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Effects of Cooperative Adaptive Cruise Control on Traffic Flow: Testing Drivers' Choices of Following Distances

Delphine Cody, Fanping Bu, Susan Dickey, David Nelson, John Spring, Christopher Nowakowski, Steven Shladover

California PATH Reports to Caltrans 2008-C2

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Final Report for Task Order 5202

October 2008

Effects of Cooperative Adaptive Cruise Control on Traffic Flow: Testing Drivers' Choices of Following Distances

Report to Caltrans on
PATH Task Order 5202

Delphine Cody, Fanping Bu, Susan Dickey, David Nelson,
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Abstract

A Cooperative Adaptive Cruise Control (CACC) system has been developed by adding a wireless communication system and new control logic to an existing commercially available adaptive cruise control (ACC) system. 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 eventual impacts of such a system on highway traffic flow capacity and stability can be estimated.

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. These vehicles will be tested in subsequent research projects to develop quantitative measurements of their performance and of how drivers from the general public choose to use the CACC. The information from the tests by these naïve drivers will indicate what the potential impacts of CACC could be on highway traffic capacity and dynamics, which has profound implications for the future of the highway system.

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.

Because the most important experiments involving these vehicles will 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 will be 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 will be recorded so that they can be compared with the baseline driving. The design of the data acquisition system and the information that it records are described here for reference.

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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.

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. This represents the first step in a multi-step sequence of projects that includes the subsequent human factors experiments to learn about how drivers use the system and what they like or dislike about it. The results of the testing of the technical performance of the system and the human factors experiments will be addressed in subsequent reports.

2 Definitions of terms

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, while in the second phase the driver will be using a prototype CACC. The naming convention is illustrated in the two figures below.

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

Figure 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. 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 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.

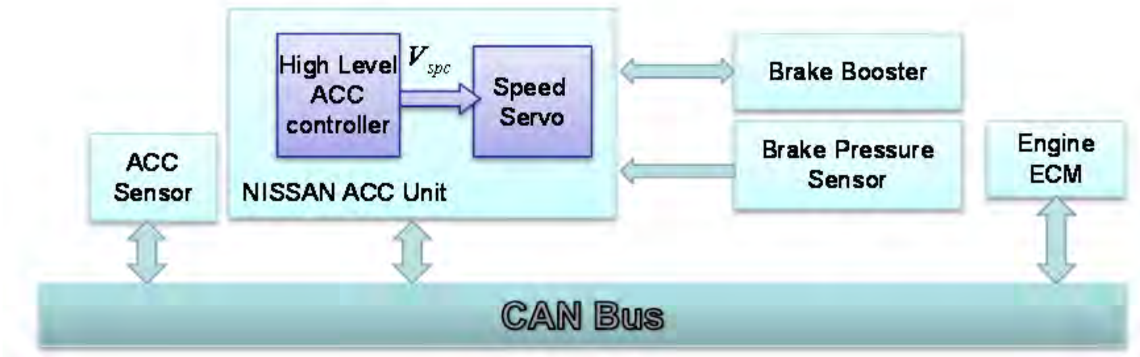


Figure 3: Configuration of Existing NISSAN ACC Controller

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, 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 4, 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.

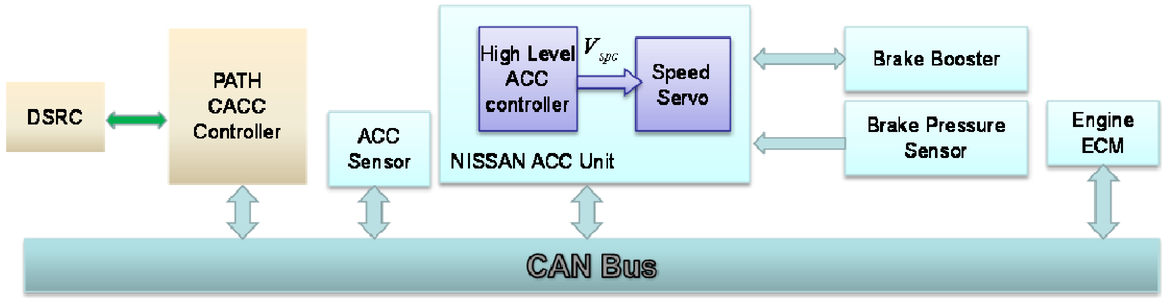


Figure 4: Add-on System Design for PATH CACC

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 4. 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 5 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.

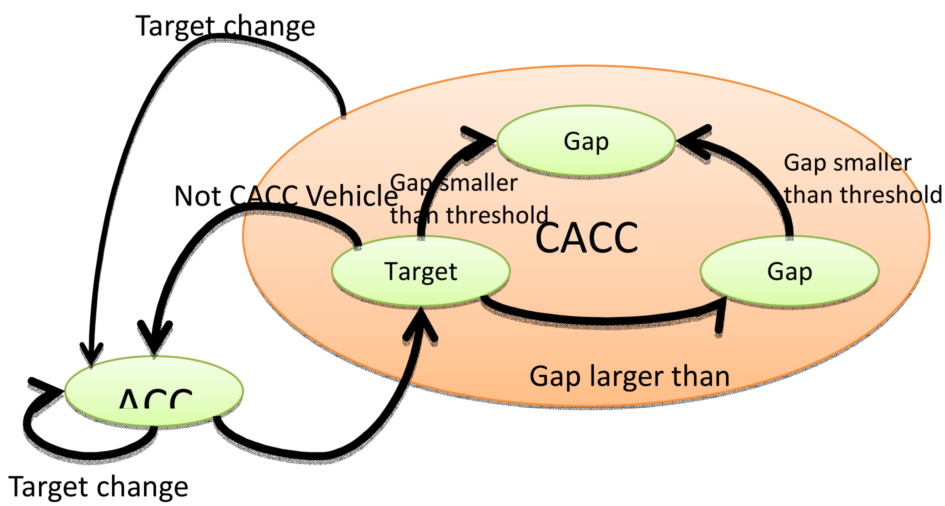


Figure 5: State Machine for PATH CACC controller

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. Since there will only be two DSRC equipped vehicles during our testing, a simple method is adopted for the target ID purpose. Figure 6 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.

