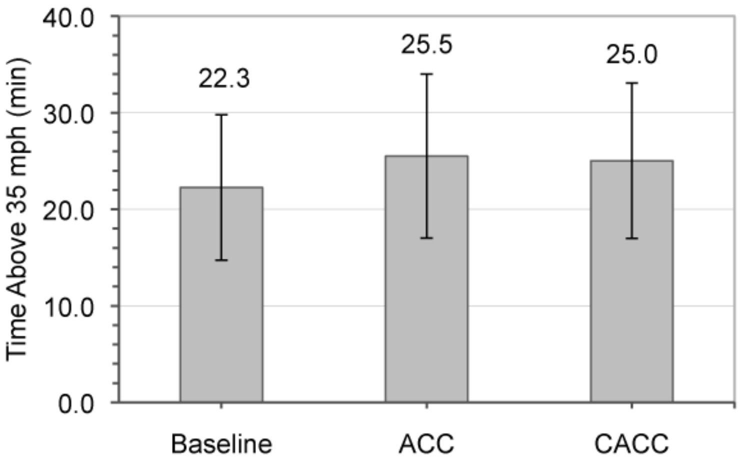

Figure 7.5: Opportunity for ACC/CACC System Use by Study Phase.

While the heavier traffic typically present later in the week may have provided less opportunity for participants to be travelling at speeds greater than 35 mph during the baseline driving trips, the analysis of the time spent travelling above 35 mph also found one of the higher order interactions to be significant, which may also account for the biases in the baseline driving condition. The interaction between gender, time of day, and cruise control system was found to be significant, Wald χ^2_2=6.785, p=.034. Typically, in small sample sizes, higher order interactions end up being the result of some bias in the sample, and in this case, that appears to hold true. As shown in Figure 7.6, the morning baseline drives for males resulted in more time spent above 35 mph, 26.2 minutes, than the other baseline drives, which ranged from 21.4 to 21.8 minutes spent above 35 mph. The reason for this appears to be a small sampling bias in the number of baseline drives that were collected for the males. For whatever reason, be it system failure or the participant simply forgetting that it was a baseline driving day, there were no morning baseline driving trips recorded for three of the male participants, who also just happened to be the three males with the shortest commutes (ranging from 23 to 28 miles).

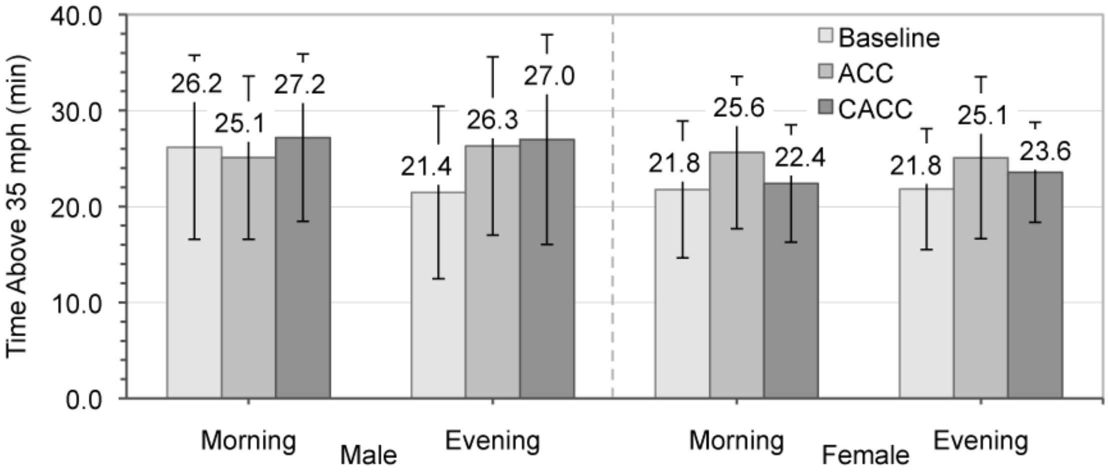

Figure 7.6: Gender by Time-of-Day by Cruise Control System Interaction.

Finally, in the analysis of the time spent above 35 mph, both time of day and day of the week were marginally significant, Wald χ^2_1=2.73, p=.098 and Wald χ^2_1=2.75, p=.097, respectively. As shown in Figure 7.7, morning commutes tended to offer more opportunity for ACC/CACC system use, and as the week progressed, there was decreasing opportunity for ACC/CACC use during the commutes. However, the mean difference in opportunity for cruise control system use between morning and evening commutes was less than a minute, and the mean difference in opportunity for cruise control system use between early in the week and later in the week was on the order of two-and-a-half minutes.

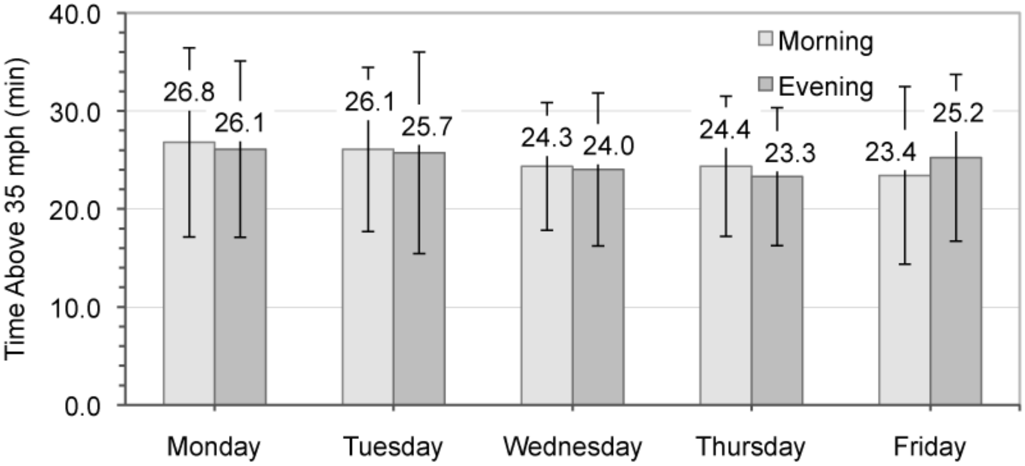

Figure 7.7: The Relationship Between Time of Day, Day of the Week, and Opportunity for System Use.

7.4 Summary and Conclusions

One of the key concerns when running a short-duration, naturalistic, field experiment on public roads is the potential for uncontrolled circumstances, such as weather or traffic patterns, to systematically bias the results. The focus of this report section was to provide a description of the study participants, and to examine the resulting data set of commuting trips to determine whether or not there were any obvious biases which may have influenced the participants' decisions to use the ACC or CACC systems. The sample collected in this study appeared to be well balanced in terms of gender, driver age, and commute length, and the commuting trips collected during this study covered a large part of the Bay Area freeway system. However, it should be noted that most of the participants' commutes were somewhat biased towards being reverse commutes. In essence, this was partially intentional as it provided participants with more opportunity to use the ACC and CACC systems, which were only designed to function at speeds greater than 35 mph.

The data set of commuting trips gathered during this experiment was examined in terms of overall commuting time and opportunity for ACC or CACC use, as measured by the number of events when the vehicle was travelling above 35 mph and the total time during each trip that the vehicle was travelling above 35 mph. Regarding the overall commuting time, morning commutes tended to be shorter than evening commutes, and commutes later in the week, Thursdays and Fridays, tended to be longer, but the difference between the mean commute length on the shortest and longest days was only on the order of 20 percent, or about 10 minutes.

Regarding the opportunity for ACC and CACC use during the commutes, there did not appear to be any significant biases in the number of times that drivers were travelling at speeds greater than 35 mph, but there were some minor biases in the amount of time that drivers spent travelling at speeds greater than 35 mph. Similar to what was found in the analysis of the overall commuting time, there were marginally significant trends showing that there was slightly more opportunity for cruise control system use during the mornings and earlier in the week. Furthermore, since baseline driving days were typically designated on Thursdays and Fridays, there appeared was typically less opportunity on baseline trips to be travelling at or above 35 mph. However, the mean reduction in the opportunity to travel at freeway speeds during baseline driving was only on the order of 10 to 15 percent, or effectively an average of about 3 minutes less per trip. Overall, there do not appear to be any major biases in the data set.

8 Baseline Vehicle-Following Behavior

8.1 Definition of Baseline Vehicle-Following Events

During the 13 days that the participants were in possession of the ACC enabled test vehicle, two days, or four commuting trips, were designated as baseline driving days, when the participants were instructed not to use the ACC system. The goal of including baseline driving days in the experiment protocol was to allow for the analysis of the participant's normal vehicle following behavior when driving manually, unaided by the ACC system. The original protocol had specified two baseline driving days, one early in the test and one late in the test.

As discussed in Section 7, the baseline driving days typically fell on the first and second Thursdays of the study, though some baseline driving trips were done on Wednesdays or Fridays. As previously noted, since the baseline driving trips fell later in the week, there was a bias towards heavier traffic and slightly less opportunity for driving at freeway speeds during the baseline driving days. The data set used in the analyses in this section consisted of a total of 51 commutes composed of 58 individual trips, as some of the commutes spanned multiple vehicle trips. The baseline driving trips were then mined for vehicle-following events.

The vehicle-following events were characterized by three criteria. First, only events when the participant's vehicle was travelling at more than 35 mph were examined, since this was the range of speeds most directly related to use of the ACC and CACC systems. Second, events were included only if they lasted more than 5 seconds. The goal of the baseline driving analysis was to look at sustained following behavior under manual driving, and following events that lasted less than 5 seconds were generally considered too transitory for the driver to consciously adjust to a comfortable following time gap. Finally, following events required a lead vehicle to be present at a following time gap of less than 4 seconds. At freeway speeds, 4 seconds was nearing the maximum range of the forward looking sensor, but more importantly, in urban traffic, following time gaps in the range of 4 seconds may not even be considered by many drivers to be vehicle following.

In addition to the main criteria laid out above, vehicle-following events that were separated by less than 2 seconds were merged into a single event in order to account for issues such as sensor target drop-outs, but it should also be noted that the term following event does not necessarily indicate that the participant was following a single lead vehicle for the entire duration of the event. A single following event may include the participant following several different vehicles, as long as the changing of the lead vehicle did not cause a break in the defined following criteria. Furthermore, although the data used in these analyses have been termed as following events, the data were not filtered or reduced to the point where it could be determined if the participant was actively engaged in vehicle following, i.e., whether or not the participant was actively adapting the vehicle's speed to the speed of the lead vehicle.

8.2 Baseline Following-Event Analysis Results

8.2.1 Overview

There were 712 vehicle-following events recorded on baseline driving trips, although some of the analyses presented in this section only use 704 of the following events. Eight of the following events occurred just prior to or just after a DAS system failure, and as such, they could only be considered as partial following events since either the beginning or end of the event was not recorded. The mean number of baseline following events per driver was 44.5 (±26.6), but the number of events per driver ranged from as few as 12 to as many as 104. The mean number of baseline following events per trip was 12.3 (±7.4), but some trips had as few as 2 or as many as 37 following events recorded.

The overall mean length or duration of the baseline following events was 1 minute 14 seconds (± 2 minutes 13 seconds); however, the median event duration was only 28.6 seconds. The distribution of the following-event durations is illustrated in Figure 8.1. Almost 70 percent of the following events lasted for less than 60 seconds, and 95 percent of the events were under 5 minutes. The shortest events were just above 5 seconds (the analysis cut-off point). The longest event was 22.4 minutes, but there were only 7 events longer than 11 minutes.

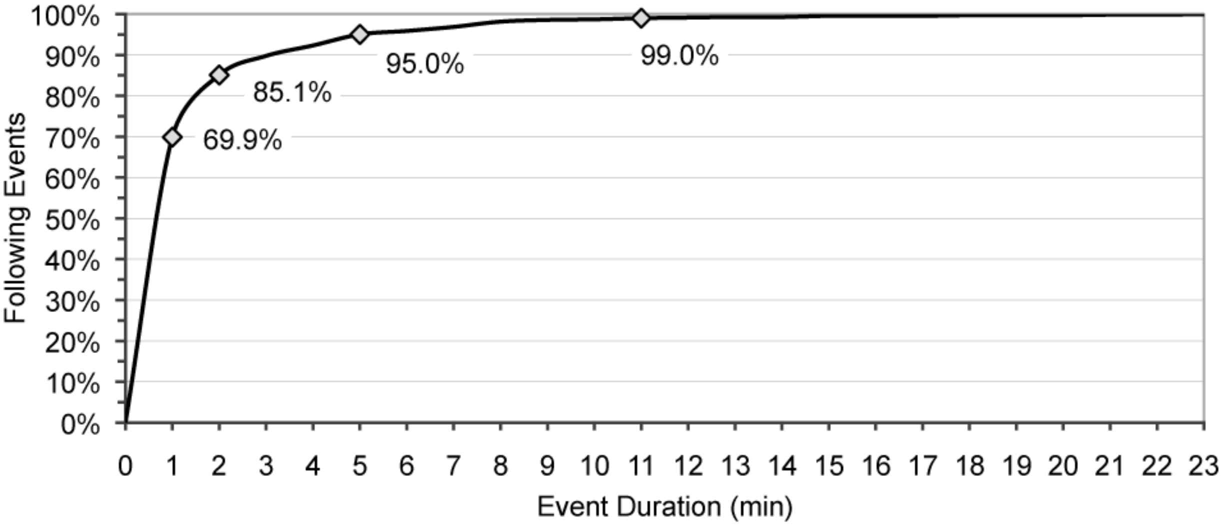

Figure 8.1: Cumulative Distribution of Baseline Following-Event Durations.

The event durations were examined using a repeated measures, generalized estimating equation based on the Gamma distribution and a log-linear link function. In the model, gender was considered a between-subjects factor and commute time of day was considered a within-subjects factor. Day of the week and day of the study were modeled as covariates. None of these factors appeared to be significant, suggesting that the sample of baseline following events was not biased towards any gender group or commuting trips.

8.2.2 *Following-Event Speeds*

For each following event, the time-weighted mean speed during the following was calculated. The mean following-event speed was 24.4 ± 5.8 m/s (54.6 ± 13.0 mph). Although the following-event mean speeds ranged from 15.8 m/s (35.3 mph) to freeway speeds in excess of 80 mph, the standard deviation of the speeds within each event was relatively low, averaging only 1.5 ± 1.1 m/s (3.4 ± 2.5 mph). This suggests that within the following events, the speed maintained by the driver did not vary widely, and that the following events were relatively steady state. However, this may have been, in part, due to the criteria that were used to define following events.

A repeated measures generalized estimating equation was used to examine whether or not there were any biases in the data set regarding the speeds during following events. In the model, gender was considered a between-subjects factor and commute time of day was considered a within-subjects factor. Day of the week and day of the study were modeled as covariates. None of these factors appeared to be significant, suggesting that, in terms of following speeds, the sample of baseline following events was not biased towards any gender group or commuting trips.

8.2.3 *Following Time-Gaps Under Manual Driving*

The mean following-event vehicle-following time-gap was 1.64 (±0.69) second, but in this case, the mean is somewhat misleading. As shown in the cumulative distribution in Figure 8.2, over 70 percent of the following done under manual driving was at or below a following time-gap of 1.6 s. Just under 80 percent of the manual following was done in the range of gap settings offered by either the ACC or CACC systems. Approximately 44 percent of the following was at time-gaps in the range offered by the ACC system, between 1.1 and 2.2 s, and 35.8 percent was at time-gaps in the range offered by the CACC system, between 0.6 and 1.1 s. Less than 3 percent of the following was done at time-gaps of less than 0.5 seconds, and only 12.6 percent of the following was done at time-gaps greater than 2.2 seconds.

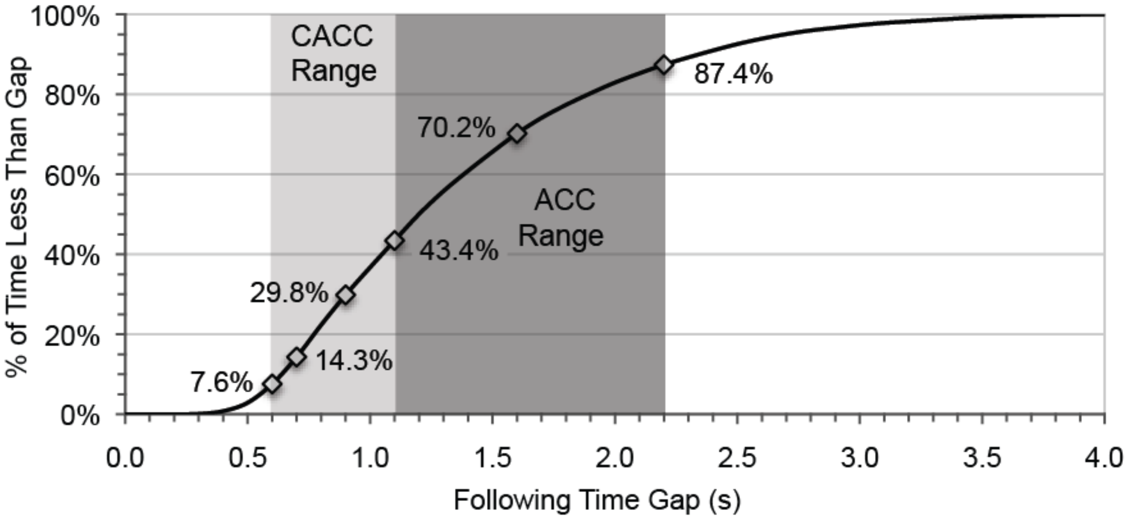

Figure 8.2: Cumulative Distribution of Baseline Driving Vehicle-Following Time-Gaps.

A repeated measures generalized estimating equation was used to examine the mean time-gaps for the following events. In the model, gender was considered a between-subjects factor and commute time of day (morning vs. evening) and baseline session (before ACC experience vs. after ACC experience) were modeled as covariates because both factors suffered from missing cells. Additionally, a main effect for the duration of the following event was modeled as a covariate, under the hypothesis that drivers may tolerate shorter following time gaps for shorter following events. The main effect of the following event duration covariate was significant, Wald χ^2_1=52.96, p<.001, and of the subject and trip factors, only the two-way interaction between gender and baseline session was marginally significant, Wald χ^2_1=2.90, p=.088.

In Figure 8.3, the mean following time gap for each following event is displayed on the x-axis, and the event duration is displayed on the y-axis. From this scatter plot, it can be seen that following events that were relatively short, 1 to 2 minutes, had mean time gaps that were fairly evenly distributed across a range from 0.5 to over 3.5 seconds. Following events with longer durations, over 2 minutes, were more apt to be clustered with the mean following time gap falling into a range between 0.5 and 2.0 seconds. There are a number of possible explanations that might account for such a relationship between the mean following time gap and the duration of the following event. As previously discussed, short following events may not be long enough for drivers to reach the point when they are really engaged in closed-loop following at their desired following distance. Additionally, longer following events will inevitably be influenced by traffic conditions. In heavier, denser traffic conditions where prolonged following would be likely, the traffic density might be influencing the driver to follow for longer periods of time at closer ranges than the driver might choose when traffic is lighter and there is more freedom to change lanes and maintain a desired speed. The nature of this relationship is certainly a topic for further research.

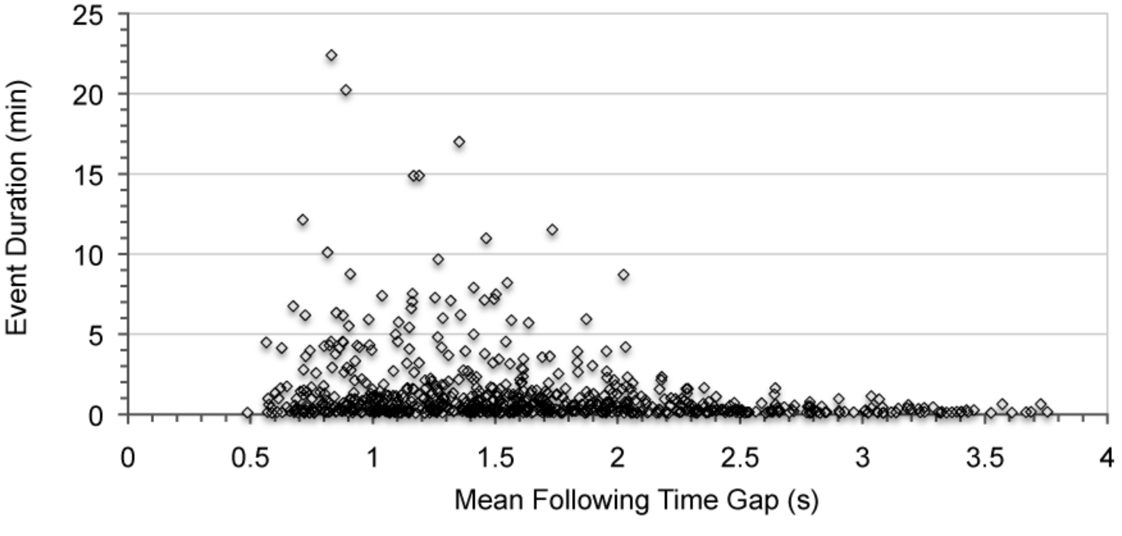

Figure 8.3: Mean Vehicle-Following Time-Gap vs. Following-Event Duration.

Regarding the two-way interaction between gender and baseline session, the trend for males showed a slight reduction in the mean manual following time gap from 1.78 s before ACC experience to 1.44 s after ACC experience, while the trend for females showed a slight increase in the mean manual following time gap, from 1.69 s before ACC experience to 1.77 s after ACC experience. Unfortunately, this trend is probably an artifact of missing baseline trip data. Three of the male drivers with relatively longer mean following time gaps only had baseline trips recorded early in the study, while the one male driver with the shortest mean following time gap only had baseline data recorded late in the study. The situation for the females was similar but reversed. Two of the females with relatively longer mean following time gaps had no baseline data recorded early in the study. If the missing cells were removed, the magnitude of the reduction in mean following time gap between baseline sessions for males would only be about 0.2 seconds, and there would be no noticeable change between baseline sessions for females.

Although the results of the regression models based on the mean following time-gaps for each following event showed no significant differences between men and women, there was a noted visual difference when comparing the male and female cumulative distributions of following time-gaps as shown in Figure 8.4. In the range of following time-gaps above 1.6 s, the cumulative distribution curves for males and females were nearly identical. However, below 1.6 s, the cumulative distribution curves indicated that the males tended to spend more time following at shorter time-gaps than the females.

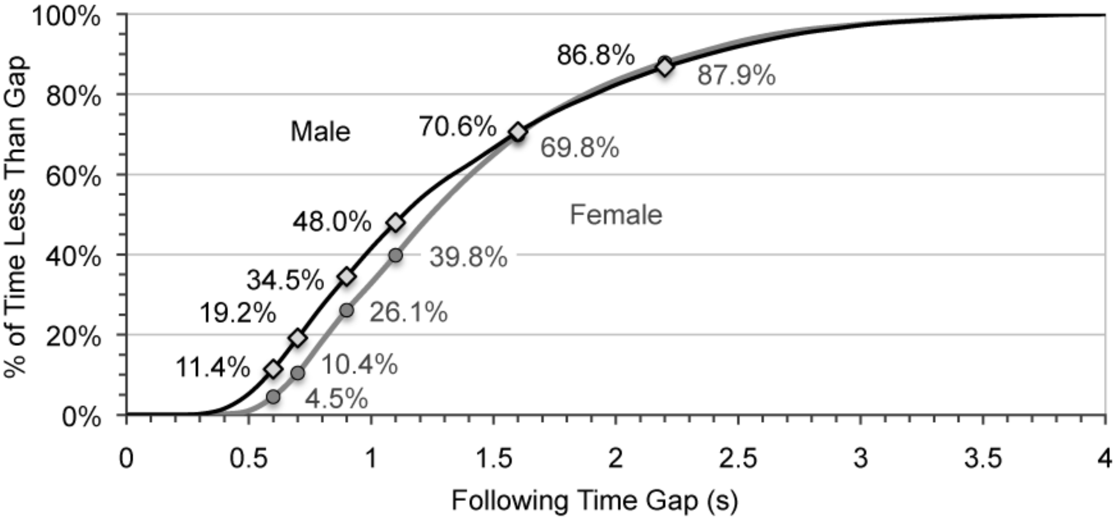

Figure 8.4: Gender Differences in the Cumulative Distribution of Following Time-Gaps.

To further examine the gender differences that were noticed in the cumulative distribution curves, the range of following time-gaps was divided into eight intervals or bins, roughly coinciding with the time-gap settings that would be available on the ACC and CACC vehicles. The shortest following time-gaps were categorized into a bin ranging from 0 to 0.5 s, and the longest following gaps were categorized into a bin ranging from 2.5 to 4.0 s. The intermediate categories were centered around the ACC and CACC time-gap settings of 2.2, 1.6, 1.1, 0.9, 0.7, and 0.6 s.

As shown in Figure 8.5, the main difference between males and females was that males spent about twice as much time, about 15.3 percent of the time, following at shorter time-gaps, 0.6 seconds or less, than did females, who spent only about 7.1 percent of the time following at short time-gaps . Conversely, 47.8 percent of the manual following done by the female drivers was centered around the 1.1 and 1.6 s time-gap settings which would be offered by the ACC system, while the only 38.1 percent of the manual following done by the male drivers fell into this same time-gap range.

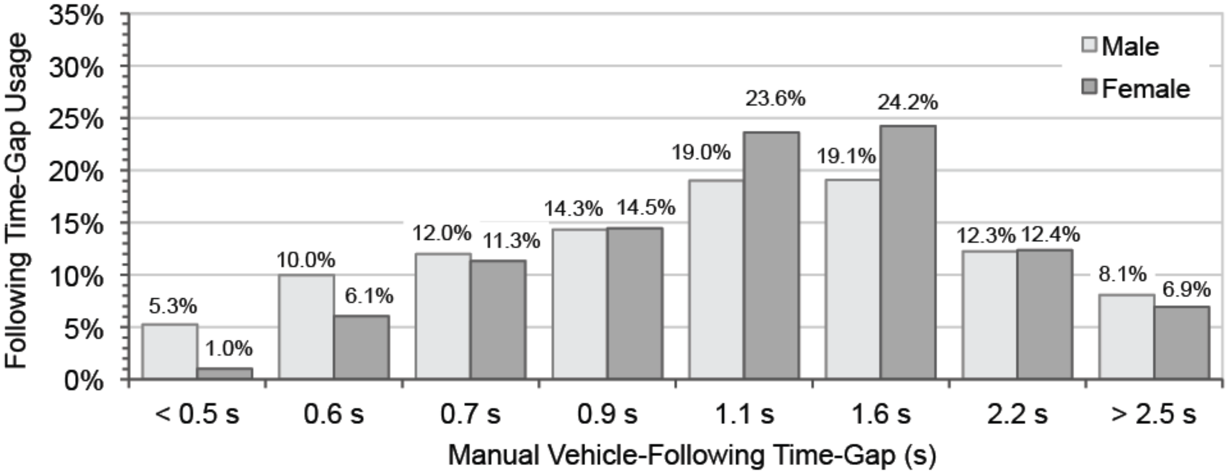

Figure 8.5: Gender Differences in the Time Spent Manually Following at Different Time-Gaps.

The first method used to test whether or not the gender differences in the distribution of manual following time-gaps were significant involved calculating an overall distribution of following time in each of the time-gap bins for each participant. A two-tailed, independent-samples, t-test, with gender as the independent measure and percent of following time in each bin as the dependent measure, was performed for each of the eight following-time-gap bins. None of the individual bin-by-bin gender differences were significant; however, it should be noted that this method considers the testing of each time-gap bin as being independent, and as such, a much larger number of participants would be needed in order to achieve enough power to estimate a population mean for the percent of time spent at each gap setting.

A second method used to examine the choice of following time-gaps under manual driving used a repeated measures, generalized linear model with gender as a between-subjects factor, time-gap bin as a within-subjects factor, and percent (of time) spent in each time-gap bin as the dependent measure. Although the time-gap-bin factor was significant, $F_{7,8}=126.97$, $p<.001$, neither gender nor the gender by time-gap-bin interaction was significant. Post-hoc, pairwise comparisons tended to confirm category differences seen on the pie charts. The times spent manually following in the ranges of the middle categories of following time-gap, from 0.9 to 2.2 s, were generally similar and differed significantly from the time spent manually following at shorter time gaps.

Finally, a third method was used to test whether or not there were gender differences in the distribution of manual following time-gaps. This method involved converting the percent of time spent following in each time-gap bin into a ranking of the time-gap bins. As examples, for each driver, the time-gap bin with the highest percentage of time was assigned a 1 for the most preferred following time-gap, and the time-gap bin with the lowest percentage of time was assigned an 8 for the least preferred following time-gap. The analysis of following time-gap preference data (ranking data) used a repeated measures, ordinal-logit, generalized estimating equation. The ordinal-logit model assumes a multinomial distribution with a cumulative-logit link function, which is the type of model typically used for the analysis of categorical preference data. Gender was considered a between subjects factor, the following time-gap bin was a within-subjects factor, and the response was the ranking of each time-gap bin. Although the main effect of gender was not significant, both the time-gap bin and the interaction between gender and time-gap were significant, Wald χ^2_7=68.74, p<.001 and Wald χ^2_7=15.74, p=.028, respectively. Although the interpretation of this regression model is less straightforward, parameter estimates are related to the calculation of the probability of a ranking in a particular category being different from a reference category. For the main effect of time-gap bin, the reference category was the shortest time-gap bin or less than 0.5 s. Since the shortest time-gap bin contained the least amount of time spent, it was generally ranked as the least desirable, and thus, the significance of this factor simply indicated that all categories were more likely to be ranked higher than the shortest time-gap bin. Similarly, the significant gender by time-gap bin interaction indicated that the females were slightly more likely to rank the 1.1 and 1.6 s time-gap bins higher than the males.

8.3 Summary and Conclusions

Most of the baseline following events that were collected during this study were relatively short, under a minute, with the mean speeds during the events ranging from just over 35 mph (the cut-off for this analysis) up to freeway cruising speeds. Only about 30 percent of the following events lasted for more than one minute, and only half the drivers had baseline following events that lasted more than 2 to 3 minutes. The overall mean following time-gap was about 1.6 s, and the mean time-gap during the following events ranged from 0.5 to just over 3.5 s. However, there was a significant covariance between the following-event duration and the mean following time-gap. When the event duration was short, under a minute, the means for the following time-gaps were spread over the full range, but when the event durations exceeded a minute or so, the mean following time-gaps were more concentrated in the 0.6 to 2.1 s range (which coincidentally covers the operating ranges of both the ACC and CACC systems).

Additionally, there was some evidence of a trend towards a gender difference in the baseline following behavior. The males in the study spent more time (about twice as much, percentage-wise) following at short time-gaps (0.6 s and under) than did the female drivers in the study. However, most of the analysis techniques did not find this trend to be significant given the small sample size in this experiment.

Finally, there can certainly be some debate over the results presented in this section, specifically on the matter of just what conditions constitute a following event. In this case, a very liberal definition of following event has been used, and as a consequence, this analysis may be giving more weight to brief following events than is deserved. It is likely that events lasting less than 60 s could have been the result of vehicles moving into or out of the driver’s lane. Although this type of event may have required a transient response from the driver, such a response may not, by some, be considered as being actively engaged in vehicle following. Furthermore, drivers may have had a higher tolerance for shorter following distances when the shorter following distances were perceived as, or expected to be, temporary. As an example, if a lead vehicle cuts into the driver's lane, a driver may choose to tolerate a shorter than desirable following distance for a number of seconds in order to avoid hitting the brake. Further data analysis beyond the scope of this report would need to be conducted to understand baseline following behavior in more detail. Such an analysis could concentrate on the starting and ending conditions of the following events. It would also need to know the conditions of how an event started and how it ended, and it would need a method to establish whether or not the driver really established a following distance equilibrium when the driver could be said to be "actively" engaged in regulating the gap behind the lead vehicle.

9 ACC & CACC Driving Behavior

9.1 ACC Usage

The results in this section are based on 173 commutes over 180 individual trips when the participants were allowed free use of the ACC system. There was a median of 11 ACC commuting trips per driver, with a minimum of 7 trips and a maximum of 17 trips. The description of drivers' behavior with the ACC system examines the behavior at three levels. At the highest level, the overall duration of ACC usage will be described. At the middle level, the specific conditions surrounding the activation and deactivation of the system will be explored in terms of speed and time-gap setting selection. Finally, at the lowest level, the distributions of the usage of the available time-gap settings will be examined.