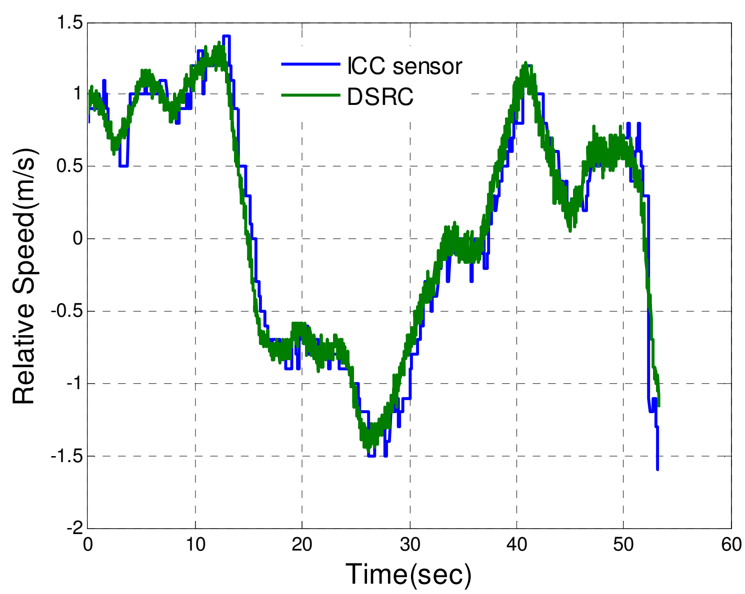


Figure 6: Comparison of relative speed output between ACC sensor and DSRC

3.2.2.3 CACC Controller Structures and Enhanced Speed Servo Loop

Figure 7 and Figure 8 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.

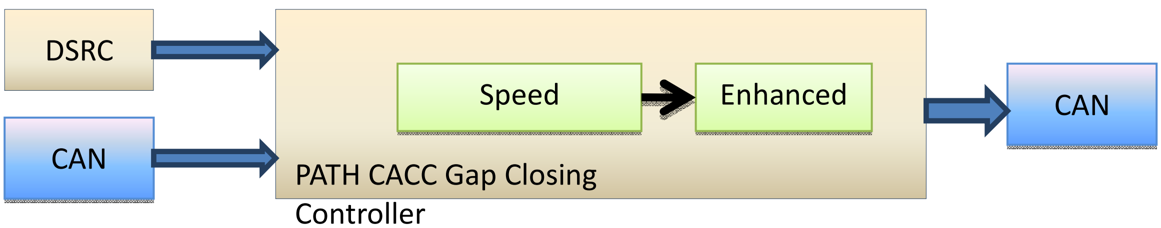


Figure 7: PATH CACC Gap Closing Controller

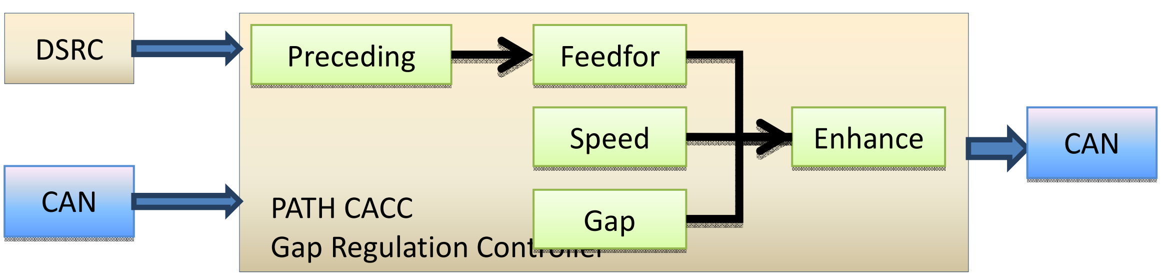


Figure 8: PATH CACC Gap Regulation Controller

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 9. All the parameters (e.g. Δv) can be tuned to provide different driver comfort levels.

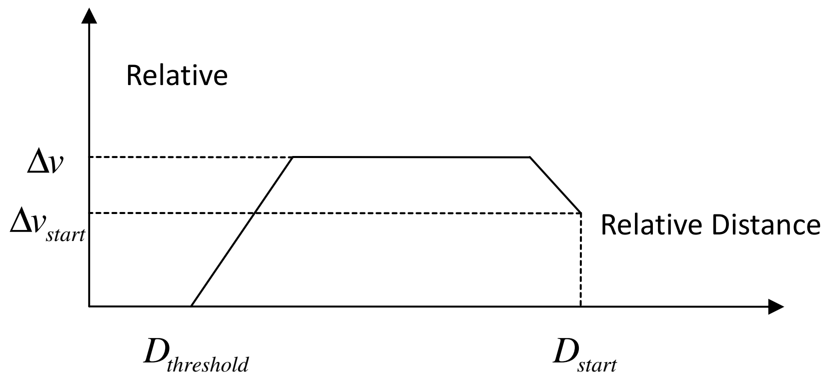


Figure 9: Trajectory Planning for CACC Gap Closing Controller

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 8, the CACC gap regulation controller consists of preceding vehicle state estimation, speed tracking and gap regulation.

A. 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.

B. 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.

C. Gap Regulation

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

3.2.3 Driver Vehicle Interface

The Driver-Vehicle Interface (DVI) for the CACC was based on the original DVI for the Infiniti ACC. Both DVIs are explained here.

3.2.3.1 ACC Driver Vehicle Interface

The ACC Driver Vehicle Interface (DVI) is composed of a set of controls located on the steering wheel and a couple of displays on the instrument panel.

Figure 10 below depicts the displays on the left side and the controls on the right side.

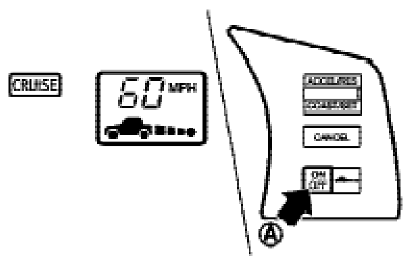


Figure 10: ACC display and controls as illustrated in vehicle owner's manual

The "CRUISE" display to the left of the instrument cluster 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. The second display contains the following information:

- The set speed (60 mph example in Figure 10)
- The set gap. Each square between the vehicle and dot represents a gap. If all squares are visible, the longest gap has been selected, and when the shortest gap has been selected, only the square closest to the dot is present.
- Whether a lead vehicle is detected by the system. If no car is detected, the icon depicting the vehicle is not displayed.

Figure 11: ACC displays (left) and controls (right)

The 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 11. This picture shows how the display looks when the ACC has first been activated, but the set speed has not yet been selected and the vehicle is not moving fast enough for a lead vehicle to be detected and indicated.

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 10 and 11. 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, as there is one more gap proposed to the drivers and no changes to the controls. On the copper-colored FX-45, which is used for the CACC driving experiments, this display is located on a special larger screen, mounted to the right of the steering wheel as shown in Figure 12.

Figure 12: CACC display (right of steering wheel)

This display allows both the driver and the experimenter to see the setting during the experiments. The additional radio transmitter icon indicates whether the vehicle-vehicle communication is operational. Note in Figure 12 that 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 DAS section for more details on data collection setup). This display is not representative of the display that would be used in a commercially available CACC, which would most likely be integrated in the same fashion as the ACC display. Therefore, the location of the screen and the number of gaps available will not be a topic for evaluation in the experiments.

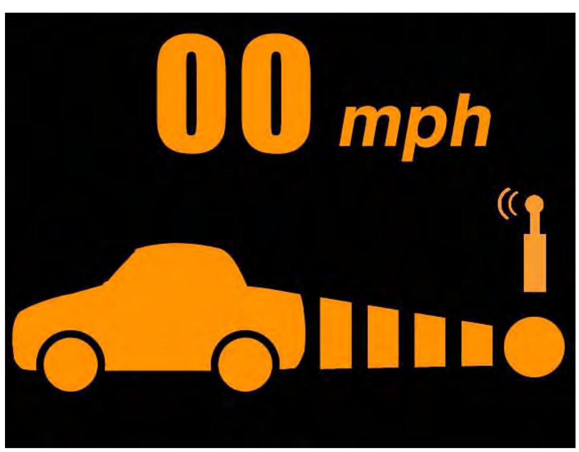


Figure 13: CACC Driver Vehicle Interface

Figure 13 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 11), 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 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 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 drivers 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 14, which illustrates the connection between the ACC and CACC computers with the engineering computer already interfaced with the CAN bus (See Figure 4).

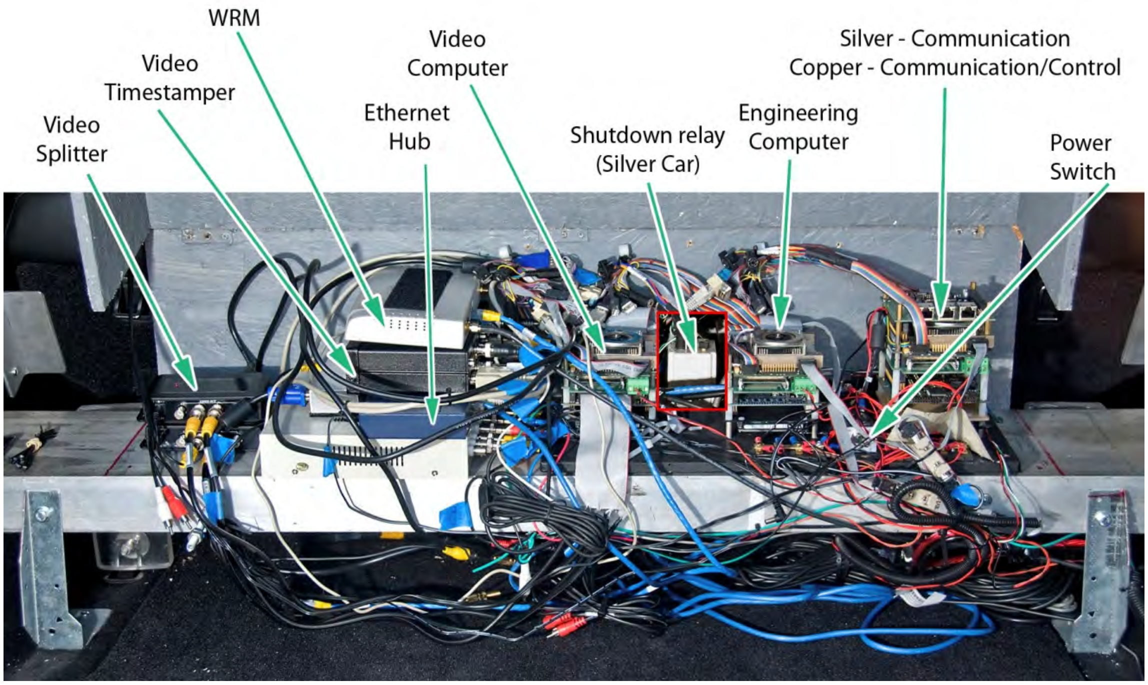


Figure 14: C/ACC DAS and Engineering Computer

Figure 15 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.