9.1.1 Duration of ACC Usage

As shown in Figure 9.1, in order to present a cumulative distribution of the duration of the individual ACC activations, the data set has been sorted into 12 bins of roughly equal sizes. The first two bins represent only 30 second increments, while the remaining ten bins represent 1 minute increments.

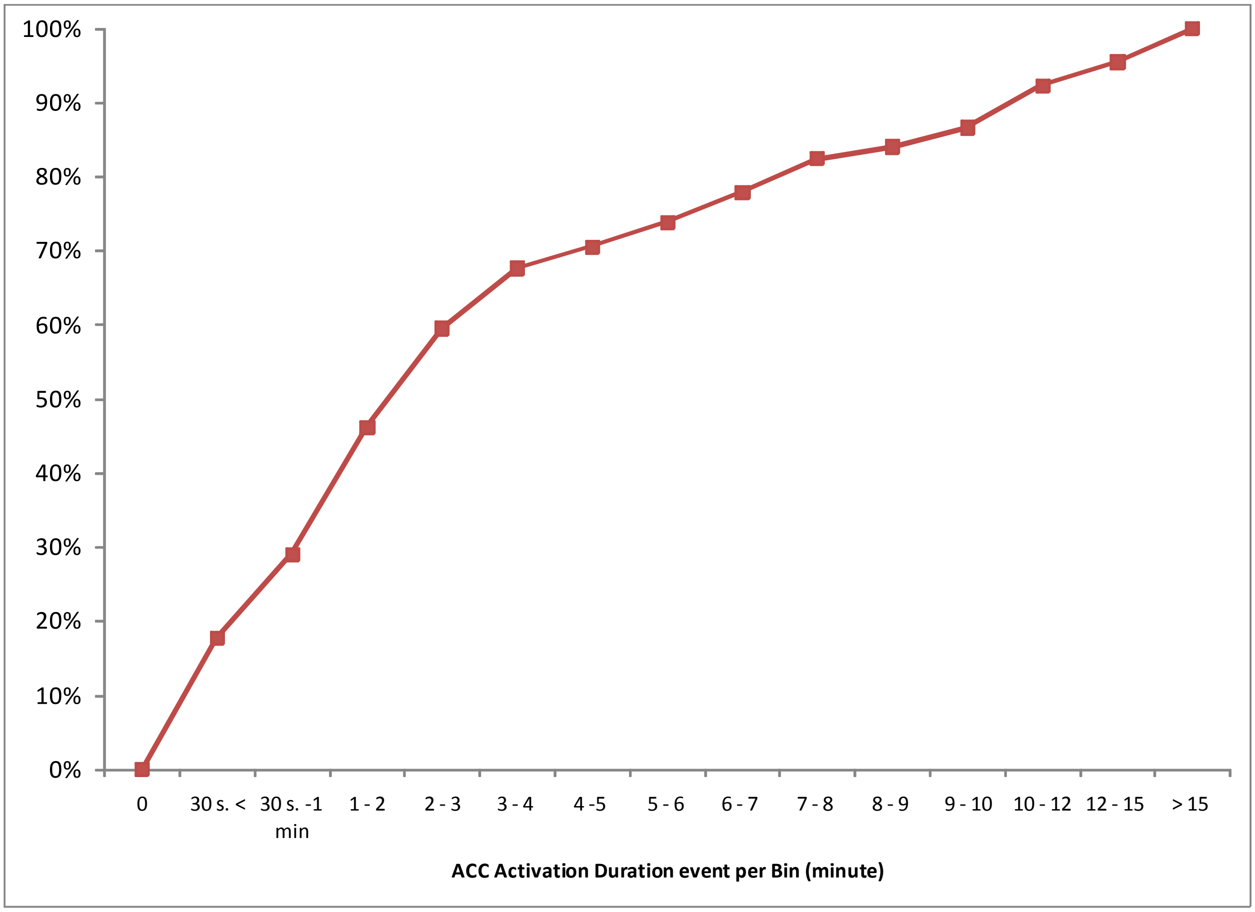

Figure 9.1: Cumulative Distribution of the Duration of Individual ACC Usage Events.

The resulting distribution shown in Figure 9.1 suggests that over 45 percent of the ACC system activations lasted for less than 2 minutes, and over 65 percent of the ACC system activations lasted for less than 4 minutes. The mean activation duration was 4.2 minutes (±5.1 minutes of standard deviation), with a minimum activation of 1.39 sec. and a maximum of 31.7 minutes.

Figure 9.2 displays the average activation event duration as well as the total number of activations per driver. The number of activations has been divided by 10 in order to facilitate the reading of the plot. The plot has also been ordered based on the number of activations. For example, the male participant for whom the smallest number of single activations was recorded is participant 8, while male the participant for whom the largest number of single activations was recorded is driver 12. This ordering shows that the larger number of activations is associated with a lower average duration of each activation. In other words, the participants who have a lower number of activations tend to have longer average activations. A possible explanation is that these drivers had commutes in less congested areas than drivers with a higher number of activations, and they were less likely to turn off the system due to traffic. This explanation will have to be validated in subsequent analysis with a characterization of the level of traffic faced by the participants on their commutes.

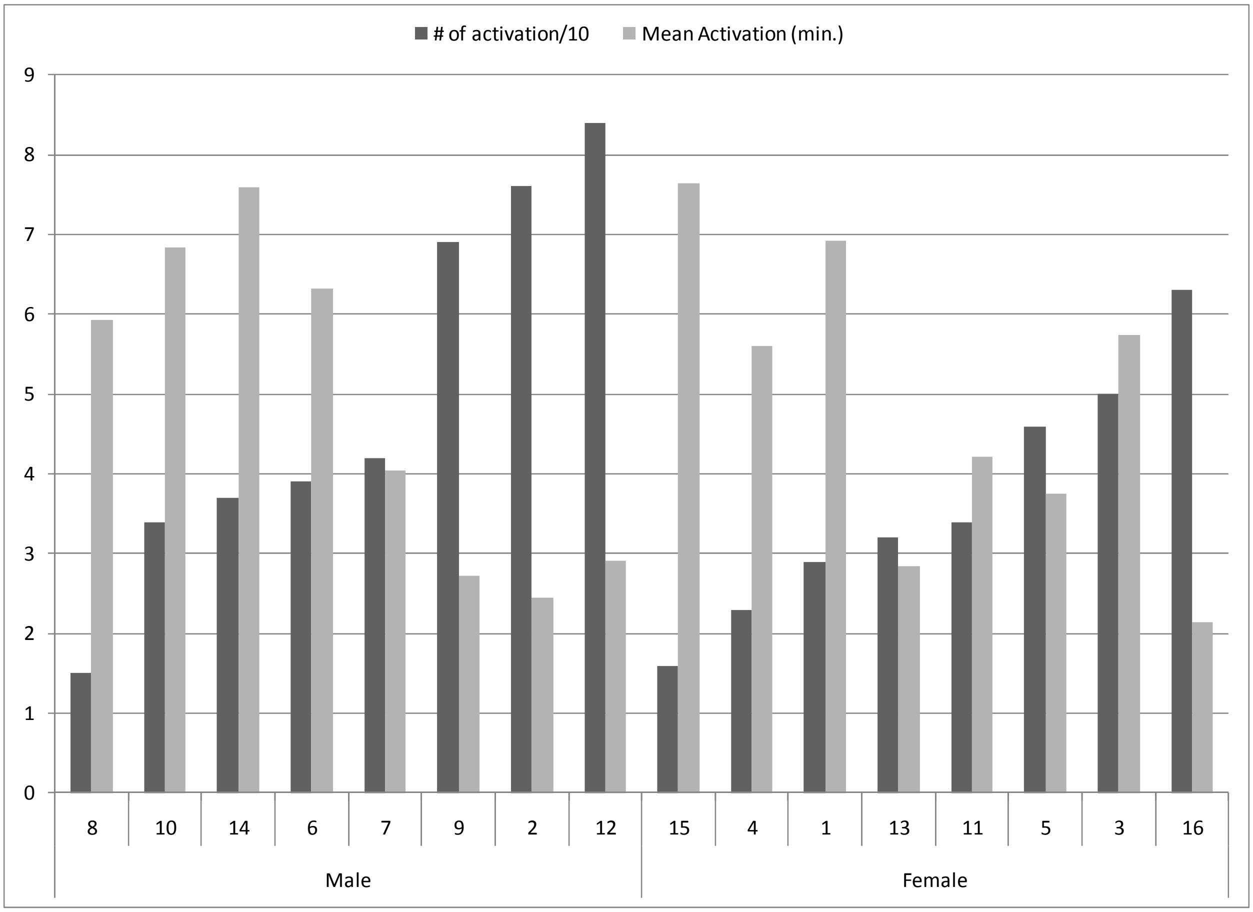

Figure 9.2: Number of ACC Activations and Average Activation Duration per Participant.

9.1.2 *Conditions at ACC System Activation and Deactivation*

The activation and deactivation elements that are presented and discussed below were extracted from the recorded time history of the commute. The goal of this analysis was to get an idea of what was going on each time the ACC system was engaged. As an example, what was the current speed, the system set speed and gap setting, was a lead vehicle present, and if so, what was the time-gap between the two vehicles relative to the system's time-gap setting? Figure 9.3 illustrates the points that were extracted regarding ACC system activations and deactivations.

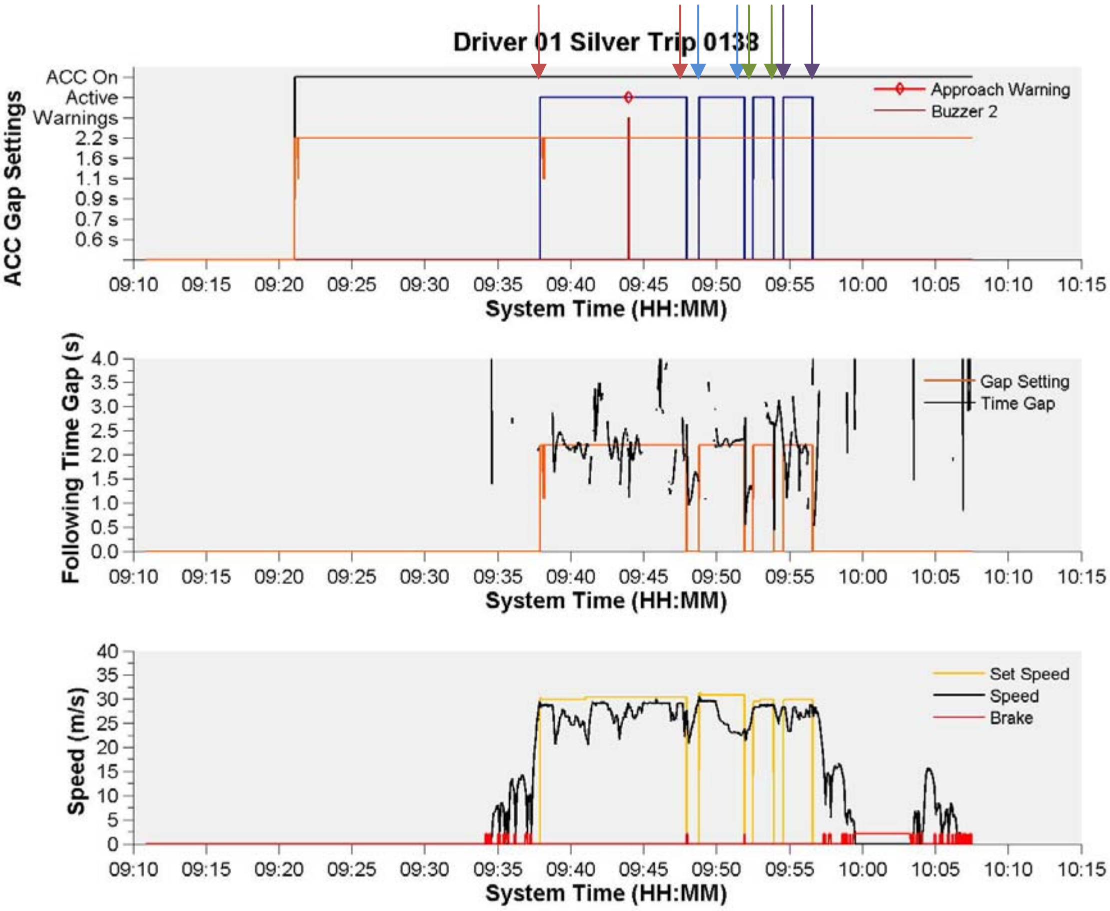

Figure 9.3: Extraction of Information About Beginning and End of System Activations.

During the trip depicted in Figure 9.3, the ACC system was turned on shortly after 9:20 AM, but the vehicle did not start moving until around 9:35 AM. During the trip, there were four ACC system activations. At each point when the system was activated or deactivated, information was extracted from the recorded data files in order to specify what the system settings were in terms of gap and speed, the actual gap and speed.

9.1.2.1 Speed Control

In Figure 9.4 (in the third graph depicting speed vs. time), there appear to be a number of distinct patterns of behavior related to setting the target vehicle speed when activating the ACC system:

1. As shown in the first and third activations, the driver may manually accelerate to his or her desired cruising speed prior to engaging the ACC system. In this case, the ACC set speed will be close to the driver's desired speed, leading to few subsequent adjustments.
2. As shown in the second and fifth activations, the driver may also choose to activate the ACC system by setting cases where the set speed will be actively increased by the driver via the system speed button control, such as the second and fifth activation.
3. Not shown is a third possible behavior. Drivers could have used the "resume" button on the ACC system. Using this feature, the vehicle's previously set speed would have become the new target speed, and the vehicle would have attempted to accelerate back up to that speed. This behavior appears to have occurred rarely.

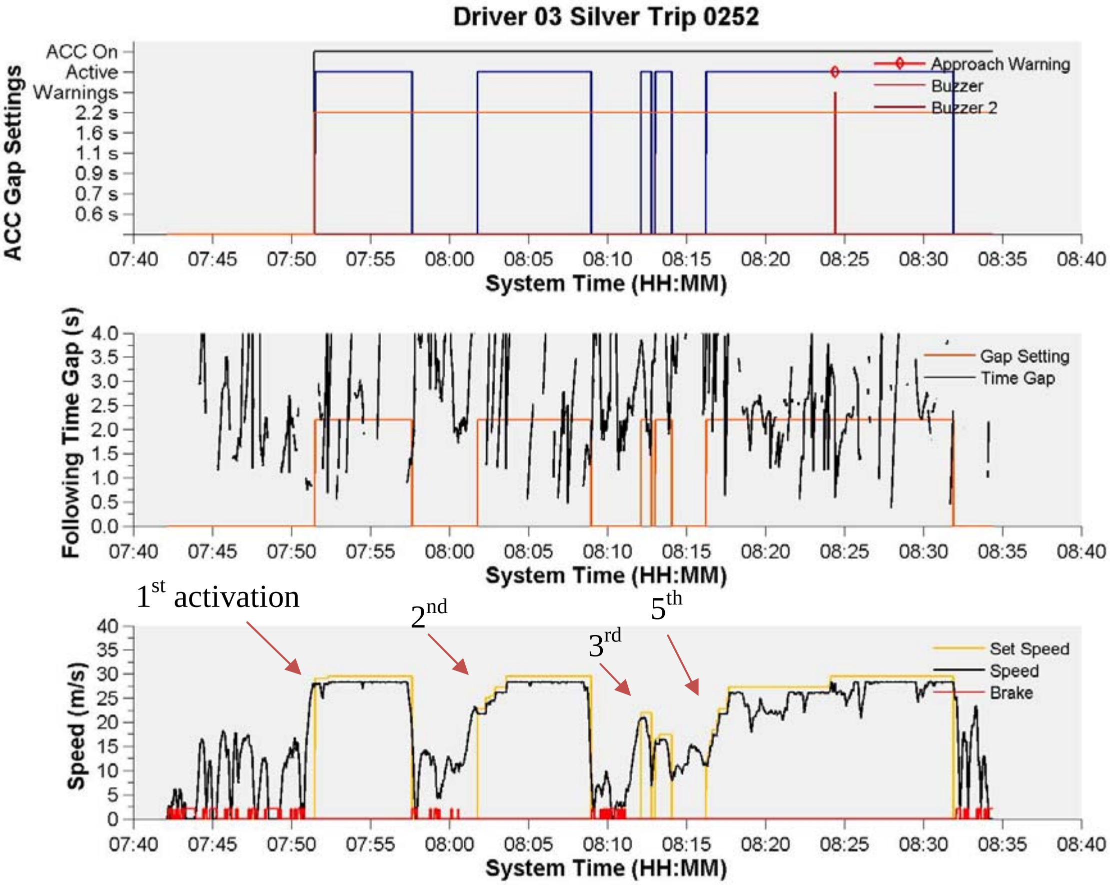

Figure 9.4: Extracting Patterns of ACC System Activation.

For the first ACC system activation of any trip, drivers always needed to use the set speed function[3] in order to activate the ACC system, but for any subsequent activation, they could have chosen to activate the system using either the set speed or resume functions. A possible way to

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[3] As a reminder, a driver can set the speed based on the actual vehicle speed, or, after the first activation, use the resume speed function to reinstate the speed that was first set.

determine which function was used for the speed setting is to plot the set speed when the system was engaged vs. the actual speed, as was done in Figure 9.5.

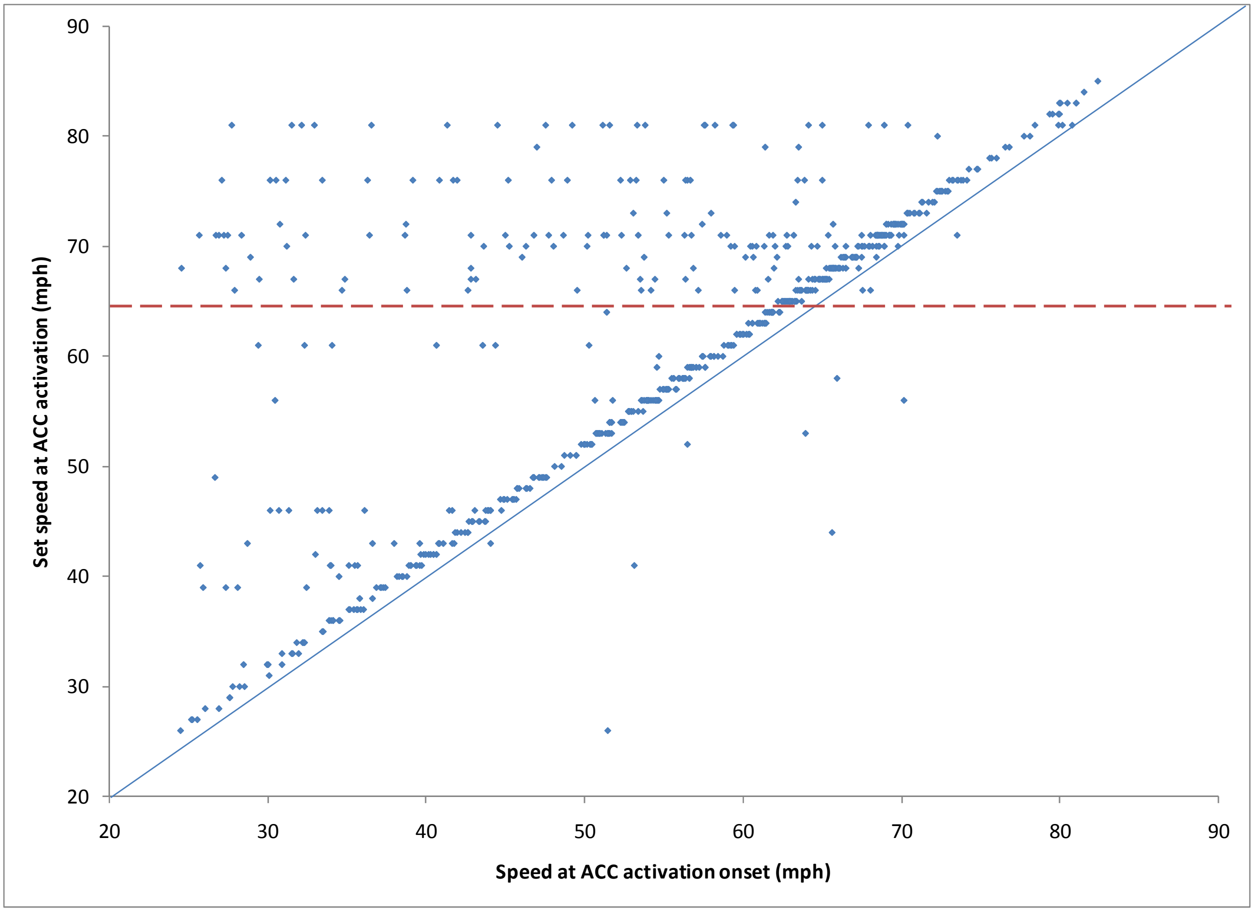


Figure 9.5: Actual Speed at ACC System Activation Onset vs Set Speed.

Two patterns can be distinguished in Figure 9.5:

Pattern 1: the set speed and the actual speed are within 3 mph of each other. This pattern is represented by the points that follow the solid line (over 70% of the cases).

Pattern 2: the set speed is higher than the actual speed when the system is engaged, and is visible in the figure by the points that are on the top left side of the figure. It is interesting to note that most of these points are also above the 65 mph limit (dotted line), which indicates that the drivers used the resume function even though there was a large difference between the set and actual speed (see for example the points where the actual speed is within 30 to 40 mph and the set speed is within 70 to 80 mph).

As shown in the previous figure, there was a bias in that drivers usually opted to reset the target speed before each ACC system activation. This bias could have a number of explanations. First, all of the participants were unfamiliar with the ACC system, so they may not have been familiar with or clearly understood the resume function. Second, the drivers may not have fully trusted the resume function, again, due to their unfamiliarity with the system. Third, the choice to use the resume function could have been due to display design, since the display does not show the previously set speed when the system is in standby mode. Drivers may have been hesitant to resume their previous speed, having forgotten the previous speed setting value. Finally, the bias could have been due to the variability in traffic conditions; however, for this case, it appears that the drivers chose to reset the target speed on each activation, even though the cruising speed seems to be about the same for each "long" stretch of system usage.

A few odd points can be seen on the right side of the line, where the set speed is lower than the actual speed. These cases have not been analyzed as of the writing of this report. Further analysis would be needed to address the speed at which the drivers settled for subsequent activations relative to a previous activation. The overwhelming use of the set speed function, as opposed to the resume speed function, is interesting in the sense that the workload for resuming the previous speed should have been lower than the workload for resetting or adjusting a new speed. It would be interesting to find out whether or not there might be a reason why the resume function was not used more frequently; however, this analysis would need additional coding regarding speed limits and/or other infrastructure factors that were not readily available in the data set that was collected.

A similar plot, Figure 9.6, shows the conditions at the ACC system deactivation. From this figure, three patterns can be identified. First, there were a handful of cases in which the system was disengaged when the vehicle speed fell below 20 mph, regardless of the ACC system speed setting. These cases are represented by the circled cases on the left side of the graph, and they most likely indicate conditions when the ACC system was automatically disengaged, since the system was not designed to work in stop and go traffic.

The second pattern consisted of cases when the set speed and the actual speed were within 3 mph of each other. These cases are depicted on the graph clustered along the solid line, and they represent a little less than half of the total cases, at 45% of the sample. It can be inferred about these cases that the deactivation occurred while the system was in speed regulation mode, instead of gap regulation mode.

The third pattern is represented by the cases between the line and the circle, for which the actual speed was lower than the set speed at the time of the ACC system deactivation. It can be inferred about these cases that the system was in gap regulation mode, instead of speed regulation mode, at the moment when the system was deactivated. For both the second and third patterns, it is hard to speculate on what conditions led to these deactivations without further analysis. These cases could represent preemptive braking for upcoming traffic conditions on the part of the participants, or they could represent deactivations that could be route-related, such as braking in order to take an exit. Such an analysis would likely require a detailed analysis of the recorded video, which was beyond the scope of this report.

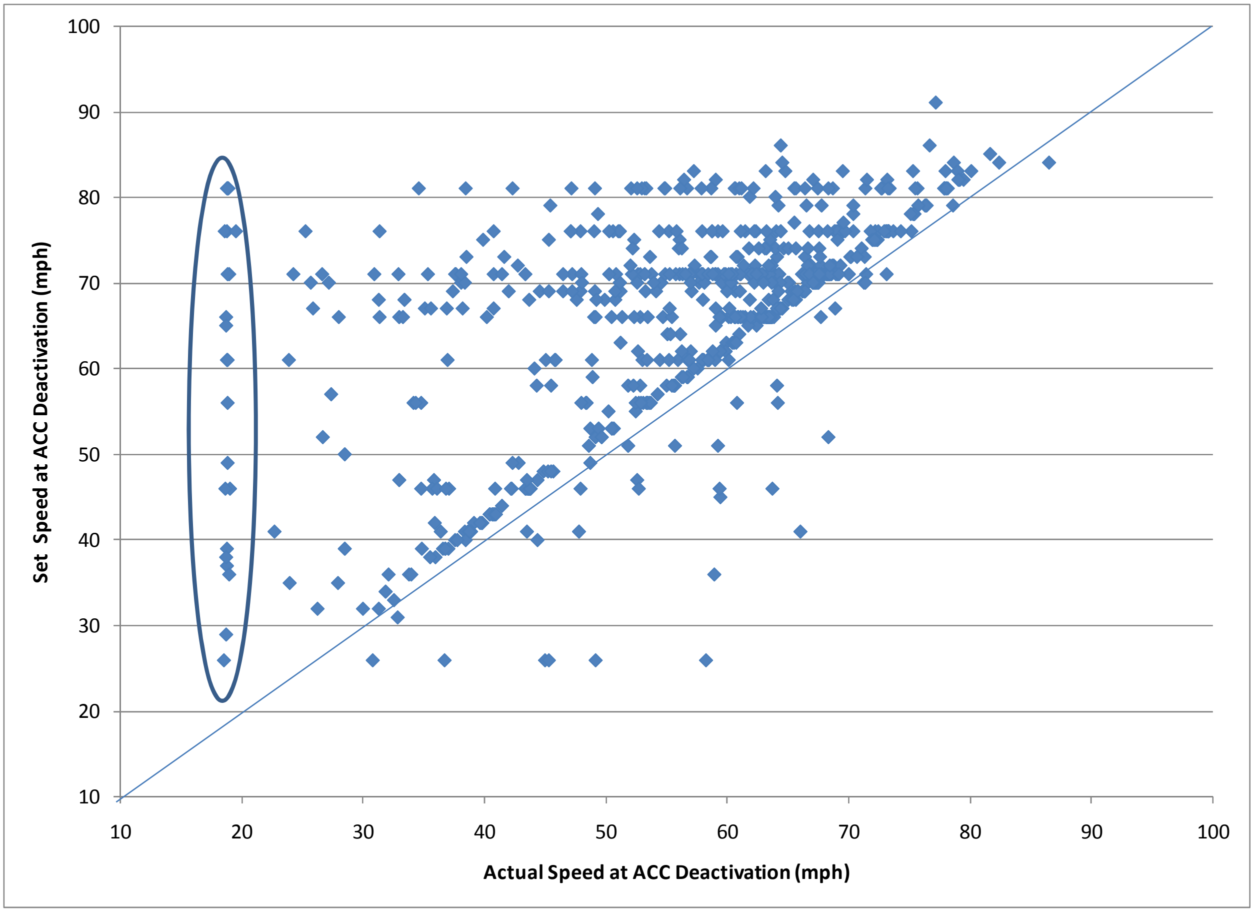


Figure 9.6: Actual Speed at ACC System Deactivation vs Set Speed.

9.1.2.2 Time-Gap Setting Choices

The time gap setting choices described in this section are described in terms of settings selected at the beginning and end of each activation, as well as the presence of a lead vehicle for these conditions and the size of the actual gap vs. the selected gap.

In order to describe the gap setting choices, the data were sorted by the sequence of activations within the trip. Figure 9.7 illustrates the number of trips having each number of activations per trip. For example, for 34 trips only one activation of the system was recorded, and for 6 trips 9 activations were recorded. This figure has been provided as a companion to Figure 9.8, which displays the distribution of gap settings per activation in sequence from the first activation per trip up to activation number 13 and above. Since the distributions calculated in Figure 9.8 are based on the number of activations shown in Figure 9.7, it is important to note that beyond 5 activations, there were fewer cases with which to calculate the distribution, and thus, the errors may be higher.

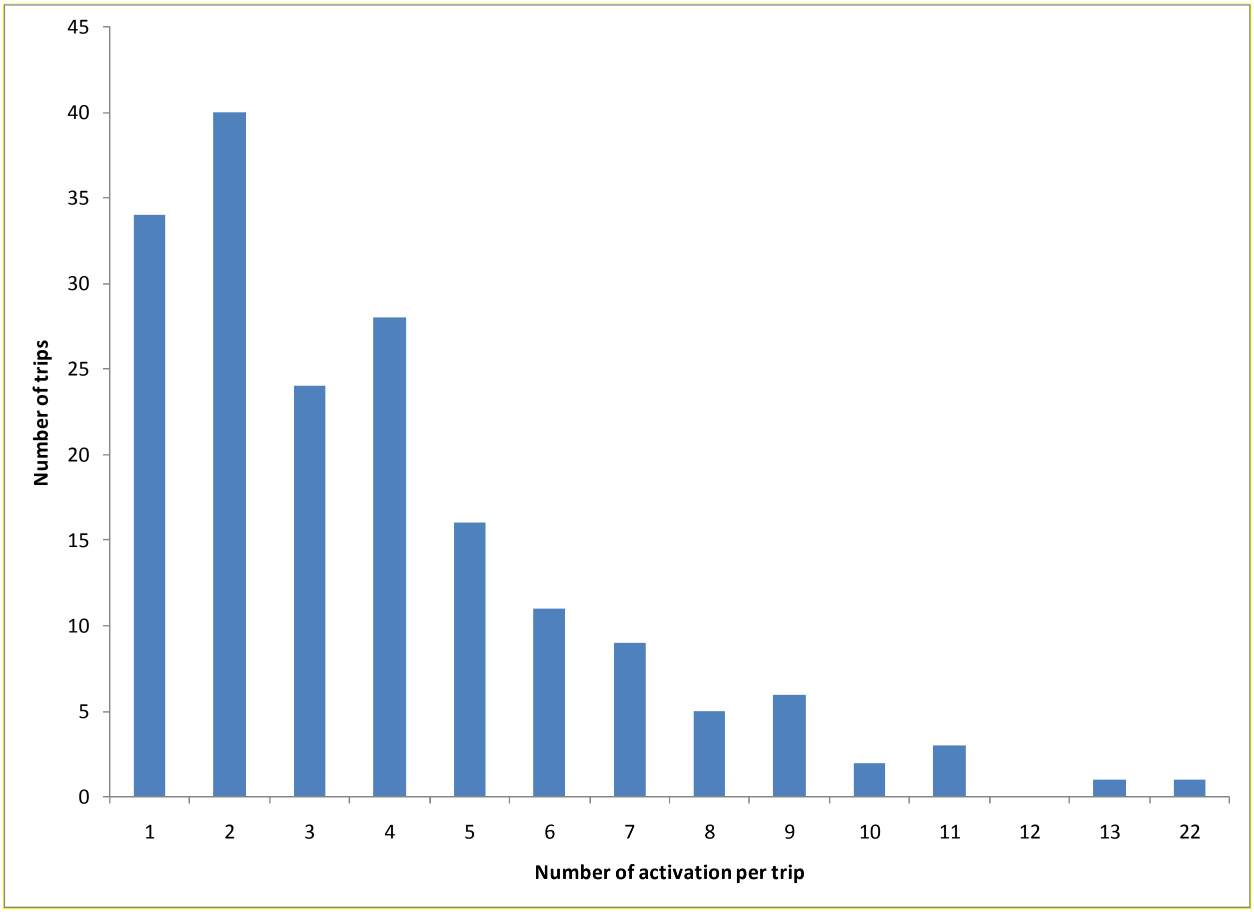


Figure 9.7: Number of Trips by the Number of Activations per Trip.