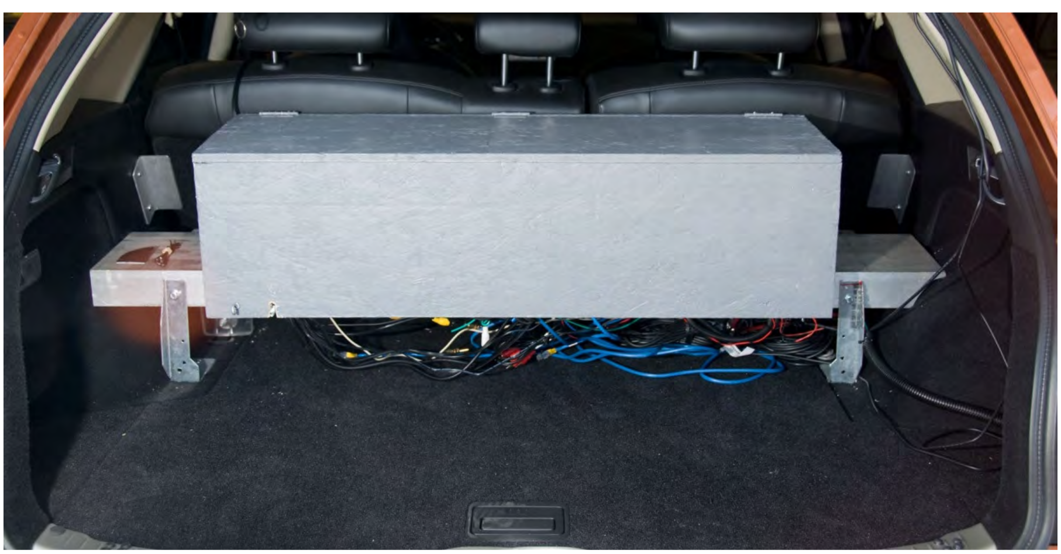


Figure 15: Computer enclosure in luggage compartment behind rear seat of vehicle, with cover closed

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 16.

Figure 16: 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 17. 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 17: 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).