The distribution in Figure 9.8 shows that the 2.2 sec time-gap setting was selected in more than 70% of the cases for the first activation and that as the number of activations within a trip increases, so does the representation of the 1.1 sec. time gap setting. The 1.6 sec. time gap setting represents 10 to 15 % of the choices for the first four activations, and its ratio diminishes as the number of activations increases. The over-representation of the longest gap setting at the first activation illustrates that the driver was given the default setting when turning the system on. Technically, the driver could have turned on the ACC system and adjusted the default time-gap setting to their preferred setting, but what appears to have happened more frequently was that the driver turned the system on, activated the ACC system at the default 2.2 second time-gap setting, and then adjusted the time-gap setting down to their preferred setting.

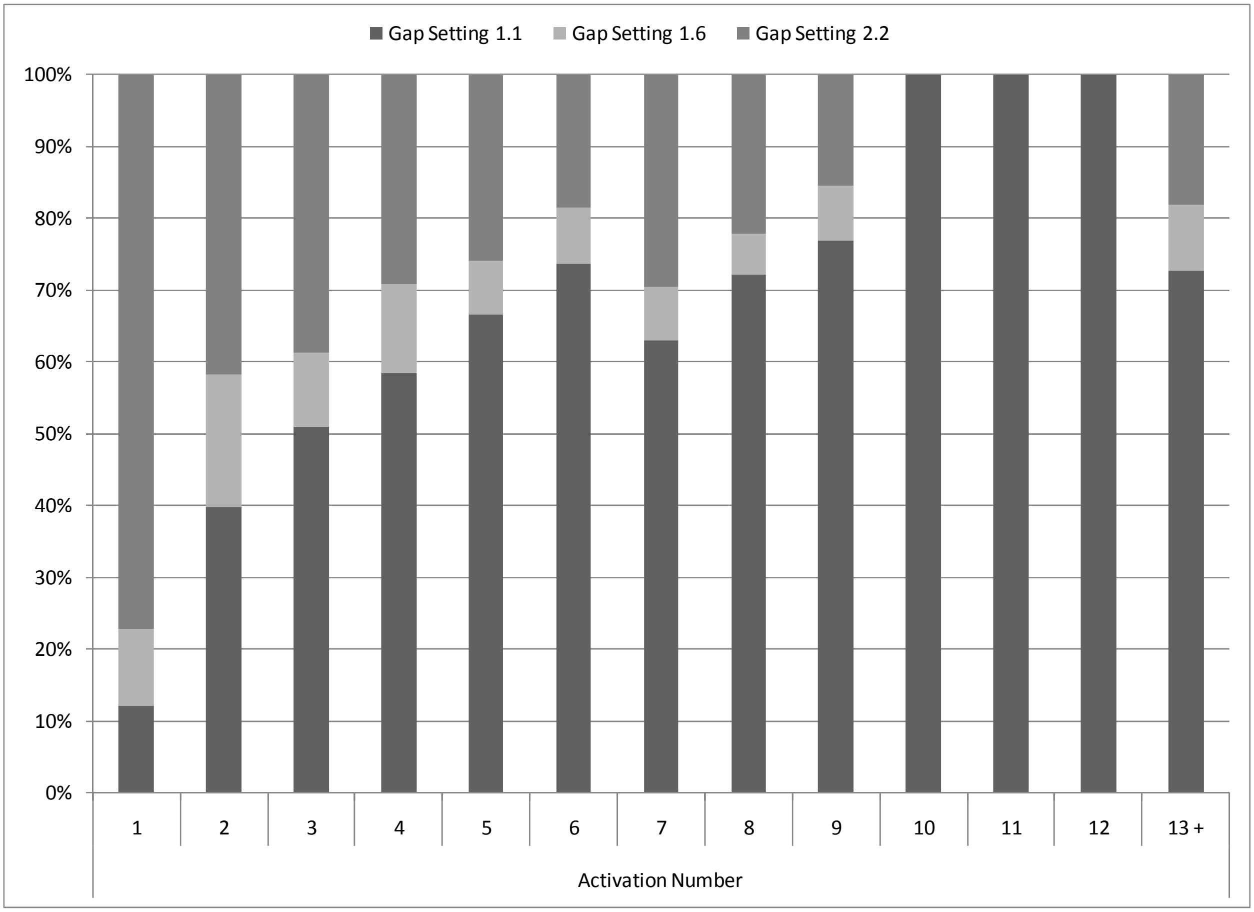


Figure 9.8: Distribution of Time-Gap Settings at Activation Onset by Activation Number per Trip.

The other aspect that was investigated in terms of gap selection at the activation of the system was the presence of a lead vehicle and, for the relevant cases, the size of the actual gap vs. the selected gap. The size of the actual gap can be shorter than, identical to or longer than the gap that the system will regulate. In order to analyze this relationship, the actual gaps had to be sorted relative to each of the gap settings. For example, an actual time gap of 1.2 will be sorted into the identical gap range for the gap setting of 1.1, while it will be in the shorter gap range category for a system setting of 1.6. Table 9.1 describes the limits of the bins for the actual gaps relative to the selected gap for the ACC system.

Table 9.1: Categorization of Actual Gaps Relative to ACC System Gap Settings.

ACC Gap setting	Classification based on range of actual gaps measured		
	Shorter gap range	Identical gap range	Longer gap range
1.1	0.2 to 0.9	0.91 to 1.3	>1.31
1.6	0.2 to 1.4	1.41 to 1.8	>1.81
2.2	0.2 to 2	2.1 to 2.4	>2.41

The sorted data are plotted in histogram form in Figure 9.9. (Note that for each category, the number of cases is displayed.) This figure supports the analysis of the vehicle following situation when the drivers decided to engage the system. In terms of presence of a lead vehicle, for all gap settings there was a fair amount of system activation that occurred when no target was in range of the system, from slightly under 20% for the 1.6 sec time gap setting to 37% for the 2.2 sec time gap setting. This last time gap setting could have had more cases without a target because of its over-representation in the first activation of the system. Further analysis will integrate how long after entering the highway the system was engaged. For example, drivers could have engaged the system for the first time immediately upon entering the highway.

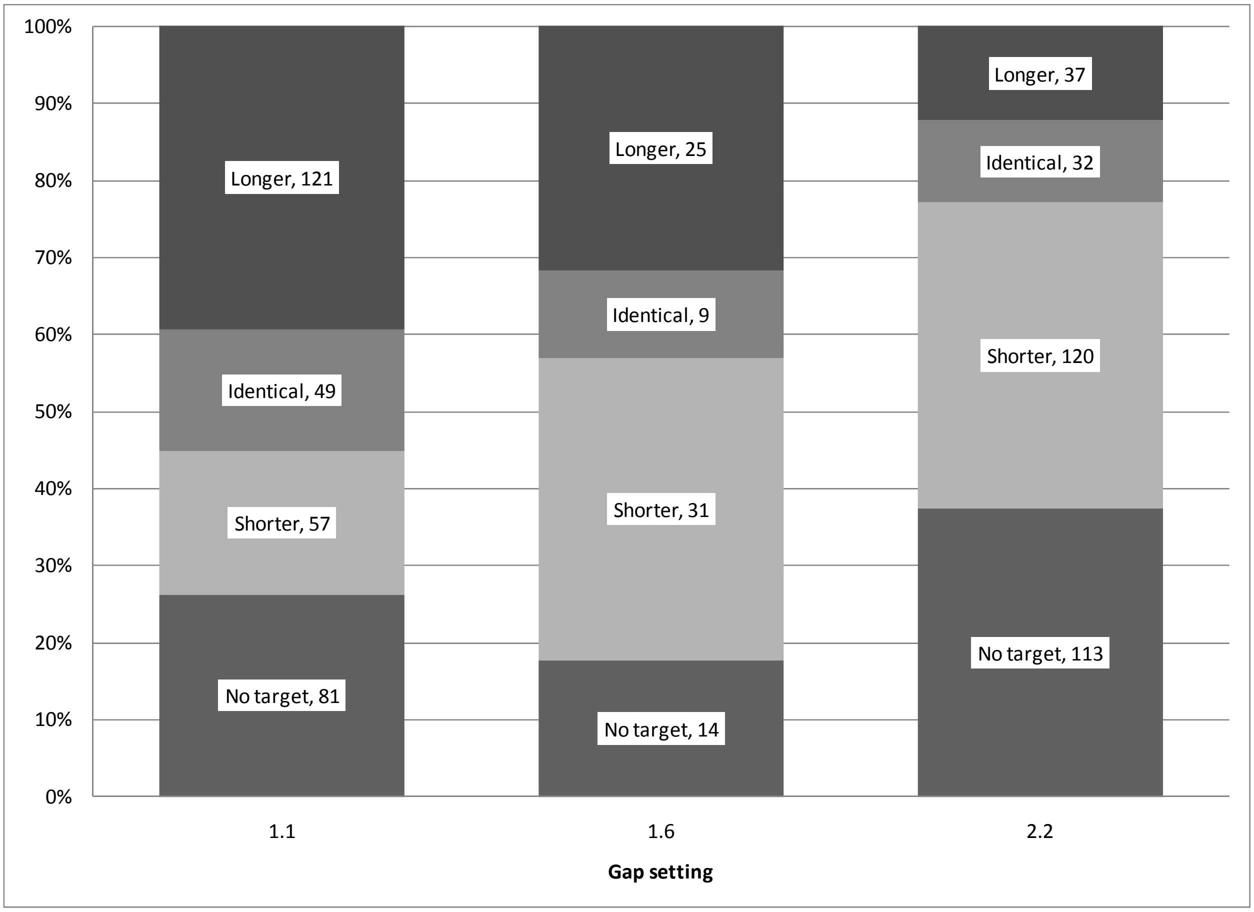


Figure 9.9: Distribution of Actual Gap Size Relative to Gap Setting at ACC Activation.

For cases when a lead vehicle was present, for the 1.1 and 1.6 sec. time gap settings, the greater part of the activations occurred when the gap with respect to the lead vehicle was longer than the gap that will be regulated by the system (39 and 31%), with the second biggest category being a shorter gap. For the 2.2 sec setting, for the greater number of cases the system was engaged when the actual gap was shorter than the gap that would be regulated.

The same parameters were used for describing the deactivation conditions. In Figure 9.10, the distribution of the gap settings at deactivation per activation occurrence follows a similar pattern as at the activation. However, it is interesting to note that while a little over 10% of the first activations started with a time-gap setting of 1.1 sec, a little over 40% of the first activations terminated with a time-gap setting of 1.1 sec, which is indicative of a setting change during the activation.

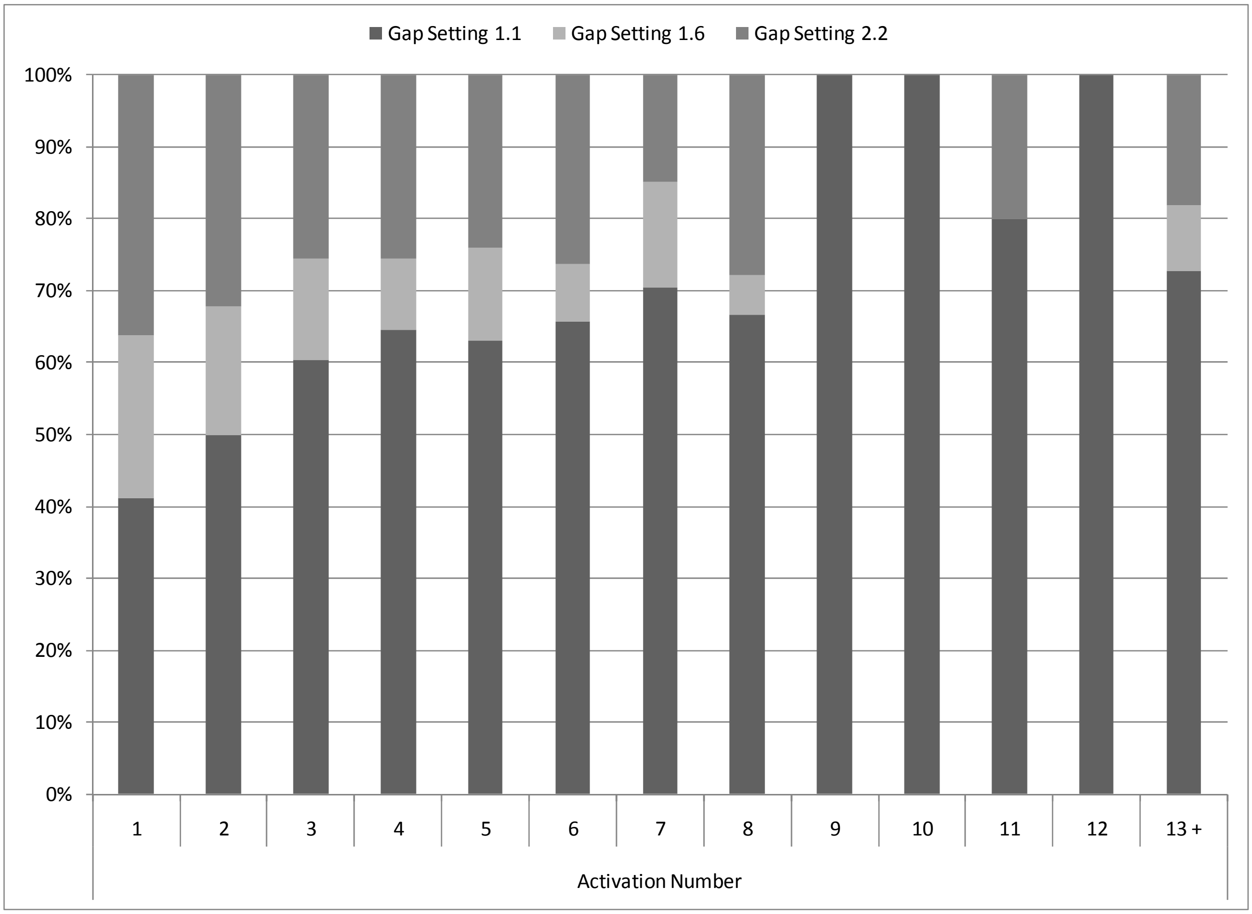


Figure 9.10: Distribution of Time-Gap Settings at Deactivation by Activation Number.

In Figure 9.11, the distribution of cases among the different categories is similar for the 1.6 and 2.2 sec time gap settings, when there was no target in range when the system was deactivated for over a third of the cases. For the cases when a target was present, the actual gap being shorter than the set gap represents the majority of the cases, which could be indicative of a decision to deactivate the system due to a cut-in at a shorter gap than the one regulated by the system. Further steps will be required to verify this assumption, such as identifying vehicle cut-ins from other lanes, as well as lane changes by the SV. The pattern seems to be different at the shortest gap setting, as for this case the trend seems to indicate that the system was deactivated either when regulating the gap or when the actual gap was larger. For this case, there was also a fair amount (25%) of deactivation when no target was in range of the sensors. A future step in the data analysis for cases when the system is deactivated when no target is present will be to identify the last deactivation of a trip and its location (highway vs. off-ramp), in order to account for deactivations when leaving the highway.

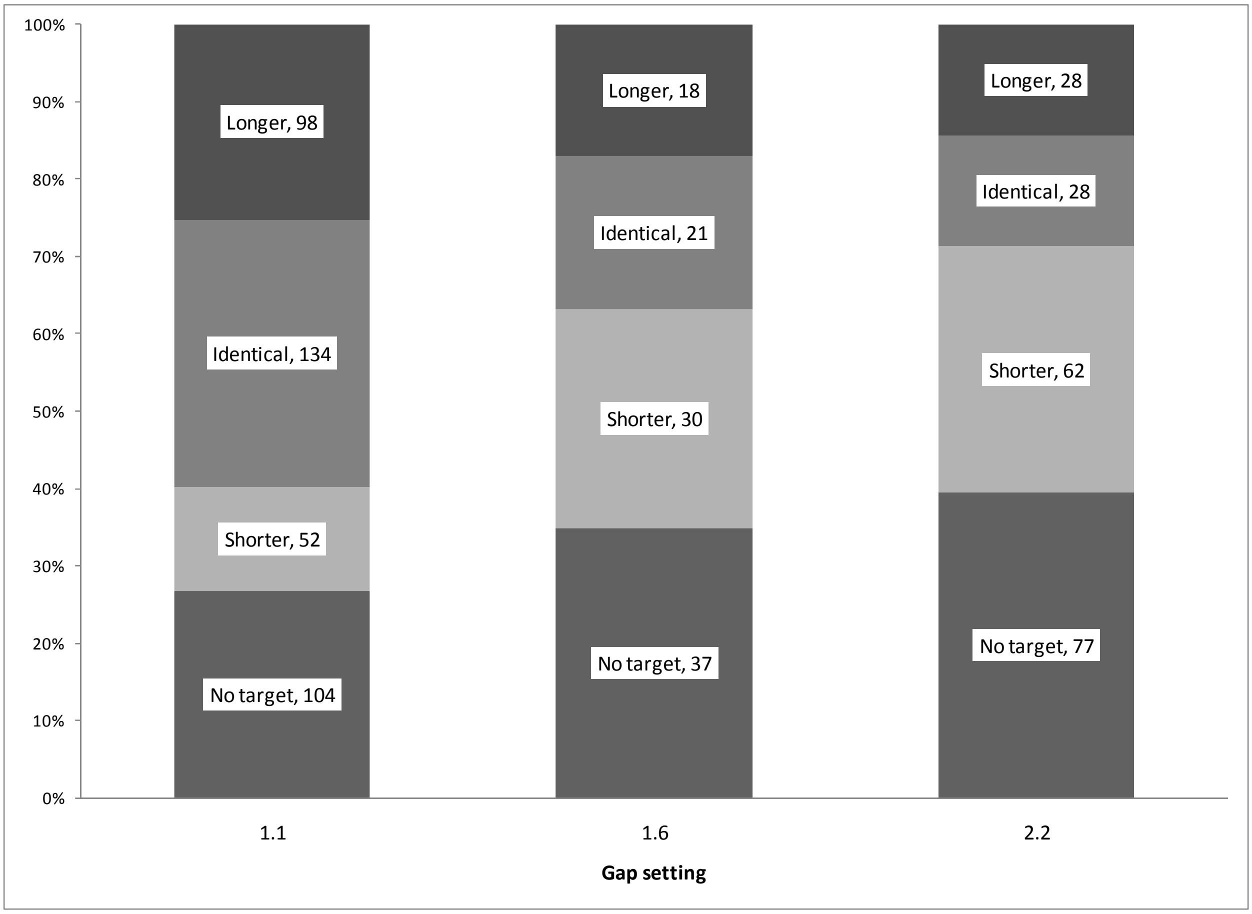


Figure 9.11: Distribution of Gap Size Relative to Gap Setting at ACC Deactivation.

9.1.3 Description of Time-Gap Setting Usage During ACC System Activations

In this section, the ACC time-gap setting usage is generally presented as an aggregate across both individual trips and drivers. Thus, drivers with more trips and/or longer commutes may be biasing the sample to some degree. This will be addressed in the analyses described in Section 9.3. Overall, as shown in Figure 9.12, the shortest ACC time-gap setting, 1.1 s, was used over 50 percent of the time, while the longest time-gap setting, 2.2 s, was used second most, at 31 percent of the time. Figure 9.12 shows the proportion of time that each of the ACC time-gap settings was selected when the ACC system was active, regardless of whether the system was in speed-control or gap-control mode.

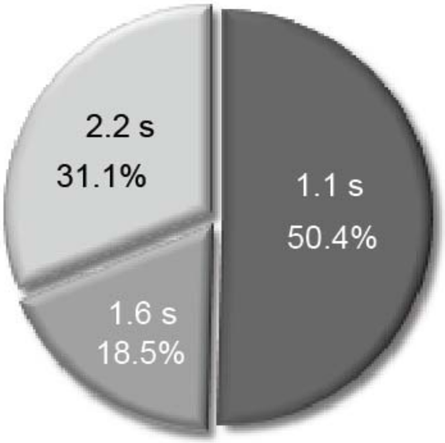


Figure 9.12: Distribution of ACC Time-Gap Setting Usage.

When the data were filtered to look at only the time-gap settings used when the ACC system was actively engaged in vehicle following, the overall distribution of time-gap setting usage did not change, and this is shown in Figure 9.13 which also shows the gender differences in the ACC time-gap setting usage patterns. The male participants spent about 20 percent more time at the shortest gap setting, 1.1 s, while the female participants spent roughly 20 percent more time at the longest gap setting, 2.2 s.

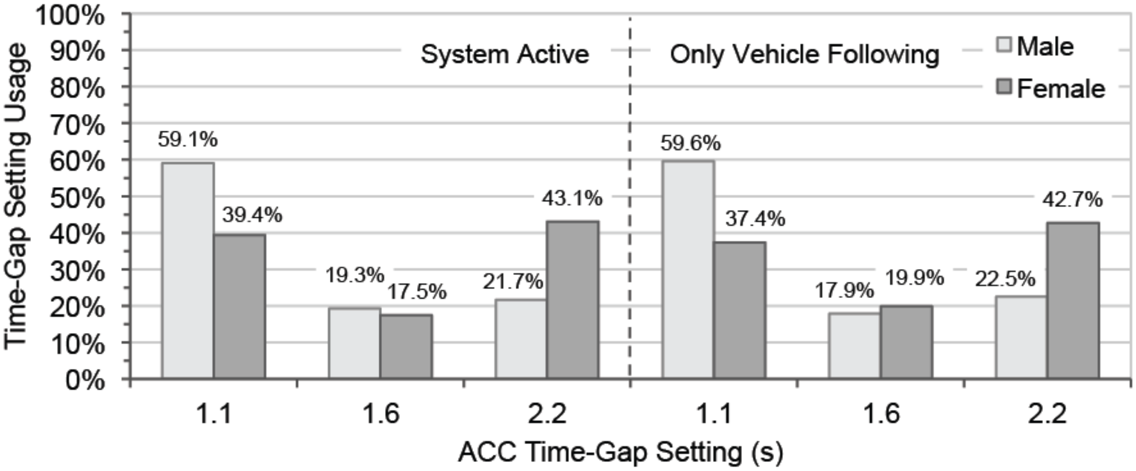


Figure 9.13: ACC Usage as a Function of System Mode and Gender.

The purpose of the ACC portion of the experiment was to familiarize the participants with the functionality and use of the commercially available ACC system, since such systems were not widely in use at the time. Thus, it stands to reason that the overall distribution of time-gap setting usage could be biased by learning effects. Participants may have been less comfortable with the system at the beginning of the testing, leading them to favor the longer gap settings, and as the test proceeded, they may have become more comfortable with the system and started choosing the shorter gap settings.

Figure 9.14 shows the evolution in the proportion of time spent at each gap setting as a function of each subsequent commute with the ACC system. As discussed previously, all drivers had at least 7 commuting trips, and all but three drivers had at least 10 commuting trips. However, only a few drivers had more than 12 commuting trips, so the percentages shown in the 10+ category may be unduly influenced by the preferences of only a few of the drivers. The overall trend indicates that on the first commuting trip with the ACC system, the longest time-gap was favored 52 percent of the time, but by only the third commute with the ACC system, the shortest time-gap setting was favored most of the time.

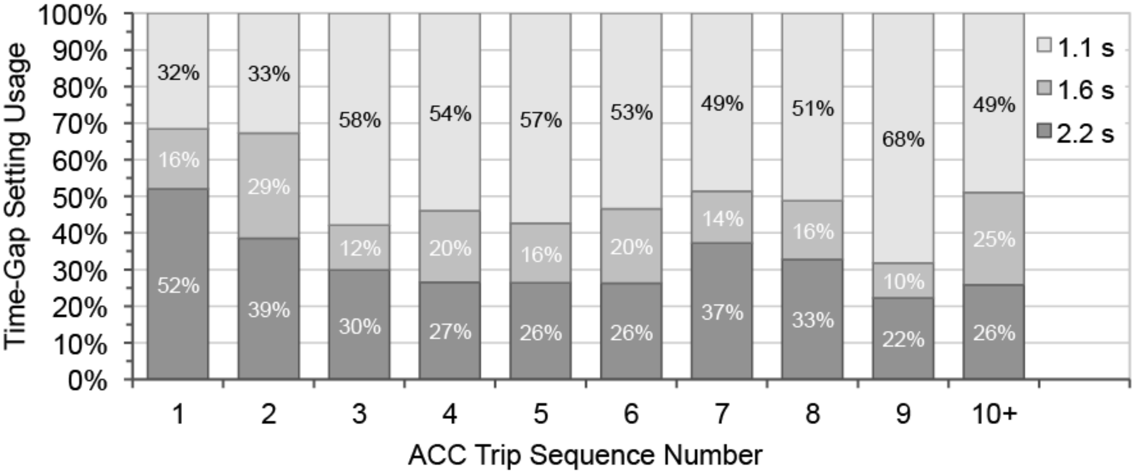


Figure 9.14: ACC Time-Gap Setting Usage as a Function of Experience with the System.

While there were some clear gender-based trends when aggregating the ACC system usage across drivers, Figure 9.15 shows that there were also very clear individual differences regarding the ACC system time-gap setting usage. Five of the male drivers used the shortest 1.1 second time-gap setting almost exclusively, one used the 1.6 second time-gap setting almost exclusively, and one used the 2.2 second time-gap setting almost exclusively. The other male driver, number 8, favored the 1.6 second time-gap setting, but appeared to spend 40 percent of the time trying the other settings. For the female drivers, three of them favored the 1.1 second time-gap setting, while three of them favored the 2.2 second time-gap setting. The other two female drivers, numbers 11 and 13, appeared to spend roughly equal amounts of time at each of the three settings.

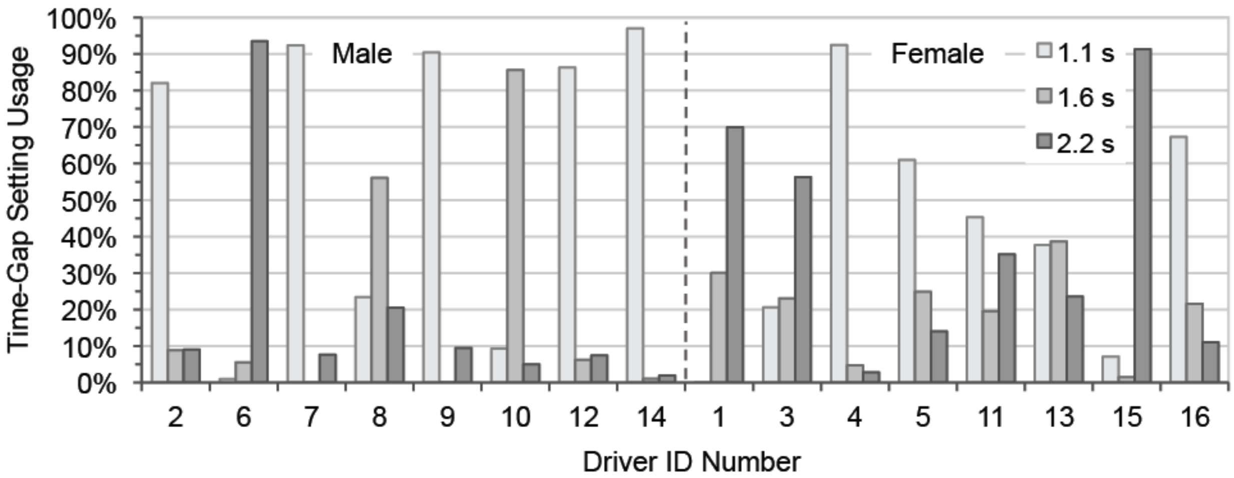


Figure 9.15: Distribution of ACC Time-Gap Setting Usage by Driver.

9.2 CACC Usage

The results in this section are based on 62 commutes when the participants were driving the CACC equipped vehicle, with an experimenter present, and asked to follow a confederate lead vehicle. Although the participant was in charge of the confederate lead vehicle and could instruct the vehicle to change lanes at any time, the CACC system could only be active when following the confederate lead vehicle. Most drivers had 4 CACC commuting trips, although three drivers had only 3 trips recorded and one had 5 trips recorded. Similar to the previous section, the description of drivers' behavior with the CACC system was examined at three levels: CACC system usage, conditions at system activation and deactivation, and the distribution of usage of the available time-gap settings.

9.2.1 Duration of CACC usage

As shown in Figure 9.16, in order to present a cumulative distribution of the duration of the individual ACC activations, the data set has been sorted into 12 bins of roughly equal size. The first two bins represent only 30 second increments, while the remaining ten bins represent 1 minute increments. Almost 60 percent of the CACC system activations lasted for less than 2 minutes (compared to the 45 percent of ACC activations discussed previously). Nearly 70 percent of the activations were less than 3 minutes. The mean activation duration was 3.0 minutes (standard deviation of 4.1 minutes), with a minimum activation duration of 1.0 seconds and a maximum of just over 25 minutes.

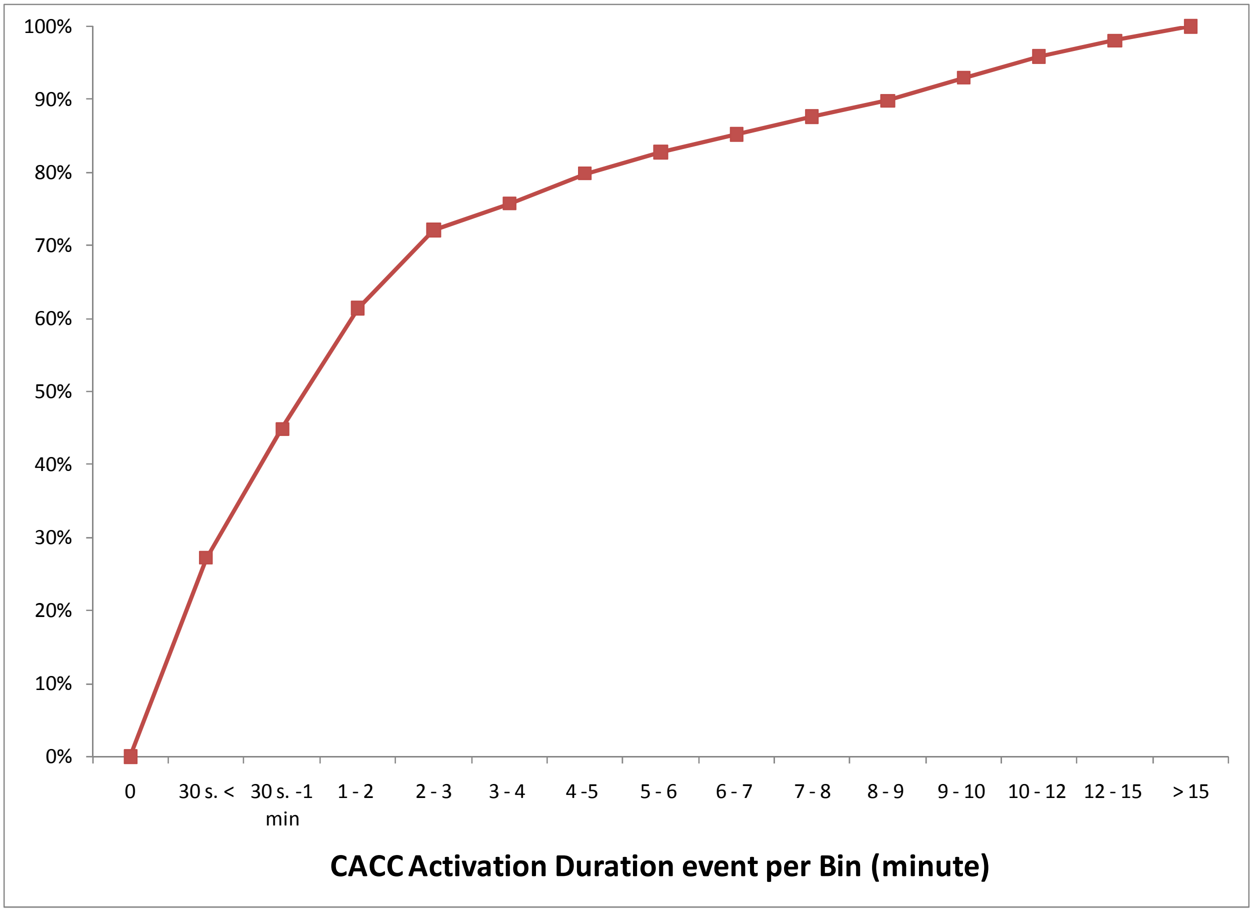


Figure 9.16: Cumulative Distribution of CACC Activation Event Durations.

The data plotted in Figure 9.17 show the average CACC system activation duration as well as the total number of activations per driver. The drivers have been ordered based both on the number of activations per participant and gender. From this perspective, participant 14 has the lowest number of activations (6) while participant 3 has the highest number of activations (91). These drivers are also at opposite ends of the spectrum in terms of average duration, as participant 14 averaged CACC usage duration of 16 min. while driver 3 averaged 1.4 minutes. In other words, the participants who have a lower number of activations tend to have longer average activations. Referring back to Figure 9.2, the ordering of the participants based on the number of cruise control system activations is not identical between the ACC and CACC testing, but it is very similar. Certainly, the four male and four female participants with the lowest number of ACC system activations were the same participants who had the lowest number of CACC system activations. This consistency further lends credibility to the notion that the differences in the number of system activations could be due to route or traffic factors, but again, this could not be verified within the scope of this report.

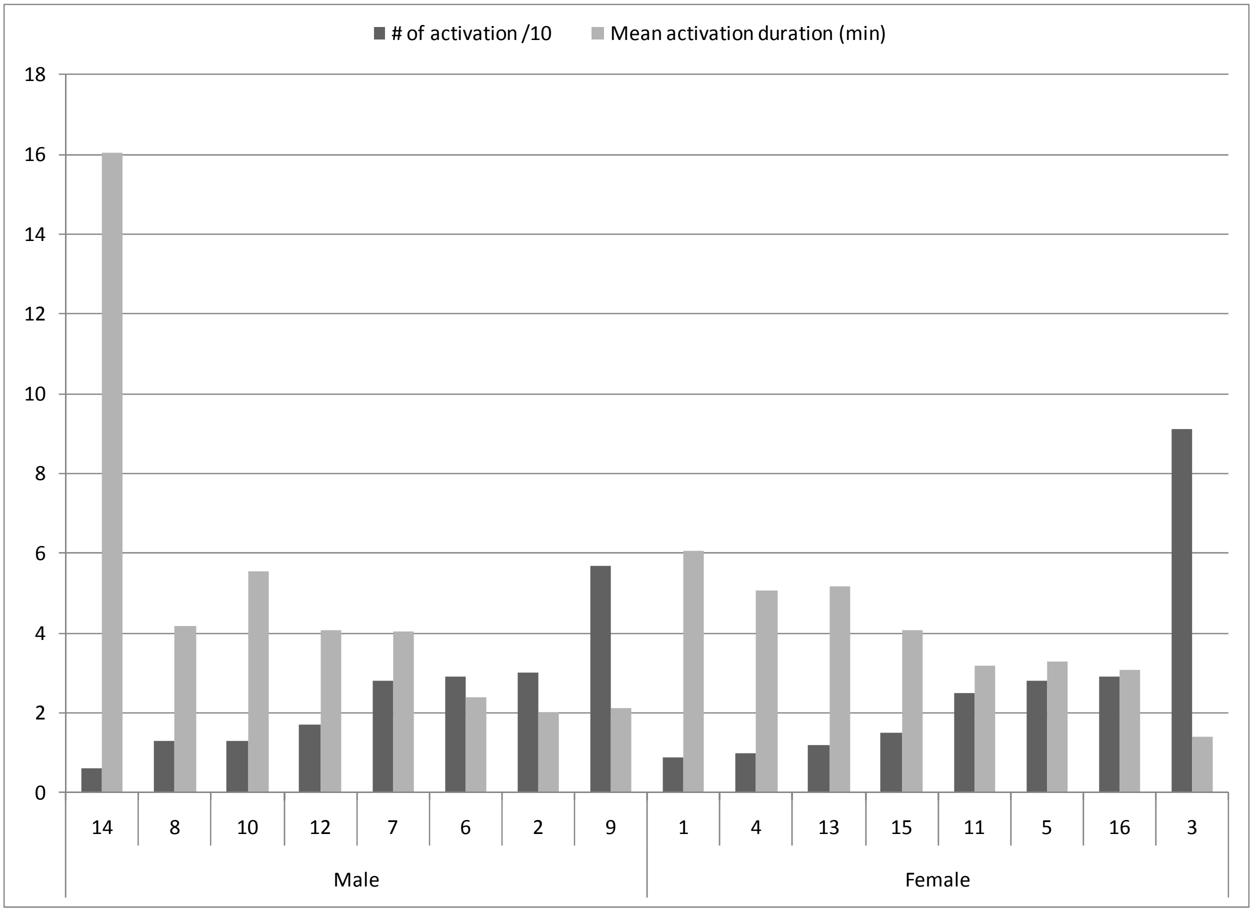


Figure 9.17: Average Duration of CACC Use and Number of Activations per Participant.

9.2.2 Conditions at CACC System Activation and Deactivation

The CACC system activation and deactivation events were extracted from the data in the same way as was described for the ACC system. At each point when the system was activated or deactivated, information was extracted from the recorded data files in order to specify what the system settings were in terms of gap and speed, as well as the actual gap and speed.

9.2.2.1 CACC Speed Control Choices

Similar to the operation of the ACC system, on the first activation of the CACC system during a trip, the drivers always needed to manually set the target speed; however, on subsequent activations, the resume function would re-engage the CACC system using the previously set target speed. Figure 9.18 shows the actual speed of the CACC vehicle when the system was activated vs. the set speed. The same patterns can be identified as for the ACC system, i.e., that the majority of the speed settings are within 3 mph of the actual speed. This pattern is represented by the points following the solid line. This indicates that drivers used the set speed function most of the time.

It also seems that there are two subgroups for the cases when the resume function was used. On the one hand, when the actual speed was lower than 40 mph, the resume function seems to have been used mainly for speed set at 50 mph, while when the actual speed was higher than 40 mph, the resume speed was above 65 mph. Further analysis would be needed to investigate the link between the first speed setting and the traffic density and how it evolved for the subsequent activations, as a reason for these two tendencies could be due to low speed imposed by heavy traffic (cases under 40 mph) or sudden changes in the speed of traffic (cases above 40 mph).

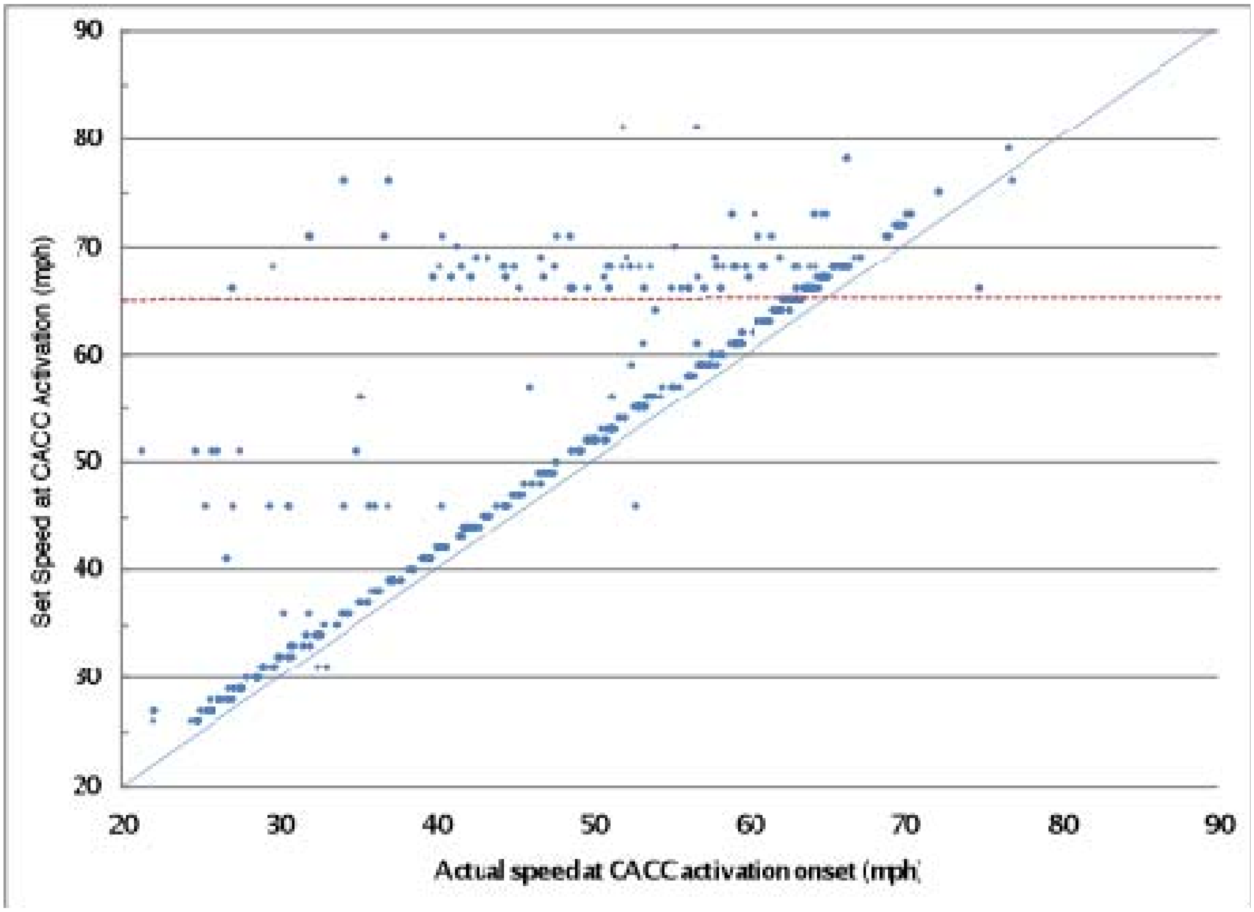


Figure 9.18: Actual Speed at CACC System Activation Onset vs Set Speed.

A similar plot, Figure 9.19, shows the actual speed vs. the set speed when the system was deactivated. Similar to the corresponding figure for the ACC system, Figure 9.6, the automatic shut-off of the system can be distinguished on the left side of the plot, at 20 mph of actual speed. Some of the data follow the solid line, meaning that for these cases, the actual and set speeds were identical at the time of deactivation, suggesting that the vehicle was in speed regulation mode. However, for the most part, the set speed was higher than the actual speed when the system was deactivated, suggesting that the vehicle was in gap regulation mode. In comparison, when using the ACC system, the deactivations were fairly evenly split between speed and gap regulation modes. This is not necessarily surprising given that the participants were following a confederate lead vehicle during the CACC system testing. Future analyses, beyond the scope of this project, would be needed to address the deactivations that occurred from non traffic-related causes (e.g. leaving the highway) and those due to traffic and to assess the role of slower traffic on the decision to turn off the system.

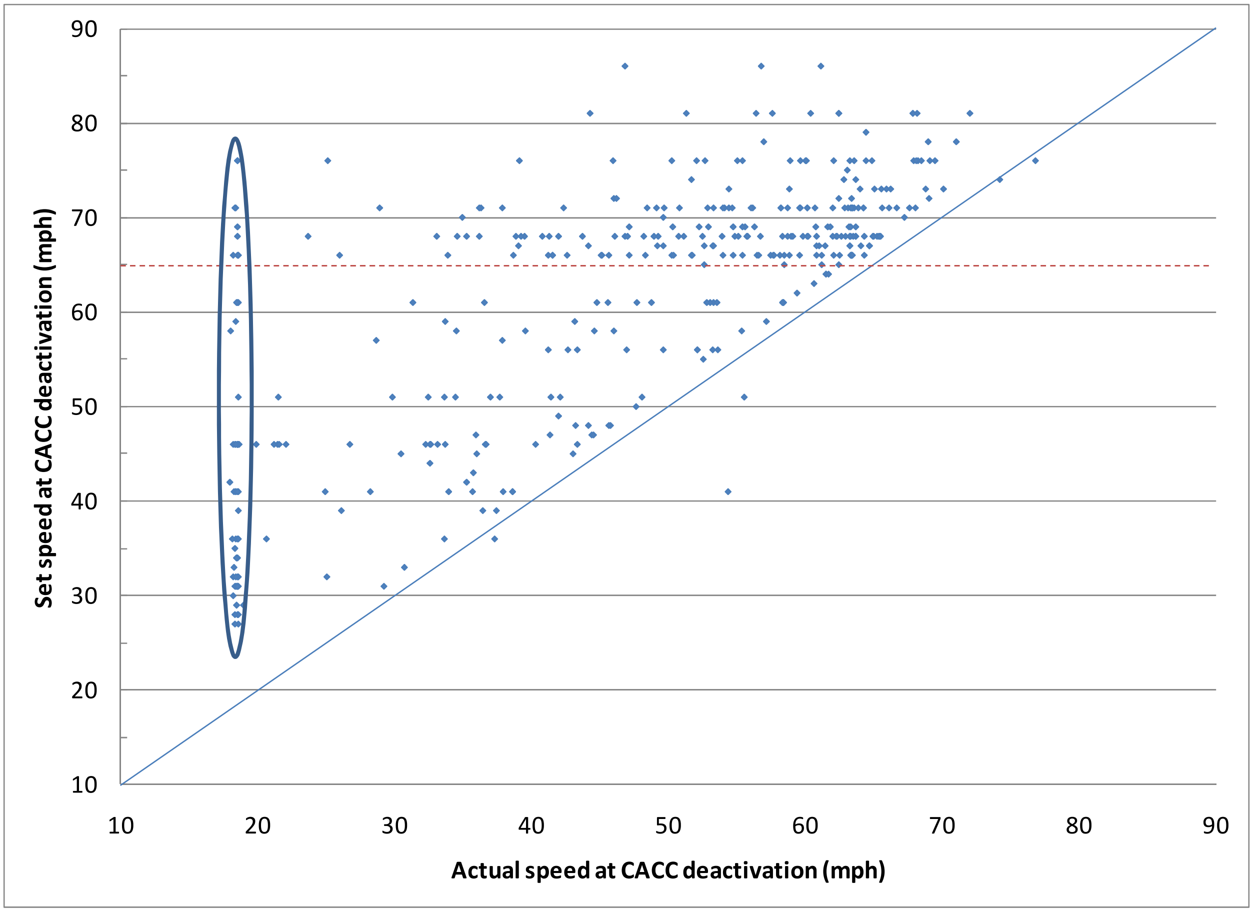


Figure 9.19: Actual Speed at CACC System Deactivation vs. Set Speed.

9.2.2.2 CACC Time-Gap Setting Choices

The time gap setting choices described in this section are described in terms of settings selected at the beginning and end of each activation, as well as the presence of a lead vehicle for these conditions, and the size of the actual gap vs. the system's gap setting. In order to describe the gap setting choices, the data were sorted by the sequence of activations within the trip. Figure 9.20 displays the distribution of the number of trips having each number of individual CACC activations; in other words, 14 trips involved 3 CACC activations. For simplicity of presentation, the results are shown for activations up to 13 per trip and then the trips with larger numbers of activations are gathered into one category labeled "More". The maximum number of activations within one trip was 26. There were no trips with 10 or 11 activations so these two categories are not displayed on the x axis.

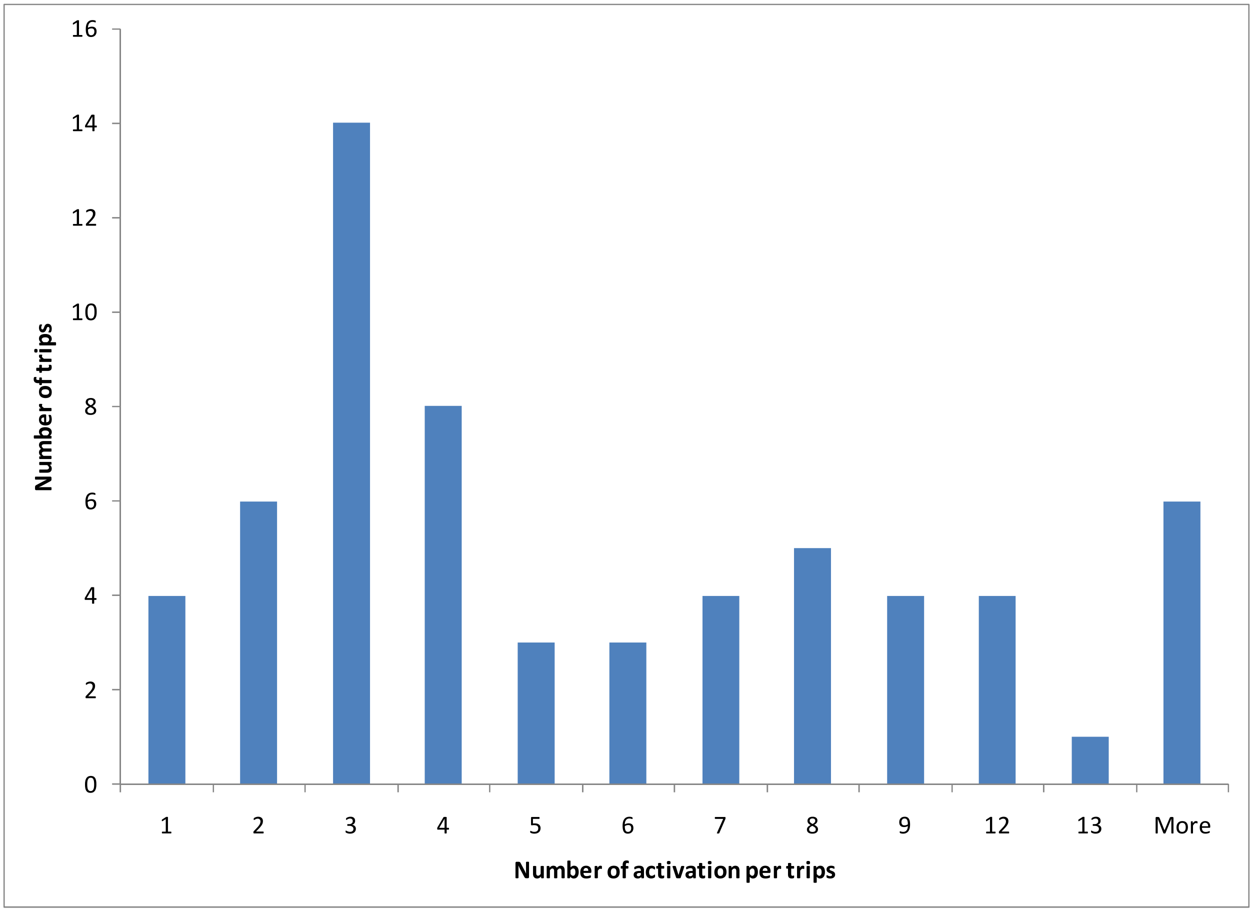


Figure 9.20: Number of Trips by Number of CACC Activations per Trip.

Figure 9.21 illustrates that the time-gap setting for the first activation during each trip was, in the majority of cases, at the longest setting. This was very similar to the results seen in the analysis of the ACC system activations and is probably explained by the system's driver interface, which defaults to the longest time-gap setting each time the system is powered on.

For the second activation, the shortest and longest time-gap settings were equally represented. However, after the third activation in a trip, the shortest time-gap setting, 0.6 s, becomes the single most used setting, hovering around being used almost 50 percent of the time. It is interesting to note that the 0.9 second time-gap setting is the least represented setting at the time of CACC system activation. This can reflect that this setting is only a transitory setting, i.e. that drivers only used the 0.9 second time-gap setting to get to a lower time-gap setting, since changing the time-gap setting could only be accomplished by cycling through the different settings from the longest setting to the shortest setting. On the other hand, the 0.7 second setting use seems to be constant within activations 2 to 5, and slightly more represented for activations 7 and 8. This indicates that the use of this setting was the end goal for at least some of the drivers.

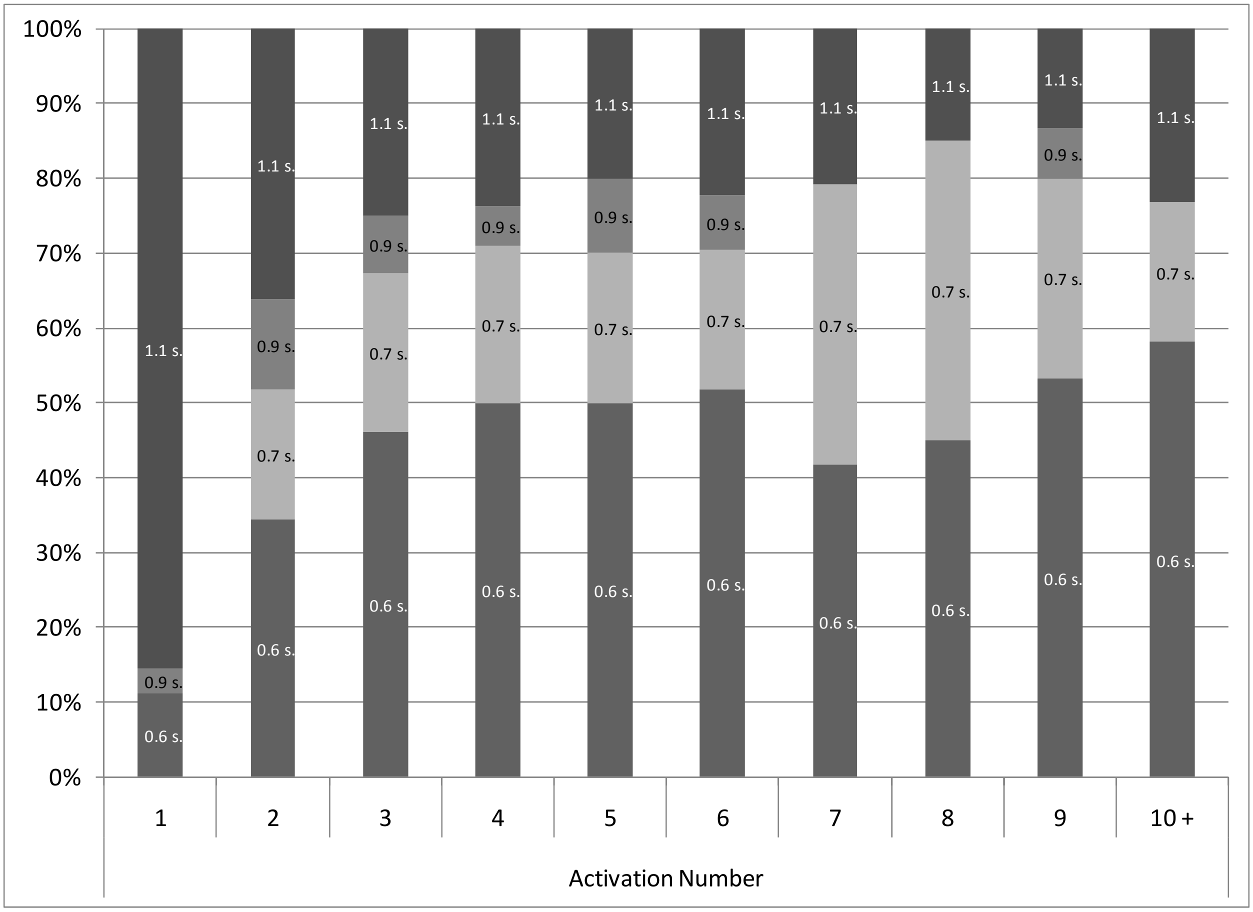


Figure 9.21: Distribution of Time-Gap Settings at Activation Onset vs. Activation Sequence within a Trip.

Similar to the analysis performed for the ACC system driving behavior, in order to analyze the relationship between the actual time-gap to the lead vehicle and the CACC system time-gap setting at the time of the system activation, the actual time-gaps were sorted into three categories, shorter, identical, or longer than the CACC system time-gap setting. Table 9.2 describes the ranges used for sorting the actual gap relative to the gap setting. This categorization supports the analysis of the vehicle following situation when the CACC system was activated or deactivated and is used to generate the figures in this section.

Table 9.2: Categorization of Actual Gaps Relative to CACC System Gap Settings.

CACC Gap setting	Classification based on range of actual gaps measured		
	Shorter gap range	Identical gap range	Longer gap range
0.6	0.2 to 0.4	0.41 to 0.8	>0.81
0.7	0.2 to 0.5	0.51 to 0.9	>0.91
0.9	0.2 to 0.7	0.71 to 1.1	>1.1
1.1	0.2 to 0.9	0.91 to 1.3	>1.3

The sorted data are plotted in histogram form in Figure 9.22, which displays the distribution of the size of the actual time-gap with the lead vehicle relative to the CACC system time-gap setting, when the system was activated. For all settings, the system was activated when a target was in range in over 95% of the cases. For gap settings 0.6, 0.7 and 0.9 seconds the actual gap was longer than the CACC time-gap setting in over 70% of the cases, while for the 1.1 second time-gap setting, the actual gap was typically either identical to or longer than the desired setting. This means that when the drivers activated the system, especially for the shortest settings, they typically let the system close the actual gap to reach the desired gap setting. This behavior is in stark contrast to the behavior seen with the ACC system, especially at the 1.6 and 2.2 second time-gap setting. With the ACC system at these longer time-gap setting, the typical behavior was to engage the system when the actual gap was less than the desired time-gap setting, resulting in the ACC system backing off to the desired setting.

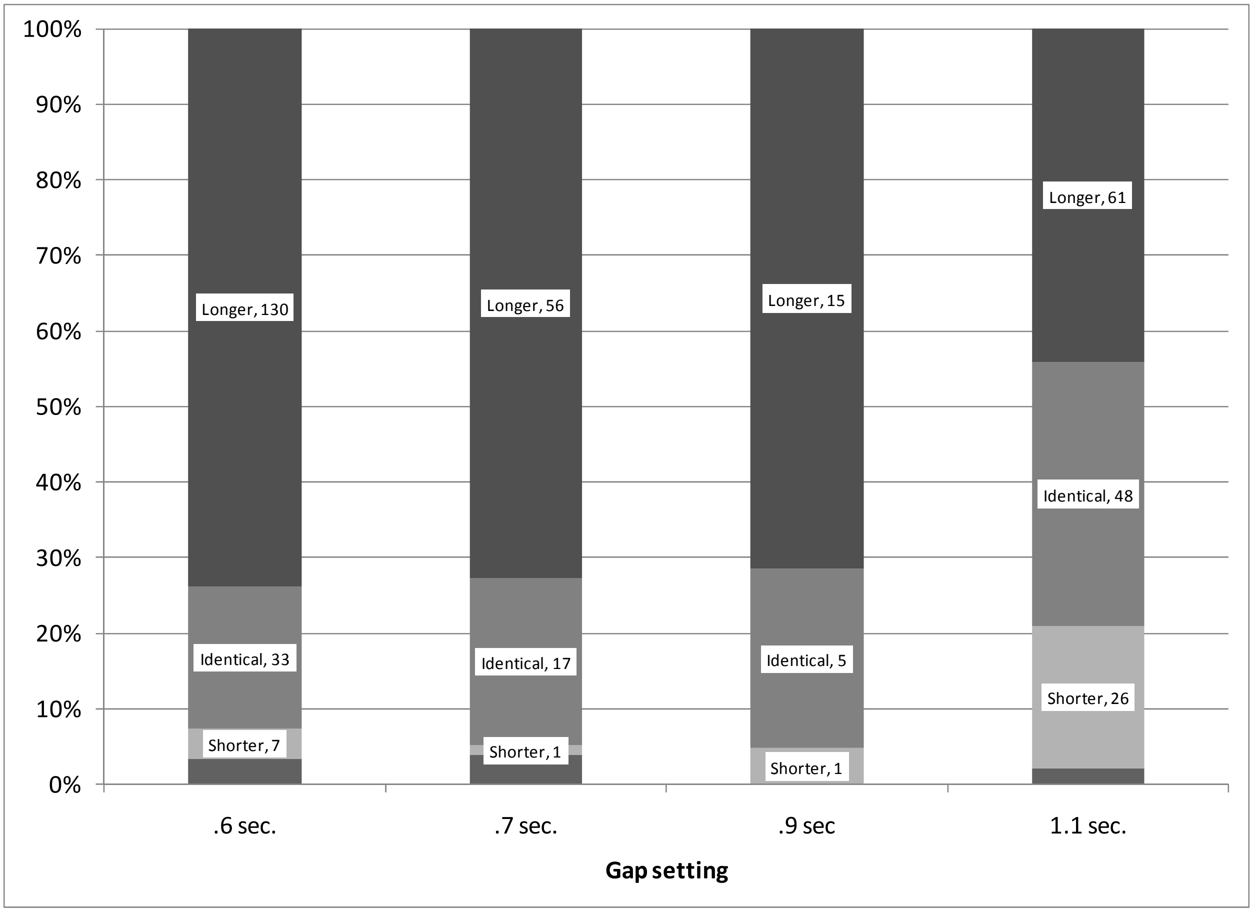


Figure 9.22: Distribution of Actual Gap Size Relative to Gap Setting at CACC Activation.

In Figure 9.23 the proportion of actual gaps relative to the CACC system's time-gap setting is shown at the time of the CACC system deactivation based on the activation sequence within the trip. The first point to highlight is the difference in the distribution of the longest gap relative to the start of the activation. In Figure 9.21, we saw that the 1.1 second time-gap setting was selected for over 80% of the first activations; however, this setting was selected only 30% of the time when the first use of the CACC system was completed and the system was deactivated.

This indicates that for 50% of the first CACC system activations, the driver changed the time-gap setting before the system was deactivated. The shift in proportion seems to be towards the two shortest gaps. A similar trend can be observed for the second activation. This trend may have been part of the same phenomenon, and it just took some of the participants two activations to remember to change the gap setting from the default to their desired setting.

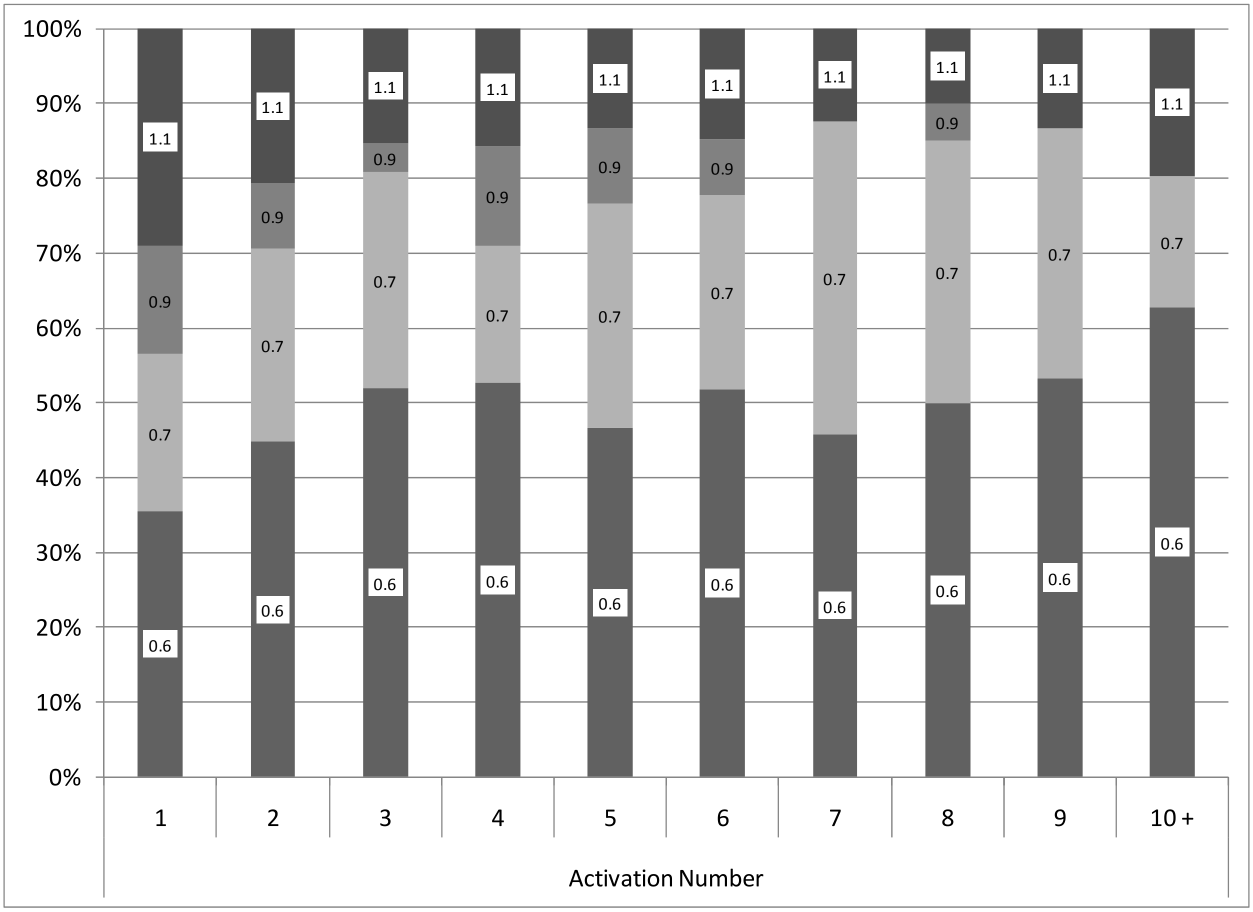


Figure 9.23: Distribution of Time-Gap Settings at System Deactivation per Activation Occurrence.