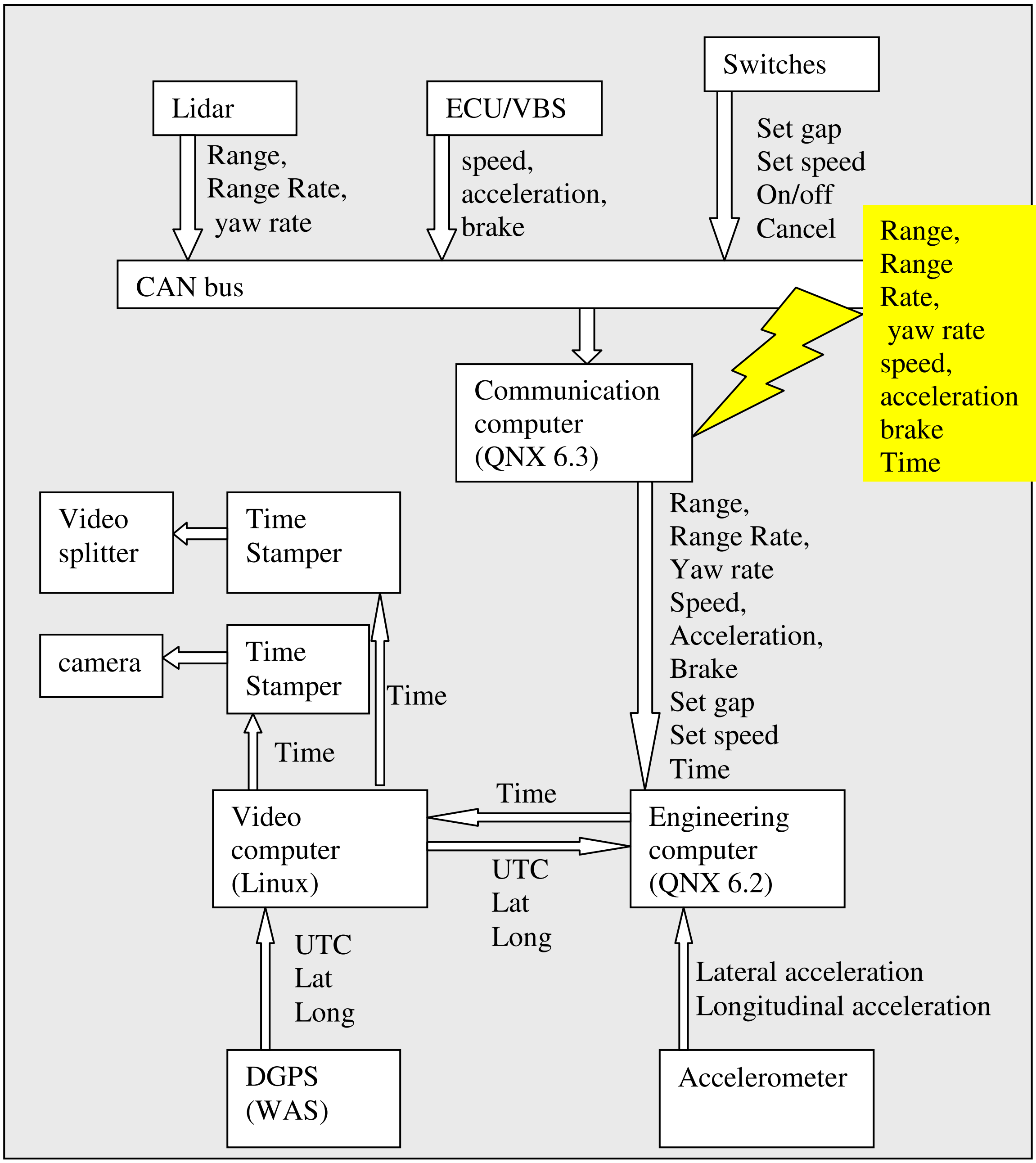


Figure 18: DAS Data Flow for ACC

The yellow box contains the information sent from the Communication Computer (the one paired with the CACC Computer in the other vehicle). This information is also recorded on the Lead Vehicle data logging computer.

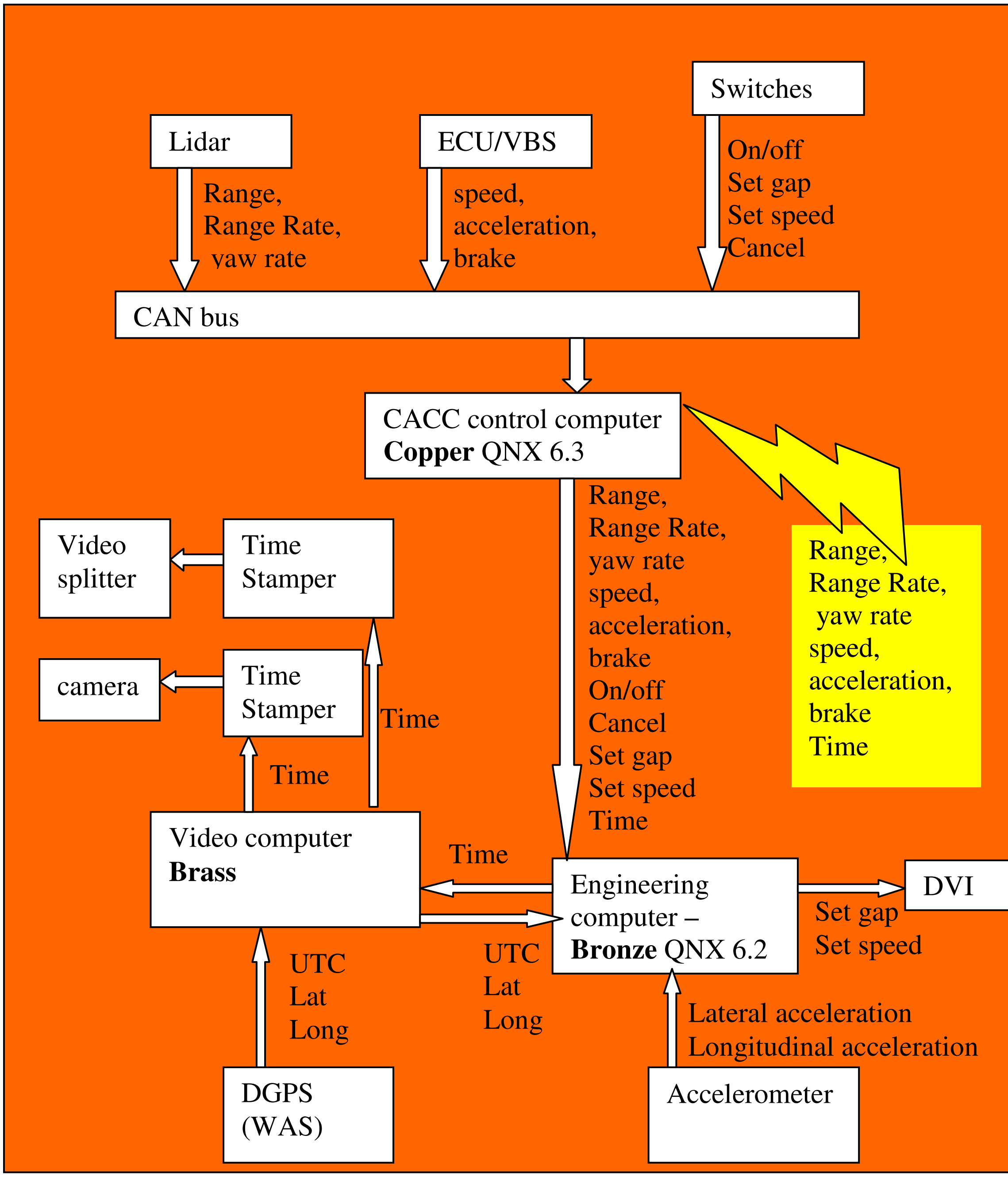


Figure 19: DAS Data flow for CACC Vehicle

The yellow box contains the information received by the CACC control computer from the lead vehicle. This information is transmitted to the Engineering computer (data logging computer)

5 Data Files

We distinguish two set of data, data created on the vehicles (engineering files, collected on the engineering computer installed on each vehicle and video files used for generating event files for information that cannot be automatically sensed); and questionnaire and surveys, where the data gathered will be about the driver's characteristics, generated by entering responses to a questionnaire on driving practice and ACC/CACC usage.

The engineering data are obtained at the end of each test. The questionnaire will be manually entered after the test and the event files will be created manually by watching the video.