Figure 9.24 displays the size of the actual gap relative to the set gap when the system was deactivated. (The numbers on the bar graphs indicate the number of cases upon which the percentages were based, since this number differs significantly among the different gap settings). For all gap settings, a target was present when the system was deactivated for 90% of the cases. For the two shortest gap cases, a majority of the actual gaps were close enough to the set gap that they were categorized as identical, which means that when drivers deactivated the system it was in gap regulation mode, as opposed to speed regulation mode. Again, this is not surprising given that the CACC testing protocol necessitated the use of a confederate lead vehicle.

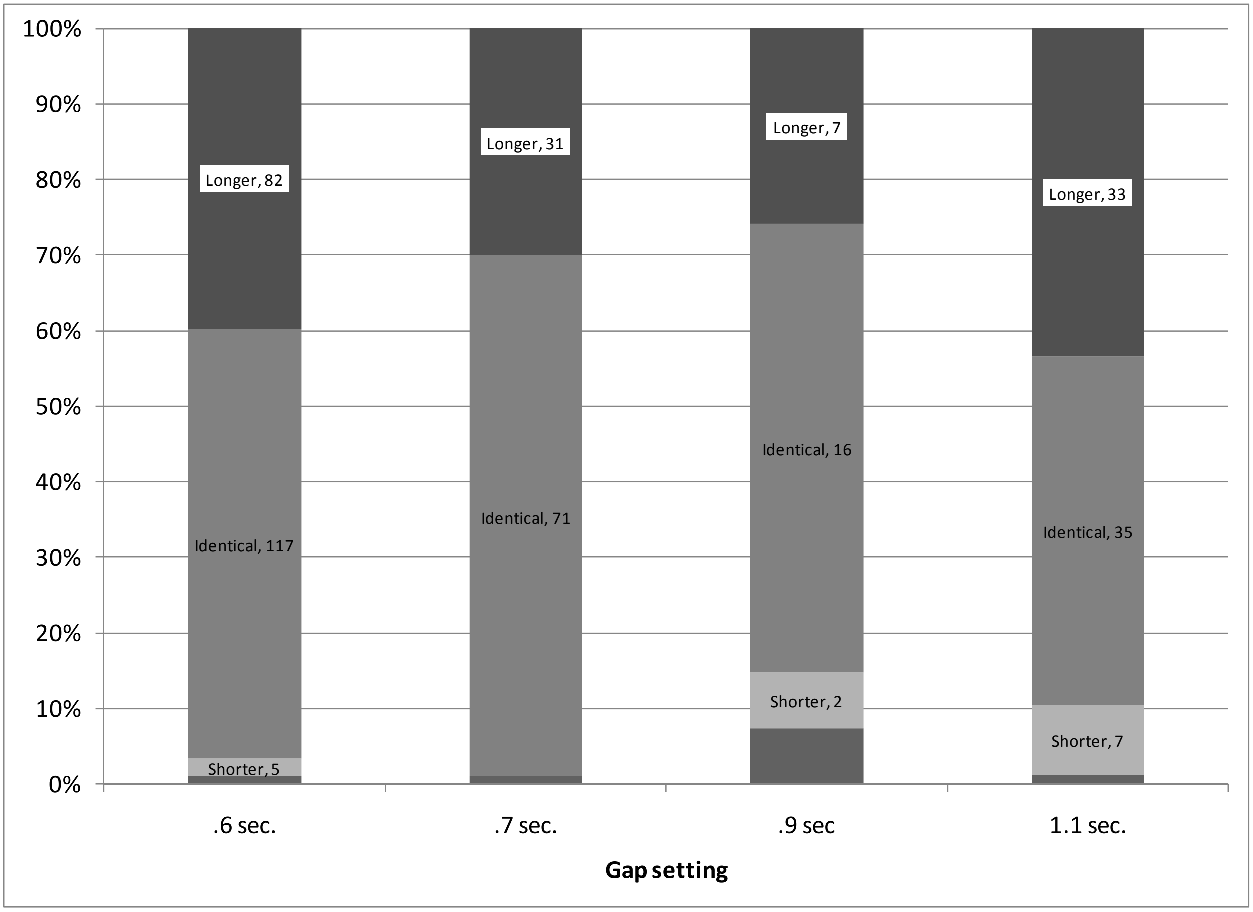


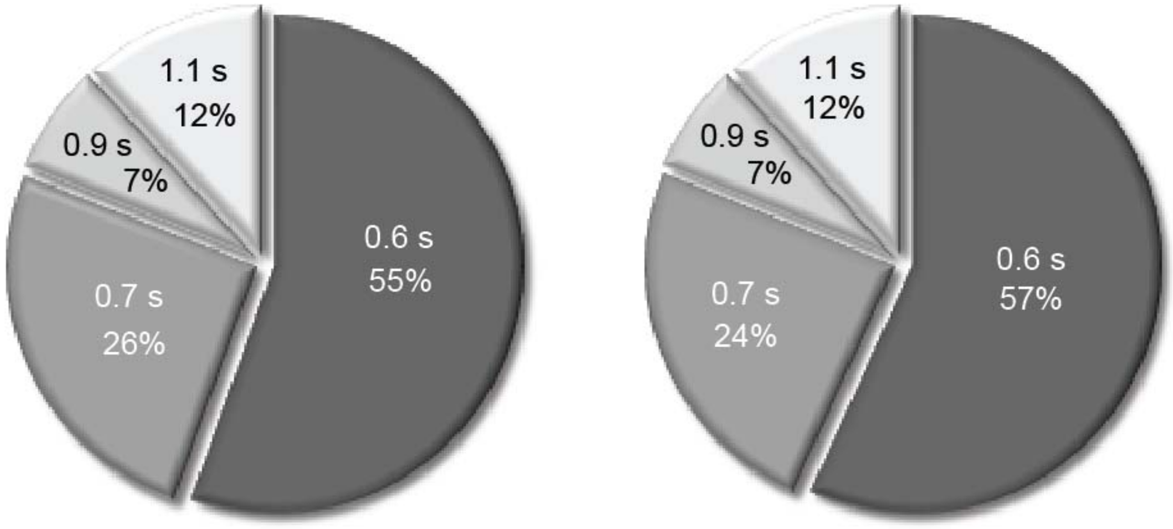
Figure 9.24: Distribution of Actual Gap Size Relative to Gap Setting at CACC Deactivation.

It is interesting to note that the actual gap is fairly evenly divided between identical and longer for the longest gap setting. Further analysis will be necessary to determine under which conditions the system was deactivated when the gap was longer than the set gap and to determine the proportion of interruptions due to the driver feeling that he/she needed to override the system vs. interruption due to other factors (e.g. leaving the highway).

9.2.3 Description of Time-Gap Setting Usage During CACC System Activations

Similar to Section 9.1.3, the CACC time-gap setting usage is generally presented as an aggregate across both individual trips and drivers. As noted previously, this means that drivers with more trips and/or longer commutes may be biasing the results of the analyses in this section to some degree, but this will be addressed in later analyses included in this report. Figure 9.25 shows the proportion of time each of the CACC time-gap settings was selected, both while the CACC system was active and while the CACC system was actively engaged in vehicle-following. Similar to the results seen with the ACC system, there was very little difference in the distribution of system time-gap setting usage between the two sets of filtered data.

Overall, the 0.6 and 0.7 second CACC time-gap settings were most frequently used, with the system being set to 0.6 seconds 55 percent of the time and 0.7 second 26 percent of the time. However, when the data set was filtered to include only the time when the CACC system was actively following the lead vehicle, the 0.6 second time-gap setting was used 57 percent of the time, while the 0.7 second time-gap setting was only used 24 percent of the time.



Overall Usage

Usage in Following Mode Only

Figure 9.25: Distribution of CACC Time-Gap Setting Usage.

Again, similar to what was found with the ACC system, there were gender differences in the distribution of the time spent using each of the CACC system gap settings. As shown in Figure 9.26, the male participants, as a whole, spent over 81 percent of the time with the CACC system set at the 0.6 s time-gap setting. The female participants were more evenly distributed in their use of the CACC system. The 0.7 second time-gap setting was used the most by the female drivers, but this setting only accounted for 38.6 percent of the system usage. The 0.6 second time-gap setting accounted for 27. 7 percent of the female usage, and the 1.1 second time-gap setting accounted for 21.8 percent of the female usage.

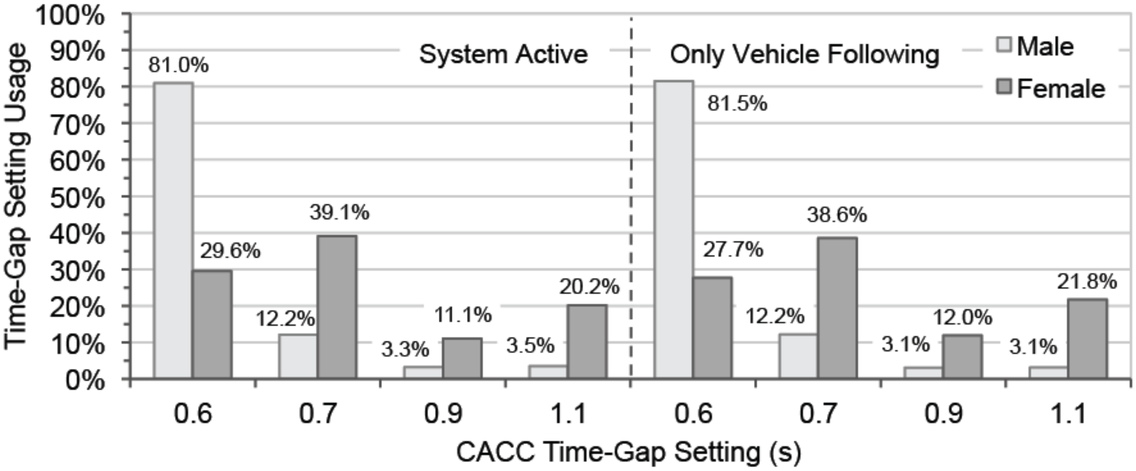


Figure 9.26: CACC Usage as a Function of System Mode and Gender.

By the time that the CACC testing began, the participants had spent nearly a week-and-a-half using the ACC system on their daily commutes, and most of the participants had at least an hour or so of trying out the different CACC system time-gap settings on a non-commute test drive. However, it was still possible that there could be some learning effects that could bias the pattern of time-gap setting usage. Figure 9.27 shows the proportion of time spent at each CACC system time-gap setting as a function of the sequence of commutes. Although it was mentioned earlier that for three drivers, we only had data for 3 of the 4 CACC trips, the original trip sequence number was maintained, so the missing trips do not affect any one category disproportionately. The percentage of usage of each time-gap settings varied from day to day, but there was not a clear learning trend as the testing progressed.

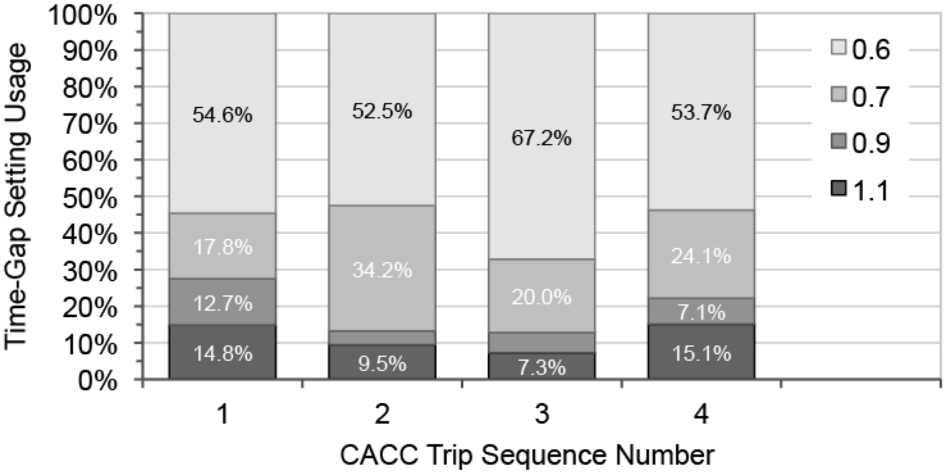


Figure 9.27: CACC Time-Gap Setting Usage as a Function of Experience with the System.

Since the ACC data showed such pronounced individual differences between drivers regarding their choice of time-gap settings, it was important to do an analogous comparison of their CACC time-gap setting usage, as shown in Figure 9.28. Six of the male drivers used the shortest time-gap setting, 0.6 s, almost exclusively, and the remaining two male drivers showed a preference for the 0.7 second time-gap setting, although for driver 8, it was only a very slight preference since this driver spent nearly equal amounts of time at the 0.6, 0.7, and 0.9 second time-gap settings. For the female drivers, only two showed a clear preference for the 0.6 second time-gap setting. Three female drivers showed a preference for the 0.7 second time-gap setting, and one showed a strong preference for the 1.1 second time-gap setting. The other two female drivers, numbers 11 and 16, showed a very slight preference for the 0.7 second time-gap setting, but it was not a very strong preference since these two drivers used some of the other settings almost as much.

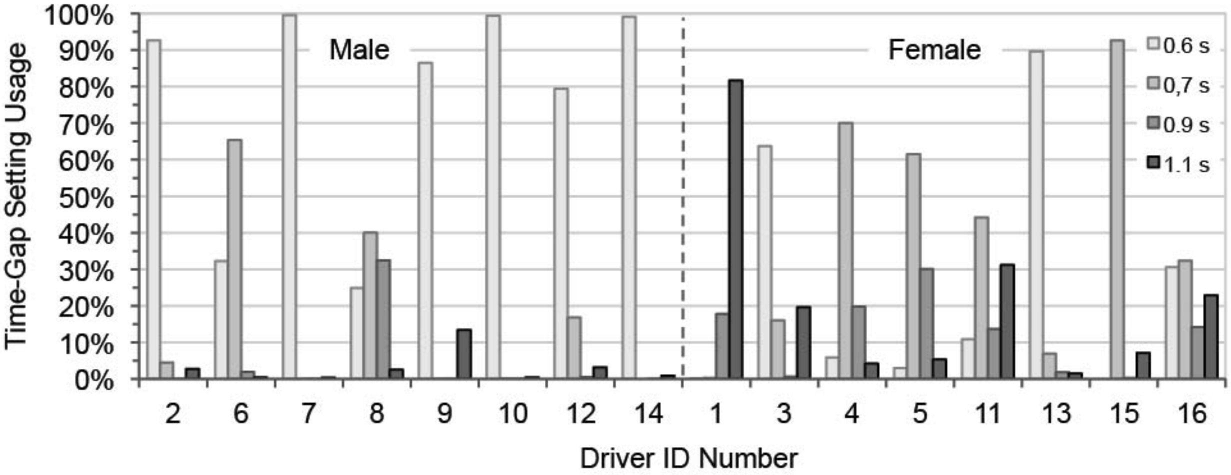


Figure 9.28: Distribution of CACC Time-Gap Setting Usage by Driver.

9.2.4 Analysis of Ride Quality Settings

The informal feedback from the first six participants indicated that there might have been an issue with the ride quality when using the CACC system, especially when following at the shorter time-gap settings. Several of the participants made comments to the effect that it seemed that the ride in the ACC system was smoother and that the CACC system was constantly accelerating and backing off when using the 0.6 s gap setting. At least one of the participants commented that she preferred the longer time-gap settings only because the ride felt smoother. Based on this initial feedback, the CACC system ride quality was adjusted midway through the experiment, allowing the two levels of ride quality to be added as a factor in the analysis. The ride quality tuning basically amounted to decreasing the aggressiveness of the CACC system in maintaining the selected time-gap setting. Thus, for the first 8 participants, the CACC system was more aggressive in maintaining the selected time-gap setting, and conversely, for the second 8 participants, the CACC system was less aggressive in quickly reaching and exactly maintaining the selected time-gap setting. The tuning of the system for the second 8 participants was done by trial and error based on the impressions of several of the project researchers.

First, it should be noted that the ride quality factor only applied to the CACC system testing, so its effect was only analyzed using the data from the CACC commuting trips. Second, the effect of the ride-quality setting on time-gap setting preferences was examined for the mean time-gap settings chosen while actively following a lead vehicle. The mean time-gap setting was calculated from the time-weighted average, on a per trip basis, using only the times when the CACC system was actively following a lead vehicle. Thus, the metric that was used filtered out any biases that may have occurred due to the fact that the CACC system always reset the time-gap setting to the 1.1 s default value whenever the system was first switched on.

A repeated measures, generalized linear model was used to test whether or not the ride quality had any effect on the participants' choices of time-gap setting. The model parameters included a full factorial of gender and ride quality as between-subjects factors and time of commute as a within-subjects factor. Since there were only 4 CACC trips per participant, typically run on Mondays and Tuesday, day of the week and day of the study were not analyzed in this model; however, a main effect for trip sequence number was also included in the model as a covariate to determine whether or not there was a practice effect.

Of the factors in the model, only the main effect of gender was significant, Wald χ^2_1=11.56, p=.001, and this effect will be examined in more detail in Section 9.3. Thus, even though some of the participants who experienced the more aggressively tuned CACC system commented about disliking this aspect of the system when using the shorter gap settings, the tuning of the ride quality midway through the experiment did not appear to significantly influence the participants' time-gap setting selection.

9.3 Comparison of ACC & CACC System Usage

9.3.1 Statistical Model Design

The prior analyses described in this section have provided a detailed, descriptive view of the participant driving behavior when using both the ACC and CACC systems, but the ultimate goal of this study was to determine whether or not drivers would be willing to accept the shorter following distances that could be offered by a CACC equipped vehicle. One way to gain insights into whether or not drivers truly accepted the shorter gap settings offered by the CACC system is to examine whether or not there were statistically significant differences between the gap settings chosen by the participants when using the different systems. However, it should be noted that there was minimal overlap between the gap settings offered by the ACC and CACC systems. The ACC system offered time-gap settings of 2.2, 1.6, and 1.1 s, while the CACC system offered time-gap settings of 1.1, 0.9, 0.7, and 0.6 s. Since the drivers were not free to select longer time-gaps when using the CACC system, care must be taken in the interpretation of statistically significance results.

The analyses described in the subsequent sections typically utilized repeated measures (mixed model), generalized linear models using the SPSS statistical software. The generalized linear model (using the SPSS generalized estimating equation function) is an extension of the more typically found ANOVA analyses; however, this analysis allows for the assumption of different underlying distributions, whereas the ANOVA is limited to an assumption of normality. Thus, analyses of counts (number of events) were modeled assuming an underlying negative binomial distribution (with a logarithmic link function), while metrics based on time were modeled with the assumption of an underlying gamma distribution (with a logarithmic link function).

In the models used in these analyses, gender was considered a between-subjects factor, while cruise control system (ACC or CACC) and commute time of day (morning or evening) were considered within-subjects factors. Age was not modeled as a factor in this study because all of the drivers recruited were of a similar age group. Since many of the analyses utilized metrics including either counts or durations (time), the overall trip duration was often included in the model as a covariate.

The trip day of the week, although explored in earlier analyses, was not used in the models comparing ACC and CACC system usage because, as noted in Section 7, the trip day of the week was confounded with the type of cruise control system in our protocol. However, the earlier analyses had concluded that despite any differences due to the trip day of the week, there appeared to be equal opportunity for cruise control system use between the ACC and CACC phases of this study.

9.3.2 ACC/CACC System Usage

Four metrics were used to characterize differences in the overall system usage between the ACC and CACC systems. In the first analysis, the number of ACC/CACC system activations per trip and the time per trip spent driving with the ACC/CACC system active were examined. In the second analysis, the number of car-following events under ACC or CACC system control, and the time spent following at the cruise control system's specified gap setting were examined. The model examined for each metric included main effects and two-way interactions for gender, cruise control system, and commute time of day, and it included the main effect for trip length modeled as a covariate. Since the tests described in this section look at either the number of events or the time spent using the system, a finding of significance for the trip length covariate simply indicated that on longer trips, there was more opportunity for system use. The term was included to provide a correction for variations in trip lengths.

The first set of metrics examined included the number and duration of cruise control system activations. Overall, the two cruise control systems were activated a median of 3 and a mean of 4.6 (±4.0) times per trip for a mean duration of 17.2 (±7.4) minutes. Individual trips had as few as 1 activation and as many as 26 activations, ranging in duration from 14 seconds to 38.5 minutes. In modeling the number of activations, the main effects for both cruise control system and trip length were significant, Wald χ^2_1=5.28, p=.022, and Wald χ^2_1=23.08, p<.001, respectively. Similarly, in modeling the time spent with the cruise control system active, the cruise control system and the trip length were again significant, Wald χ^2_1=15.69, p<.001, and Wald χ^2_1=9.78, p=.002, respectively.

The median number of ACC activations per trip was 3 (mean of 3.8), while the median number of CACC activations per trip was 4 (mean of 6.7). However, as shown in Figure 9.29, there was also a larger distribution of CACC trips with higher numbers of cruise control system activations than seen with the ACC system. Most likely, this was an artifact of the testing protocol, since the CACC would only work when following the confederate lead vehicle and the system had to be deactivated whenever there was a vehicle cut-in or other maneuvers resulting in the separation of the test vehicles.

The mean time spent driving with the ACC system active was 16.2 (±7.6) minutes, and the mean time spent driving with the CACC system active was 20.0 (±5.9) minutes, meaning that participants used the CACC system for almost 4 minutes per trip more than they used the ACC system. Given that previous analyses already established that there was more or less equal opportunity for cruise control system use between testing conditions, this finding might indicate that the CACC system was more versatile in being able to handle the traffic conditions. However, this finding may also have been a result of a number of experimental artifacts. First, an experimenter was present in the CACC vehicle, which may have inadvertently influenced the participant to use the system, and second, the participant was following a confederate lead vehicle, which may also have inadvertently served as a reminder to use the CACC system.

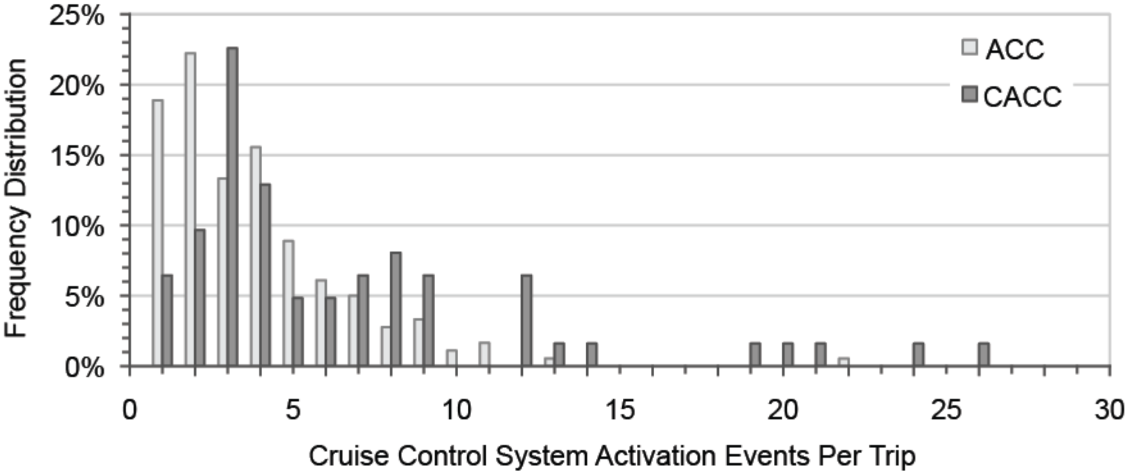


Figure 9.29: Frequency Distribution of ACC/CACC System Activation Events Per Trip.

The second set of metrics examined included the number and duration of discrete vehicle following events while the cruise control system was active. Overall, the two cruise control systems were actively engaged in following a median of 11 times per trip for a mean duration of 10.3 (±6.4) minutes. Individual trips had as few as 0 and as many as 46 active following events, with the longest active following event lasting 32.6 minutes. In modeling the number of active cruise control system following events, the main effects for both cruise control system and trip length were significant, Wald χ^2_1=19.12, p<.001, and Wald χ^2_1=11.6, p=.001, respectively. However, the trend in the number of following events was the exact opposite of the trend seen in the number of ACC/CACC system activations. The median number of ACC active following events per trip was 12, while the median number of CACC active following events per trip was only 7. As shown in Figure 9.30, there was a smaller percentage of CACC trips with higher numbers of discrete following events when the cruise control system was actively engaged.

Examining the corollary metric, time spent with the cruise control system actively following a lead vehicle, both the cruise control system and the trip length were again significant, Wald χ^2_1=15.69, p<.001, and Wald χ^2_1=9.78, p=.002, respectively. However, in this analysis, the interaction between cruise control system and commute time of day was also significant, χ^2_1=8.24, p=.004. The main effect of cruise control system on the time spent actively following a lead vehicle was quite dramatic with almost a 10-minute difference between the two systems.

When using the ACC system, the mean vehicle-following time was 7.9 (±4.7) minutes, while the mean vehicle following time when using the CACC system was 17.3 (±5.7) minutes. The interaction between cruise control system and commute time of day was less dramatic, as shown in Figure 9.31. With the ACC system, about a minute more of vehicle-following was done during the morning commute, while with the CACC system, about a minute-and-a-half more vehicle following was done during the evening commute.

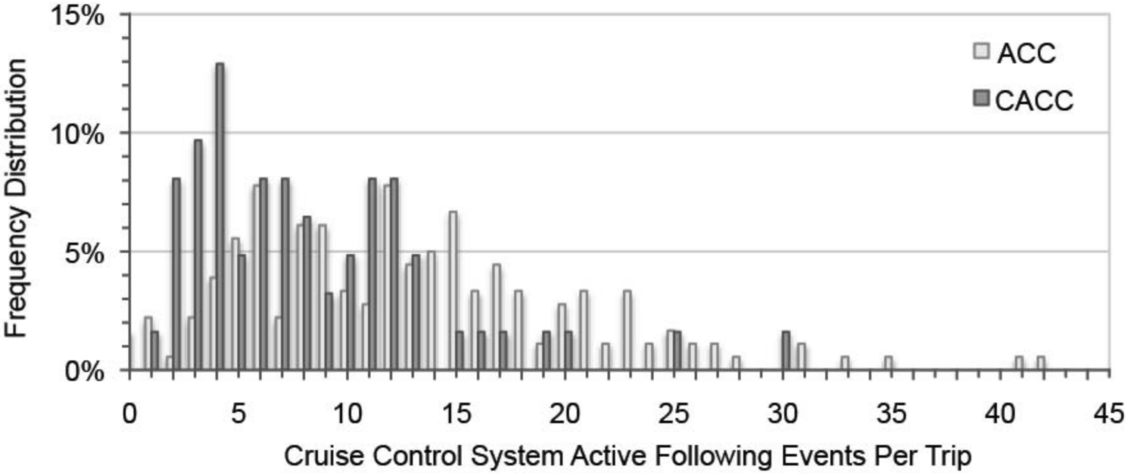


Figure 9.30: Frequency Distribution of ACC/CACC Active Following Events Per Trip.

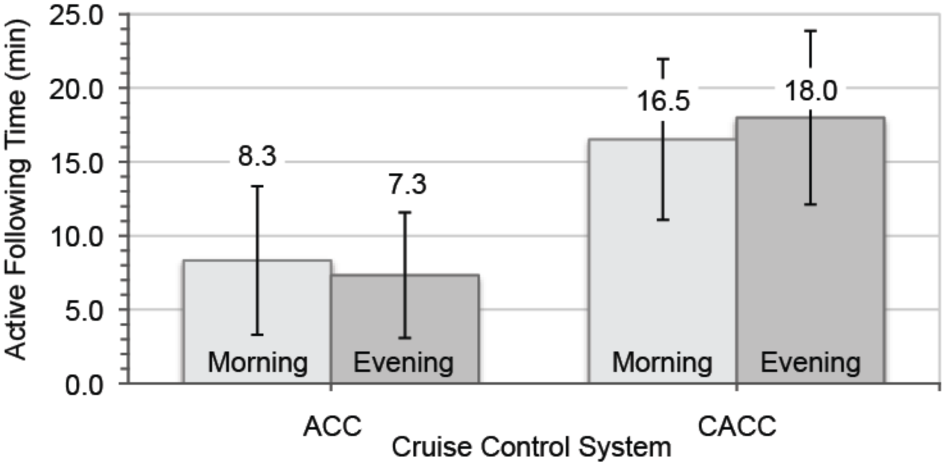


Figure 9.31: Time Spent with the ACC/CACC System Actively Following a Lead Vehicle.

Looking at all of the analyses discussed in this section, the CACC system was used, on average, for about 4 minutes more per trip than the ACC system. It also appears vehicle-following with the ACC system consisted of shorter but more frequent events, while the vehicle following with the CACC system consisted of fewer, longer events. Certainly much of the increased vehicle-following with the CACC system was an artifact of the experiment protocol which was geared towards testing the shorter gap settings available on the CACC system. Since the CACC system could only follow the confederate lead vehicle during the experiment, drivers were not free to pass a slower-than-desired lead vehicle as they could do when acclimating to the ACC system. Thus, given the details of the experiment's design, it would only be speculation to suggest that increased time both using the CACC system and using it in vehicle-following mode were in any way related to driver preferences, and not simply an artifact of the protocol.

9.3.3 Mean System Time-Gap Setting Preference

A number of different techniques have been used in this and subsequent sections to try to examine the ACC and CACC system time-gap preferences of the drivers in this experiment. In this section, the metric used to examine the time-gap setting preferences was the time-weighted, mean time-gap setting (in seconds) used by the driver whenever the cruise control system was on and active during a commuting trip. The model that was used to analyze the mean system time-gap setting included a full factorial of gender, cruise control system, and time of day, with the main effect for trip length being modeled as a covariate. The main effects for both gender and cruise control system were significant, Wald χ^2_1=5.99, p=.014, and Wald χ^2_1=228.71, p<.001, respectively. Unlike in the previous system usage analysis, neither commute time of day nor overall trip length appeared to have a significant impact on the preferred system time-gap setting.

Given the relatively small overlap between the available ACC and CACC time-gap settings, it was not a surprise that there was a significant difference in the overall mean time-gap setting. However, as shown in Figure 9.32, the large difference in the overall mean gap settings between the two systems does really suggest that drivers were comfortable with the shorter gap settings offered by the CACC system since the mean gap setting for the CACC system was 0.71 (±0.13) seconds. The overall mean for the ACC system, by comparison, was 1.54 (±0.41) seconds. If the drivers had not been comfortable with the shorter gap settings offered by the CACC system, the expected overall mean time-gap setting should have been closer to 1.1 seconds, the maximum time-gap setting offered on the CACC vehicle. Also shown in this figure is the gender effect. From this analysis the males appeared to prefer shorter time-gap settings than the females, or at least, the males spent more time with the cruise control systems set to shorter time-gap settings than did the females.

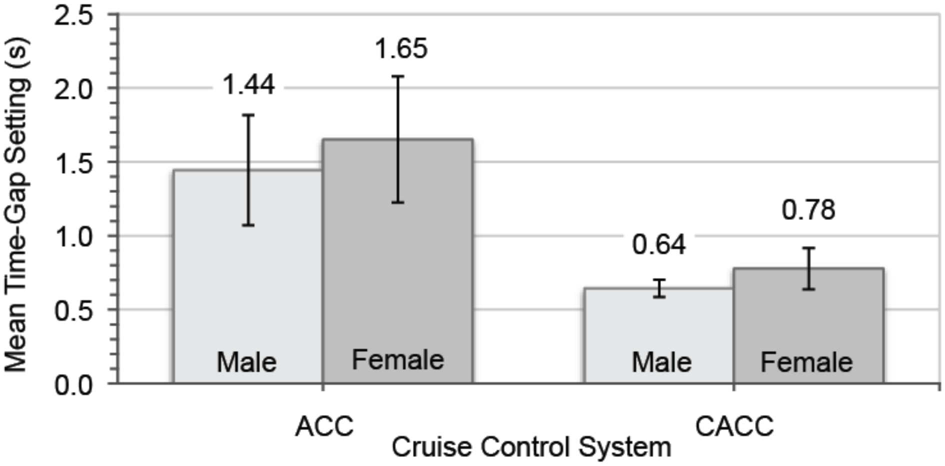


Figure 9.32: Overall Mean Time-Gap Settings.

9.3.4 *Mean System Time-Gap Setting Preference During Vehicle Following*

One of the advantages of the ACC/CACC system is that it can function in two modes, either maintaining a set speed or maintaining a set following time-gap to a lead vehicle. The way that the user interface is set up, every time the system is powered on, the time-gap setting is reset to the longest setting. Thus, it was possible that the user interface may have biased the overall mean system time-gap setting results described in Section 9.3.3. Drivers may have switched on the system and driven in speed maintenance mode at the default time-gap setting until they were actually in a vehicle-following situation, at which point the drivers might have remembered to reduce the following time-gap setting to their preferred level.

The subsequent analysis examined only the time-gap settings used when ACC or CACC systems were actively following a lead vehicle. Similar to the previous analysis, the metric used was the time-weighted, mean time-gap setting (in seconds) used by the driver during each commuting trip. The model that was used to analyze the mean system time-gap setting included a full factorial of gender, cruise control system, and time of day, with the main effect for trip length being modeled as a covariate. Consistent with the results based on the overall mean time-gap setting analysis, the main effects for both gender and cruise control system were again significant, Wald χ^2_1=7.74, p=.005, and Wald χ^2_1=246.59, p<.001, respectively. As shown in Figure 9.33, filtering the data set to examine only the time-gap settings used when the system was actively in vehicle-following mode did not change the results of the mean gap-setting analysis. The mean time-gap setting for the ACC system was still 1.54 s, and the mean time-gap for the CACC system was still approximately 0.72 s.

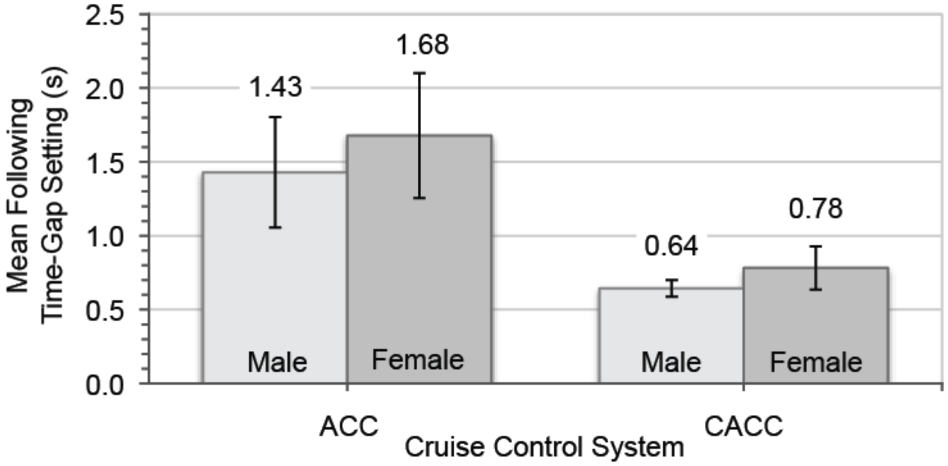


Figure 9.33: Mean Vehicle-Following Time-Gap Settings.

While there was an overall effect on the mean following time-gap setting due to gender, there were also some fairly large individual differences when moving from the ACC to the CACC system. Figure 9.34 cross plots the mean CACC following time-gap setting against the mean ACC following time-gap setting for each of the drivers. There was a definite clustering of most of the male participants around the shortest time-gap settings for both the ACC and CACC systems, 1.1 s and 0.6 s, respectively. Conversely, the female participants were not very highly clustered for ACC system, but there was a large clustering around the 0.7 second time-gap setting for the CACC systems.

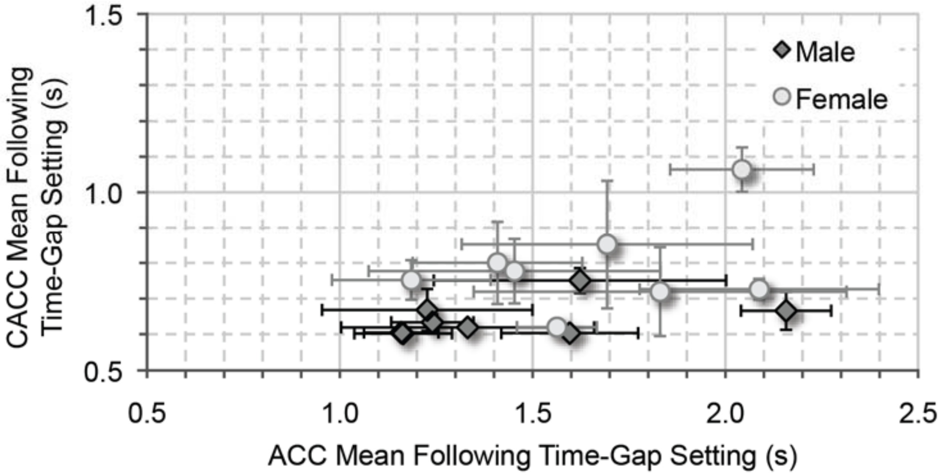


Figure 9.34: Mean Following Time-Gap Setting by Driver.

9.3.5 <u>Preferred Gap Setting by Usage</u>

In the previous section, the time-weighted mean cruise-control-system time-gap setting was examined; however, there are some issues with using a mean as a metric when there were really only a finite number of discrete settings from which to choose. Another way to examine the time-gap setting preferences is illustrated in Figure 9.35. In this figure, the percentage of time that each discrete time-gap setting was used was aggregated across trips for each driver, and then averaged across drivers. Most males clearly preferred the shortest gap setting offered by either system most of the time, while the female participants' preferences were more evenly spread over the range of gap settings. The fact that there was more dispersion in the usage of the different gap settings for the ACC system, especially among males, was probably due to the fact that the purpose of the ACC testing was to familiarize the participants with the system, and the drivers were encouraged to experiment and try all of the gap settings. During the CACC testing, the drivers had already experienced a week and a half of driving with ACC system, and many of the participants quickly homed in on a preferred gap setting after the CACC practice drive, which is not included in this analysis.

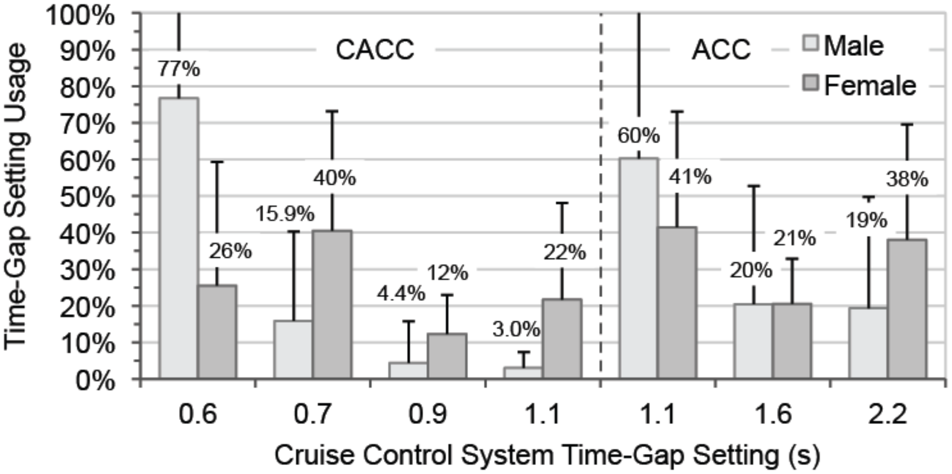


Figure 9.35: Time-Gap Setting Preferences by Usage.

After calculating the driver's usage for each of the different gap settings, the gap settings were given a rank order based on usage. Table 9.3 displays the preferred, or most used, time-gap setting when following a lead vehicle for each phase of the experiment. When following manually during the baseline phase of the experiment, nine of the drivers spent the most time at a following time-gap of 1.6 seconds. Four of the drivers, (3 males and 1 female) spent the most time at following time-gaps in the 0.6 to 0.9 second range, and two of the drivers (both females) spent the most time at a following time-gap of 1.1 seconds.

For the ACC system, nine of the drivers spent the most time at a following time-gap of 1.1 seconds, three of the drivers settled on the 1.6 second time-gap setting, and the remaining 4 of the drivers spent the most time using the 2.2 second time-gap setting. For the CACC system, most of the males preferred the 0.6 second time-gap setting, while most of the females preferred the 0.7 second time-gap setting. Only one participant, driver number 1, a female, showed a pattern of ACC and CACC system usage that suggested that she never became comfortable using the short time-gap settings. With the ACC system, she almost exclusively used the 2.2 second time-gap setting, and upon moving to the CACC system, she briefly tried the shorter time-gap settings, but settled on almost exclusively using the 1.1 second time-gap setting. However, in response to the survey questions (discussed in depth in Section 9.4), this participant did not appear to simply dislike the ACC system. She preferred the ACC system to manual driving, and preferred to use the 2.2 second gap setting, even though she appeared to mostly keep a 1.6 second following time-gap when manually driving.

Another interesting group of participants includes drivers 3, 6, and 15. Each of these drivers appeared to prefer the longest gap setting when using the ACC system, but then switched to preferring relatively short gap settings when using the CACC system. Driver 3 showed a clear case of practice bias. During the ACC testing, she primarily used the 2.2 second gap setting for the first 8 commutes, and then worked her way down to the preferring the 1.1 second gap setting over the last 4 commutes. Driver 6 used the 2.2 second gap setting with the ACC system almost exclusively. When the CACC testing started, he tried the shortest gap setting, backed off to the 0.7 second gap setting for most of the first three commutes, and then on the last CACC commute, returned to the 0.6 second time-gap setting. Driver 15 used the ACC's 2.2 second gap setting and the CACC's 0.7 second gap setting, each for over 90 percent of the time, without much exploration of the other gap settings. The performance difference between the ACC and CACC systems may have accounted for such a drastic shift in the preferred time-gap setting for participants 6 and 15, it's also possible that in these cases the presence of the experimenter or of the confederate lead-vehicle during the CACC testing could have been a factor. Perhaps the change in task from driving solo to following a specific lead vehicle influenced the drivers to select shorter gap settings in the CACC testing in order to limit cut-ins.

Table 9.3: Following Time-Gap Usage Preferences by Driver.

Driver	Gender	Most Frequently Used Following Time-Gap (seconds)		
		Manual Driving	ACC	CACC
2	Male	1.6	1.1	0.6
6	Male	1.6	2.2	0.7
7	Male	0.6	1.1	0.6
8	Male	1.6	1.6	0.7
9	Male	0.9	1.1	0.6
10	Male	2.5	1.6	0.6
12	Male	1.1	1.1	0.6
14	Male	0.9	1.1	0.6
1	Female	1.6	2.2	1.1
3	Female	1.6	2.2	0.6
4	Female	1.1	1.1	0.7
5	Female	1.6	1.1	0.7
11	Female	1.1	1.1	0.7
13	Female	1.6	1.6	0.6
15	Female	0.7	2.2	0.7
16	Female	1.6	1.1	0.7

9.4 Questionnaire Results – Subjective Impressions

The participants were given two questionnaires. The first was given to them after about eight days of driving the ACC vehicle. The second was given to them at the end of the test, after they had driven both the ACC and CACC vehicles. The questionnaire covered four basic topics:

1. Comfort and Convenience
2. Safety
3. Driving with the System
4. Road and Traffic Conditions

All of the 16 participants filled out the ACC questionnaire, however, only 14 of the participants filled out the CACC questionnaire. As responses are compared between the two system using paired sample tests, the results are provided for the 14 participants who filled out both questionnaires. The questions were of three forms distributed among the topics presented above:

- Rating questions with response values ranging from 1 to 7
- Ranking questions, in which the participant expressed what system or driving mode was favored, usually from most preferred to least preferred
- Open ended questions, regarding the understanding of the system and eventual issues met when using the system.

The results that are presented differ for the rating and ranking questions. The mean and standard deviation are provided for the rating questions, while an index of preference was made for the ranking questions. The index was made by attributing a score based on the ranking, where the highest score indicates the highest preference. Responses to the open questions can be found in Appendix D. The results of the questionnaire are presented below for each of the topics they covered.

9.4.1 Comfort and Convenience

This topic was covered by 12 questions. The results are covered in Table 9.4, with the question that was asked, whether the answer was of the form of a rating or ranking, and the responses to both the ACC and CACC questionnaires. The responses are discussed below the table.

Table 9.4: Impressions About Comfort and Convenience.

Questions[4]	**Answer**	**ACC**	**CACC**
4 *(2)*. Overall, how comfortable did you feel driving the car using the C/ACC system?	Rating	1 to 7 (most comfortable)	
	Mean	5.93 (.92)	6.21 (.7)
8 *(6)*. How easy was it to drive using the C/ACC system?	Rating	1 to 7 (most difficult)	
	Mean	2.29 (1.8)	1.64 (.93)
12 *(11)*. What was your level of comfort for each of these gaps with the ACC?	Rating	1 to 7 (most comfortable)	
Long gap	Mean	5.86 (1.56)	5.64 (1.7)
Medium gap		5.93 (1.49)	5.64 (1.4)
Short gap		4.79 (2)	5.29 (1.43)
Shortest gap		-	5 (2.3)
16 *(14)*. How long did it take you to be comfortable using the C/ACC system?		1.25 days (.45)	0.75 days (.40)
18 *(16)*. How comfortable were you driving the C/ACC system in comparison to the manual driving?	Rating	1 to 7 (more comfortable)	
	Mean	4.71 (1.63)	5 (1.46)
26 *(24)*. How likely is it that you would have become more comfortable using the C/ACC system given more time?	Rating	1 to 7 (very likely)	
	Mean	5.57 (2.1)	5.86 (1.8)

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[4] Most of the questions were identical for both system and are merged for simpler presentation. The first question number refers to the ACC questionnaire, the second question number refers to the CACC questionnaire. For questions pertaining to the ACC and CACC system, the system's name takes the form of C/ACC.

30 *(29)*. Compare these operation modes (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*) for comfort	Rank	Preference index Highest score = most comfortable	
	MD	42	27
	CC	35	22
	ACC	50	42
	CACC	-	48
33 *(25)*. Compare these operation modes (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*) for convenience	Rank	Preference index Highest score = most convenient	
	MD	34	24
	CC	38	24
	ACC	55	42
	CACC	-	52
36 (35). Compare these operation modes (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*) for driving enjoyment	Rank	Preference index Highest score = most enjoyable	
	MD	39	26
	CC	36	22
	ACC	52	43
	CACC	-	50
44 *(46)*. Rank, in order of preference, the following modes of operation (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*) for personal use.	Rank	Preference index Highest score = most desirable	
	MD	39	27
	CC	35	20
	ACC	52	41
	CACC	-	50

Participants felt relatively comfortable driving with the ACC and overall rated their level of comfort with the CACC even higher, which can be interpreted either as a higher level of comfort with the CACC or the result of a longer exposure to the technology, as pointed out by the responses to question 26/24 indicating for both systems that drivers still expected to become more comfortable with the system if given more time with it. A similar case can be made about the ease expressed by the drivers for driving with either system, and where the CACC received a slightly better rating than the ACC. The time needed for learning to use the system was considerably shorter for the CACC, since the drivers were already familiar with the ACC.

In terms of comfort with each of the gap settings, the medium gap with the ACC received the highest rating in terms of comfort, although the difference with the other gaps is relatively negligible. The responses to the CACC questionnaire do not permit to identify one of the gaps as either most or least comfortable overall.

When drivers ranked the operation modes, it is clear that the conventional cruise control system was the least liked of all options across all of the questions. The responses to the ACC questionnaire indicate that the system is deemed equally comfortable to manual driving and received higher scores than manual driving in terms of convenience, driving enjoyment and personal use. The responses to the CACC questionnaire indicate a similar trend, with the CACC and ACC receiving higher scores than manual driving, and the CACC system receiving slightly higher scores than the ACC.

In the ACC questionnaire, in response to question 40: Would you rather have: An ACC, a CC or no system, all but one participants chose the ACC, while participant 12 prefers to have no system.

In the CACC questionnaire, to the question: Between the ACC and CACC system, did you prefer one of the systems? All participants replied yes, with 2 participants (1 and 5) preferring the ACC and the other 8 preferring the CACC. To question 40: Which would you rather have? Participants 8 and 12 answered no system, 1 and 5 the ACC, while the 6 other participants chose the CACC.

9.4.2 Safety

This topic was covered by ten questions. The results are summarized in Table 9.5. The participants thought that there is potential for these systems to increase safety. The responses to the ACC questionnaire indicate that drivers found it easiest to maintain a safe following distance with the ACC, but they still rated manual driving as the operation mode allowing them to reach their destination the most safely. Greater exposure to the system might also explain the difference in rating for the ACC, which receives a similar rating to the CACC and manual driving after the CACC test for this same question. However, the rating for the ease with which to maintain a safe gap seems to have been affected by the CACC test for the manual and ACC mode of operation, as these two modes receive lower ratings for the ease to maintain a safe gap on the CACC questionnaire. Even though the ACC and CACC are seen as the mode with which it is easiest to maintain a safe gap, the responses do not seem as overwhelming as they were for the ACC only.

The participants did not feel that either system affected their awareness or responsiveness to other vehicles, or that they were relying too heavily on the system. The responses also indicate that the participants did not feel that they experienced a lot of unsafe following distances with either system.

Table 9.5: Impressions about safety.

Questions	Answer	ACC	CACC
5 *(3)*. Do you think C/ACC is going to increase driving safety?	Rating	1 to 7 (Strongly agree)	
	Mean	5.21 (1.25)	5.29 (1.13)
9 *(7)*. Compare safety under these operation modes (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*)	Rank	Preference index Highest score = most safe	
	MD	49	37
	CC	30	20
	ACC	48	43
	CACC	-	44
13 *(9)*. Under which mode of operation did you feel you reached your destination most safely?	Rank	Preference index Highest score = most safely	
	MD	49	35
	CC	32	20
	ACC	48	44
	CACC	-	45
17 *(15)*. When driving the C/ACC system, compared to manual driving, were you more or less aware of the actions of vehicles around you than you normally are?	Rating	1 to 7 (More aware)	
	Mean	4.79 (1.67)	5 (1.57)
19 *(21)*. How frequently did you get into situations when you relied too heavily on the C/ACC to handle situations that it could not handle?	Rating	1 to 7 (Never)	
	Mean	5.64 (1)	5.79 (1.3)
25 *(23)*. How much effort did it take to maintain a safe following distance when using each of the following modes of operation?	Rating	1 to 7 (Very easy)	
Manual driving Cruise Control ACC CACC	Mean	5.29 (1.4) 3.21 (1.5) 6.36 (.5) -	3.93 (1.7) * 3.14 (1.6) 5.71 (1.2) 5.8 (1.29)
28 *(28)*. How often, if ever, did you experience “unsafe” following distances when using the C/ACC system?	Rating	1 to 7 (Never)	
	Mean	5 (1.6)	5.36 (1.82)
29 *(40)*. Driving the C/ACC system, compared to manual driving, did you find yourself more or less responsive to actions of vehicles around you?	Rating	1 to 7 (more responsive)	
	Mean	4.62 (1.38)	4.69 (1.49)
34 *(NA)*. While using the ACC system, how often, if ever, did the system fail to detect a vehicle that you were approaching or following?	Rating	1 to 7 (Never)	
	Mean	5.75 (1.21)	NA
37 *(36)*. How safe did you feel using the C/ACC system?	Rating	1 to 7 (very safe)	
	Mean	6.07 (.9)	5.93 (1.14)

9.4.3 *Driving with the system*

This topic was covered by ten questions. The results are covered in Table 9.6 and the responses are discussed after the table.

Table 9.6: Impressions about driving style.

Questions	Answer	ACC	CACC
7 *(5)*. In general, under which mode of operation (Manual, Conventional Cruise, C/ACC) did you feel like you reached your destination fastest?	Ranking	Preference index Highest score = fastest	
	MD	50	39
	CC	29	22
	ACC	33	39
	CACC	-	41
10 *(43)*. Do you feel the following adjustment function is useful?	Rating	1 to 7 (Strongly agree)	
	Mean	5.36 (2)	6.5 (.94)
15 *(13)*. Which mode of operation (Manual, Conventional Cruise, C/ACC) required you to apply the brakes most often?	Ranking	Preference index Highest score = least often	
	MD	Missing Data	24
	CC	Missing Data	27
	ACC	Missing Data	39
	CACC	-	51
23 *(NA)*. What did you think of the acceleration provided by the ACC system when pulling into an empty adjacent lane to pass other vehicles?	Rating	1 to 7 (too fast)	NA
	Mean	3.75 (.96)	
24 *(22)*. What did you think of the deceleration rate provided by the C/ACC system when following a vehicle?	Rating	1 to 7 (too hard)	
	Mean	3.93 (1.07)	4 (1.4)
32 *(32)*. Did you feel more comfortable performing additional tasks, (e.g., adjusting the climate control or the radio) while using the C/ACC system as compared to driving under manual control?	Rating	1 to 7 (strongly agree)	
	Mean	5.29 (1.38)	4.79 (1.62)
35 *(33)*. As you got used to the C/ACC system, how would you rate the change of your level of confidence in the system?	Rating	1 to 7 (Less confident)	
	Mean	2 (.78)	2.5 (1.4)
39 *(38)*. When using the C/ACC system, did you ever feel that you didn't understand what the system was doing, what was taking place, or how the C/ACC system might behave?	Rating	1 to 7 (very infrequently)	
	Mean	5.07 (1.9)	5.36 (1.7)

41 *(42)*. In general, under which mode of operation did you feel like you reached your destination with the least stress related to driving?	Ranking	Preference index Highest score = least stress	
	MD	34	21
	CC	38	22
	ACC	55	43
	CACC	-	52
42 *(8)*. While driving with the C/ACC, how confident did you feel about the system?	Rating	1 to 7 (Not confident)	
	Mean	2.5 (1.82)	2.14 (1.02)
45 *(47)*. When you were driving with the C/ACC, were you driving slower or faster than you normally drive?	Rating	1 to 7 (faster)	
Heavy traffic		3.43 (1)	3.21 (1.3)
Medium traffic		3.71 (.6)	3.86 (1.1)
Light traffic		3.57 (.85)	4.07 (1.1)

When ranking the mode of operation for reaching their destination the fastest, manual driving received the highest score under the ACC questionnaire, while the ACC and CACC system scored similarly to manual driving under the CACC questionnaire. However, the participants rated that they were going rather slower with either system vs. manual driving for any traffic density, though the difference in speed seems to become more neutral for the light traffic condition for the CACC.

Drivers expressed a high confidence in both systems and felt that their level of confidence increased as they became more familiar with the systems. They also rated the systems as the least stressful mode of operations, requiring the least amount of braking under the CACC questionnaire. The ranking of systems based on the amount of braking for the ACC questionnaire showed no preference for any mode. This seems to indicate that the drivers were most likely still becoming familiar with the ACC system when filling out the first questionnaire, and that as their level of comfort increased; they used the brake less often.

9.4.4 Road and traffic conditions

This topic was covered by four questions. The results are covered in Table 9.7. Traffic density impacted the perception of both systems relative to manual driving. With the ACC, drivers rated that they were following vehicles further away under heavy traffic but similarly to manual driving when traffic was moderate or light. The ratings for the CACC show that drivers felt that they followed at about the same range with the system as they would under manual control for heavy traffic, but followed closer when using the system with moderate or light traffic.

Traffic density also affected how comfortable the participants were using the system. They rated that they were less comfortable with the system under heavy traffic and rather comfortable when using either system when the traffic was light, more so for the ACC. The density slightly affected the perception of the participants' speed vs. the surrounding vehicles. Drivers felt that they were going slightly slower under heavy traffic and at about the same speed as traffic under moderate and light traffic conditions.

Table 9.7: Impressions about the impact of road and traffic conditions on ACC and CACC use

Questions	Answer	ACC	CACC
6 *(4)*. When using the C/ACC system in each of the following traffic conditions, did you follow other vehicles closer or further than you normally do?	Rating	1 to 7 (Further)	
Heavy traffic	Mean	4.57 (1.55)	3.5 (1.55) *
Moderate traffic		4.43 (1.3)	3.57 (1.6)
Light traffic		4.29 (1.38)	2.86 (1.3) *
14 *(12)*. How comfortable were you using the C/ACC system when driving in the following traffic environments?	Rating	1 to 7 (Very comfortable)	
Heavy traffic		3.93 (2.1)	4.57 (2)
Moderate traffic		5.71 (1.2)	5.57 (1.28)
Light traffic		6.5 (1.34)	5.71 (1.49)
20 *(17)*. When you were driving with the C/ACC, was your speed generally slower or faster than the speeds of neighboring vehicles?	Rating	1 to 7 (Faster)	
Heavy traffic	Mean	3.71 (1)	3.93 (1.1)
Medium traffic		3.93 (.92)	4.14 (.67)
Light traffic		4.5 (1.16)	4.21 (1.25)
27 *(27)*. How comfortable were you using the C/ACC system on hilly roads?	Rating	1 to 7 (Very comfortable)	
		5.91 (1.3)	5.45 (1.21)

9.5 Summary of Driver ACC and CACC Usage

The overall purpose of this experiment was to determine whether or not the driving public would be comfortable with the very short, sub second, time-gap settings that could be offered by a Cooperative Adaptive Cruise Control (CACC) system. However, since the level of public awareness and market penetration of ACC systems remains very low, the experimental test plan included about a week-and-a-half of testing with a conventional ACC system to allow the participants to become familiar with the technology that currently exists in stand-alone ACC systems.

From this perspective, the direct comparisons between the driving behavior when using the ACC and CACC systems, especially in terms of what system was preferred, need to be interpreted with care. Although most participants settled in on a preferred time-gap setting with the ACC system in the first two commutes, there were a few participants who either spent much more time exploring the different time-gap settings offered by the system or did not seem to explore the different settings at all.

For the ACC system, the shortest time-gap setting, 1.1 s, was used most frequently, nearly 50 percent of the time when aggregated over all of the participants' commuting trips, but there were some fairly significant gender differences. On the whole, most of the males preferred the shortest time-gap setting, while most of the females preferred the middle, or 1.6 s, time-gap setting, but at least one male and two females spent the majority of the ACC testing period using only the longest, 2.2 second, time-gap setting.

Based on the subjective questionnaires, the ACC system was well received by the majority of the participants (however noting that only 14 participants returned both of the surveys). All but one of the participants would rather have an ACC system than not, and all of the participants expressed high levels of comfort and confidence in the system.

For the CACC system, the shortest time-gap setting, 0.6 s, was again used most frequently, over 55 percent of the time when aggregated over all of the participants' commuting trips, but also, again, there were some fairly significant gender differences. On the whole, most of the males preferred the shortest time-gap setting, while most of the females preferred the 0.7 second time-gap setting, but at least two of the females preferred the 0.6 second setting. Only one participant in the study (a female) showed a pattern of always using the longest time-gap setting on both the ACC and CACC systems, suggested that she was not comfortable with the sub second time-gap settings that could be offered by the CACC system.

Similar to the survey results for the ACC system, the participants responded that they were highly comfortable with both the CACC and the gap settings provided by it. The rankings were very similar for both systems, with a moderate preference for the CACC (but this could have been associated with this system being driven after the ACC). The participants felt that the time-gap settings offered by the ACC system were closest to the time-gaps that they would keep while driving manually in light to moderate traffic, but the time-gap settings offered by the CACC system were closer to the time-gaps that they would keep while driving manually in heavy traffic. This statement was somewhat confirmed when examining the baseline manual driving data, which showed that overall, the time-gaps kept by the participants were most frequently in the 1.6 second range.

References

1. J. VanderWerf, S.E. Shladover and M.A. Miller, "Conceptual Development and Performance Assessment for the Deployment Staging of Advanced Vehicle Control and Safety Systems", California PATH Research Report No. UCB-ITS-PRR-2004-22.

2. S.E. Shladover, J. VanderWerf, M. Miller, N. Kourjanskaia and H. Krishnan, "Development and Performance Evaluation of AVCSS Deployment Sequences to Advance from Today's Driving Environment to Full Automation", California PATH Research Report No. UCB-ITS-PRR-2001-18.