5.1 Files created on the vehicles

5.1.1 Engineering files

Filenames are constructed in the form 'xymmddttttsss.dat', where:

- 'x' is replaced by a single character representing the vehicle on which the data is 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 a commercial ACC.
- 'y' is replaced by a single character representing type of data:
    - '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.
- 'mm' is replaced by a two-character number representing current month.
- 'dd' is replaced by a two-character number representing day of month.
- 'tttt' is replaced by a four-character trip number from 0000 to 9999.
- 'sss' is replaced by a three-character serial number from 000 to 999.

Data are recorded every 50 msec (20 Hz sampling rate), files are 2 minutes long, and the 3 sets of files are saved in trip directories under the parent directory /big/data. The trip directories are named after the convention 'eyymmddtttt', where:

- 'e' is the indication that the directory contains engineering (instead of video) data.
- 'yy' is replaced by a two-character number representing current year.
- 'mm' is replaced by a two-character number representing current month.
- 'dd' is replaced by a two-character number representing day of month.
- 'tttt' is replaced by a four-character trip number from 0000 to 9999. This trip number is duplicated in the file names within the directory for redundancy.

Table 1: Contents of C/ACC data file (file beginning with character 'a')

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	0-8
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 2: Contents of Communication file from lead vehicle (file beginning with character 'c')

Column	Description	Unit
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	0-8
15 = O	Front right wheel speed	rpm
16 = P	Driver brake	0/1

17 = N	Target lock	0/1
18 = Q	Car space (ACC gap selection)	1-3
19 = R	Set speed	km/h
20 = S	Brake pressure	bar
21 = T	Distance from silver Nissan to target vehicle	m
22 = U	Relative speed (between silver Nissan and its ACC target vehicle)	m/s
23 = V	Yaw rate	deg/s
24 = W	Vehicle Speed	km/h

Table 3: Contents of Driver behavior and target data file (file beginning with character 'd'):

Col #	Xcl	Parameters	unit
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	1=on, 0=off
11	K	Car space (ACC or CACC gap selection)	2-3-4-5 for copper 1-2-3 for silver
12	L	Target approach warning	
13	M	MainSW – Cruise control enabled	1 = on, 0 = off
14	N	ACC Buzzer	
15	O	ACCBuzzer2nd	
16	P	ACCBuzzer3rd	
17	Q	Set speed	km/h
18	R	Accel. PedalPosition (from driver)	percent
19	S	VirtualPedalPosition (from driver, ACC or CACC)	percent
20	T	DriverBrake	1 = on, 0 = off
21	U	ACCMainSW – Cruise control activated	1 = on, 0 = off
22	V	Brake pressure	bar
23	W	Speed	km/h
24	X	utc_time	HHMMSS:ss
25	Y	longitude	degree
26	Z	latitude	degree
27	AA	altitude	m

28	AB	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 target vehicle	m
33	AG	rel_speed compared to target vehicle	m/s

5.1.2 Video Files

Filenames are constructed in the form 'xymmddttttsss.avi', where:

- 'x' is replaced by 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.
- 'y' is replaced by a single character representing the video channel
  'f' is used for the single video looking out of the front window.
  'q' is used for the four (quad) video streams that have been combined into one.
- 'tttt' is replaced by a four-character trip number from 0000 to 9999.
- 'sss' is replaced by a three-character serial number from 000 to 999.

The files are of the same time length as the engineering files.

Video data are recorded continuously at a 500 kbit rate; files are 2 minutes long, and the 2 sets of files are saved in trip directories under the parent directory /big/data. The trip directories are named after the convention 'vyymmddtttt', where:

- 'v' is the indication that the directory contains video data.
- 'yy' is replaced by a two-character number representing current year.
- 'mm' is replaced by a two-character number representing current month.
- 'dd' is replaced by a two-character number representing day of month.
- 'tttt' is replaced by a four-character trip number from 0000 to 9999. This trip number is duplicated in the file names within the directory for redundancy.

Figure 20: Example of video file content (left is front view, right is quad view)

Figure 20 illustrates the view provided by the two video files. The figure on the left represents the front scene. At the bottom of the image is the time, in hours, minutes, seconds and milliseconds and the date. On the right image is the quad view, which integrates, from the top left corner, the rear view, the view of the steering wheel, the view of the foot above the pedals, and the driver's face.

5.2 Questionnaires and surveys

5.2.1 Event files

These files will be created post data collection, and will consist of coding events that could not be captured by sensors. For example, the focus of the analysis will be on vehicle following events, and we will need to characterize the beginning and end of a following event (e.g. lane change by the SV or POV, catching up with slower vehicle, faster vehicle opening the gap). We will need to determine how much of this can be recognized automatically and how much has to be double-check coded by a human.

5.2.2 Drivers' characteristics files

This information will be entered on either Excel or SPSS based on the questionnaires that will be filled out by the participants.

5.2.3 ACC and CACC comfort assessment questionnaire

A questionnaire for assessing the level of comfort of the drivers with each system has been developed. The questionnaire will be presented in the subsequent report describing the experimental design, data collection protocol, data analysis and results.

5.3 Data organization and processing

In order to describe the data organization, we will start by a summary of the testing condition as there will be a need to compare the three following conditions:

- Baseline driving, when the driver is not using either the ACC or CACC. This condition will be used in order to categorize the driving style in terms of vehicle following control.
- ACC use:
- CACC use

The baseline data have been collected during two specific days, Day 1 and 8. Any data that is collected during the days where the ACC or CACC *can* be used but either system is *not* being used cannot be considered baseline data, because one of our goals is to understand the conditions of use of the system. For example, if the ACC system is not used when traffic is fairly dense we would skew our data into having shorter time gaps for the baseline than if we used data from trips driven when there is no possibility to use the system.