Appendix A: DAS Software Architecture

List of processes for the communication (**silver**) computer on the silver Nissan:

1. database server (script file start_q including qserve, nserve, datahub)
2. CAN driver (can_man)
3. CAN message interpretation (veh_nissan2)
4. wireless communication (wrmsnd)
5. send info to "**stainless**" computer (sndengmsg)

List of processes for the **copper** computer on the copper Nissan:

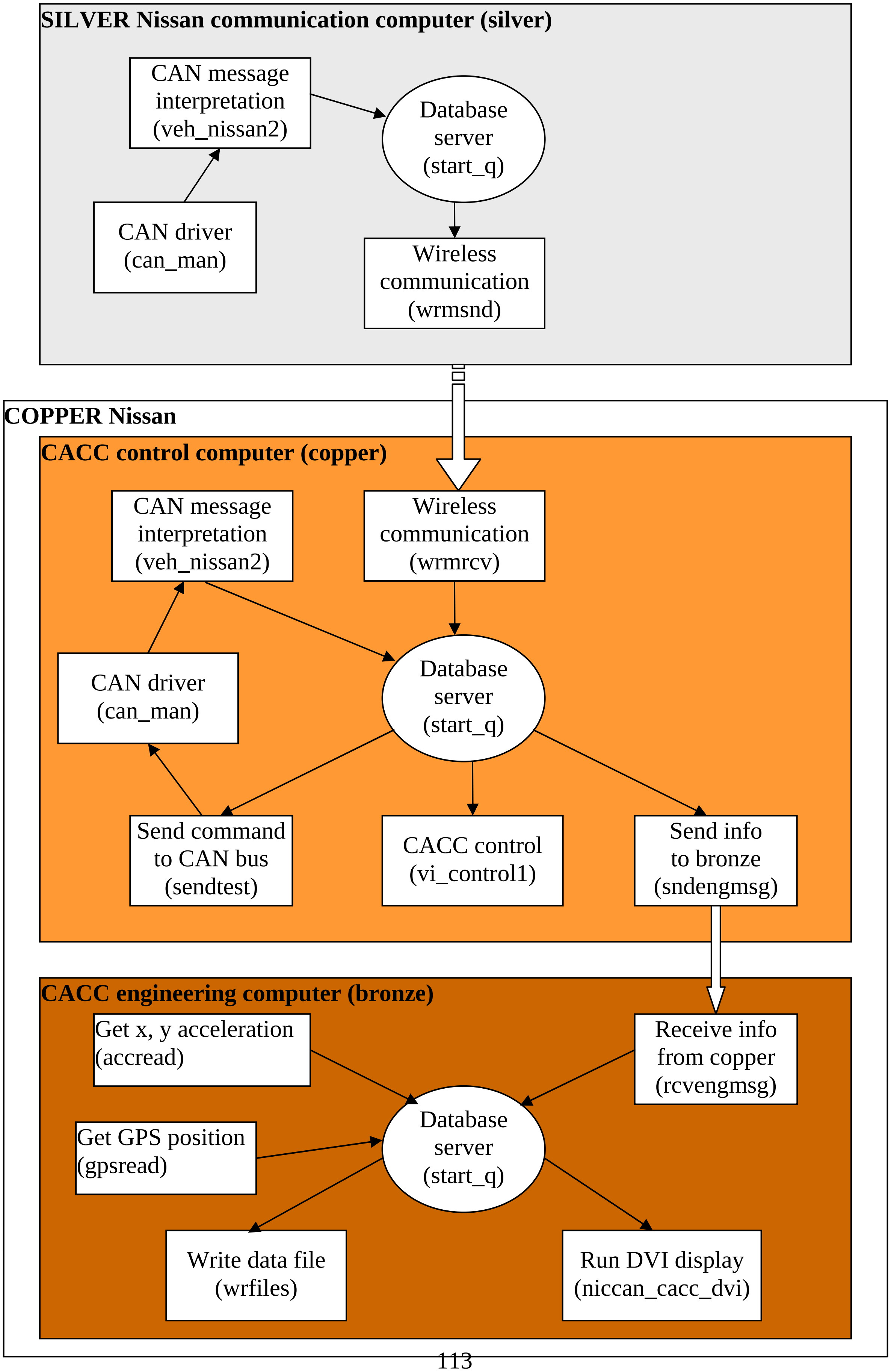
1. database server (script file start_q including qserve, nserve, datahub)
2. CAN driver (can_man)
3. CAN message interpretation (veh_nissan2)
4. wireless communication (wrmrcv)
5. CACC control (vi_control1)
6. send info to "bronze" computer (sndengmsg)
7. send command to CAN bus (sendtest)

List of processes for the **bronze** computer on the copper Nissan and the **stainless** computer on the silver Nissan:

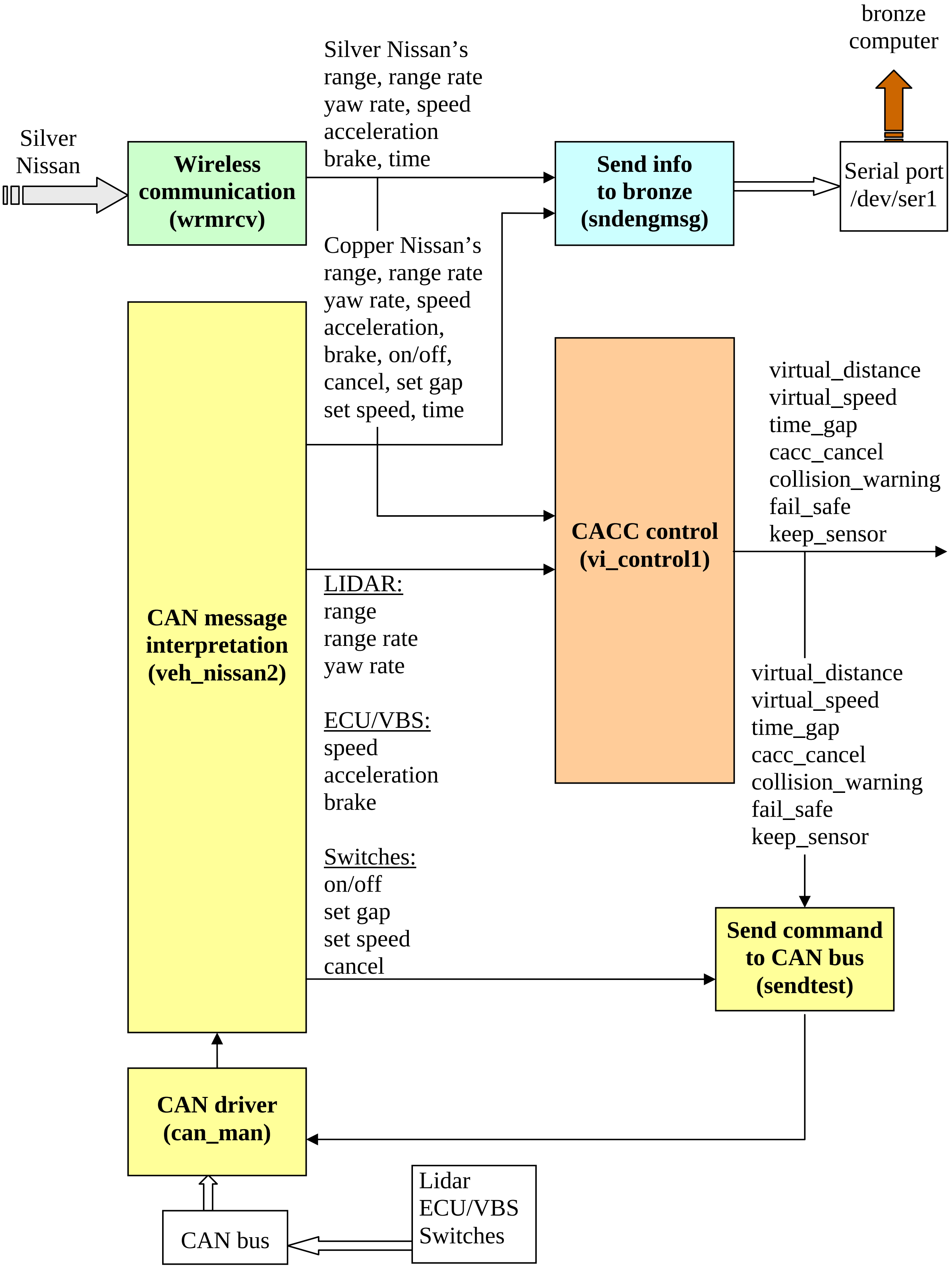
1. database server (script file start_q including qserve, nserve, datahub)
2. receive info from "copper" computer (rcvengmsg)
3. run the DVI display (nissan_cacc_dvi)
4. write data file (wrfiles)
5. read GPS position (gpsread)
6. read x and y acceleration (accread)

The interactions among these processes are shown schematically in the diagrams on the following pages. The CACC control process writes the structure DB_CACC_CONTROL to the database every 20 msec:

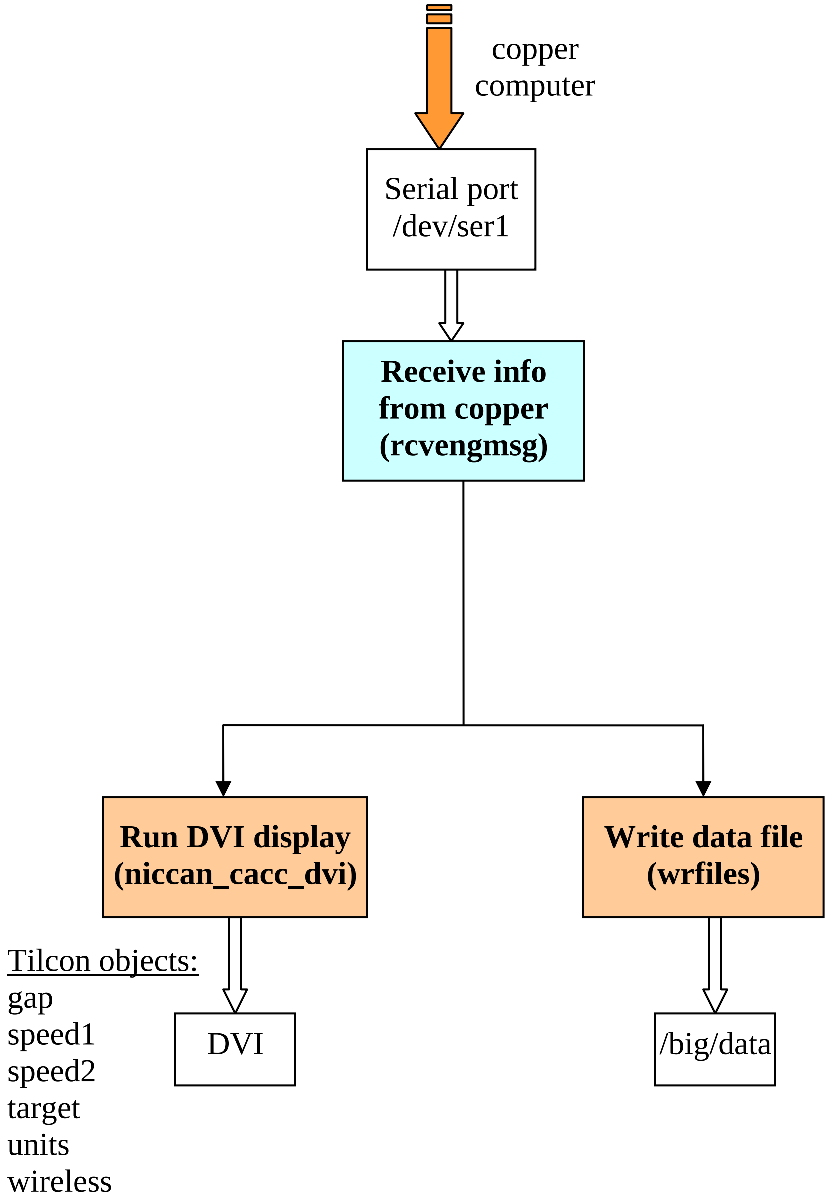
- virtual distance
- virtual speed
- time gap
- cacc cancel
- collision warning
- fail safe
- keep sensor


SILVER Nissan communication computer (silver)
CAN message interpretation (veh_nissan2)
Database server (start_q)
CAN driver (can_man)
Wireless communication (wrmsnd)
COPPER Nissan
CACC control computer (copper)
CAN message interpretation (veh_nissan2)
Wireless communication (wrmrcv)
CAN driver (can_man)
Database server (start_q)
Send command to CAN bus (sendtest)
CACC control (vi_control1)
Send info to bronze (sndengmsg)
CACC engineering computer (bronze)
Get x, y acceleration (accread)
Receive info from copper (rcvengmsg)
Get GPS position (gpsread)
Database server (start_q)
Write data file (wrfiles)
Run DVI display (niccan_cacc_dvi)

Processes on the Copper Nissan **copper** computer (CAN Message contents):



Processes on the Copper Nissan **bronze** computer:



Appendix B: Participant Consent Materials

Letter & Consent Materials Mailed to Participants Before the Start of the Study

Current Date

Subject: Information Packet for Participation in Driving Behavior study using two forms of Cruise Control

Dear Participant:

Thank you for your interest in the study. Enclosed in this packet you will find 4 items:

(1) Consent Forms: These are included so you may have time to read over the specifics of the study. You will be asked to sign these forms before participation in the study begins. If you have questions or concerns, feel free to contact us.

(2) A DMV Personal Record Request Form: We are required by the University to verify your driving record before allowing your participation in the study. Please fill out the top portion of the left side of this form. Be sure to sign the form, and fill in boxes A & B. Cut along the centerline, and mail the left portion to the DMV in the provided envelope. The right portion can be kept for your records.

(3) A Money Order: The $5 money order is included to pay the DMV record request fee. Please add your driver license number to the front of the money order.

(4) Preaddressed Envelope: Please use this preaddressed and prepaid envelope to mail the DMV record request form and money order and the money order to the DMV.

Best regards,

Jessica O'Connell
Associate Development Engineer
California PATH, UC Berkeley
(510) 665-3623

Enclosures (4)

Informed Consent for Testing Drivers' On-Road Behavior and their Choices of Following Distance when using Two New Cruise Control Systems

Welcome to the California PATH Research Program. PATH stands for Partners for Advanced Transit and Highways. We are part of the University of California at Berkeley and this project is under the direction of Professor Alex Skabardonis who is a Professor of Civil Engineering. I would appreciate your participation in my research study on driving behavior. In this research study, we wish to collect data about the way people drive when using new cruise control systems for automobiles. We are studying systems that are called Adaptive Cruise Control and Cooperative Adaptive Cruise Control systems. Both of these systems regulate your speed while driving just like the usual cruise control systems with which you may be familiar. These new systems regulate the distance of your car relative to the car directly in front of you (this distance is called gap). You are able to make some choices about the size of the gap between you and the vehicle ahead. The Adaptive Cruise Control is a system existing on the market. The Cooperative Adaptive Cruise Control is an experimental prototype not yet on the market.

We are examining the impact of these devices on driving safety, comfort and convenience. We are particularly interested in how the use of the prototype Adaptive Cruise Control and Cooperative Adaptive Cruise Control might modify driver behavior. We believe this is important research that will contribute to enhancing automobile safety and comfort, but we want to ensure that these devices are designed with the driver in mind.

While participating in this study, you will be driving an Infiniti FX 45 on local roadways. This vehicle is equipped with a market version of an Adaptive Cruise Control and a prototype version of an Adaptive Cruise Control called a Cooperative Adaptive Cruise Control. At no time during this study will you be asked to perform any unsafe driving actions. If you agree to take part in the research, I will ask permission to inspect your driving record. Your record will be obtained either by having you fill out and mail a record request form to the California DMV or by consenting to an electronic check using a third party provider. I will look only for information about moving violations less than three years old and Driving Under the Influence (DUI). The driving records will be destroyed after the screening procedure regardless of whether or not you are selected (or choose) to participate in the research.
This vehicle will be delivered to your residence on a Wednesday evening. This is the schedule that we will follow for the test:

Phase 1:
- Wednesday evening: learning how to use the ACC with experimenter in the car, possibly driving back from work, ½ an hour of experimenter presence at your residence.
- Thursday to Wednesday: use the vehicle as you would use your own.
- Wednesday morning or evening: assessment of ACC use: possibly drive your commute with experimenter on board.
- Thursday to Sunday: use the vehicle as you would use your own.

Phase 2:
- Saturday or Sunday, spend a 2-hour test drive with an experimenter on-board to familiarize yourself with the CACC vehicle and system.
- Monday, Tuesday, and Wednesday (if needed), test of the CACC vehicle with experimenter on-board during your morning and evening commute.

While using the Infiniti, you will:
1. be the only person to drive the vehicle
2. not carry any passenger other than the experimenter
3. operate the vehicle in accordance with all traffic laws
4. not drive the research vehicle while impaired by alcohol or any controlled substance
5. not take the vehicle outside of the continental United States
6. be the sole individual responsible for all tickets and violations for the duration which the research vehicle is assigned to you
7. report as early as possible to PATH any problems, mechanical malfunctions

While using the Infiniti with the experimenter, you will

1. be asked to drive on a route that is usually the one you take for your commute
2. you will ***not*** be asked to drive:
    a. at dusk,
    b. at night,
    c. in heavy traffic,
    d. during inclement weather

An informational package describing the ACC and CACC systems and detailing the test procedure will be sent to your address 2 weeks before the tests.

Vehicle insurance coverage will be provided by the University of California as long as the vehicle is used as described above. If you violate any of the laws of California or the terms outlined above while driving the Infiniti, the University's vehicle insurance coverage will not be in effect and you will be held liable for any damages. Passengers other than the experimenter will not be covered, which means that you cannot carry any passenger other than the experimenter.

Video cameras will record the front and rear scene as well as your face at all times. We will use these video recordings in order to assess the type of traffic you were in, and to make sure that you are the driver using the vehicle during the days the vehicle will be under your care. You have the right to restrict the use of the video recording and to change your mind about the how restricted or limited use may be of the tape. You can specify the use of the video by filling out the video release form attached to this form.

There is no direct benefit to you from the research. I hope that the research will benefit society by improving our knowledge about driver behavior and using this knowledge to improve the development of advanced transportation concepts and prototypes.

All of the information that I obtain about you during the research will be kept confidential. I will not use your name or identifying information in any reports of my research. I will protect your identity and the information I collect from you to the full extent of the law (this does not include subpoena). Should you be involved in an accident while driving the study car, the videotapes taken may be subpoenaed as evidence.

After this project is completed, I may make the data collected during your participation available to other researchers or use the data in other research projects of my own. If so, I will continue to take the same precautions to preserve your identity from disclosure. Your identity will not be released to other researchers.

You will be paid a total of $100 for your participation. If you decide to withdraw from the study before the completion, you will be paid a prorated amount based on the number of days of participation. Fuel costs will either be reimbursed at the end of your participation with receipts, or you may be provided with the option to use a fuel card. If you choose this option, you will be asked to sign an additional fuel card user agreement.

If you are injured as a result of taking part in this study, care will be available to you. The costs of this care may be covered by the University of California depending on a number of factors. If you have any questions regarding this assurance, you may consult the Committee for Protection of Human Subjects, University of California, 2150 Shattuck Avenue, Rm. 313, Berkeley, CA 94704-5940, PH: 510-642-7461, email: subjects@berkeley.edu.

Your participation in this research is voluntary. You are free to refuse to take part, and you may stop taking part at any time. If you have any questions about the research, you may contact the lead investigator, Christopher Nowakowski, at (510) 665-3673.

I have read this consent form. I agree to take part in the research.

________________________________ _______________

Signature Date

PHOTOGRAPHIC, AUDIO, AND/OR VIDEO RECORDS RELEASE CONSENT FORM

As part of this project we have made a photographic, audio, and/or video recording of you while you participated in the research.

We would like you to indicate below what uses of these records you are willing to consent to. This is completely up to you. We will only use the records in ways that you agree to. In any use of these records, your name will not be identified.

1. The records can be studied by the research team for use in the research project.

Photo __________ Audio __________ Video __________

initials initials initials

2. The records can be shown to subjects in other experiments.

Photo __________ Audio __________ Video __________

initials initials initials

3. The records can be used for scientific publications.

Photo __________ Audio __________ Video __________

initials initials initials

4. The records can be shown at meetings of scientists interested in the study of ***driving behavior***

Photo __________ Audio __________ Video __________

initials initials initials

5. The records can be shown in classrooms to students.

Photo __________ Audio __________ Video __________

initials initials initials

6. The records can be shown in public presentations to nonscientific groups.

Photo __________ Audio __________ Video __________

initials initials initials

7. The records can be used on television and radio.

Photo __________ Audio __________ Video __________

initials initials initials

I have read the above description and give my consent for the use of the records as indicated above.

Signature ____ Date ______________

University of California, Berkeley

Fuel Card Agreement Form

For the purpose of the data collection that you agreed to participate in, you are entrusted with the use of a Fuel Card. The conditions of use and your role as a card user are detailed below.

Fuel Card User

The Fuel Card User assumes responsibility for the physical security of a State of California Fuel Card (Voyager Card) and its PIN (Personal Identification Number). The Fuel Card User assumes responsibility for all card transactions during the time frame when the card is in their possession. These transactions can be audited for appropriate use. If there are improper charges, see below, the participant is financially responsible to repay PATH for those charges.

The Fuel Card User shall:

- Ensure physical security of Fuel Card. The card may **not** be left in the custody of a vendor.
- Do **not** record the PIN on the fuel card, card jackets, or other documents stored with the card.
- Ensure all transaction receipts are kept and provided with the return of the card.
- Report if the card is lost or stolen immediately (within 24 hours).

A Voyager Fuel Card can be used to purchase:

- Fuel, oil, coolant, and other fluids
- **In out-of-area emergencies only:** parts and labor for towing, road service, and mechanical repairs. (If possible, verify with PATH researchers first.)

A Voyager Fuel Card should **not** be used to purchase:

- Food or beverages.
- Parts and labor for towing, road service, and mechanical repairs within range of our local vendors (Berkeley, Oakland, Albany, Emeryville). In these situations, please use the agreements with our local vendors. Details are provide in the vehicle handbook located in the vehicle's glovebox.
- Other goods or services.

Agreement

In reference to the card listed below, I agree with the responsibilities and guidelines outlined above and as stated on the Fuel Card Control/Transaction Limit information sheet.

Card Number: ____

____ ____

Card Fuel User (Print & Sign) Date Fuel Card Custodian (Print & Sign) Date

Optional Consent for Electronic DMV Records Check

I authorize California PATH, UC Berkeley to use the personal information that I have provided below, including my name, address, DOB, SSN, and driver's license number, to check my DMV record using the online, third-party service, Volunteers Select Plus, offered by Choice Point. The company's privacy policies are available for you to review at the following websites:

http://www.volunteerselectplus.com/	http://www.privacyatchoicepoint.com/

The DMV record report generated by ChoicePoint will only be used to verify your eligibility to volunteer for this study. The researchers at California PATH can, at your request, provide you with a copy of the results of your electronic DMV records request. You also have the right under Section 1786.22 of the California Civil Code to contact ChoicePoint directly during normal business hours to obtain your file for your review. You may obtain such information as follows:

1. In person at a ChoicePoint office. You will need to furnish proper identification prior to receiving your file. You may have someone accompany you and should inform such person that they will also have to present reasonable identification. If you want ChoicePoint to disclose to or discuss your information with this third party, you may be required to provide a written statement granting ChoicePoint permission to do so.

2. By certified mail, if you make a written request (and provide proper identification) to have your file sent to a specified addressee.

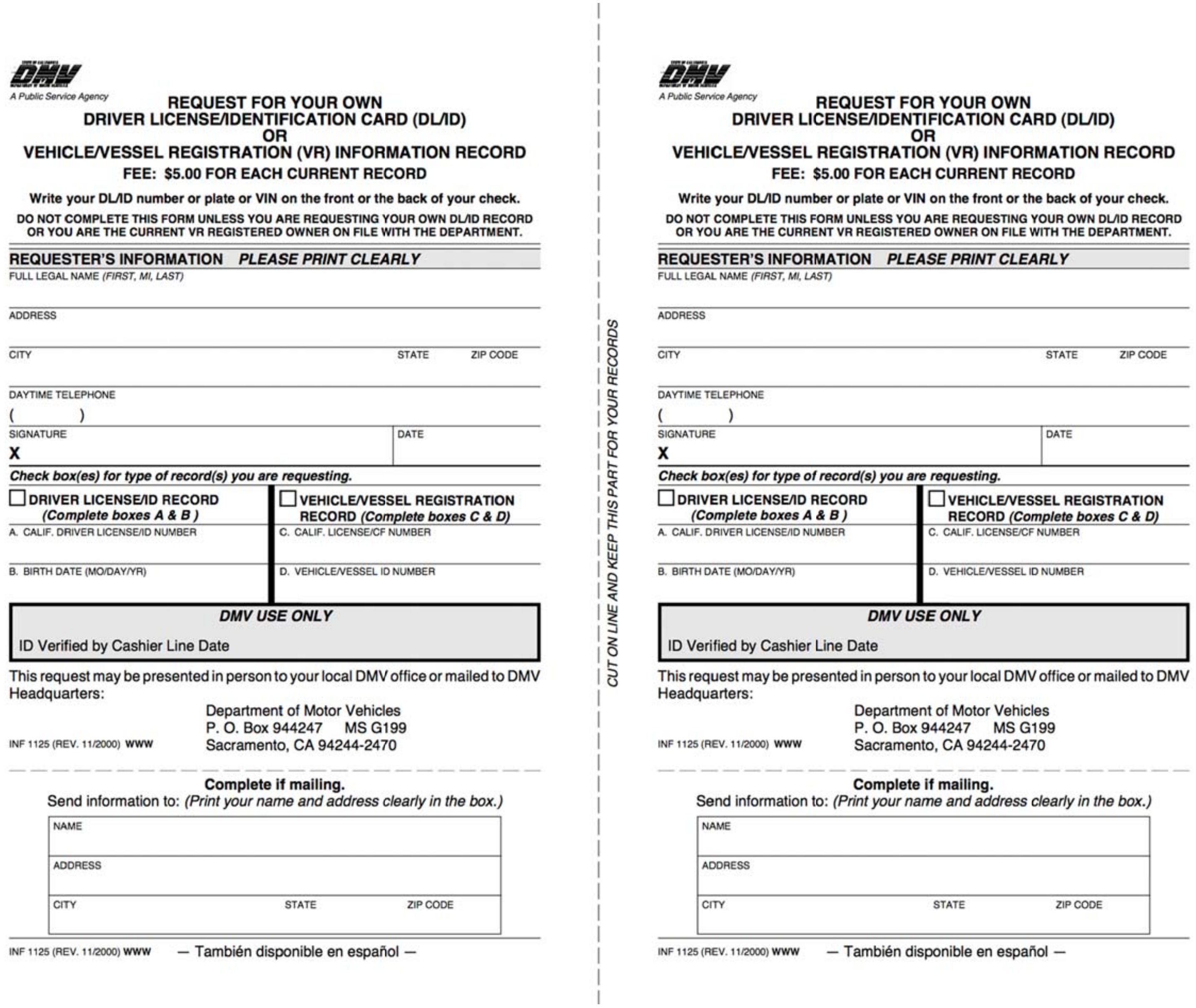
3. By telephone, if you have previously made a written request and provided proper identification.

Electronic copies of our DMV records stored on ChoicePoint's servers are deleted 30 days after being requested. The information that you provided below and any electronic or paper copies of your DMV records held by California PATH will be destroyed 30 days after your participation in this research has been completed.

Name	
Address	
Date of Birth	
Social Security Number	
Driver's License Number	

______________________________ ____________
Signature Date

Direct Mail DMV Record Request Form



A Public Service Agency

REQUEST FOR YOUR OWN
DRIVER LICENSE/IDENTIFICATION CARD (DL/ID)
OR
VEHICLE/VESSEL REGISTRATION (VR) INFORMATION RECORD
FEE: $5.00 FOR EACH CURRENT RECORD

Write your DL/ID number or plate or VIN on the front or the back of your check.

DO NOT COMPLETE THIS FORM UNLESS YOU ARE REQUESTING YOUR OWN DL/ID RECORD OR YOU ARE THE CURRENT VR REGISTERED OWNER ON FILE WITH THE DEPARTMENT.

REQUESTER'S INFORMATION ***PLEASE PRINT CLEARLY***

FULL LEGAL NAME *(FIRST, MI, LAST)*

ADDRESS

CITY STATE ZIP CODE

DAYTIME TELEPHONE
( )

SIGNATURE DATE
X

Check box(es) for type of record(s) you are requesting.

☐ **DRIVER LICENSE/ID RECORD** ***(Complete boxes A & B)***	☐ **VEHICLE/VESSEL REGISTRATION RECORD** ***(Complete boxes C & D)***
A. CALIF. DRIVER LICENSE/ID NUMBER	C. CALIF. LICENSE/CF NUMBER
B. BIRTH DATE (MO/DAY/YR)	D. VEHICLE/VESSEL ID NUMBER

DMV USE ONLY

ID Verified by Cashier Line Date

This request may be presented in person to your local DMV office or mailed to DMV Headquarters:

Department of Motor Vehicles
P. O. Box 944247 MS G199
Sacramento, CA 94244-2470

INF 1125 (REV. 11/2000) **WWW**

Complete if mailing.
Send information to: *(Print your name and address clearly in the box.)*

NAME

ADDRESS

CITY STATE ZIP CODE

INF 1125 (REV. 11/2000) **WWW** — También disponible en español —

CUT ON LINE AND KEEP THIS PART FOR YOUR RECORDS

A Public Service Agency

REQUEST FOR YOUR OWN
DRIVER LICENSE/IDENTIFICATION CARD (DL/ID)
OR
VEHICLE/VESSEL REGISTRATION (VR) INFORMATION RECORD
FEE: $5.00 FOR EACH CURRENT RECORD

Write your DL/ID number or plate or VIN on the front or the back of your check.

DO NOT COMPLETE THIS FORM UNLESS YOU ARE REQUESTING YOUR OWN DL/ID RECORD OR YOU ARE THE CURRENT VR REGISTERED OWNER ON FILE WITH THE DEPARTMENT.

REQUESTER'S INFORMATION ***PLEASE PRINT CLEARLY***

FULL LEGAL NAME *(FIRST, MI, LAST)*

ADDRESS

CITY STATE ZIP CODE

DAYTIME TELEPHONE
( )

SIGNATURE DATE
X

Check box(es) for type of record(s) you are requesting.

☐ **DRIVER LICENSE/ID RECORD** ***(Complete boxes A & B)***	☐ **VEHICLE/VESSEL REGISTRATION RECORD** ***(Complete boxes C & D)***
A. CALIF. DRIVER LICENSE/ID NUMBER	C. CALIF. LICENSE/CF NUMBER
B. BIRTH DATE (MO/DAY/YR)	D. VEHICLE/VESSEL ID NUMBER

DMV USE ONLY

ID Verified by Cashier Line Date

This request may be presented in person to your local DMV office or mailed to DMV Headquarters:

Department of Motor Vehicles
P. O. Box 944247 MS G199
Sacramento, CA 94244-2470

INF 1125 (REV. 11/2000) **WWW**

Complete if mailing.
Send information to: *(Print your name and address clearly in the box.)*

NAME

ADDRESS

CITY STATE ZIP CODE

INF 1125 (REV. 11/2000) **WWW** — También disponible en español —

Appendix C: ACC & CACC Participant Questionnaires

Adaptive Cruise Control Survey

The questions in this survey address your driving experience with the Adaptive Cruise Control (ACC) system. You will find three types of questions:

- Questions on a scale from 1 to 7, where you will indicate the side to which you feel closest by circling a number, for example:

  I liked driving this car.

  Strongly disagree 1 2 3 4 5 6 7 Strongly agree

  You would circle 7 if you strongly agree with the statement.

- Rank order items from 1 to 3, where the ranking is explained at the end of the question.

- Open ended questions, for which you will write answers.

Feel free to add comments around questions if you think it helps better express your opinion.

The information gathered through this questionnaire is confidential. The use of this information will respect your privacy and no names will ever be mentioned when using this data.

---

1 - Are you familiar with cruise control (speed only) systems?

☐ yes ☐ no

If yes, for approximately how long have you been using one? ________

Please rate your level of expertise

Novice 1 2 3 4 5 6 7 Expert

2 - Are you familiar with ACC systems?

☐ yes ☐ no

If yes, for approximately how long have you been using one? ________

Please rate your level of expertise

Novice 1 2 3 4 5 6 7 Expert

3 - Please describe the ACC system and how it works, in the way that you would describe it to another driver who has not yet seen or used the system.

____

____

4 - Overall, how comfortable did you feel driving the car using the ACC system?

Uncomfortable 1 2 3 4 5 6 7 Comfortable

5 - Do you think ACC is going to increase driving safety?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

6 - When using the ACC system in each of the following traffic conditions, did you follow other vehicles closer or further than you normally do?

Heavy traffic
Closer 1 2 3 4 5 6 7 Further

Moderate traffic
Closer 1 2 3 4 5 6 7 Further

Light traffic
Closer 1 2 3 4 5 6 7 Further

7 - In general, under which mode of operation did you feel like you reached your destination fastest? (Rank 1 fastest to 3 slowest)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

8 - How easy was it to drive using the ACC system?

Easy 1 2 3 4 5 6 7 Difficult

9 - Compare safety under these operation modes (from 1 most safe to 3 least safe)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

10 - Do you feel the following distance adjustment function is useful?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

11 - Were there times when the system became uncomfortable or inconvenient, causing you to manually disengage the system? (If so, please describe)

____

____

12 - What was your level of comfort for each of these gaps with the ACC?

Long gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Medium gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Short gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

13 - Under which mode of operation did you feel you reached your destination most safely? (from 1 most safely to 3 least safely)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

14 - How comfortable were you using the ACC system when driving in the following traffic environments?

Heavy traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Moderate traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Light traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

15 - Which mode of operation (Manual, Conventional Cruise, ACC) required you to apply the brakes most often? (Rank 1 least braking to 3 most braking)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

16 - How long did it take you to be comfortable using the ACC system?

____

____

17 - When driving the ACC system, compared to manual driving, were you more or less aware of the actions of vehicles around you than you normally are?

Less aware 1 2 3 4 5 6 7 More aware

18 - How comfortable were you driving the ACC system in comparison to the manual driving?

Uncomfortable 1 2 3 4 5 6 7 More comfortable

19 - How frequently did you get into situations when you relied too heavily on the ACC to handle situations that it could not handle? [SD or S]

Frequently 1 2 3 4 5 6 7 Never

20 - When you were driving with the ACC, was your speed generally slower or faster than the speeds of neighboring vehicles?

Heavy traffic
Slower 1 2 3 4 5 6 7 Faster

Medium traffic
Slower 1 2 3 4 5 6 7 Faster

Light traffic
Slower 1 2 3 4 5 6 7 Faster

21 - Did the system ever surprise you? (If so, please describe)

____

____

22 - How comfortable would you feel if your driving-age child, spouse, parents or other loved ones drove a vehicle equipped with ACC? (*Some of the cases may not apply to you; in this case, please mark the N/A box*)

Driving-age child (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Spouse (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Parents (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

23 - What did you think of the acceleration provided by the ACC system when pulling into an empty adjacent lane to pass other vehicles?

Too slow 1 2 3 4 5 6 7 Too fast

24 - What did you think of the deceleration rate provided by the ACC system when following a vehicle?

Too gentle 1 2 3 4 5 6 7 Too hard

25 - How much effort did it take to maintain a safe following distance when using each of the following modes of operation?

Manual driving (no ACC)
Difficult 1 2 3 4 5 6 7 Very easy

Cruise Control (speed control only)
Difficult 1 2 3 4 5 6 7 Very easy

Adaptive Cruise Control (speed and distance)
Difficult 1 2 3 4 5 6 7 Very easy

26 - How likely is it that you would have become more comfortable using the ACC system given more time?

Not likely 1 2 3 4 5 6 7 Very likely

27 - How comfortable were you using the ACC system on hilly roads?

Uncomfortable 1 2 3 4 5 6 7 Very comfortable

28 - How often, if ever, did you experience “unsafe” following distances when using the ACC system?

Frequently 1 2 3 4 5 6 7 Never

29 - Driving the ACC system, compared to manual driving, did you find yourself more or less responsive to actions of vehicles around you?

Less responsive 1 2 3 4 5 6 7 More responsive

30 - Compare (rank) these operation modes for comfort (from 1 most comfortable to 3 least comfortable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

31 - If you could add one feature to the system, what would it be and why?

____

____

32 - Did you feel more comfortable performing additional tasks, (e.g., adjusting the climate control or the radio) while using the ACC system as compared to driving under manual control?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

33 - Compare (rank) these operation modes for convenience (from 1 most convenient to 3 least convenient)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

34 - While using the ACC system, how often, if ever, did the system fail to detect a vehicle that you were approaching or following?

Often 1 2 3 4 5 6 7 Never

35 - As you got used to the ACC system, how would you rate the change of your level of confidence in the system? (circle 4 if your level of confidence remained the same)

More confident 1 2 3 4 5 6 7 Less confident

36 - Compare (rank) these operation modes for driving enjoyment (from 1 most enjoyable to 3 least enjoyable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

37 - How safe did you feel using the ACC system?

Not safe 1 2 3 4 5 6 7 Very safe

38 - If you could remove one feature/display method, what would it be and why?

39 - When using the ACC system, did you ever feel that you didn’t understand what the system was doing, what was taking place, or how the ACC system might behave?

Very frequently 1 2 3 4 5 6 7 Very infrequently

40 - Would you rather have:

☐ An ACC ☐ a (speed only) cruise control ☐ no system

41 - In general, under which mode of operation did you feel like you reached your destination with the least stress related to driving? (Rank 1 least stress to 3 most stress)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

42 - While driving with the ACC, how confident did you feel about the system?

Very confident 1 2 3 4 5 6 7 Not confident

43 - Did the system ever distract you or lead you to make an inappropriate maneuver or error in judgment? (If so please describe)

44 - Rank, in order of preference, the following modes of operation for personal use. (Rank 1 most desirable to 3 least desirable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

45 - When you were driving with the ACC, were you driving slower or faster than you normally drive?

Heavy traffic
Slower 1 2 3 4 5 6 7 Faster

Medium traffic
Slower 1 2 3 4 5 6 7 Faster

Light traffic
Slower 1 2 3 4 5 6 7 Faster

Cooperative Adaptive Cruise Control Survey

The questions in this survey address your driving experience with the Cooperative Adaptive Cruise Control (CACC) system. You will find three types of questions:

- Questions on a scale from 1 to 7, where you will indicate the side to which you feel closest by circling a number, for example:

  I liked driving this car.

  Strongly disagree 1 2 3 4 5 6 7 Strongly agree

  You would circle 7 if you strongly agree with the statement.

- Rank order items from 1 to 3, where the ranking is explained at the end of the question.

- Open ended questions, for which you will write answers.

Feel free to add comments around questions if you think it helps better express your opinion.

The information gathered through this questionnaire is confidential. The use of this information will respect your privacy and no names will ever be mentioned when using this data.

1 - Please describe the CACC system and how it works, in the way that you would describe it to another driver who has not yet seen or used the system.

2 - Overall, how comfortable did you feel driving the car using the CACC system?

Uncomfortable 1 2 3 4 5 6 7 Comfortable

3 - Do you think CACC is going to increase driving safety?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

4 - When using the CACC system in each of the following traffic conditions, did you follow the preceding vehicle closer or further than you normally do?

Heavy traffic
Closer 1 2 3 4 5 6 7 Further

Moderate traffic
Closer 1 2 3 4 5 6 7 Further

Light traffic
Closer 1 2 3 4 5 6 7 Further

5 - In general, under which mode of operation did you feel like you reached your destination fastest? (Rank 1 fastest to 4 slowest)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

6 - How easy was it to drive using the CACC system?

Easy 1 2 3 4 5 6 7 Difficult

7 - Compare safety under these operation modes (from 1 most safe to 4 least safe)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

8 - While driving with the CACC, how confident did you feel about the system?

Very confident 1 2 3 4 5 6 7 Not confident

9 - Under which mode of operation did you feel you reached your destination most safely? (from 1 most safely to 4 least safely)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

10 - Were there times when the system became uncomfortable or inconvenient, causing you to manually disengage the system? (If so, please describe)

____

____

11 - What was your level of comfort for each of these gaps with the CACC?

Long gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Medium gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Short gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Shortest gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

12 - How comfortable were you using the CACC system when driving in the following traffic environments?

Heavy traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Moderate traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Light traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

13 - Which mode of operation (Manual, Conventional Cruise Control, ACC, CACC) required you to apply the brakes most often? (Rank 1 least braking to 4 most braking)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

14 - How long did it take you to be comfortable using the CACC system?

____

____

15 - When driving the CACC system, compared to manual driving, were you more or less aware of the actions of vehicles around you than you normally are?

Less aware 1 2 3 4 5 6 7 More aware

16 - How comfortable were you driving the CACC system in comparison to the manual driving?

Uncomfortable 1 2 3 4 5 6 7 More comfortable

17 - When you were driving with the CACC, was your speed generally slower or faster than the speeds of neighboring vehicles?

Heavy traffic
Slower 1 2 3 4 5 6 7 Faster

Medium traffic
Slower 1 2 3 4 5 6 7 Faster

Light traffic
Slower 1 2 3 4 5 6 7 Faster

18 - How comfortable would you feel if your driving-age child, spouse, parents or other loved ones drove a vehicle equipped with CACC? *(Some of the cases may not apply to you; in this case, please mark the N/A box)*

Driving-age child (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Spouse (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Parents (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

19 - Did the system ever surprise you? (If so, please describe)

____

____

20 - When driving the CACC system, compared to ACC driving, were you more or less aware of the actions of vehicles around you than you normally are?

Less aware 1 2 3 4 5 6 7 More aware

21 - How frequently did you get into situations when you relied too heavily on the CACC to handle situations that it could not handle? [SD or S]

Frequently 1 2 3 4 5 6 7 Never

22 - What did you think of the deceleration rate provided by the CACC system when following the lead vehicle?

Too gentle 1 2 3 4 5 6 7 Too hard

23 - How much effort did it take to maintain a safe following distance when using each of the following modes of operation?

Manual driving (no ACC)
Difficult 1 2 3 4 5 6 7 Very easy

Cruise Control (speed control only)
Difficult 1 2 3 4 5 6 7 Very easy

Adaptive Cruise Control (speed and distance)
Difficult 1 2 3 4 5 6 7 Very easy

Cooperative Adaptive Cruise Control (speed and shorter distance)
Difficult 1 2 3 4 5 6 7 Very easy

24 - How likely is it that you would have become more comfortable using the CACC system given more time?

Not likely 1 2 3 4 5 6 7 Very likely

25 - Compare (rank) these operation modes for convenience (from 1 most convenient to 4 least convenient)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

26 - Driving the CACC system, compared to manual driving, did you find yourself more or less responsive to actions of vehicles around you?

Less responsive 1 2 3 4 5 6 7 More responsive

27 - How comfortable were you using the CACC system on hilly roads?

Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Between the ACC and CACC system, did you prefer one of the systems?

☐ yes ☐ no

If yes, which system and why?

____

____

28 - How often, if ever, did you experience "unsafe" following distances when using the **C**ACC system?

Frequently 1 2 3 4 5 6 7 Never

29 - Compare (rank) these operation modes for comfort (from 1 most comfortable to 4 least comfortable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

30 - Did you feel more comfortable performing additional tasks, (e.g., adjusting the climate control or the radio) while using the CACC system as compared to driving under manual control?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

31 - How comfortable were you driving the CACC system in comparison to the ACC driving?

Less comfortable 1 2 3 4 5 6 7 More comfortable

32 - If you could add one feature to the system, what would it be and why?

____

____

33 - As you got used to the CACC system, how would you rate the change of your level of confidence in the system? (circle 4 if your level of confidence remained the same)

More confident 1 2 3 4 5 6 7 Less confident

34 - How likely is it that you would have become more comfortable using the CACC system if you could have used it to follow any vehicle?

Not likely 1 2 3 4 5 6 7 Very likely

35 - Compare (rank) these operation modes for driving enjoyment (from 1 most enjoyable to 4 least enjoyable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (Speed and distance)

__ Cooperative Adaptive Cruise Control (Speed and shorter distance)

36 - How safe did you feel using the CACC system?

Not safe 1 2 3 4 5 6 7 Very safe

37 - Did you feel more comfortable performing additional tasks, (e.g., adjusting the climate control or the radio) while using the CACC system as compared to driving with the ACC system?

More comfortable 1 2 3 4 5 6 7 Less comfortable

38 - When using the CACC system, did you ever feel that you didn’t understand what the system was doing, what was taking place, or how the CACC system might behave?

Very frequently 1 2 3 4 5 6 7 Very infrequently

39 - Would you rather have:

☐ An ACC ☐ a cruise control ☐ no system ☐ A CACC

40 - Driving the CACC system, compared to driving the ACC system, did you find yourself more or less responsive to actions of vehicles around you?

Less responsive 1 2 3 4 5 6 7 More responsive

41 - If you could remove one feature/display method, what would it be and why?

____

____

42 - In general, under which mode of operation did you feel like you reached your destination with the least stress related to driving? (Rank 1 least stress to 4 most stress)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

43 - Do you feel the following distance adjustment function is useful?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

44 - How likely is it that you would have become more comfortable using the CACC if you could have set your own speed?

Not likely 1 2 3 4 5 6 7 Very likely

45 - Did the system ever distract you or lead you to make an inappropriate maneuver or error in judgment? (If so please describe)

____

____

46 - Rank, in order of preference, the following modes of operation for personal use. (Rank 1 most desirable to 4 least desirable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shortest distance)

47 - When you were driving with the CACC, were you driving slower or faster than you normally drive?

Heavy traffic
Slower 1 2 3 4 5 6 7 Faster

Medium traffic
Slower 1 2 3 4 5 6 7 Faster

Light traffic
Slower 1 2 3 4 5 6 7 Faster

Appendix D: Answers to open questions in ACC and CACC questionnaires

ACC Questionnaire Written Responses

(Listed by question number)

Q3. Please describe the ACC system and how it works, in the way that you would describe it to another driver who has not yet seen or used the system.

<u>*Females:*</u>

O1-3 ACC is regular cruise control plus the ability to maintain a preset (but variable) following distance. The maximum speed is set VIA the cruise control, but ACC will automatically accelerate and brake the vehicle in order to maintain the following distance the driver sets.

O3-3 Adaptive Cruise Control is a safety feature that allows setting both the speed and the following distance relative to the car in front. The speed adjusts automatically (not above the set limit) to maintain the following distance. There is a drawback: ACC doesn't work in stop and go traffic.

O4-3 Adaptive cruise control is like cruise control, where you can set your car's speed, but then the car adapts to a set distance, too, gauging by lasers in front how far the car ahead is!

O5-3 A system that automatically slows or speeds up per setting by driver. Instead of the regular cruise control system, this system allows you to set the spacing between your vehicle and the vehicle in front of you. Based on that distance, your vehicle will ensure that it maintains that distance.

11-3 Set max cruise speed and adjusts it proportionally to maintain one of 3 desired distances from car in front of you. If car is far enough in front or there is no car in front cruise speed will attain set maximum

13-3 It's cruise control, but adjusts the speed on its own when there is a car in front of you. It doesn't stop when the car in front of you suddenly breaks, and stops though

15-3 ACC is cruise control with the added benefit of detecting cars that are too close, therefore ACC disengages when that situation arises.

<u>*Males:*</u>

O6-3 Radar determines the distance between you and the car ahead and adjusts your speed accordingly.

O7-3 Its cruise control that adjust the speed of the car based on the distance of the car in front of you. If you set the speed at 80 and no car is in front of you then the car will maintain a speed of 80 but when an object (car) comes in front of the car it will automatically adjust the speed to the car in front until the object clears your path then it speeds back up to set speed.

O8-3 You know how regular cruise control, you set the speed and if you have to slow down you hit the brakes and it turns off. This one automatically slows down if you have to, then speeds back up automatically.

O9-3 It is a cruise control that changes its speed based on the car's speed in front of you

1O-3 The system uses a laser to measure the distance between your car and the one ahead of it. It then uses braking action to keep the specified distance between your car and the other car constant. The driver can set the maximum speed and trailing distance of the cruise control. As with any cruise control a slight tap of the brake or accelerator will disengage the system

12-3 Yes, prior to this test I was only aware of them
Using a radar LIDAR detection system it senses the proximity of a vehicle in front of you and keeps your vehicle =at a predetermined distance slowing or speeding your vehicle depending on the speed of the other vehicle up to the set speed of the ACC system

14-3 A fancy cruise control that automatically slows you and speeds back-up based on traffic

Q5. Do you think ACC is going to increase driving safety? 1-7 disagree/agree

Male:

12-5 ACC brings with it potential many hazards. i.e. overconfidence and less awareness of your surroundings

Q7. In general, under which mode of operation did you feel like you reached your destination fastest? (Rank 1 fastest to 3 slowest) MD,CC,ACC

Male:

O9-7 Cruise control is faster than ACC because a lot of times I deactivate CC and go on manual mode

Q9. Compare safety under these operation modes (from 1 most safe to 3 least safe) MD,CC,ACC

Male:

14-9 All 3 pretty much equal

Q11. Were there times when the system became uncomfortable or inconvenient, causing you to manually disengage the system? (If so, please describe)

Female:

O1-11 I didn't like the way it would handle in heavier traffic when other cars would merge in front of me into the open gap—it would brake suddenly because it wouldn't slow down until the other car was almost completely done merging. This was also similar to the way it behaved when driving in the far right lane and other cars were entering the highway from the on-ramp.

O3-11 Yes, sometimes cars change lanes and suddenly get in front. Although they were not quite cutting in front (still some distance between the car I drove and the car changing lanes) when the car I was driving was on ACC speeding up to the set speed, many times I felt it might not stop in time to avoid bumping into the car that just changed lanes.

O4-11 i) in very heavy traffic (0-25 mph), ii) exiting the highway, iii) at toll bridges and approaching.

O5-11 The distance setting for closest to vehicle in front was not as comfortable. I do not trust the distance setting and found that it was not as consistent as the other two distance settings.

11-11 yes, approaching traffic jams, if someone cut in front of me, off ramps, or around curves in a road

13-11 Yes, during slower traffic I had to disengage the system

16-11 On occasion (while using ACC) I became uncomfortable when the car in front of me would abruptly stop or slow, the system would slow the ACC vehicle down at almost near the (car in front of me) bumper.

Male:

O2-11 With short gap wet, abrupt changes in traffic speed were not seen quickly enough. For example, traffic slowing abruptly from 65 to near stopped, the distance where the car would slow was far too short for comfort.

O6-11 When traffic came to a sudden stop and brake high speed. The car would not brake as quickly as I would like.

O7-11 A car at away point cut me off and I felt like the car wasn't slowing down fast enough.

O9-11 1. When turning at high speeds – sometimes the sensor don't detect the car in front because of the angle. 2. When I see cars that are at full stop and I'm still running at more than 40 mph. 3. Stop and go traffic

1O-11 Yes. When the traffic ahead of my vehicle had stopped rapidly.

12-11 Yes, occasionally the ACC system would race the vehicle toward traffic not giving a sign that it would slow until the distance became uncomfortable; when traffic would come to a quick stop ahead; when a vehicle pulled in front from an adjacent lane

14-11 In general, the system closes gaps pretty quickly in light traffic, e.g. the preceding car is far enough ahead that the system is not really responding to it, and moving at freeway speed. If the preceding car slows quickly, the ACC comes up quite quickly before realizing that traffic has slowed

Q13. Under which mode of operation did you feel you reached your destination most safely? (from 1 most safely to 3 least safely) MD,CC,ACC

Male:

14-13 All 3 about equal

Q16. How long did it take you to be comfortable using the ACC system?

Female:

11-16 A day

13-16 one day

15-16 2 days

16-16 2-3 days

Male:

O7-16 It was comfortable right away.

O9-16 3 hours of using the system

1O-16 15 minutes

12-16 I became comfortable a day or two into using it. My overall comfort with its idiosyncrasies took several more days.

14-16 About 2 trips

Q19. How frequently did you get into situations when you relied too heavily on the ACC to handle situations that it could not handle? 1-7 frequently/never

Male:

O9-19 I understand the limits of the ACC

Q21. Did the system ever surprise you? (If so, please describe)

Female:

O1-21 I was pleasantly surprised at the way it handled when other vehicles would merge after passing (accelerating as they merged in front of you). I expected more braking because of the small distance available but it performed the way I would have driven.

O3-21 Not really.

O4-21 Just with how responsive/reactive it is—I was surprised at how quickly it responds to other cars sudden movements (e.g., lane changes) and that you can “feel” the car reacting.

O5-21 Only when using the close distance setting. Seemed to break closer than I would when driving manually.

11-21 No

13-21 No, not really

15-21 Yes. When a car cut me off the system braked & flashed.

16-21 A couple of times the system would speed up (to decrease the gap) to the car in front of me

Male:

O2-21 NO

O7-21 No

O8-21 Yes. On curves, even if there wasn’t a car in front of me it would pick up a car on the side and slow down. Also, when driving less than the set speed for awhile, it is surprising to suddenly speed up.

O9-21 One time when the sunlight directly hit the sensor it malfunctioned

1O-21 Yes. On sharp turns it would loose contact with the vehicle ahead and try to accelerate to cruise speed. The reaction time when a vehicle pulls in front of the vehicle is too slow.

12-21 On a couple of occasions it seemed to lose contact with the vehicle in front and began to surge forward

Q23. What did you think of the acceleration provided by the ACC system when pulling into an empty adjacent lane to pass other vehicles? 1-7 slow/fast

Male:

14-23 It lagged, and then accelerated fairly hard

Q26. - How likely is it that you would have become more comfortable using the ACC system given more time? 1-7 not likely/very likely

Male:

O9-26 I'm already comfortable w/ it

Q28. How often, if ever, did you experience "unsafe" following distances when using the ACC system? 1-7 frequently/never

Male:

14-28 Very rarely

Q30. Compare (rank) these operation modes for comfort (from 1 most comfortable to 3 least comfortable) MD,CC,ACC

Male:

O9-30 These are based on light traffic condition

Q31. If you could add one feature to the system, what would it be and why?

Female:

O1-31 Add sensors to the side to detect when another vehicle is in the process of merging in front of your vehicle. This would avoid the only unsafe situation I encountered.

O3-31 Make ACC accessible at stop and go traffic too. I think it will increase safety by avoiding constantly maintaining the distance from the car in front it can avoid fender-benders.

O4-31 Not sure, maybe an added gauge (digital) telling me what my actual speed is (vs. set speed)

O5-31 Can not think of anything to add. The system seems to work great!!

11-31 Not sure

13-31 It could stop on its own

15-31 Voice Activated like GPS.

Male:

O2-31 Instead of distance only, it would be interesting to have an ACC based on (or including) speed of the vehicle in front. A minimum gap threshold could be set, but add a model for a gap closing rate as well as to avoid rapid discontinuities in forward vehicle speed.

O8-31 Add a light to tell when you are going slower than the speed you set it at.

O9-31 1. If the system could also detect other cars on the road not just the car in front. 2. Option level on aggresiveness of the system

1O-31 A display for the cruise control mounted higher on the dash so it is easier to see

12-31 I would add a package of features that increase the system's perception of the traffic around and improve its intelligence in handling/managing it. It would also have more finesse, detecting and reacting subtly to the changes in speed of the traffic ahead. It would be best if the system only ever needed to perform emergency braking in an actual emergency. It would also be nice if it would gradually increase speed once a vehicle moves away by following its speed change or at least a mall transition as the other vehicle begins to increase speed

14-31 Ability to look beyond one car to avoid closing gaps and then breaking fairly hard when it is obvious that traffic ahead is slowing

Q38. If you could remove one feature/display method, what would it be and why?

Female:

O1-38 N/A I though the system was fairly well designed regarding the user interface.

O3-38 Climate control is difficult to set for higher temperatures. It distracts from driving while trying to figure out how to adjust the climate.

O4-38 Not sure yet—system still too new for me to determine what I am not using, or taking for granted!

O5-38 Modify the closest setting. Distance for slowing or stopping seems to be too close. I was not comfortable with the system at the distance setting.

11-38 Nothing

13-38 The set speed, because the set speed was always slower than the other cars on the road

15-38 None.

Male:

O2-38 I thought the longest gap was too long and didn't like having to reset it each time engaged to shorter gap. Speed increase is a bit hair trigger, if not paying attention goes quickly to 90 mph.

O8-38 The off/on button. I don't know why it is needed.

O9-38 If the sensors decrease the speed as it senses lesser of the vehicle in front vice-versa. This will be useful for shifting lanes and passing vehicles

Q40. Would you rather have: MD,CC,ACC

Male:

O8-40 ACC, If there was no added cost. Otherwise, no system.

Q43. - Did the system ever distract you or lead you to make an inappropriate maneuver or error in judgment? (If so please describe)

Female:

O1-43 n/a

O3-43 NO

O4-43 NO

O5-43 NO
11-43 Not really

13-43 No

15-43 None.

Male:

O2-43 NO
Further comment: I felt more comfortable with land changes, especially in traffic, because I could take my eyes off the forward vehicle and look at my blind-spot and know that my car would give me some indication that the car in front was slowing (i.e., braking).

O7-43 No

O9-43 No

1O-43 The display is mounted too low on the dash. It did distract me look down to set the speed.

12-43 Only if I relied on it too heavily. Due to traffic pulling in front of the FX or traffic slowing rapidly I had to make sure I monitored the distance

Q45. When you were driving with the ACC, were you driving slower or faster than you normally drive? 3 traffic density ranges 1-7

Male:

14-45 Slower when the system slowed to follow another car, say from 65 to 55, and I didn’t realize I had slowed, and therefore didn’t change lanes as promptly as I normally would

CACC Questionnaire Written Responses

(Listed by question number)

Q1. Please describe the CACC system and how it works, in the way that you would describe it to another driver who has not yet seen or used the system.

Female:

O1-1 The CACC system can be used when driving with another car. It works like a regular cruse control and allows automatic adjustment of the following distance relative to the car ahead of you, with a maximum speed that you set via the cruise control. The vehicle automatically slows down and speeds up to stay with the speed of traffic.

O3-1 CACC is an enhanced safety feature of ACC. It requires a wireless connection between the computer systems controlling the operation of the leading car and the car behind. The response of the car following is slightly smoother and seemed to me more timely at closest following distance than with ACC.

O4-1 The ACC is a type of cruise control where you can not only set the speed for your car, but you can also determine the distance (generally 1-, 2-, or 3- car lengths) from which you will remain behind any vehicle in front of your car, and your car adapts itself to maintain that distance, regardless of the speed you've set. The CACC does the same, only with shorter set-distance ranges, and an extra set distance to select.

O5-1 A user can set the amount of space between you and the car in front to maintain during your drive. The system will either slow or speed up based on your cruise control speed. I is very cool!

13-1 It is cruise control, but it changes the speed automatically depending on the car in front of you, and it shuts off when the speed goes below 25mph

15-1 The CACC system is a alternative cruise control system. Once engaged the CACC is better equipped to gage distance and speed as per the system.

16-1 The CACC system works by the 2 vehicles communicating together. Once the CACC car's speed is set, it creates a gap between the 2 vehicles, not allowing the CACC vehicle to go any faster than the lead ACC vehicle.

Male:

O2-1 The system uses ACC with the added feature of communication between vehicles. A following distance (time) gap is set by the trailing car of a two car set. The forward car transmits speed information to the rear car. As the forward car slows or speeds up, the communication allows the rear car to maintain the gap during transients without significant delay in response.

O6-1 It is an automatic speed control system between two cars that uses radio to communicate speed and distance information to maintain distance and speed.

O8-1 You set the cruise control and there’s a sensor that keeps you at a certain distance from the car in front. The idea is to keep you close but keep traffic flowing, so there’s no back up.

O9-1 It is a modified version of ACC which is more advance. It directly communicates w/ the car in front through a dedicated signal.

1O-1 The system works like a normal a cruise control except it has the capability to adjust to changing traffic speed conditions. The driver can select the maximum speed for the vehicle and how close they wish to follow the traffic ahead. The vehicle will then accelerate or brake to adjust to the current traffic speed.

12-1 CACC controls the vehicle speed by sensing the vehicle in front acting as a space cushion. It uses a radar unit to detect vehicles in front and adjusts the speed down to match or up until it reaches your max sitting. CACC also reads data from the vehicle in front about the status of the brakes and engine to assist in early detection of speed variations

14-1 It automatically keeps your distance from the car in front of you. It speeds up and slows down as traffic dictates

Q7. Compare safety under these operation modes (from 1 most safe to 4 least safe)MD,CC,ACC,CACC

Male:

14-7 All were very similar

Q9. Under which mode of operation did you feel you reached your destination most safely? (from 1 most safely to 4 least safely)MD,CC,ACC,CACC

Male:

14-9 Very little difference

Q10. Were there times when the system became uncomfortable or inconvenient, causing you to manually disengage the system? (If so, please describe)

Female:

O1-10 I did disengage the system once or twice when driving when the vehicle I was following braked suddenly. I could see that traffic would come close to a stop.

O3-10 Yes, when cars would cut in front when the following distance was set to closest. In this situation, I wasn't sure that the ACC will kick-in in time to avoid impact.

O4-10 i) In heavy traffic that slowed down <40 mph; ii) exiting the highway.

O5-10 When I set the distance to the shortest distance, it was too close for my comfort so I would use the brakes before the system.

13-10 Yes, when another car came into the lane I was in (came between me, and the lead car). Another time is when I had to slow down really fast.

15-10 N/A

16-10 Yes, only in heavy traffic or when the car in front of me braked hard.

<u>*Male:*</u>

O2-10 Short gap, rapidly slowing traffic

O6-10 Acceleration at times was jerky. Also sudden stops made me more willing to brake.

O8-10 Yes, when cars cut in and the speed decreased quickly. It could make you lose control if not ready for it.

O9-10 Two incidents. Both incidents the vehicle I was driving was not able to communicate w/ the car in front.

1O-10 When another car moved in between my vehicle and the chase vehicle I had to disengage the system. The abruptness of the brakes action of the CACC vehicle was a bit uncomfortable

12-10 Yes. Whole in stop and go traffic; When traffic in front stopped abruptly

14-10 Only when another car squeezed between me and the lead car

Q14. How long did it take you to be comfortable using the CACC system?

<u>*Female:*</u>

O1-14 fairly quickly, in 1 drive (30 minutes)

O3-14 Almost instantaneously once I got used to the ACC.

O4-14 one day
O5-14 Not long. It was very easy to use.

13-14 A day

15-14 2 days

16-1 maybe 20 minutes after driving

Male:

O2-14 One to two days

O6-14 After the initial introduction about one hour.

O8-14 A few trips

O9-14 30 minutes

1O-14 2 Minutes

12-14 After becoming familiar with ACC it only took a brief familiarization with the CACC to become comfortable

14-14 Almost immediately

Q17. When you were driving with the CACC, was your speed generally slower or faster than the speeds of neighboring vehicles? 3 traffic densities, 1-7 response

Male:

O9-17 Can't say cause I was just following the lead car

Q19. Did the system ever surprise you? (If so, please describe)

Female:

O1-19 I found the acceleration to be much more jerky/abrupt and not as smooth as the ACC system.

O3-19 Not in an unpleasant manner.

O4-19 i) reaction—that the vehicle responded so quickly and that you could feel the response, which is comforting to know that it's working; ii) that the system stopped itself when driving on a wet highway (not raining).

O5-19 No, loved the system.

13-19 No, not really

15-19 Yes! The pull back when the system detects another vehicle in range.

16-19 Acceleration & deceleration was more noticeable in the CACC vehicle.

Male:

O2-19 NO

O6-19 No.

O8-19 See answer to question 10

O9-19 Yes. When it failed to communicate to the lead car

1O-19 The abruptness of acceleration or braking did surprise me

12-19 No

14-19 No

Q24. How likely is it that you would have become more comfortable using the CACC system given more time? 1-7 Not likely/likely

Male:

O9-24 Already comfortable

Q27. Between the ACC and CACC system, did you prefer one of the systems? Yes/no, If yes, which system and why?

Female:

O1-27 Yes, ACC—the following distances are similar to what I usually keep when driving manually. The CACC felt a little too close.

O3-27 Yes, probably the CACC – it seemed to me to start breaking more promptly to maintain the following distance—this observation is based on the very limited experience with the system. More time would have given more information by exposing me to probably more situations.

O4-27 Yes, CACC—appreciated the shorter distances and more options for distances.

O5-27 Yes, I did prefer the ACC system because of the distance settings. The shortest setting on the CACC was too close for me. The ACC seemed to have distance settings that I would use.

13-27 Yes, CACC, it had a closer gap, which was more comfortable.

15-27 CACC=more control

16-27 Yes, I'd prefer the CACC system because it allowed me to safely keep a comfy distance between the CACC car and the ACC car.

Male:

O2-27 Yes, I preferred the gap flexibility of the CACC system. Although, the driving experience was more contrived.

O6-27 Yes, I like the faster brake response of the CACC but wish the acceleration was more smooth.

O8-27 Yes, you set closer to the vehicles and less people cutting in front.

O9-27 yes, CACC the gaps are shorter

1O-27 Yes. The CACC system allowed for greater accuracy and faster response times

12-27 Yes, CACC, I prefer the ability to close the following gap. It would be nice if it could get closer and had the option of the middle distance option on the factory system

14-27 Yes, the CACC was more relaxing to use, but I also probably felt more confident following the test vehicle as opposed to a complete stranger

Q29. Compare (rank) these operation modes for comfort (from 1 most comfortable to 4 least comfortable) MD,CC,ACC,CACC

Male:

14-29 All pretty similar; comfortable with all, but the more advance the system the easier overall driving experience

Q32. If you could add one feature to the system, what would it be and why?

Female:

O1-32 I would add one more distance setting to be slightly longer than the current maximum distance and eliminate the closest distance setting.

O3-32 Perhaps adjusting the feature to work at stop and go traffic conditions.

O4-32 A separate reading for actual speed (digital) versus set speed.

O5-32 Illuminate the cruise control settings on the steering column. If you are not used to the system, it is difficult to see at night or in darker conditions. Also, the short distance setting is a little too close for my comfort.

13-32 The system can start beeping when it wants me to brake.

15-32 N/A

16-32 None

Male:

O2-32 No ideas specific to CACC.

O6-32 Distance display.

O8-32 Add a way to set the cruise control speed at the speed you are going. It would be like setting the speed, but able to do it after the speed has been set.

O9-32 If it can detect other vehicles aside from the one in front

12-32 Smoothing out the speed transition

14-32 Ability to look further ahead in light traffic and slow sooner. No need to close the gap to the next car and then slow quickly

Q34. How likely is it that you would have become more comfortable using the CACC system if you could have used it to follow any vehicle? 1-7 Not likely/likely

Male:

O9-34 Already comfortable

Q41. If you could remove one feature/display method, what would it be and why?

Female:

O1-41 I would remove the closest distance setting, because I was not comfortable driving that close to the vehicle ahead of me.

O3-41 not applicable

O4-41 not applicable

O5-41 I would remove to shortest distance method – the car in front would be too close for my comfort level.

13-41 I don't know, I don't think so

15-41 N/A

16-1 None

Male:

O2-41 No suggestions.

O6-41 There were no feature/display methods I would want removed.

O8-41 None

O9-41 Same as my answer on ACC

12-41 Not sure I would actually want to remove something

14-41 No changes

Q44. How likely is it that you would have become more comfortable using the CACC if you could have set your own speed? 1-7 not likely/likely

Male:

O9-44 I don't understand the question

Q45. Did the system ever distract you or lead you to make an inappropriate maneuver or error in judgment? (If so please describe)

Female:

O1-45 NO

O3-45 NO

O4-45 NO

O5-45 NO, The system worked as I had hoped. I really love the fact that it would maintain a proper distance between the vehicles.

13-45 No

15-45 N/A

16-45 No

Male:

O2-45 NO

O8-45 None

O9-45 None that I can remember

12-45 No

14-45 No