Table 4 below summarizes the test condition for each day. Of special interest will be the data collected on days 1, 2, 5, 6, 7, 8, 9, 12 and 13. Because days 3, 4, 10 and 11 are weekends, we do not expect the participants to go to work, however, California being California, it will be worthwhile to double-check this assumption with the data.

Table 4: 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

In summary:

- Baseline Driving: Days 1 and 8
- ACC use: Days 2, 5, 6, 7, 8, 9
- CACC use: Days 12 and 13

For each of the Baseline, ACC and CACC days, we will distinguish further between the morning and evening commute trips. The focus on commute trips can be justified by the desire to “block” additional sources of variability, since the “main” variation among trips will be caused by traffic conditions, and eventually by the driver (if the level of fatigue varies from day to day), although the latter is not information that we will have access to.

The trips will be further divided into sections. For this study, we focus on highway driving; therefore, we will work mostly on the data that is collected when the participants enter the highway. We expect the different sections to be:

- On-ramp: when the participant enters the highway
- Cruising: longer highway sections where the participant mostly regulates speed and distance
- Merge: sections where the participant favors being in specific lanes in order to follow a direction
- Split: same as above
- Exit: when the participant exits the highway.

The main question to answer is whether drivers are comfortable with the shorter gaps provided by the CACC. In order to do so, we want their opinion about the system, but also a set of more “objective” data, related to their use of the system. In order to do so, we want to observe:

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

The part of their driving that we will focus on will be essentially:

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

In order to so, we will:

1. describe each trip/section in terms of chronological time where the driver is following a vehicle and times where the driver is driving "alone", i.e. no targets are sensed. We can have two graphs:
    - one in time for each trip
    - one in distance summarizing all of the trip to see if there are locations where the ACC/CACC is systematically used/not used

   For each trip will have the number of vehicle following episodes and their duration

2. Characterize each following episode in terms of:

    - duration
    - Initiation (e.g. SV catches up with slower POV, SV changes lane, POV changes lane) – this will likely be filled in by hand, although we can try to look at some data and see if we can sort them automatically
    - 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 episode, we will have a chronological file (from beginning to end time) with time, lead vehicle speed, ACC vehicle speed, time gap to lead, TTC, and several figures plotting the vehicle speed, time gap, and brake pressure. We will refine the content of the plots once we get data.

4. Identify every lane change and causes for the lane change, mostly distinguishing between lane change for overtaking and lane change for following a specific direction.

5. Characterize system use

    - For each trip using one of the systems
        - Number of episodes when the system is used
        - Length of each of these episodes
        - Sections where 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/disengagement, for example, we want to know if the ACC is disabled by the driver under conditions in which he/she uses the CACC and then what happens with the CACC.
   - Number of disengagements of each system (we expect that the participant should need to disengage the CACC less often than the ACC).
   - Comparison of usage throughout the commute.

6 Conclusions

This report has described the design and development of the CACC system and the data acquisition system that will be used in future experiments to collect data about how drivers use the system. Those experiments are expected to show how willing drivers will be to take advantage of the shorter time gaps that the CACC enables. Because the experiments will include baseline data about how the test drivers drive under normal traffic conditions both with and without ACC, it should become possible to estimate the extent to which the CACC capability will produce shorter gaps in highway traffic, potentially leading to significant increases in the capacity per lane compared to today's manual driving.

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 – 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)

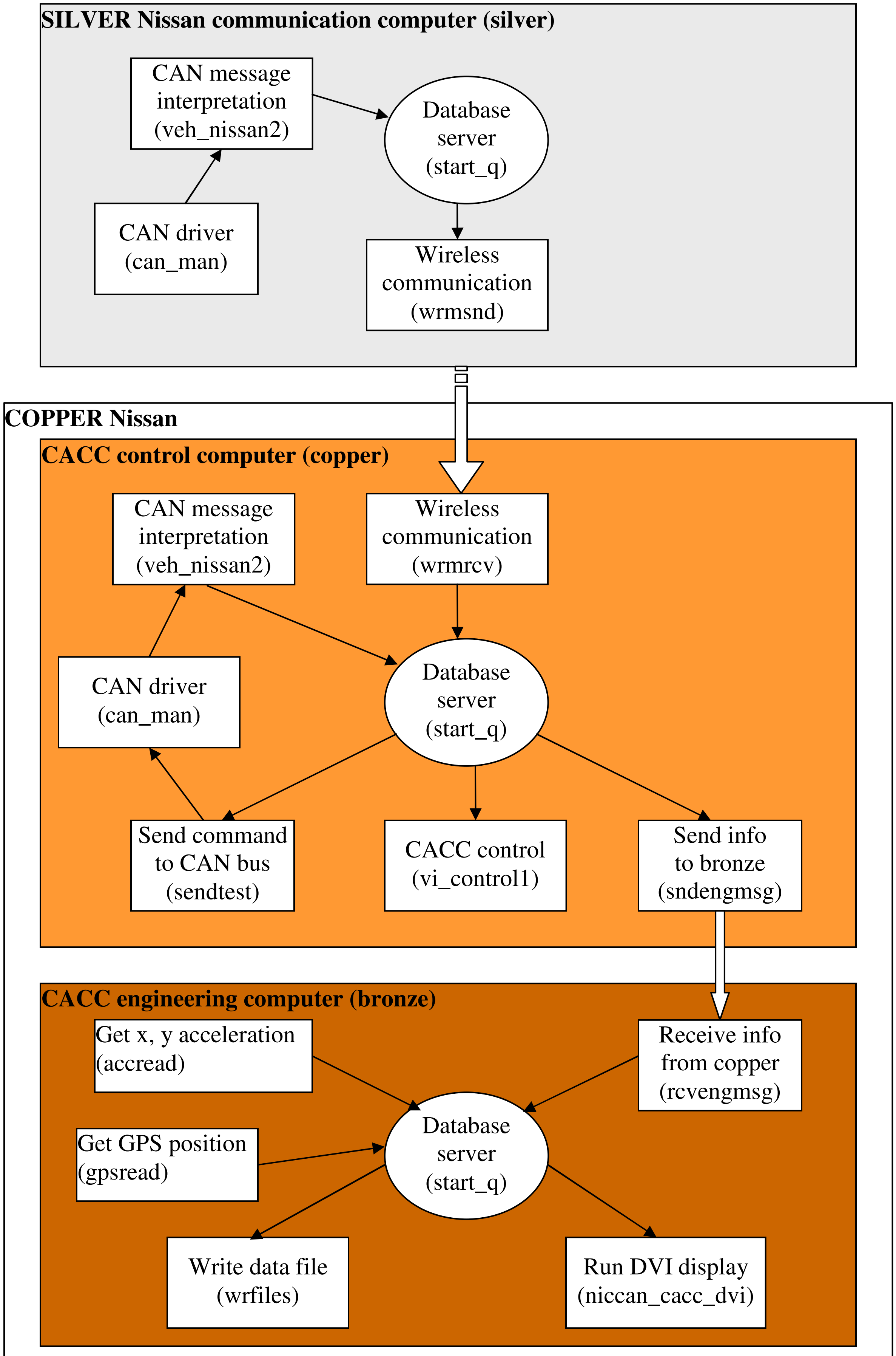
List of processes for the **bronze** computer on the copper Nissan and the **stainless** computer on the silver Nissan:

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)

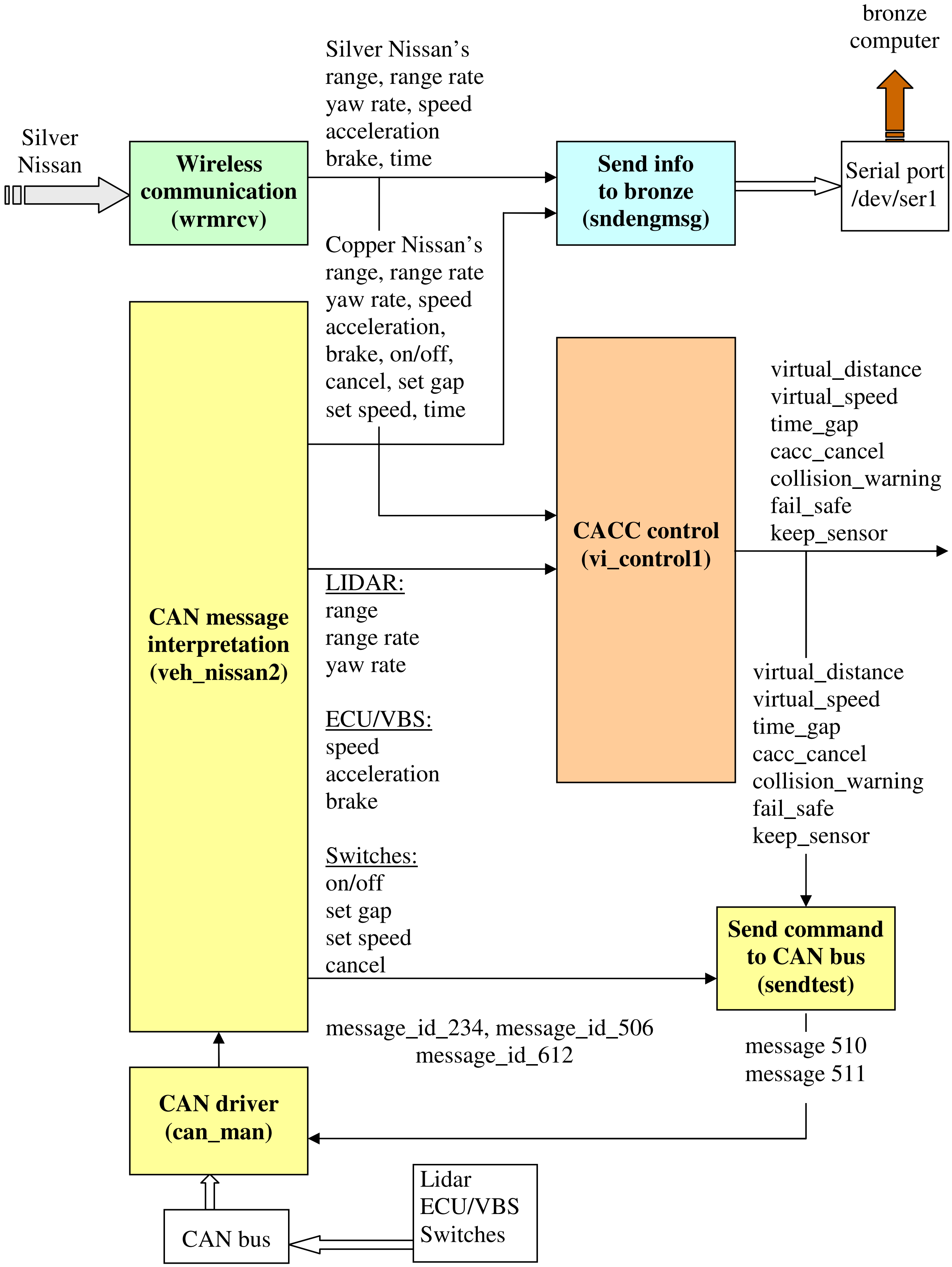
The interactions among these processes are shown schematically in the diagrams on the following pages.

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: