Interim Report

Intelligent Cruise Control Operational Test

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Interim Report

Intelligent Cruise Control Operational Test

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P. Fancher, R. Ervin, J. Sayer, M. Hagan, S. Bogard, Z. Bareket, M. Mefford, J. Haugen

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UMTRI's partners in the FOT are Automotive Distance Control Systems (ADC) GmbH, Haugen Associates, and the Michigan Department of Transportation. The Volpe National Transportation Systems Center is the independent evaluator.

16. Abstract

This interim document reports on a cooperative agreement between NHTSA and UMTRI entitled Intelligent Cruise Control (ICC) Field Operational Test (FOT). The overarching goal of the work is to characterize safety and comfort issues that are fundamental to human interactions with an automatic headway keeping system.

This report (1) summarizes the status of the FOT and (2) presents preliminary results and findings deriving from the testing activities now in progress. It describes the work done to prepare and instrument a fleet of 10 passenger cars with infrared ranging sensors, headway control algorithms, and driver interface units as needed to provide an adaptive cruise control (ACC) functionality. The vehicles have been given to lay-drivers to use for two weeks as their personal cars.

Based upon data from 35 drivers, objective and subjective results support the following preliminary observations:

- ACC driving is reported to be comfortable and is perceived as stress-relieving.
- The kinesthetic sensation of ACC-induced deceleration was often cited by drivers as a vigilance-enhancing cue, perhaps implying a safety benefit.
- Drivers appear to learn how to use ACC quickly and to converge on a strategy that meshes with their driving style .
- The data contain a natural type of "bias" by which manual driving appears riskier than ACC driving in part because denser, more conflict-laden, traffic induces drivers to turn the ACC system OFF.
- Under virtually all conditions in which ACC is engaged, drivers choose (and the system provides) headway distances that are greater than those seen when the same person drives manually.
- ACC driving results in fewer "near approaches" to the preceding vehicle than does manual driving.
- Headway-keeping behavior differs markedly with driver age. Younger drivers are typically more aggressive, operating at shorter headways.
- Given the properties of the ACC system being studied, a minimal impact on the accident record would be expected from observations to date. A major element of this expectation derives from the drivers' choice to use ACC only in rather benign traffic environments.

When completed, the FOT is expected to present findings based on results from over 100 drivers / participants.

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Autonomous Intelligent Cruise Control, Longitudinal Control, Crash Avoidance, ACC, ICC, Operational Field Test

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd ❑ 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2 = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2 = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (Lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp ❑ 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] ^{O}F ❑ y ^{O}C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

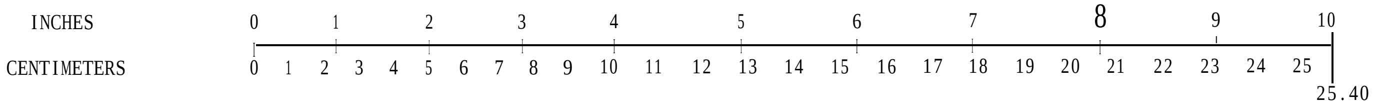
VOLUME (APPROXIMATE)

1 milliliters (ml) ❑ 0.03 fluid ounce (fl oz)
1 liter (1) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

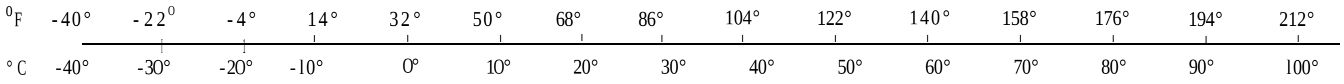
TEMPERATURE (EXACT)

[(9/5) y + 32] ^{O}C ❑ x ^{O}F

QUICK INCH-CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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EXECUTIVE SUMMARY

This document provides an interim reporting on the Field Operational Test (FOT) of a driver assistance innovation called Adaptive (or Intelligent) Cruise Control (ACC). The test is being conducted by the University of Michigan Transportation Research Institute (UMTRI) under sponsorship by NHTSA, in partnership with the ACC sensor supplier, ADC, which is a joint venture of the Leica and TEMIC companies, and with Haugen Associates and the Michigan Dept. of Transportation.

The ACC system is incorporated into a fleet of ten passenger cars, each employing a grille-mounted sensor that detects vehicles ahead and controls both the speed and headway of the test vehicle so that the driver can proceed through moderate freeway traffic without adjusting cruise buttons or touching the throttle or brake. The field test places the ACC-equipped vehicles in the hands of randomly-invited citizens for use as their personal car for two weeks. (Later in the project, some drivers will also be given the vehicle for a total of five weeks.) Thus, the vehicles are put into naturalistic use, without constraining where the person drives, or when, or how. Each driver is also free to choose between operating manually or with conventional cruise control during the firs week and between manual or ACC driving during the second (or subsequent) weeks.

Given this basic test approach, the overarching goal is to characterize the issues that are fundamental to human interaction with an automatic headway keeping system. Although only one system design is being fielded, it is hoped that the results will be generically instructive. Clearly, the issues in question cover the safe and convenient operation of the vehicle as well as potential impacts on traffic flow, fuel economy, and so forth.

The ACC system under study here can be described in terms of the sensor, the controller, and the driver's interface. The sensor is an infrared device that measures distance and the rate of closure to vehicles in the lane ahead, steering its sensing beam to the right or left as needed to follow lane curvature. The controller acts on the sensory data to modulate the throttle and also downshift the transmission as required to satisfy the driver-selected minimum for headway or spacing to a vehicle ahead. Since brakes are not incorporated into this ACC system, the vehicle has only modest deceleration available for controlling headway-a characteristic that is believed to figure strongly in the field experience reported here. The driver selects among three minimum headway buttons ranging from “closer” to “farther” and otherwise operates the ACC system through the normal cruise control buttons located on the face of the steering wheel.

The ACC systems have been fitted into 1996 Chrysler Concorde sedans. The vehicles each employ a complex instrumentation package that operates untended in the vehicle’s trunk. The package collects a broad array of quantitative data from the driving process and stores selected clips of video from a forward-looking camera.

The experimental design involves a sampling of normal drivers according to age, and prior cruise control usage. Although more than 100 persons will drive the test vehicles before the project is concluded, this report presents data drawn from the first 35 subjects. The table below summarizes the scope of usage covered by this first group of drivers (“CCC” in the table refers to the usage of Conventional Cruise Control). Approximately 26% of the mileage was covered with ACC control actually engaged (“Eng.,” in the table) out of a total of 26,000 miles.

No. of Drivers: 35	All Trips	CCC Off	CCC Used	ACC Off	ACC Used
Trips	2659	916	325	938	480
Distance, miles	26,225.6	3,449.9	8,059.5	3,178.0	11,538.2
Dist. Not Eng., miles	15,656.l	3,449.9	4,405.6	3,178.0	4,622.7
Dist. Eng., miles	10,569.5	NA	3,653.9	NA	6,915.6
Duration, hours	723.6	146.0	181.0	139.2	257.3

Because some eighty variables are sampled continuously at 10 cycles per second, a data record of tremendous proportions is being amassed. Only a high level scan of these data, compiled mostly as histograms, is presented and discussed in this interim report. Supplementing the quantitative data, participating drivers have also given subjective assessments of ACC driving through response to a debriefing questionnaire and through participation in focus groups. Together, the subjective and objective results support the following preliminary observations:

1) ACC driving is reported to be comfortable and is perceived as stress-relieving, especially on long trips.

2) Drivers are comfortable using this ACC system under some traffic environments in which conventional cruise control would have been disengaged.

3) ACC operation did not pose any obvious safety threat to either the driver of the equipped vehicle or to others nearby. The kinesthetic sensation of ACC-induced deceleration was often cited by drivers as a vigilance-enhancing cue, perhaps implying a safety benefit. A few anecdotes of relaxed visual attention to the road ahead were also

reported, however, presumably as the driver adapted to the perceived benefit of the deceleration cue.

4) Drivers appear to learn how to use ACC quickly. As exposure time grows, the individual readily converges on preferred ACC headway settings as well as an operating strategy that meshes with his or her driving style .

5) Because the choice of control mode closely correlates with prevailing traffic conditions and road type, the data contain a natural type of bias by which manual driving appears riskier than ACC driving in large part because denser, more conflict-laden, traffic induces drivers to turn the ACC system off. A simple attempt to dis-aggregate the data so that ACC driving is compared with manual driving only under comparable conditions is reported here, but more sophisticated means are being pursued.

6) Under virtually all conditions in which ACC is engaged, however, drivers choose (and the system provides) headway distances that are greater than those seen when the same person drives manually. Some drivers have recognized this difference in their own behavior and have cited it as a perceived benefit of the system.

7) Related to this observation, ACC driving results in fewer "near approaches" to the preceding vehicle than does manual driving. Continuously monitored values of time-to-collision are markedly longer under ACC control.

8) Headway-keeping behavior differs markedly with driver age. Younger drivers are typically more aggressive, traveling generally faster than the average traffic around them and operating at shorter headways. Some drivers in this more aggressive category perceive that ACC control impedes their normal pattern of driving such that they may tend not to use it.

9) Drivers select set speed values under ACC control rather like they do under conventional cruise control-that is, nearly matching the prevailing speed of traffic. This may be one aspect of driver behavior that adapts with increasing ACC experience.

10) Given the properties of the ACC system being studied, a minimal impact on the accident record would follow from observations to date. A major element of this expectation derives from the drivers' choice to use ACC only in rather benign traffic environments.

11) This ACC system would likely also have a minimal impact on traffic operations, mostly because it becomes turned off when traffic approaches the density levels at which highway capacity is challenged.

The field test has yet to collect approximately 70% of its data. Included in the remaining testing is the coverage of some 24 drivers operating the vehicle for a total of five weeks each. Data processing will be expanded beyond the histogram domain, with heavy emphasis upon time-related phenomena, especially that of driver intervention upon the ACC-engaged state of operation. Possible extensions to the field test are also under consideration, particularly with braking incorporated into the ACC controller. Such an extension would address the higher levels of deceleration capability that are expected to appear on marketed vehicles over the next few years.

1. INTRODUCTION AND BACKGROUND

1.1 Introduction to the Report

This document constitutes an interim report on a cooperative agreement between NHTSA and UMTRI concerning a field operational test (FOT) of intelligent cruise control (ICC). The ICC systems employed in this study are known as and referred to as ***adaptive cruise control*** (ACC) by the partners in the FOT. UMTRI's partners in the FOT are Automotive Distance Control Systems (ADC) GmbH (a joint business venture of Leica and Temic to develop and market advanced distance control technology), Haugen Associates, and the Michigan Department of Transportation.

Per the U.S. DOT's requirements for FOTs, the program also involves an independent evaluation led by personnel from the Volpe National Transportation Systems Center (a part of the U.S. DOT). Volpe is aided in their evaluation effort by their subcontractor, Science Applications International Corporation (SAIC). Although there is an open exchange of test data, plans, and ideas between the partner's group and the independent evaluator's group, this report is entirely the responsibility of UMTRI and its partners.

The material presented here has been prepared by UMTRI to provide NHTSA with an understanding of the conduct and preliminary findings of the field operational test (FOT). To that end, this interim report summarizes the status of the FOT and presents preliminary results and findings deriving from the testing activities now in progress.

Although a particular ACC system is undergoing testing in this project, it is intended that this report characterize issues that to the maximum extent possible are fundamental to human interaction with an automatic headway-keeping system. Nevertheless it is clear that specific features of the fielded system have directly determined various details in the human use of the FOT vehicles.

Each of the ten field-test vehicles involves a 1996 Chrysler Concorde sedan that was purchased and modified to incorporate an ACC functionality. The vehicles were equipped with Leica ODIN 4 infrared ranging sensors. These prototype sensors are part of an electronics package that provides range and range-rate information in a form that is convenient for use in assembling and evaluating an ACC system. Based upon this framework developed by Leica, a headway control algorithm was created by UMTRI and installed in the vehicles.

A communication network has been developed so that the conventional cruise control system existing on the vehicle can be used as a velocity controller that responds to commands from the headway controller. This network also includes communication with the transmission controller in the vehicle so that a transmission downshift from fourth to third gear can be used to extend the control authority of the ACC system, thereby increasing the deceleration capability of the system without using the vehicle's braking system. In addition the vehicles have been extensively instrumented to collect data on driving performance and the driving environment. All of these systems and features have been functioning in the field operational tests that began in July 1996.

The preliminary results presented here portray the driving experience of 35 lay driver/participants who operated one of the ten ACC-equipped passenger cars. These drivers operated a vehicle for one week without ACC and the next week with ACC available. These two week periods of operation took place in the driver/participants natural driving environment sometime in the period from July through December 1996.

The results and findings presented in this report use the set of data from the 35 driver/participants to address questions associated with the following operational issues:

- the nature of speed and headway keeping behavior of drivers with and without an ACC system
- when, where and how drivers will use ACC
- driver's ability to adapt to different driving situations while using ACC
- concerns with ACC operation
- the levels of comfort and convenience and safety drivers associate with ACC
- the performance of a current state of the art ACC system

The data also provide a starting point for an expanded evaluation of ACC by Volpe and SAIC evaluators as well as by UMTRI and DOT researchers.

Further information and expansion on the preliminary results and findings are provided in section 4 of the main body of the report.

The main body of the report starts by presenting general background information concerning ACC systems and the control of speed and headway. (See section 2.) The tasks performed to prepare and instrument the vehicles for the tests are described in section 3. Section 3 presents information on the system for gathering and processing data as well as for archiving data in a form that is useful for future analyses and for responding to queries concerning new ideas. The current status of the project is characterized in section 3.6 by presenting data concerning the number of trips and miles traveled under various control and operating conditions.

In section 4, preliminary results and findings are presented and supported by evidence based upon the data obtained so far. The concluding section (section 5) of the report does three things. It summarizes the preliminary findings, it describes the anticipated amount of information to be obtained and its significance once the project is completed, and it postulates where this work is going and what might be done next.

1.2 Background on the FOT Project

1.2.1 Project Basis

Intelligent, or adaptive, cruise control systems (ICC or ACC) are under active development by car companies and their suppliers throughout the world. Such systems, which automatically control headway or range to a vehicle in front, are intended to become the next logical upgrade of conventional cruise control (CCC). However, validation of the comfort, convenience and safety implications (positive and negative) of such systems has heretofore not been undertaken using normal consumers as test subjects.

This project is a field operational test (FOT) which will ultimately involve more than 100 such test subjects. FOT’s are intended to serve as the transition between research and development and the full-scale deployment of ITS technologies. The tests permit an evaluation of how well newly developed ITS technologies work under real operating conditions and assess the benefits and public support for the product or system.

1.2.2 Project Objectives

The general goal of this project is to characterize issues that are fundamental to human interaction with an automatic headway-keeping system. The extent to which this goal is realized clearly depends upon the extent to which results from using this particular ACC system can be generalized to other ACC systems.

In addressing this overall goal, the field operational test is expected to:

- evaluate the extent to which ACC systems will be safe and satisfying when used by the public

- consider the influences of key system properties such that the results can help in finalizing the design of production systems
- identify design and performance issues that call for further development, market research, industry recommended practices, or public policy
- contribute to the evolutionary process leading to the deployment of ACC systems as a user service
- develop an understanding of how the functionality provided by ACC systems contributes to the safety and comfort of real driving
- qualify how drivers use and appraise the functional properties provided by ACC systems
- develop an appreciation for the public issues and societal benefits to transportation associated with ACC systems

(The focus of this interim report is on the operational issues given in section 1.1.)

1.2.3 Project Approach

Figure 1 provides a conceptual overview of the FOT. As illustrated in the figure, the work done to provide a test system has involved acquiring system elements, assembling ACC systems and installing them in the test vehicles, designing and building a data acquisition system, and arranging for a pool of drivers.

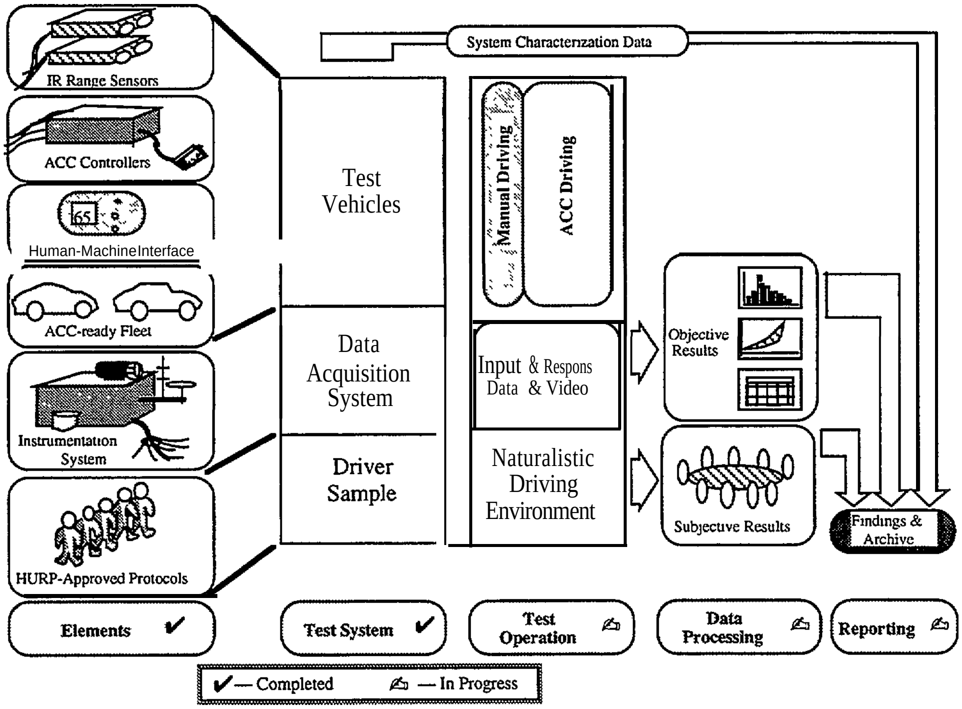


Figure 1. FOT Conceptual overview

Key elements of the project approach are:

- use of infrared-based ACC sensors and associated electronic systems which are engineering prototypes designed by Leica of Switzerland and provided under contract by ADC, a joint venture of Leica and TEMIC
- development and installation of headway control algorithms and communication links as needed to provide ACC functionality in the 10 test vehicles
- development and installation of human-machine interface as needed to provide ACC functionality in the 10 test vehicles
- development and installation of a data acquisition system (DAS) providing quantitative data regarding various driving performance measures along with measures of the driving environment (including video and GPS data)
- selection of test subjects through cooperation with the Michigan Secretary of State office, filling specific cells of subjects for age and CCC system level of familiarity. The basis for use of test subjects is meeting requirements of NHTSA Human Use Research Project (HURP) protocols
- familiarization training whereby drivers undergo training with UMTRI human factors personnel and then drive the test cars unaccompanied for periods of either two or five weeks (the first week of test car use is restricted to manual driving to provide a basis for comparison with the later ACC driving)
- data acquisition providing quantitative data regarding various driver performance parameters both at the end of each trip via cellular phone and when the vehicle is returned to UMTRI to change drivers
- driver qualitative data, obtained through survey questionnaires, debriefings and focus group meetings

1.2.4 ACC System: Sensing, Control, and Application Hardware

The ACC system includes headway sensors, an EBOX and a VAC, each of which is described below. (This hardware is supplied by Leica AG.)

Leica ODIN4 Headway Sensors

Two separate sensors, a sweep sensor and a cut-in sensor, are installed in the Chrysler grill area. The sensor respective coverage areas are illustrated in Figure 2.

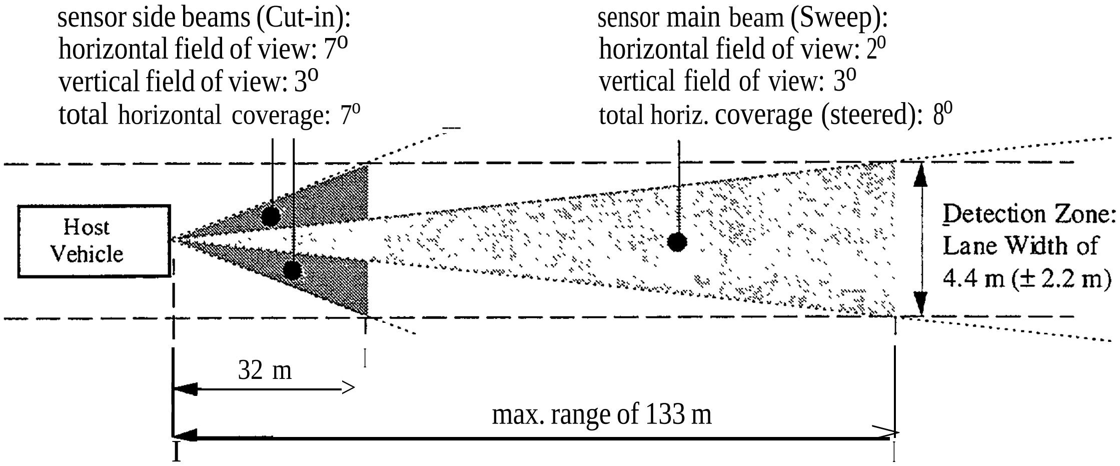


Figure 2. ODIN4 Sensors coverage areas

- The sweep sensor is a steered laser beam which is directed left or right by a solid state gyro which dynamically responds to road curvature. This sensor detects targets in the far field (6 to 150 meters).
- The cut-in sensor has a fixed beam and limited range, being used to sense vehicles that might cut-in close to the front of a test vehicle (0 to 30 meters).
- Both sensors operate by transmitting pulses of infrared light energy at a wavelength of 850 nanometers and a frequency of 10,000 pulses per second. The time of flight for an echo pulse to be received is used to determine range and range rate to a target vehicle.

EBOX

The EBOX contains the solid state gyro; the system power supply; electrical interfaces to the sensors; an external power supply; a Leica diagnostic connection; and CAN bus and RS232 interfaces.

Vehicle Application Controller (VAC)

The VAC contains software code and algorithms, including the UMTRI code and algorithms, used to provide the ACC control functions.

1.2.5 ACC Functional Description

In short, the ACC system provides the following functional operations:

- Establish and maintain a desired range if there is a preceding target vehicle with three driver-selectable headway settings — nominally 1.0, 1.4 or 2.0 seconds.

- Automatically accelerate and decelerate smoothly to maintain desired headway; automatically accelerate to set speed when a target disappears.
- Establish and maintain a desired speed (set speed) if there is no preceding target.
- Alert the driver to the existence of a perceived target; and to the operating status of the ACC.
- Decelerate the car when necessary, using throttle reduction; provide added deceleration by transmission downshifting if needed.
- Ignore targets that have a velocity less than 0.3 of the speed of the ACC vehicle to eliminate false alarms from fixed objects.
- Minimize missed targets that have poor reflective characteristics or unusual geometry.
- Provide a concern button for use by the driver to denote any ambiguous or dangerous driving situations. (The data acquisition system saves 30 seconds of video data prior to the time the concern button was pushed to capture pictures of the incident.)

2. TECHNICAL BACKGROUND

In this project an approach that uses speed to control headway is employed. Figure 3 provides a sketch showing the basic motion variables that are used in the headway controller. The following fundamental quantities are needed to describe headway and speed control:

V_p -- velocity of the preceding vehicle
V — velocity of the ACC-equipped vehicle
R — range from the ACC-equipped vehicle to the preceding vehicle
R_h — desired range from the ACC-equipped vehicle to the preceding vehicle (In the situation shown in Figure 3, the ACC-equipped vehicle is closer to the preceding vehicle than the desired range.)
dR/dt — range-rate, the relative velocity between the vehicles (Range rate is also denoted by RDot in this report.)

Knowledge of these quantities plus the accelerations of these vehicles allows a complete kinematic analysis of the relative motion between the following and preceding vehicles.

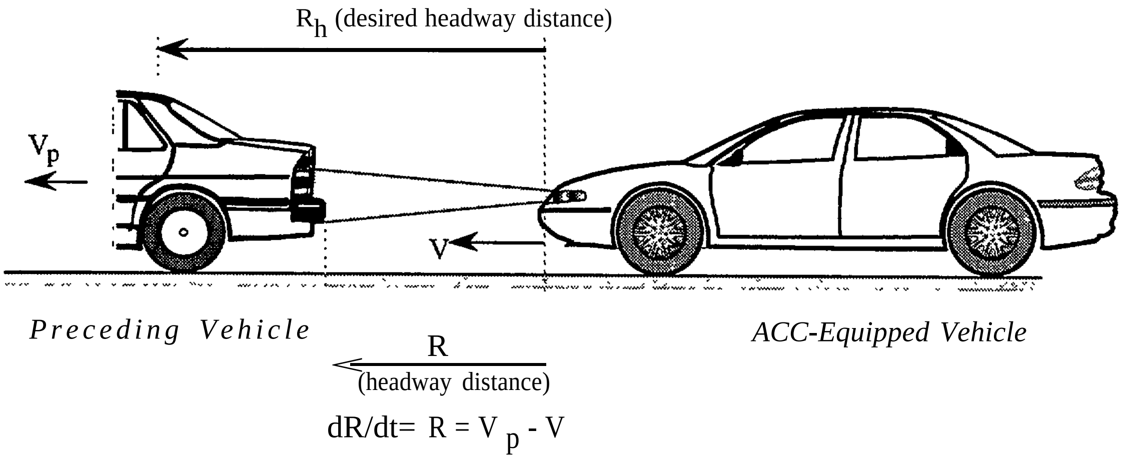


Figure 3. Headway control

The range versus rate range diagram (Figure 4) is useful for explaining the concepts behind the headway control algorithm employed in the ACC system used in the FOT. Conceptually, the control objective is to perform headway control in accordance with the following equation:

$$T \cdot dR/dt + R - R_h = 0 \tag{1}$$

where the coefficient T determines the closing rate.

The equation for the control objective appears as a straight line in the range-rate/range diagram. See the line labeled "dynamics line for headway control" in Figure 4. The slope of that line, -T, serves as a control-design parameter.

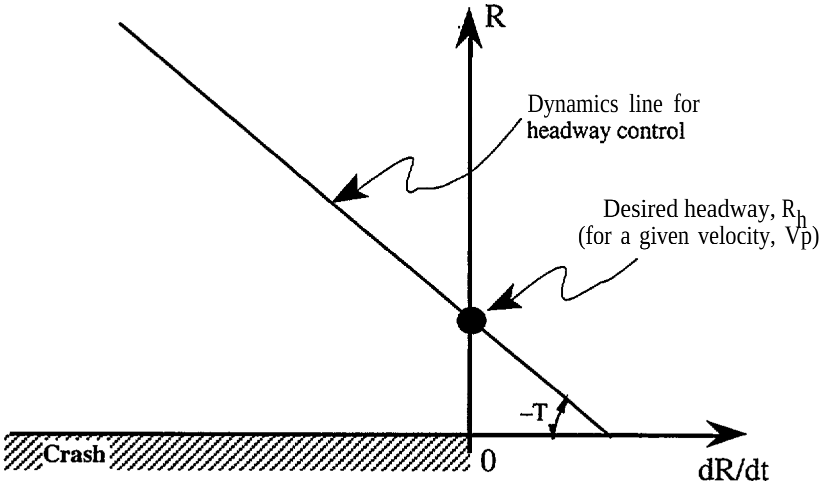


Figure 4. Range rate versus range

The point at $R = R_h$ and $dR/dt = 0$ is the ultimate objective for the ACC equipped vehicle. The desired headway at steady following is a linear function of V_p, the velocity of the preceding vehicle; viz.,

$$R_h = V_p \cdot T_h \qquad (2)$$

where T_h is the desired headway time, which is a control system parameter. (In the ACC system used in the FOT, the driver can change T_h. See section 3.1.6.)

The headway distance varies with velocity, thereby providing a fixed margin in time for the system or the driver to react to changes in the speed of the preceding vehicle. The underlying concept here is similar to that which is behind the commonly used advice, "Allow one car length for each ten miles per hour of speed."

The speed of the preceding vehicle is given by:

$$V_p = dR/dt + V \qquad (3)$$

using equation (3), measurements of V, R, and dR/dt are sufficient to evaluate the terms in equations (1) and (2). This means that the difference between the desired control state and our current situation, expressed as an error (e) in velocity is as follows:

$$e = dR/dt + \frac{(R - R_h)}{T} \qquad (4)$$

where the quantities on the right side of the equation are evaluated using inputs from the sensors and the values of the control parameters, T and T_h.

For a vehicle with a cruise-control system, there is already an existing velocity-control system. To make a headway and speed control, one needs to send a velocity command (V,) to the cruise-control unit, so that the desired headway will be attained and maintained. The general idea is that if the vehicle is too far away, one must speed up, and if the vehicle is too close, one must slow down.

As in sliding control methodology [1], equation (1) may be considered as a “sliding surface” towards which the controller attempts to converge, while equation (4) describes the prevailing error at any given time. Considering equations (3) and (4) together, the error is minimized to zero when the vehicle speed becomes:

$$V = V_p + \frac{(R - R_h)}{T} \tag{5}$$

This velocity value can be viewed as the desired speed for the ACC-equipped vehicle, or the velocity command (V,) to achieve the desired headway (R_h); viz.,

$$V_c = V_p + \frac{(R - R_h)}{T} \tag{6}$$

Equation (6) is the basis for a simple design method for extending (or adapting) a speed controller to include an outer control loop that achieves a headway control function.

A major consideration with such an approach is the amount of control authority. If, for example, the ACC-equipped vehicle travels at 70 mph and the prevailing conditions call for a commanded speed (V_c) of 60 mph, the vehicle can only decelerate so fast before the control authority saturates (its coastdown deceleration). During the time that $V \neq V_c$ the error is also not zero, and the expression given by equation (1) is not satisfied. In graphical terms, we cannot follow the straight line (the control objective) in Figure 4 when the deceleration (or acceleration) has been saturated at the system’s maximum control authority. The further we get from the control objective line, the more critical our situation becomes from a headway-keeping standpoint, and hence the more urgent our response should be.

From the discussion above, it appears that one might divide the range versus range-rate space portrayed in Figure 4 into zones based on response urgency, or in other words, based on deceleration levels that are required to attain certain headway clearances (and to avoid a crash).

A trajectory of constant deceleration (a) in the range versus range-rate space is described by:

$$R = R_a + \frac{\left({}^{dR}\!/_{dt} \right)^2}{2 \cdot a} \tag{7}$$

Equation (7) describes a parabola that intersects the vertical axis (range) at some point R_a (see Figure 5). This point can be viewed as a design factor which may vary from some arbitrary headway threshold all the way down to zero, when crash avoidance is the objective. The higher the parabola's deceleration rate is, the more "flat" the parabola becomes.

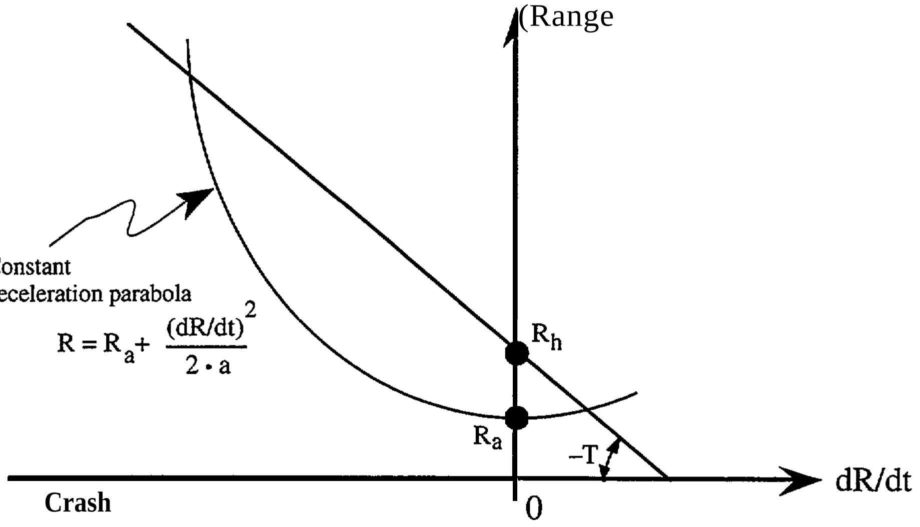


Figure 5. Constant deceleration parabola

With regards to the particular control algorithm employed in the FOT vehicles, the design value of constant deceleration (a) used was 0.05 g. This value corresponds to the Concorde's coastdown deceleration on a flat road at highway speeds. As long as the range and range-rate data from the sensors are above the parabola, the vehicle uses only coastdown to decelerate. However, if the sensor data are below the parabola, then even with full coastdown authority the ACC-equipped vehicle will end up closer than R_a to the preceding vehicle. In order to avoid that situation, higher deceleration rate (that is, control authority) is needed.

The software of the electronic transmission controllers in the ten test vehicles have been modified in cooperation with Chrysler. This modification allows the control algorithm to command a single transmission downshift. By downshifting, a deceleration rate of about 0.07 g can be obtained. This added deceleration (compared to 0.05 g by coastdown only) provides for a higher control authority. With the more flat parabola that is associated with higher deceleration, the range/range-rate trajectory might get back above the parabola and eventually achieve a headway range that is above R_a, or even closer to the objective R_h.

A depiction of the architecture of this ACC system that uses throttle and transmission algorithms to control speed and headway is shown in Figure 6. The figure shows the sensor's range and range-rate signals as inputs to the control system. The velocity of the ACC-equipped vehicle serves as the feedback signal used in an outer control loop and in two inner loops: one inner loop for throttle actuation and the other inner loop for transmission downshift actuation.

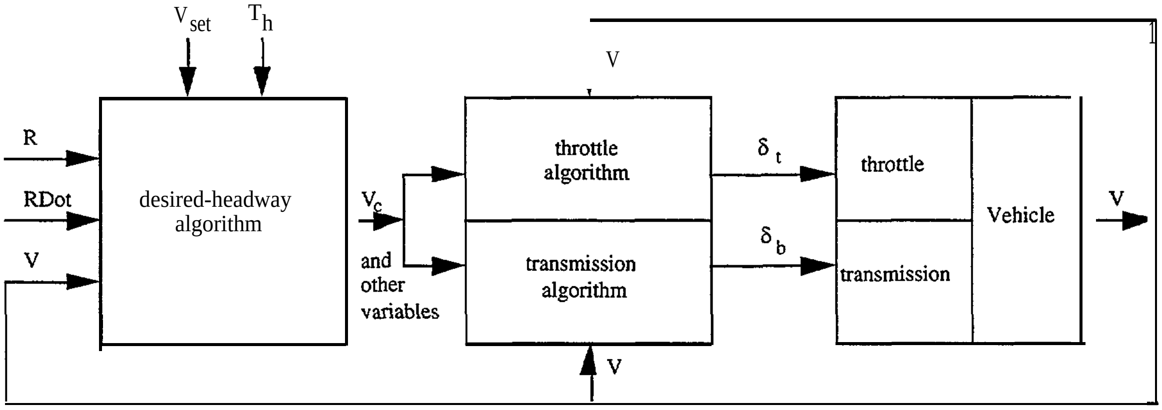


Figure 6. Control architecture for FOT ACC system

The control concept is based upon an overall goal for the ACC system. This goal is expressed by equation (1). At any given time, the system's state relative to that goal is given by the error in equation (4). When the goal is obtained, the error becomes zero.

In order to better explain the control idea, its basic generalized form is illustrated in Figure 7. The outer loop (which includes the inner loop as a special actuation loop) involves a "planner" element that looks at the sensed information, including the velocity of the vehicle and the external quantities R and RDot and decides what "command" to give to the "controller." The controller uses this command to generate control signals that cause the vehicle to respond in a manner that is consistent with the goal.

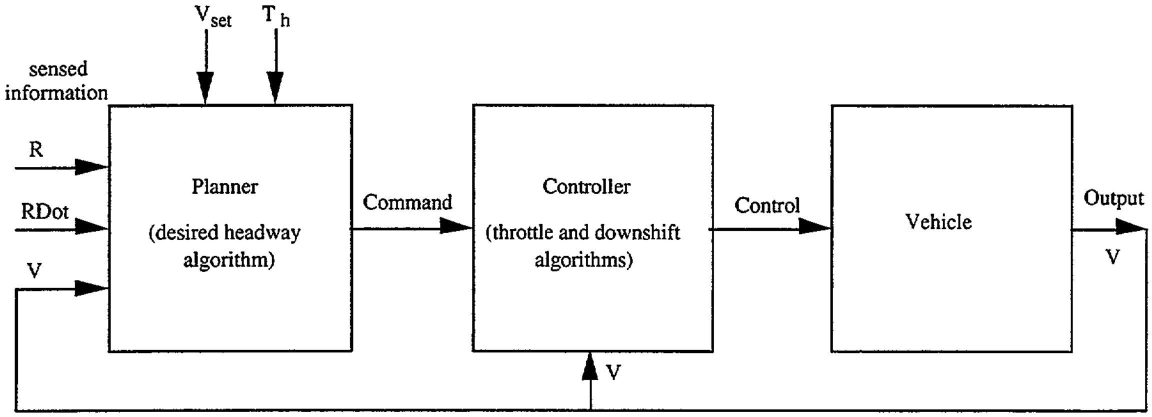


Figure 7. Control architecture with a planner

Throughout the above discussion, the variable T_h, which is the desired headway time for following, has been shown to hold a prime importance. Clearly, it is a variable whose value greatly depends upon individual preferences. The design of the ACC system employed in this FOT allows the driver to select one of three possible values for that variable. The functional structure of the system is depicted in a block-diagram form in Figure 8.

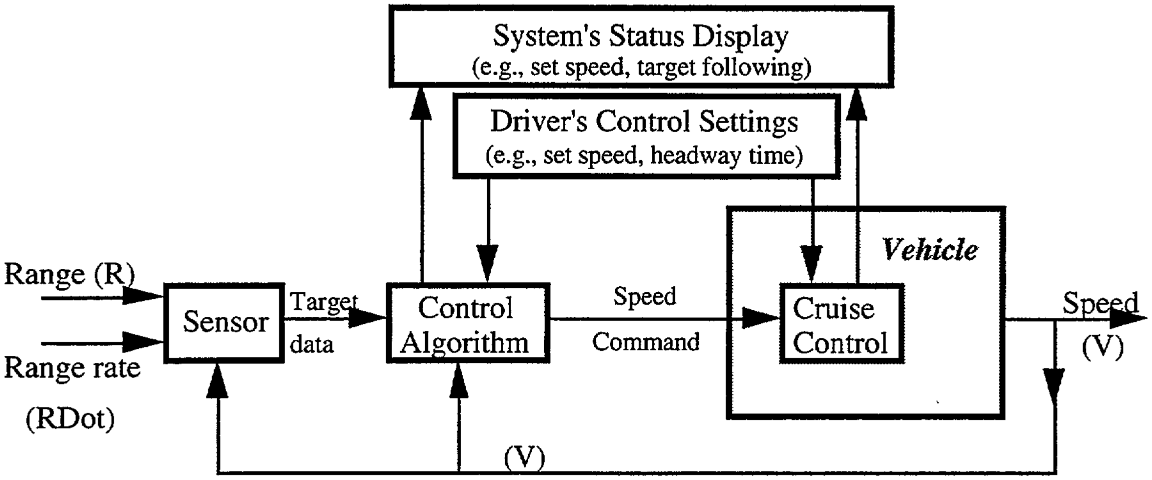


Figure 8. ACC System structure

In this design the driver can also provide other inputs that are essential to the operation of the ACC system: engaging/disengaging the system, setting speed, or pressing the brake. At the same time the system provides the driver with feedback about its operating status: what the set speed is, what its activation state is, and whether targets are tracked. It is evident from the participants' responses so far, that such feedback (though it may come in many different forms) is desirable.

3. PROJECT STATUS

Table 1 lists the tasks and milestones for the FOT project. It indicates those tasks that have been completed, tasks that are in progress, and tasks that have not started yet. As indicated, the field operational test (task 10) is underway. Preparations for conducting the test have been completed.

With regards to the sequence of milestones listed in Table 1, this interim report is the first deliverable describing results and findings from the FOT. The interim report provides a preview of the type of data and findings that are expected to appear in the final report.

Table 1. Tasks and milestones

No.	Name	Status
1	Startup	Completed
2	Develop test definition and project plan	Completed
3a	Design instrumentation package	Completed
3b	Build instrumentation package	Completed
3c	Install instrumentation package	Completed
4	Plan field operational	Completed
5	Conduct pilot testing	Completed
6	Develop data processing system	In progress
7	Characterize system	Completed
8	Prepare test fleet	Completed
9	Apply for Field-test human-use approval	Completed
10	Conduct field operational test	In progress
11	Process test data	In progress
12	Final report and data	Not started yet
Milestones		
1	Kick-off briefing	Accomplished
2	Test definition & Project plan	Accomplished
3	Operational test plan	Accomplished
4	Pilot test Briefing	Accomplished
5	Interim operational test report	Met by this report
6	Field operational test Briefing	Not accomplished yet
7	Final technical Briefing	Not accomplished yet
8	A video summary of FOT	Not accomplished yet
9	Equipped test vehicles to NHTSA	Not accomplished yet
10	Non-proprietary ACC software to NHTSA	Not accomplished yet
11	Final Report	Not accomplished yet

3.1 Pre-Testing Tasks

3.1.1 Vehicle Purchase

The vehicles procured for this project are ‘96 Chrysler Concorde (see Figure 9). The Chrysler Concorde is a five-passenger sedan which belongs to the family of Chrysler platform cars. This family also includes the Dodge Intrepid, Eagle Vision, Chrysler New Yorker and Chrysler LHS. The New Yorker and LHS have bigger trunks and C-shaped, C-pillars, but other than these features they are mechanically similar to the other cars.

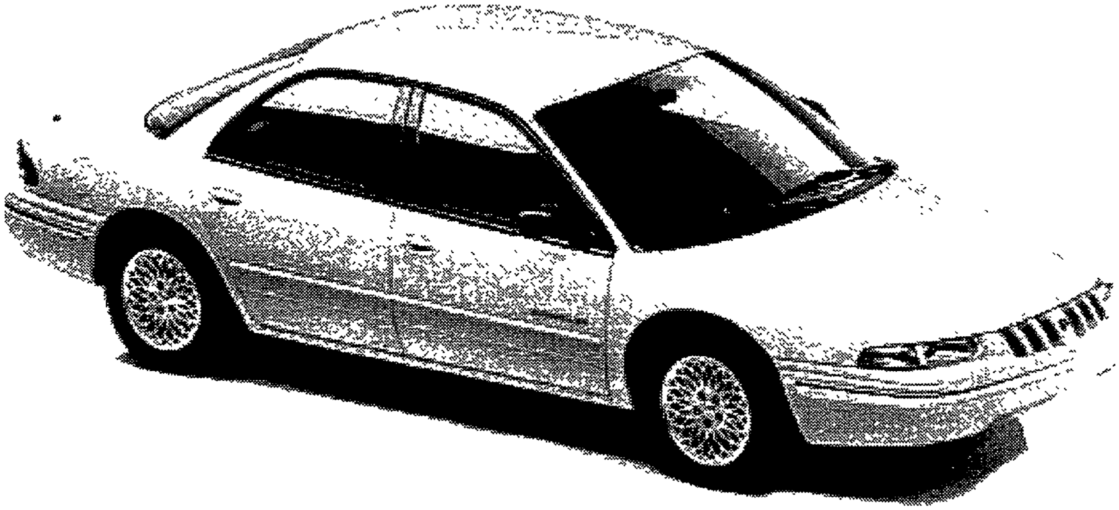


Figure 9. Chrysler Concorde

The primary motivation for using the Chrysler Concorde as the FOT vehicle platform is based on Leica’s existing experience with integrating an ACC system onto the Chrysler LH platform. Early experience indicated that a careful tailoring of the ACC application to the selected vehicle must be made if good performance is to be ensured. Tailoring requires suitability of the electronics interface and matching of the control system parameters to the longitudinal response properties of the vehicle. As the provider of the ACC system, Leica had already integrated ACC onto the Chrysler LH platform. This fact was found to be most helpful during the pretesting task of designing the system’s installation.

Following are highlights from the vehicle’s specification which also served as guidelines when procuring the cars:

1. Model 1996 Chrysler Concorde LX, option package 26C.
2. Engine —3.5-liter (215 CID) 24-valve V6, 214 hp, 221 lb-ft.

3. Transmission — Four-Speed Automatic Transaxle with overdrive, electronically controlled.
4. Brakes — power-assisted, 4-wheel disc antilock system.
5. Steering — Variable assist, speed-sensitive rack-and-pinion power steering with tilt steering column.
6. Suspensions — Front: Independent system with gas-charged (MacPherson-type) struts and double ball-joint stabilizer bar, Rear: Independent multilink suspension.
7. Mirrors — Inside mirror has a power anti-glare system, both external mirrors are remotely controlled and heated.
8. Dual Air Bags — Driver and front-seat passenger are both protected by an air bag supplemental restraint system.
9. Rear Defroster — Electric heating elements fused to the glass of the rear window.
10. Trunk — Low-Liftover edge of open trunk, and large cargo space to accommodate both luggage and data collection equipment.
11. Other equipment — Factory installed seat belts for all passengers, cruise control, power windows and locks, and air conditioning. Antitheft alarm was installed separately.

3.1.2 Pilot Testing and Human Use Annroval

Since ACC has not yet reached the maturity of commercial products, the test systems must be treated as engineering prototypes. Thus, the ACC implementation in our test vehicles, and the protocols for its use, were subjected to careful preliminary testing before operational testing began.

Two phases of pilot testing were performed: supervised and unsupervised. Six lay persons were included in each of the two pilot testing phases. In the supervised testing phase participants received the standard instruction and were accompanied on a 2.5 hour route through metropolitan Detroit on interstate and state highways. During supervised testing ACC was always available to the participants. The overall scope of issues for full operational testing was scrutinized, including the performance of the ACC system, functioning of the instrumentation and remote data recovery system, the quality of the recovered data, and details of participant recruitment and orientation methods.

The application that sought approval for the use of human participants in supervised pilot testing was submitted early in the contract period. Approval was received from the Human Use Review Panel (HURP), NHTSA, USDOT on the 27th of February, 1996. An application seeking additional approval from the University of Michigan was submitted to the Human Subjects in Research Review Committee (HSRRC), Institutional Review Board Behavioral Sciences Committee. Approval from the University was also received in late February 1996.

The second phase of pilot testing (unsupervised) was similar to the operational test conditions, in that participants were not accompanied by researchers and they possessed the research vehicle for two days. Again, participants received the standard instruction. The application that sought approval for the use of human participants in unsupervised pilot testing was approved by the Human Use Review Panel (HURP), NHTSA, USDOT in April, 1996. An application seeking additional approval from the University of Michigan was submitted to the Human Subjects in Research Review Committee (HSRRC), Institutional Review Board Behavioral Sciences Committee. Approval from the University was received May 14, 1996. This approval also addressed full scale operational testing.

3.1.3 Experimental Design

The sample of participating drivers was selected according to a design that stratified the population by age and by prior use of conventional cruise control. An essential element of the design was that each driver’s operation with ACC will be compared with the same individual’s driving in the “manual” mode of operation.

The experimental design was based, in part, on findings from the FOCAS project [5]. Specifically, the independent variables of participant age and conventional-cruise-control usage were previously found to influence both objective and subjective dependent measures.

The operational test procedures and the associated data acquisition system have been designed with the following independent variables in mind:

- driver
- road type
- traffic situation
- weather
- time of day

Only the driver category of independent variables (age and conventional-cruise-control usage) is treated in the context of a controlled experimental design. The other variables are uncontrolled in the sense that they represent whatever situations the driver encounters in his or her normal driving pattern. The independent variables include three levels of participant age (20-30, 40-50, 60-70 years) and two levels of conventional-cruise-control usage (rarely/never use, frequently use). The gender of participants is being balanced.

Participants were recruited with the assistance of the Michigan Secretary of State (Michigan's driving license bureau). A random sample of 3,000 drivers was drawn from the population of licensed drivers in eight counties in South Eastern Michigan. Potential participants identified from the Department of State records were contacted through U.S. mail to solicit their participation in the field operational test. Interested persons were asked to contact UMTRI. All information obtained through the Department of State records was treated with strict confidentially.

Individuals who contacted UMTRI by telephone with an interest in participation received a brief overview of the field test from a research assistant. Potential participants were further informed of any benefits or risks associated with participation. If individuals found the conditions of participation to be generally agreeable, and after a series of questions were asked, a specific date and time was arranged for the participant to visit UMTRI for orientation and training.

Following a prepared ACC orientation accompanied by a research professional, each driver/participant first operates the assigned vehicle in a manual mode for one week, thereby affording within-subject comparisons as the basic experimental control. In the manual mode, data from the ranging sensor and other transducers is collected continuously to capture the individual's normal car-following behavior, but ACC is initially disabled. The same participant then operates the vehicle for a period of one week to one month with the ACC functionality available. Use of the test vehicles by anyone other than the selected individuals is prohibited.

Consenting drivers operate the test vehicle in an unsupervised manner, simply pursuing their normal trip-taking behavior using our test vehicle as a substitute for their personal vehicle. Objective data in digital form is recovered periodically throughout the day from each test vehicle using cellular modem. Qualitative (subjective) information is recovered using questionnaires, direct interviews, and focus groups.

Continual monitoring of the remotely-collected data permits tracking the ACC usage and determination of the possible need for administrative intervention (for example, if the ACC system is not being used by the subject at all.) The objective data is processed to derive suitable measures of the convenience and safety-related aspects of ACC operation, relative to the manual driving behavior of each test participant.

The primary emphasis in the experimental design is on relatively long exposures of individual lay drivers and upon a sampling scheme that roughly mirrors the population of registered drivers, but with simple stratification that reflects variables previously seen to interact with the manual-versus-ACC driving paradigm.

3.1.4 Instrumentation and Data Handling

The on-board instrumentation package was designed, built, and installed in three main development phases:

1. Define Requirements -The essential objective data needs of the project versus practical car data recording limits were defined. Also, subjective data collection methodology was defined to include items such as predrive surveys; in-car logs; postdrive surveys; and focus group meetings.
2. Pilot Instrumentation Package — An instrumentation package per the defined requirements was designed and installed in a car. The instrumentation design was verified and modified as needed in the pilot test program before being finalized for the full 10 car test fleet.
3. Fleet Instrument Packages — The pilot instrumentation design was finalized and modified based on the pilot testing program. Once the design was completed, identical-data-acquisition system packages were built and installed in all 10 cars and performance verified prior to the operational test program.

During each trip, data from the various transducers is collected using the instrumentation package. Whenever a trip is completed, some of the data that were collected is summarized and transmitted to UMTRI via the cellular modem. The complete set of data acquired during the vehicle's operation by a particular driver is downloaded at UMTRI when the vehicle is returned.

The instrumentation package is described in the "Test Definition and Project Plan" document [2]. There are two computer systems in the package. One system is for the prioritized recording of video data. The other does the on-line processing of the basic data from the Leica sensor, the control algorithm, the automotive electronics bus, the man-machine interface, and the GPS.

A detailed description of the cellular communication and GPS systems is provided later in section 3.4.

Data collection within the instrumentation package proceeds in simultaneous formats, as follows:

- time history sampling of primary and derived variables at 10 Hz in floating point form for continuous variables and in binary (true/false) form for logical variables (these data are stored on the disk drive that is part of the basic data computer (the main computer))
- capture of event-related video episodes, each of 30 seconds duration (this function entails a disk management routine that ensures saving only the most important video episodes on a disk that becomes full. The system provides for storage of 160 video episodes at 10 frames per second)
- capture of time-related video exposures, each of 2.5 seconds duration
- real-time processing of data variables to provide histograms and counts of pertinent events (these data are communicated at the end of each trip to a cellular modem/server at UMTRI)

The computers on-board each vehicle not only control the gathering of data but they also do on-line data processing. The main computer calculates the derived floating point and logical variables, and it sorts the time history data into bins in order to form floating point and logical histograms.

Several stages exist for the processing of test data, namely: (1) validation of data integrity and system operation; (2) interpretation of field data; and, (3) quantification of system performance.

UMTRI staff can recognize (via transmissions from the cellular modem) many of the problems or limitations that have arisen during any trip from the moment of starting the engine until the ignition is turned off.

In summary, the results of the study are derived from comparisons of headway control performance between normal (manual) driving and driving with the ACC systen in operation. These comparisons are done from several perspectives involving :

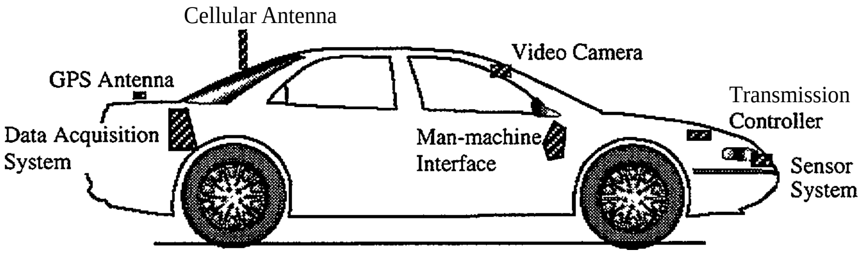
- Safety
  - — available reaction time (headway time margin)
  - — time to impact
  - — deceleration needed to avoid impact
  - — scores in evaluating time margin or deceleration margin for following
  - — subjective evaluation of safety
- Convenience
  - — physical and mental work in activating the controls

  - needed level of precision and timing in activating the controls
  - subjective ratings of ease of use and control effort
- Comfort
  - smoothness of transitions (jerk) and levels of acceleration
  - subjective ratings of user friendliness
  - drivers feelings related to safety margins and range maintenance
  - level of comfort with the vigilance demands of ACC supervision

3.1.6 Vehicle Preparation

The vehicle preparation task involved the installation, modification and checkout of seven different systems on-board each test vehicle. Figure 10 shows the seven systems and their locations on each test vehicle. Many of the systems shown involved substantial preassembly before they could be installed. Also of significance was the installation and routing of a wire harness that provided power and data connectivity between the different systems. Figure 10 also includes a list of the major tasks for the vehicle preparation process. A total of 37 tasks were identified. The sequence of the tasks was optimized to help avoid repeated disassembly and modification of the vehicle components and existing subsystems.

__1. Fab, assemble, and check instr. chassis
__ 2. Fab chassis cover plate
__3. Fab cover plate attachment
__4. Fab GPS antenna backplate
__ 5. Fab board & box for brake lamp mod
__ 6. Fab MMI mod board
__7. Modify Leica's MMI controller box
__8. Stuff & assemble MMI display
__9. Build up camera ass'y
__10. Fab cut-in Plexiglas cover
__ 11. Fab sensor foam inserts



__12. Add supplemental wiring
__13. Install connectors on wiring
__ 14. Dress wiring
__ 15. Install brake lamp mod box
__16. Mount cellular antenna
__ 17. Mount GPS antenna
__ 18. Install & connect instr. chassis
__19. Re-install seat belts & back seat
__ 37. Mod. trunk carpet
__ 20. Remove dashboard
__ 21. Install concern button
__22. Wire concern button
__23. Defeat "Rec" air button
__24. Install MMI controller
__25. Install MMI display and hood
__26. Install MMI cover & labels
__27. Install buzzer
__ 28. Dress wires, attach connectors
__29. Position and install camera
__30. Fuse and attach battery connections
__ 31. Mod Chrysler's trans. connector
__ 32. Install wire to Chrysler's trans. controller
__ 33. Shrink-wrap sensor connectors
__34. Align sensors; modify mounting as needed
__35. Install sensor foam inserts
__36. Install cut-in Plexiglas cover

Figure 10. Vehicle preparation checklist

Sensors System

With the sensors, Leica provided an installation kit which includes an adjustable mounting. Once the sensor is firmly clamped into this mounting, it is possible to adjust its orientation using several adjustment means. Installing the sensors in the vehicle involved modifying the adjustable mounting, affixing it to the vehicle's front bumper, and modifying the grill to accommodate the sensors. All the sensor-mounting activities have been carried out by UMTRI.

The adjustable mounting includes a subframe onto which the sensor is attached. This subframe can be slid up or down, and it can also be pitched and yawed. To accommodate installation in the grill between the bumper and the cooling radiator, it was necessary to modify some parts of the adjustable mounting. Special brackets were fabricated and welded to the bumper frame, and the modified adjustable mountings were bolted onto these brackets.

Special openings were cut in the grill to accommodate the sensors. Also, provisions were made to allow access to the adjustment screws of the mountings without any parts removal. The installed sensors are shown in Figure 11. The transmitter and receiver of the sweep sensor are shown on the driver's side of the grill; those of the cut-in sensor are shown on the passenger's side of the grill.

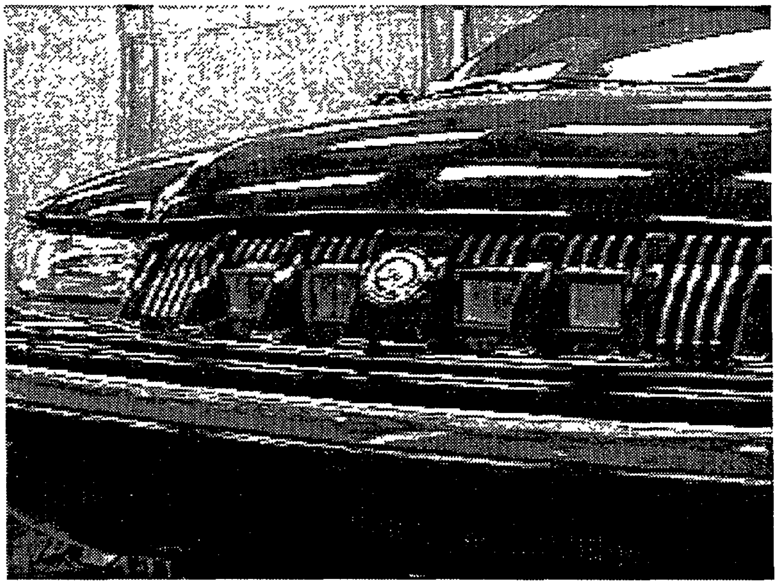


Figure 11. Sensors installed in the grill

Video Camera

The CCD video camera is mounted on the inside of the windshield, behind the rear-view mirror (see Figure 12). It has a wide-angle forward view, and it continuously digitizes and stores captured video to internal buffers in the video computer of the DAS.

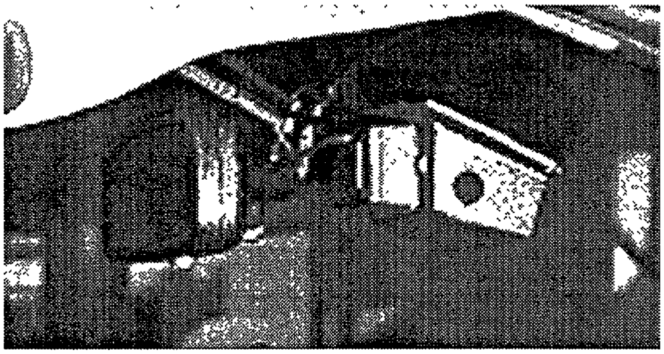


Figure 12. Forward-looking CCD camera

Man-Machine Interface

An integral part of the ACC system is the driver interface. The interface used for conventional cruise control was maintained in its OEM configuration and incorporated into the control of the ACC system. However, several new elements were added in order to accommodate use of the ACC system. The driver interface is illustrated in Figure 13.

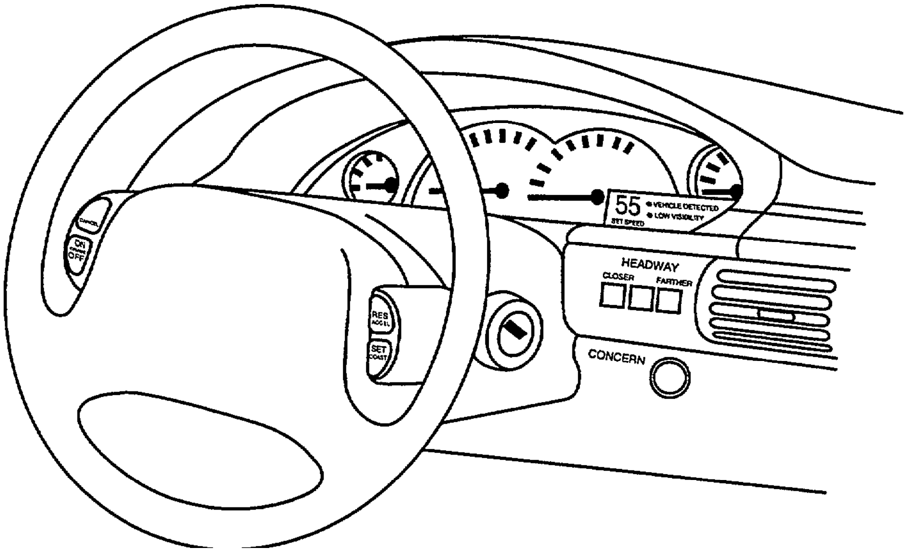


Figure 13. Chrysler Concorde instrument panel with ACC controls and displays

The items included in the headway controller’s driver interface include a display for presenting the set speed to the driver, a light accompanied by an audible tone for indicating when visibility is poor, and a light for indicating when the ACC system has recognized a preceding vehicle. In addition there is a set of switches for the driver to use in selecting headway time (labeled as "HEADWAY" in Figure 13). The right button labeled "Farther", the left button labeled "Closer", and the center button unlabeled. By pushing these buttons the driver can select nominal headway times of 2.0, 1.0, and 1.4 seconds, respectively.

Data Acquisition System

The entire data acquisition system (DAS) is mounted in the vehicle's trunk compartment adjacent to the rear surface of the rear passenger seat. The system is mounted in a chassis which houses the primary and video processor subsystems and associated peripherals. The chassis also supports the VAC and E-box for the headway control system as well as the cellular communication equipment. A structure of Dow blue Styrofoam (R-10.8) with insulated cover encloses the electronics and provides a thermally stabilized environment. This covering is modified to suit the particular demands of each seasonal temperature cycle. The covering also protects the equipment from damage or meddling by the participants. The structure consumes about a third of the trunk, however it does not interfere with access to the spare tire. Figure 14 below shows the DAS chassis in the trunk (without the covering).

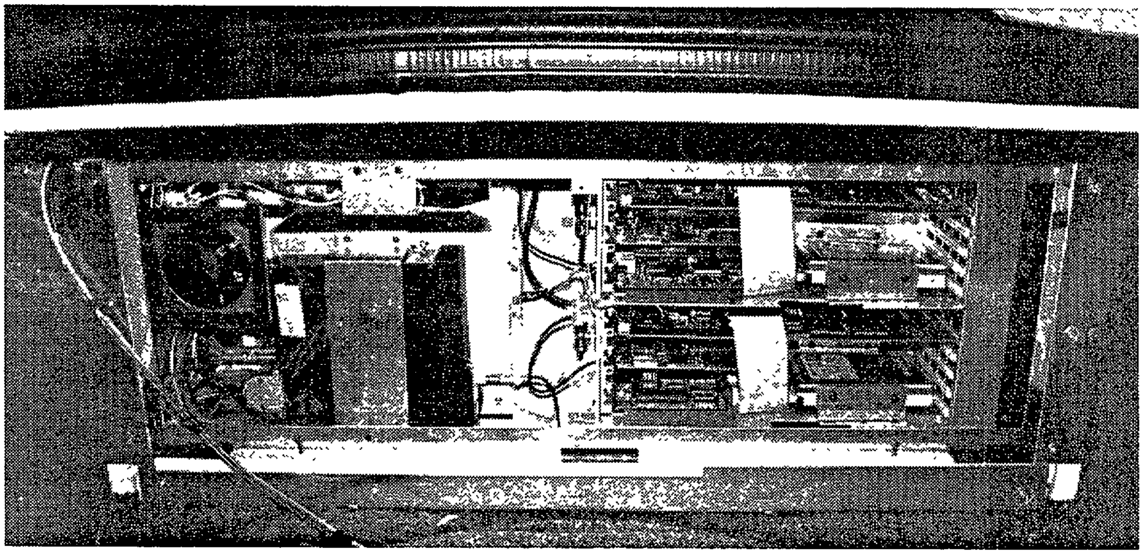


Figure 14. DAS Chassis mounted in the vehicle's trunk

Primary components that are contained within the chassis are DAS processor subsystem, video DAS processor subsystem (subsystems includes disk drives, power supplies, and I/O support cards), GPS receiver, cellular modem transceiver, environmental controller, 12V battery, power delivery system, and Leica's VAC and E-box subsystems. A detailed description of the cellular communication and GPS systems is provided later in section 3.4.

Following the installation and preparation, each vehicle was given a final verification checkout. This checkout consisted of the following tasks:

- power-up check
- ACC communications check
- MMI communication check (LED & buttons algorithm)
- ACC functional check
- cellular data transfer
- alarm installed and functioning
- verify equipment tracking sheet
- mileage run-in

Transmission Controller

Using a special-purpose tool (DRB-2) provided by Chrysler, UMTRI personnel modified the software of the electronic transmission controllers in the ten test vehicles. This modification was needed to allow the transmission to downshift by a command from the control algorithm (see technical discussion in section 2).

3.2 Vehicle and System Maintenance

Maintenance and monitoring of the test fleet, from both the automotive and the system operation aspects, are vital to the success and safety of the field operational test. The high mileage that these cars are expected to accumulate, and the experimental system that is installed in them, demand careful monitoring. The likelihood that drivers will treat these cars as "rentals," combined with the complexity of the system, make the maintenance task challenging.

The headway sensors used in this project are prototype sensors. As such, certain inspections and maintenance activities are required to be performed periodically to maintain the sensors' operative status. Part of the routine maintenance activities was dedicated to the sensors. These activities included sensors alignment and sensors inspection (by means of both software and hardware). As a result of sensor inspection, additional maintenance activities often ensue.

Vehicle and system maintenance encompass efforts by UMTRI staff, and work performed by an authorized Chrysler service shop. The maintenance task is carried out through three sub-tasks, as follows:

- on-line system monitoring — This is accomplished with diagnostic tools incorporated into the system software and the data processing. This form of monitoring ensures (within feasible limits) proper system operation, and that UMTRI is automatically notified (via the cellular modem) of any problems or limitations that have arisen. This maintenance feature depends upon monitoring the data transmitted to UMTRI by cellular phone during the operational test.
- home-base inspection — Each time a test vehicle is brought back to UMTRI between subjects, it is thoroughly checked and prepared prior to delivering it to the next participant. A comprehensive checklist has been prepared and evaluated. This checklist covers items such as:
  - safety, readiness, and functionality of all automotive systems
  - ensuring content of driver equipment (e.g., emergency tools, maps, etc.)
  - ensuring content of documentation (e.g., instructions, insurance, etc.)
  - data acquisition system (e.g., downloading, integrity, resetting, etc.)
  - ACC system functionality per specs, and alignment of the sensors
- OEM maintenance — Needed repairs and periodic maintenance per the manufacturer-recommended schedule will be performed by an authorized Chrysler service shop in Ann Arbor, Michigan. From the standpoint of service, the test fleet is quite unique. That is, expensive equipment items and new wiring have been installed throughout the vehicle, and OEM equipment has been modified (e.g., wired access to the engine controller, new transmission software, etc.). For these reasons, we have arranged for one dedicated point of Chrysler service-a dealer who will assign dedicated maintenance personnel who are acquainted with the special nature of our vehicles. The intention is these vehicles will be serviced only by the selected dealer unless road emergencies necessitate other arrangements.

3.3 System Characterization Procedures

Tests to characterize the performance of the overall system are conducted by UMTRI engineers on public roads covering a broad set of operating scenarios. Each test elicits a certain response that can serve as a meaningful description of system properties. Data is collected using the same data-acquisition package as is installed in each car for operational testing. Test variables that are controlled include the host vehicle speed, lead vehicle speed, state of the control system, and relatively simple steering and braking maneuvers. In each test, the properties of the system are characterized independent of human behavioral variables. A comprehensive description of the characterization-tests procedure is provided in Appendix A, which also includes example plots of test results.

Each of the test measurements is conducted with negligible road grade and head wind. Further, some of the tests require that a ***Co-op Vehicle*** is engaged to execute preplanned interactive movements between the host vehicle and a preceding vehicle. In these cases, the co-op vehicle is simply another passenger car driven by a collaborating staff member.

3.4 Data Acquisition System

Figure 15 shows a block diagram of the data acquisition system. It consists of five subsystems:

- power, interface, and control
- main computer
- GPS
- cellular communications
- video computer

The main computer system collects and records data from the headway control system, the vehicle (via the headway control system), and the GPS system. The data are organized by trip (ignition on to ignition off). The main computer system also performs on-line data processing to generate derived channels, histograms, summary counts, and video episode triggers.

The video computer system continuously samples output from a windshield mounted camera and saves 2.5-second exposures every five minutes and 30-second episodes when triggered by the main system.

After the ignition is turned off, the main system sends a summary trip file to the UMTRI server using the cellular communications system. When a car returns to UMTRI, the on-board Ethernet network is connected to the building network and the numerical and video data is transferred to the project server.

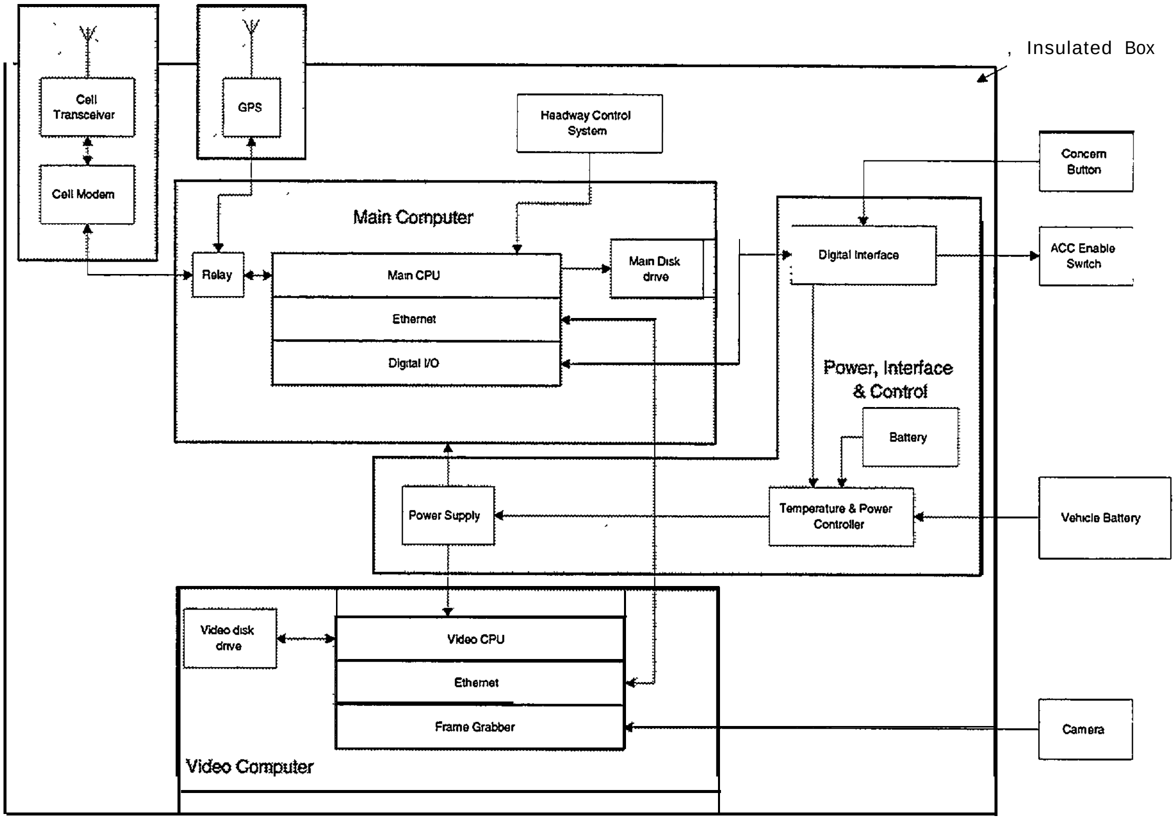


Figure 15. Data acquisition system hardware

3.4.1 Power, Interface and Control

The power, interface, and control subsystem provides power sequencing of the various components and closed-loop heating or cooling of the chassis. It includes:

- two triple-output (5, +-12 volt) ac-dc converters for the computers
- 9-volt regulator for camera power
- 3-volt lithium battery for the GPS battery-backup RAM
- three 12-volt 17.5 amp-hour lead acid batteries
- microcontroller with 11 channel l0-bit A/D and 12 digital inputs/outputs
- circulation and exhaust fans
- 50-watt heater
- three temperature sensors

The microcontroller continuously monitors the chassis and camera temperatures, battery voltages, and state of the ignition switch and updates histograms of these variables in nonvolatile memory (EEPROM). The histograms are downloaded and inspected via a RS232 serial line when the participant returns the vehicle.

The vehicle power system and the chassis batteries are connected only when the ignition is on. Power for heating and cooling of the system comes from the three chassis batteries. The camera temperature is maintained above -5 degrees C by turning it on (self-heating). If the temperature of the chassis goes below 4 degrees C, a 50-watt heating element and a circulation fan are activated. The microcontroller ceases closed-loop heating when the battery voltage drops below 10.0 volts. This assures that the chassis can be powered up when the next ignition-on event occurs. If the chassis temperature is out of operating range (2 to 50 degrees C), the microcontroller does not turn the computers on and logs a missed trip in its EEPROM.

3.4.2 Main Computer

The Main Computer includes:

- a 5-slot passive backplane and chassis
- an IBM-AT compatible CPU card with 90 MHz Pentium processor, 8 MB RAM, two serial ports, printer port, and hard disk controller
- 1.6 GB disk drive
- Ethernet network adapter
- digital I/O expansion card

Figure 16 shows how the system operates. When the vehicle is started, the interface and control system activates the main system, which turns on the GPS and video systems. The GPS system sends (via a RS-232 serial line) encoded position and velocity packets every time it computes a new position. The main system decodes these packets, calculates a grade estimation and heading from the velocity information, and stores the time, latitude, longitude, altitude, grade, and heading to a position file. The GPS time at power-up is used to set the main and video computer clocks.

The headway controller sends (via a second RS-232 serial line) an encoded packet of information every 0.1 seconds. The main system decodes this packet and extracts the appropriate sensor and vehicle information channels. Derived channels are then calculated and selected information is logged to a time-history file. Some logical channels are logged to a transition file. Each transition-file record indicates a channel number, the time of the false-to-true transition, and the duration that the signal was true, An episode-processing task monitors the incoming and calculated channels for the occurrence of significant episodes (e.g., ACC overrides, near encounters, concern button presses, etc.). When an episode is detected, the main system logs it to the transition file and sends a message (via Ethernet network) to the video system. Transition counts, histograms, errors, and other trip summary information are logged to a trip log at the end of each trip.

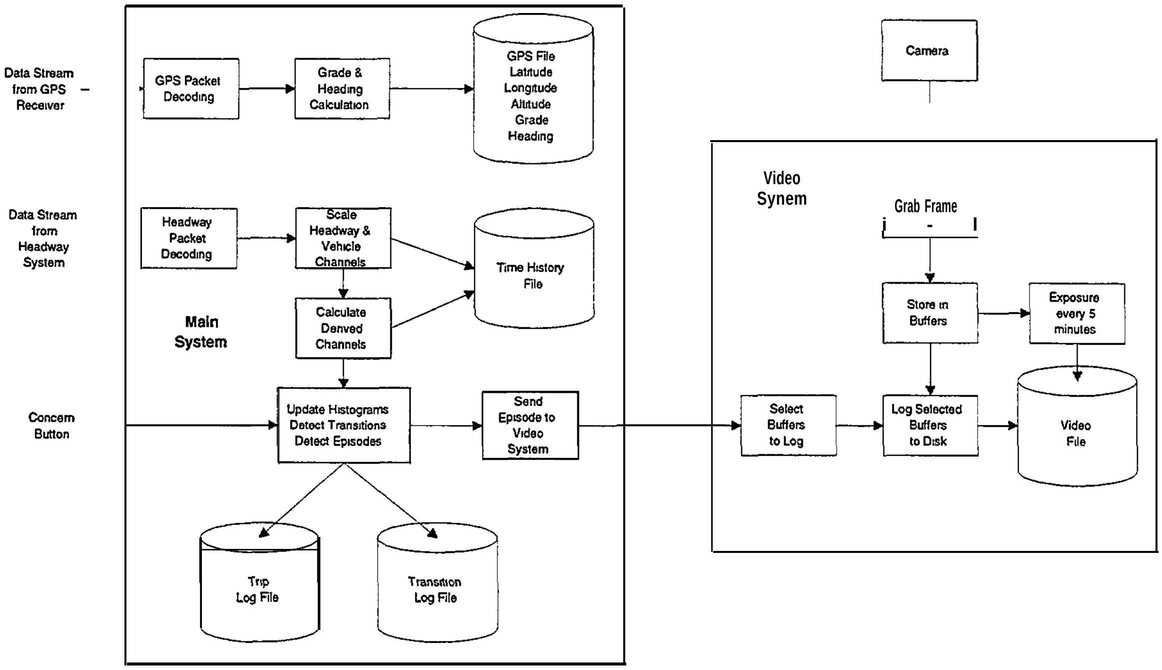


Figure 16. Data acquisition system operation

The video system continuously digitizes and stores captured video to internal buffers. When a message from the main system occurs, the video system selects a number of buffers (representing a time period that captures the event) and records these buffers to disk.

When a trip ends, the main system turns off the GPS and video systems and activates the cellular system. The trip log files are then transferred to the UMTRI server using standard Internet protocols (FTP, TCP/IP, and PPP). Then the main computer signals the microcontroller which turns the computer off.

3.4.3 GPS

The GPS system uses a Trimble six-channel receiver model SVeeSix-CM3 (which tracks up to eight satellites) with real-time clock and active antenna that is mounted on the center of the trunk lid. The receiver stores the almanac, ephemeris, and configuration data in battery-backup RAM. This minimizes the time from power-up to first computed position. If the receiver has been powered down for less than four hours, the saved data is considered valid and the acquisition time is typically less than 30 seconds. If more than four hours, the time to first fix is around 40 seconds.

The main computer communicates with the receiver via a 9600 baud RS232 serial line using the Trimble Standard Interface Protocol (TSIP). TSIP is a binary packet protocol that permits full control of the receiver's operating parameters and output format. Table 2 shows the packets that are automatically sent by the receiver and processed by the data acquisition software. The main computer causes the receiver to operate in 3D-manual and overdetermined modes. Position and velocity packets are sent twice a second as long as at least four satellites are visible. Reacquisition time for a momentary satellite loss is typically under 2 seconds. The over-determined 3D solution (which smoothes the position output and minimizes discontinuities caused by constellation changes) requires five or six visible satellites.

Table 2. GPS Packet information

Packet Type	Description
Health	Satellite tracking status and operational health of the receiver
Time	GPS time reported in weeks since January 6, 1980 and seconds since Sunday morning at midnight of the current week
Position	Single precision position in Latitude-Longitude-Altitude (LLA) coordinates
Velocity	Single precision velocity in East-North-Up (ENU) coordinates

3.4.4 Cellular Communications

The cellular communications system consists of an AT&T KeepInTouch 14.4 Kbps cellular modem that uses the Enhanced Throughput Cellular protocol, a Motorola 3 watt transceiver, and a window-mount antenna. The main acquisition and communications programs maintain a list of trip files to be transmitted to the UMTRI server. When a trip is over, the system executes a connection script that initializes the modem (which usually connects at rates of 4800, 7200, or 9600 baud), dials the phone, and logs in to the server with a PPP account name and password. If the call is not answered (busy cellular system or server) a second attempt is made. Files are transferred using FTP until either all the files in the list have been sent or five minutes has lapsed since the driver turned of the ignition. The system then executes a disconnect script and turns itself off.

3.4.5 Video Computer

The Video Computer includes:

- a 5-slot passive backplane and chassis

- an IBM-AT compatible CPU card with 90 MHz Pentium processor, 32 MB RAM, two serial ports, printer port, and hard disk controller
- 2.1 GB disk drive
- Ethernet network adapter
- CX100 Frame Grabber

The CX100 frame grabber is programmed to capture an image of 486 rows by 512 pixels in NTSC high resolution mode. Each image frame contains two interlaced fields (243 rows by 512 pixels) as shown in Figure 17.

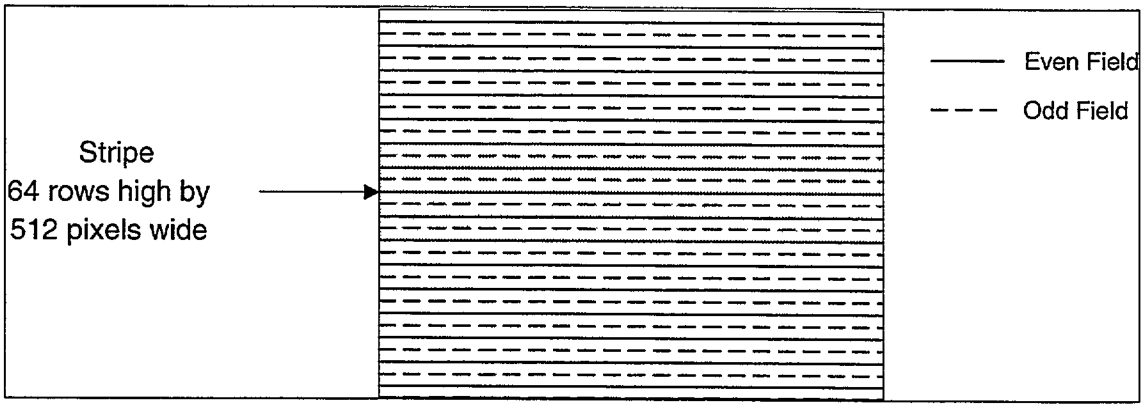


Figure 17. Video image frame structure

The video software samples a stripe from the even field, which is 64 rows by 512 pixels, every six frames, or 0.1 seconds. The stripe is marked with a date/time stamp derived from the system clock which reflects the time the stripe was copied into a stripe buffer (not the time the frame grabber digitized the field) and stored in a stripe buffer selected from a pool of 600 buffers.

The system maintains a circular list of the last 300 stripes. At 5-minute intervals, an exposure task wakes up and saves the last 25 stripes (2.5 seconds) to a file (819,200 bytes). The system hard disk contains 420 contiguous preallocated exposure files labeled from "1.exp" to "420.exp". The files are created once and never deleted, which minimizes write time and prevents the disk from becoming fragmented. They are overwritten in sequential order and a current list of file and driver-trip information is stored in a directory file called "director.exp".

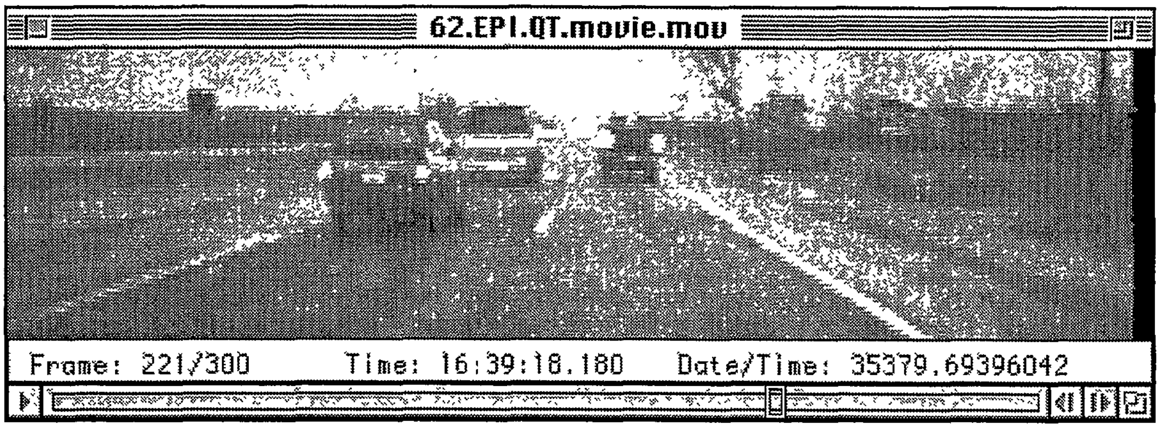
When the main system detects an episode, it sends a message that contains the episode type, driver number, trip number, date/time stamp, and the importance of the episode (a number between 0.0 and 1.0). The video system copies the list of the last 300 buffers and increments the buffer use counts so they will not be returned to the “available” or “free” pool until they are written to disk. The episode is scheduled to be recorded after a 15-second wait period. If another more important episode occurs during this period, the previously scheduled one is deleted and the new one is scheduled. Thus cascaded triggers that are close in time generate only one video episode. The system hard disk contains 160 contiguous pre-allocated episode files (9,830,400 bytes each) labeled from “l.epi” to “160.epi”. Table 3 shows the nine types of episodes that vie for this file space.

Table 3. Episode types

Episode Type	Minimum	Maximum
Concern button	50	50
Manual Brake Intervention - 1”’ week	10	50
Manual Near Encounter - 1st week	10	50
Cruise Brake Intervention	10	50
Cruise Near Encounter	10	50
Manual Brake Intervention - 2nd week	20	50
Manual Near Encounter - 2nd week	20	50
ACC Brake Intervention	20	50
ACC Near Encounter	20	50

The episodes files are filled in order from 1 to 160 as long as the number of each type is less than its maximum. Once all of the files are filled, a set of preemption rules applies. The current list of episodes is stored in a directory file called “director.epi”.

The exposures and episode binary files are converted to “QuickTime movies,” which can be played on Macintoshes or PCs running Windows (3.1, 95, or NT). The images are doubled in height to recapture the original aspect ratio (only the even rows are contained in the sample) and compressed. The resulting exposure movies are 200 to 350 K bytes in size. The longer episodes are from 3.5 to 4 Megabytes. The first frame of each movie is a title frame showing the driver number, trip number, date/time of the trigger or exposure, and the importance. Subsequent frames display the frame number and frame timestamp at the bottom. Figure 18 shows a frame from an exposure movie.



62.EPI.QT.movie.mov

Frame: 221/300 Time: 16:39:18.180 Date/Time: 35379.69396042

Figure 18. Snapshot from an exposure movie

3.5 Data Processing Procedures

This section outlines the data flow and current data processing for the FOT. There are many stages of data processing in this project. They range from the simple calculation of derived signals in real-time, on-board the test vehicle's data acquisition system (DAS), to the storage of files in a database format that allows flexible query generation and inter-connectedness of the data.

On average a subject will take 76 trips, drive 828 miles, and spend 21 hours in the FOT vehicle during the twelve day test period. From a data-processing perspective, an average driver generates around 300 numerical data files with a total file storage size of 115 Megabytes (MB). Likewise, the typical driver generates approximately 3 10 video files with a total file size of 794 MB. This means to-date the study has collected over 23,000 numerical and video data files that constitute nearly 34.5 Gigabytes (GB) of information.

This process is very computationally and network intensive. The end goal is to deliver a portable and very concise numerical and video history of the driving experience of each FOT driver. Figure 19 shows the general flow of the numerical and video data. The following sections discuss this figure starting with the primary and derived data channels. Then the on-line processing of these channels to make histograms is discussed. This is followed by a discussion on file types, databases and video files, and finally the permanent storage of the data on CD-ROM.

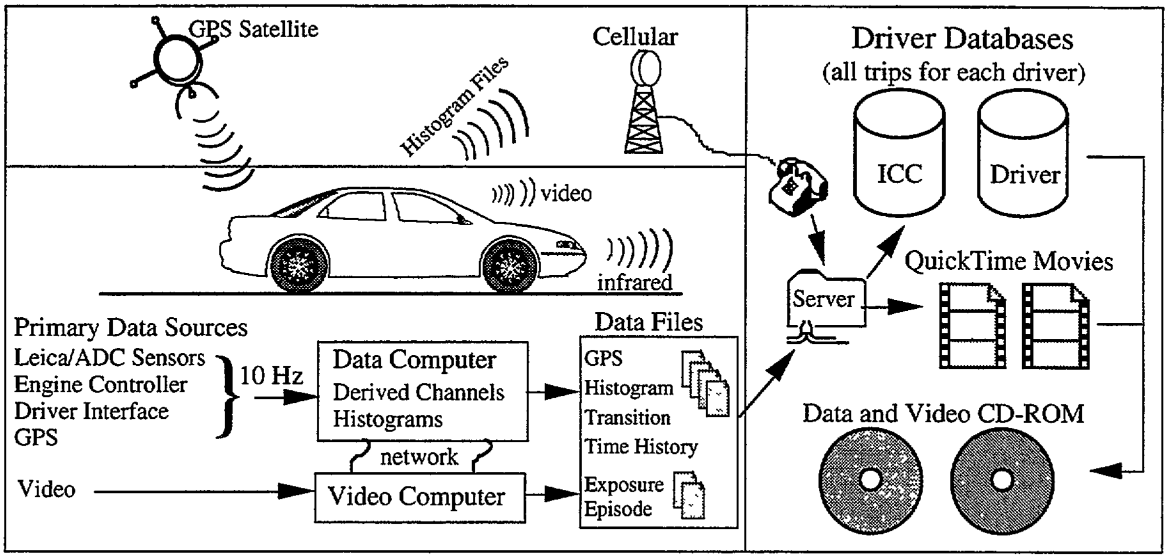


Figure 19. Data processing and flow for the field operational test.

3.5.1 On-board Data Processing

The DAS installed on the FOT vehicles is designed to collect, process and store both numerical and video data files using two on-board computers. The data are collected and stored on trip-by-trip basis. A trip is defined as the time between turning on and off the test vehicle's ignition. The rate of data sampling for the DAS is 10 Hz. The discussion below focuses first on the numerical side of the data processing. The video data processing is explained later in this section.

Primary and Derived Channels

The numerical data flow starts with the collection of 32 primary signals from various sources on-board each FOT vehicle. These sources are shown on the left in Figure 19 and include the Leica/ADC infrared sensors, the vehicle's engine control unit, the video camera, the GPS, and the driver/vehicle interface. A list of the 32 primary signals is given in Table 4. This table shows the name, type, description, and units of each signal. It also has a column called Logged. This column indicates if the signal is permanently stored on the computers internal hard disk[1].

---

[1] Some of the logical signals are stored in a more compact format than that used for time histories. This format is explained later in this section under Transition Files. The following nomenclature is used in the column "Logged", to indicate which file the data is logged into: "H" – time history; "G" – GPS history, "T" – transition table

Table 4. Primary channels

Name	Type	Description	Units	Logged
ACC Mode	Integer	O=off, l=standby, 2=cruise, 3=headway		H
Accel	Logical	True if accel button is pressed		T
AccEnable	Logical	True after 1st week		
Altitude	Float	Altitude	m	G
Backscatter	Float	Backscatter (0 to 1023)		H
Blinded	Logical	True if ODIN 4 blinded bit is on		
Brake	Logical	True if brake pedal is pressed		H
Cancel	Logical	True if cancel button is pressed		T
CC-ACC On	Logical	True if cruise or ACC switch is on		
Cleaning	Logical	True if ODIN 4 cleaning bit is on		
Coast	Logical	True if coast button is pressed		T
Concern	Logical	True if concern button is pressed		T
CurveRadius	Float	Curve radius	ft	
Date/Time	Double	Days since 12/30/1899 + fraction of day	days	H
Downshift	Logical	True if controller requests downshift		T
East Velocity	Float	East velocity, + for east	m/sec	
Headway Time	Float	Selected headway time	sec	
HeadwaySwitch	Integer	headway switches , 1,2, or 4		
Latitude	Float	Latitude, + for north	radians	G
Longitude	Float	Longitude, + for east	radians	G
NewTarget	Logical	True for .3 sec with new target		H
North Velocity	Float	North velocity, + for north	m/sec	
Range	Float	Distance to target	ft	H
RDot	Float	Rate of change of range	ft/sec	H
ReducedRange	Logical	True if ODIN 4 reduced range bit is on		
Resume	Logical	True if resume button is pressed		T
Set	Logical	True if set button is pressed		T
Throttle	Float	Throttle percent		H
Tracking	Logical	True when tracking a target		H
Up Velocity	Float	Up velocity, + for up	m/sec	
ValidTarget	Logical	Target and velocity filter		H
VCommand	Float	Velocity commanded by controller	ft/sec	H
Velocity	Float	Vehicle velocity	ft/sec	H
Vset	Float	Cruise speed set by driver	ft/sec	H

The numerical data processing begins as these primary channels are read into the memory of the DAS. The computer then calculates what are called ***derived channels.*** These channels are combinations and manipulations of the primary signals. Examples of derived channels include: V_p (Velocity of the preceding vehicle), road grade, distance, near, following, etc. There are 66 derived channels. The 3 1 floating-point derived channels are given in Table 5. The remaining 35 are logical channels and are listed in Table 6. Both tables show the name of the derived signal, a description (which includes its derivation), units, and whether it is logged or saved in the data computers memory.

Table 5. Floating point derived channels

Name	Description	Units	Logged
AvgBackScatter	1 second moving Avg of BackScatter		
AvgDNearEncounter	4 second moving Avg of DNearEncounter	g's	
AvgVDot	4 second moving Avg of -VDot	g's	
CDot	Derivative of DegreeOfCurvature	deg/sec	H
D	RDot^2 / (2·(Range- 0.7 • Vpp32.2)	g's	
DecelAvoid	RDot^2 / (2·Range·32.2)	g's	H
DegreeOfCurvature	5728.996 / CurveRadius	Deg	H
Distance	Integral of velocity	miles	H
DistanceEngaged	Integral of velocity while engaged	miles	
DNearEncounter	RDot^2 / (2·(Range - .3·Vp)·32.2)	g's	
DScore	if DScoreRegion then DScore= (D-.03) / .47; if TScoreRegion then DScore= 1		H
EngMaxAvgDNear	Maximum value of AvgDNear while EngNearEncounter is true	g's	
EngMaxAvgVDot	Maximum value of AvgVDot while EngBrakeIntervention is true	g's	
Flow	Velocity / (Range+L)	veh/sec	
Grade(GPS)	UpVelocity / sqrt(NorthVelocity + EastVelocity^2)		G
Heading	Heading angle calculated from NorthVelocity and EastVelocity	deg	G
HeadwayTimeMargin	Range / Velocity	sec	H
Hinderance	Velocity / VSet-		
ManMaxAvgDNear	Maximum value of AvgDNear while ManNearEncounter is true	g's	
ManMaxAvgVDot	Maximum value of AvgVDot while ManBrakeIntervention is true	g's	
RangeCheck	.7 . Vp + RDot^2 / (2·.5·32.2)	ft	
RangeNear	.5 • Vp +RDot ^{2} / (2·.1·32.2)	ft	
Rpt03	Range - RDot^2 / (2·.03·32.2)	ft	
Thpt03	Rpt03/Vp if RDot c 0 or Range/Vp if RDot >= 0	sec	H
TimetoImpact	-Range RDot	sec	H
TrackingError	TimeConstant • RDot + Range - Th·Vp	ft	
TScore	if TScoreRegion then TScore= (.7-ThO) / .7		H
Vdot	derivative of Velocity / 32.2	g's	H
VehicleResp	VCommand - Velocity	fps	
VP	Velocity + RDot	fps	H
VpDot	derivative of Vp / 32.2	g's	H

Table 6. Logical derived channels

Name	Description	Logged
AccBi	15-sec oneshot - AccEnable AND EngBrakeIntervention	T
AccFollowing	Following AND .9Rh < Range <1. 1Rh	H
AccNe	15-sec oneshot - AccEnable AND EngNearEncounter	T
AccTracking	AccMode > 2	
AlwaysTrue	Always True	
BackscatterWarn	Backscatter > min	H
CccBi	15-sec oneshot - NOT(AccEnable) AND EngBrakeIntervention	T
CccNe	15-sec oneshot - NOT(AccEnable) AND EngNearEncounter	T
Closing	NOT(Near) AND RDot <-5	H
Cutin	Range c RangeNear AND RDot >0	H
DScoreRegion	ValidTargetVgt35 AND RDot <= 0 AND Range > RangeCheck	
Engaged	AccMode > 1	T
EngBrakeIntervention	15-sec oneshot - Brake AND Vgt50 AND AverageVDot > .05 AND WasEngaged	
EngNearEncounter	15-sec oneshot - ValidTargetVgt50 AND AverageDNear > .05 AND WasEngaged	
Following	NOT(Near OR Cutin) AND -5 <= RDot <= 5	H
HeadwayLong	True if long headway switch is pressed	T
HeadwayMedium	True if medium headway switch is pressed	T
HeadwayShort	True if short headway switch is pressed	T
LDegOfCurvature	DegreeOfCurvaturel > 3 AND V>50	
LVpDot	VpDot < -.05g’s	
ManlBi	15-sec oneshot - NOT(AccEnable) AND ManBrakeIntervention	T
ManlNe	15-sec oneshot - NOT(AccEnable) AND ManNearEncounter	T
Man2Bi	15-sec oneshot - AccEnable AND ManBrakeIntervention	T
Man2Ne	15-sec oneshot - AccEnable AND ManNearEncounter	T
ManBrakeIntervention	15-sec oneshot - Brake AND Vgt50 AND AvgVDot > .05 AND NOT WasEngaged	
ManNearEncounter	15-sec oneshot - ValidTargetVgt50 AND AverageDNear > .05 AND NOT WasEngage	
Near	Range < RangeNear AND RDot <0	H
Separating	NOT(Cutin) AND RDot > 5	H
Stopped	Velocity <3	
TScoreRegion	ValidTargetVgt35 AND RDot <= 0 AND Range <= RangeCheck	
ValidTargetVgt35	ValidTarget AND V>35	
ValidTargetVgt50	ValidTarget AND V>50	
Vgt35	Velocity > 35	
Vgt50	Velocity > 50	
WasEngaged	True if enaged within the last 15 seconds	

Floating Point Histograms

During each trip some of the primary and derived floating-point channels are made into histograms by the on-board computer. The counting and binning for the histograms is done *on-the-fly* as the signals are derived and processed. Table 7 shows the twenty-seven floating-point histograms that are currently being made and permanently stored. If data for a particular histogram is collected continuously during a trip, its enabling channel is listed as Always True. For other histograms the enabling channel is either a primary or derived logical channel and it must be *hi* or true in order for counting to occur in that particular histogram. For example, the Throttle histogram is only loaded when the enabling channel, Velocity > 30 mph is true.

Table 7. Floating point histograms

Name	Source Channel	Enabling Channel	Sorting Channel
BackScatterFhist	Backscatter	Vgt35	None
CDotFhist	CDot	Vgt35	Engaged
DecelAvoidFhist	DecelAvoid	ValidTargetVgt35	Engaged
DegOfCurvatureFhist	DegreeOfCurvature	Vgt35	Engaged
DScoreFhist	Dscore	DScoreRegion	Engaged
FlowFhist	Flow	ValidTargetVgt50	Engaged
HindranceFhist	Hindrance	Engaged	None
HtmFhist	HeadwayTimeMarg	Following	Engaged
RangeFhist	Range	ValidTarget	Vgt35
RangeFollowingFhist	Range	Following	Engaged
RangeVgt35FhistV	Range	ValidTargetVgt35	Engaged
RDotFhist	RDot	ValidTarget	Vgt35
RDotVgt35Fhist	RDot	ValidTargetVgt35	Engaged
Thpt03Fhist	Thpt03	ValidTargetVgt35	Engaged
ThrottleFhist	Throttle	Vgt35	Engaged
TimeToImpactFhist	TimeToImpact	ValidTargetVgt35	Engaged
TrackingErrorFhist	TrackingError	AccTracking	None
TScoreFhist	TScore	TScoreRegion	Engaged
VCommandFhist	VCommand	Vgt35	Engaged
VDotFhist	VDot	Always True	Vgt35
VDotVgt35Fhist	VDot	Vgt35	Engaged
VehnessFhist	VehicleResp	Engaged	AccTracking
VelocityFhist	Velcoity	Always True	None
VelocityVgt35Fhist	Vgt35	Vgt35	Engaged
VpDotFhist	VpDot	ValidTargetVgt35	Engaged
VpFhist	VP	ValidTargetVgt35	Engaged
VSetFhist	VSet	Engaged	None

As shown in Table 7, most histograms have a sorting channel. The sorting channel separates the counts into two histograms depending on the state of the sorting channel variable. For example, the sorting channel for the Throttle histogram is the Engaged logical channel. When this channel is true, i.e., the velocity of the test vehicle is being controlled by either conventional or adaptive cruise control, one set of bins for the Throttle histogram is filled. If the driver turns the cruise control off, then engaged is false, and the other set of bins for the throttle histogram is filled. (Of course, in this example the vehicle must maintain a speed greater than 30 mph for either set of bins to be filled because the enabling channel is Velocity > 30 mph). In short, there are really two histograms when a sorting channel is used.

One two-dimensional histogram is processed by the DAS. This is a normalized Range, Range-Rate histogram. The normalizing channel is the speed of the preceding vehicle (V_p). The histogram is enabled by the ValidTargetVgt50 logical channel and is sorted by the Engaged channel.

Besides creating histograms, the DAS also calculates three statistical figures for each histogram. These figures are the most-likely-value (which histogram bin has the greatest number of counts), the mean and the variance, where the later two are defined as follows:

$$mean = \bar{x} = \sum_{i=1}^{nbins}(x_i \cdot n_i) \, / \sum_{i=1}^{nbins}(n_i) \tag{9}$$

and

$$variance = \sum_{i=1}^{nbins}(\bar{x}_i - x_i)^2 \cdot n_i \, / \, (\sum_{i=1}^{nbins} n_i) - 1 \tag{10}$$

where:

$\bar{x}$ = mean,
$nbins$ = number of bins,
n_i = count in each bin, and
x_i = value of the bin center

Logical Histograms

There are twenty logical histograms recorded by the DAS for each trip of each test vehicle. Table 8 shows the names, source channels, enabling channels and sorting channels for these histograms. Unlike the floating-point histograms, the logical histograms all have five bins. The first bin records the number of transitions (count of false to true changes) for the logical source channel. The second and third bins contain the number of counts that the source channel was true and false, respectively. The fourth and fifth bins contain the number of counts that corresponds to the longest consecutive time that the source channel was true and false, respectively. The enabling and sorting channels have the same meaning as in the floating-point histograms.

Table 8. Logical histograms

Name	Source Channel	Enabling Channel	Sorting Channel
AccFollowingLhist	AccFollowing	ValidTargetVgt35	Engaged
AccTrackingLhist	AccTracking	Engaged	None
BackscatterWarnLhist	BackscatterWarn	Vgt35	vgt35
BlindedLhist	Blinded	Vgt35	Engaged
BrakeLhist	Brake	Vgt35	WasEngaged
CleaningLhist	Cleaning	Vgt35	Engaged
ClosingLhist	Closing	ValidTargetVgt35	Engaged
CutinLhist	Cutin	ValidTargetVgt35	Engaged
DScoreRegionLhist	DScoreRegion	ValidTargetVgt35	Engaged
FollowingLhist	Following	ValidTargetVgt35	Engaged
LVpDotLhist	LVpDot	ValidTargetVgt35	Engaged
NearLhist	Near	ValidTargetVgt35	Engaged
NewTargetLhist	NewTarget	Vgt35	Engaged
ReducedRangeLhist	ReducedRange	Vgt35	Engaged
SeparatingLhist	Separating	ValidTargetVgt35	Engaged
TrackingLhist	Tracking	Vgt35	Engaged
TScoreRegionLhist	TScoreRegion	ValidTargetVgt35	Engaged
ValidTargetLhist	ValidTarget	AlwaysTrue	Engaged
ValidTargetVgt35Lhist	ValidTarget	Vgt35	Engaged
ValidTargetVgt45Lhist	ValidTarget	Vgt45	Engaged

3.5.2 Data File Formats

For each trip, the DAS records and saves six different file formats. Four of these contain the numerical information for the trip and the other two contain the video information. A short description of each file formats follows.

- *GPS Files* - The GPS data is written in a time-history format to the DAS hard-disk. The channels of this file include: time, latitude, longitude, altitude, grade, heading. These data are written to the file at 0.5 Hz. Typically, these files are 6OKB in size. In addition to logging a complete record of the test vehicle’s position, start and end lateral, longitudinal and altitude GPS coordinates for each trip are saved in a more accessible format within the histogram file type.
- *Histogram files* - The data for all the floating-point and derived histograms are saved in the histogram files. These files are between 11 and 15 KB. The histogram files

also contains a trip summary table. The contents of the table are listed in Table 9 below. Unlike the other DAS files, the histogram files are transferred to UMTRI at the end of each trip via the cellular phone that is built into the DAS system. These files are then monitored as they are received to identify problems with the test equipment or anomalous results. Test drivers can then be contacted and appropriate measures taken to correct the problem.

- *Transition files* - The transition file format is a concise way of tracking logical events that occur relatively infrequently, such as cruise-control button pushes by the driver. Instead of recording these events in a time-history format (which can consume large amounts of disk storage space) a table containing the event name, its start time and duration is constructed. Using this information, a time-history of the logical variable can be re-created if necessary. Transition files are typically less than 1 KB in size. (These variables are denoted by a "T" in the logged column of the tables above.)
- *Time-Historyfiles* - With the exception of the video files, the time-history files constitute the bulk of the data storage and archive. There are thirty-five channels in each time history file (denoted by an "H" in the logged column of the tables above). For an average trip a time history file is 1.3 MB.
- *Video files* - There are two types of video files: exposure and episode. Episodes are the capture of event-related video of 30 seconds duration. A total of 10 event types have been formulated, each yielding a criterion upon which decisions are made automatically for recording a concurrent clip of video data onto the video-storage hard disk. These files are 9.8 MB in size. Exposure files provide a brief video sample recorded every 10 minutes* regardless of the operational state. This information is used to derive a regular spot-record of the highway and traffic conditions. These files are 0.8 MB in size.

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[2] The sampling interval has been lowered to 5 minutes following an analysis of the trip summary information for the drivers to date. This will give a more complete picture of the driving environment for each trip and make better use of the storage capability of the hard disk on the video DAS.

Table 9. Trip table fields and descriptions

Field Name	Description
AccBi	Count of brake interventions while ACC is engaged
Accel	Count of Accel button hits
AccEnable	Switch indicating if ACC or CCC is enabled
AccNe	Count of near encounters while ACC is engaged
AccOn	Count of ACC button hits
Blinded	Count of blinded transitions
Brake	Count of brake pedal applications
Cancel	Count of cancel button hits
CccBi	Count of brake interventions while CCC is engaged
CccNe	Count of near encounters while CCC is engaged
Cleaning	Count of cleaning transitions
Coast	Count of Coast button hits
Concern	Count of concern button hits
Distance	Distance travelled during the trip, miles
DistanceEngage	Distance travelled with the cruise control is engaged, miles
DownShift	Count of down shift transitions
DriverID	Driver identification number
Duration	Duration of the trip, minutes
EcuError	Count of ECU error transitions
EndAltitude	Altitude of the end of the trip
EndLatitude	Geographical latitude of the end of the trip
EndLongitude	Geographical longitude of the end of the trip
EndTime	End time of trip, days since 12/30/1988 + fraction of day
Engaged	Count of ACC engaged transitions
FileError	Count of File system error transitions
GpsError	Count of GPS error transitions
ManlBi	Count of manual brake interventions while CCC is enabled
ManlNe	Count of near encounters while CCC is enabled
Man2Bi	Count of manual brake interventions while ACC is enabled
Man2Ne	Count of Near encounters while ACC is enabled
NetworkError	Count of network error transitions
NewTarget	Count of new target transitions
OdinError	Count of Odin error transitions
ReducedRange	Count of reduced range transitions
Resume	Count of Resume button hits
Set	Count of Set button hits
StartAltitude	Altitude of the start of the trip
StartLatitude	Geographical latitude of the start of the trip
StartLongitude	Geographical longitude of the start of the trip
StartTime	Start time of trip, days since 12/30/1988 + fraction of day
Stopped	Count of vehicle stops transitions
SystemError	Count of System error transitions
Tracking	Count of tracking transitions
TripID	Trip identification number
VacError	Count of Vat error transitions
ValidTarget	Count of valid target transitions
Version	DAS software version number
Vgt50	Count of velocity greater than 50 mph transitions

3.5.3 Database and CD-ROM storage

An ultimate purpose of the data-gathering and processing activities is to build a database that can be used to study manual and ACC control of speed and headway. As illustrated in Figure 19, the database system for each driver is composed of two databases called the "ICC" Database and "Driver" Database. The "ICC" Database contains all the histogram and trip summary information. The "Driver" Database contains the transition, GPS, and time-history information. A third aggregate "ICC Master" Database is also being created. It contains all the information stored in each of the driver's "ICC" Databases. Interrogations and communications amongst these data bases are made possible by coding each section of data by driver, then trip , and then type of data. Each set of databases for each driver is being written to CD-ROM for permanent archive and data exchange. The two types of video files are also being saved in a compact format and written to CD-ROM.

3.6 Project Status as Characterized by Amount and Type of Driving in the FOT

The results and findings included in this report cover 35 of the 38 drivers that have participated in the study as of January 1997. The data from three drivers were excluded from the study for the following reasons: a) driver 2 had to return the test vehicle after only driving for approximately 5 miles, b) driver 16 had an equipment failure half way through the test period, and c) driver 28 returned the car due to a faulty head lamp switch.

Table 10 below shows a summary of the total number of trips, miles (miles are separated into distance not engaged or manual driving and distance engaged or CCC and ACC engaged driving) and duration, in hours, for the 35 valid drivers. The columns of the table show statistics for all trips, for trips with no cruise control used (CCC Off and ACC Off) and for trips in which the cruise control was turned on at least once during the trip (CCC Used and ACC Used).

Table 10. Summary of distance and time, all trips

No. of Drivers: 35	All Trips	CCC Off	CCC Used	ACC Off	ACC Used
Trips	2659	916	325	938	480
Distance, miles	26,225.6	3449.9	8,059.5	3,178.0	11,538.2
Dist. Not Eng., miles	15,656.l	3,449.9	4,405.6	3,178.0	4,622.7
Dist. Eng., miles	10,569.5	NA	3,653.9	NA	6,915.6
Duration, hours	723.6	146.0	181.0	139.2	257.3

A total of 2,659 trips have been taken by the 35 drivers. Of the total trips, 1,241 (47 percent) were taken during the first week while CCC was enabled and 1,418 were taken during the second week while ACC was enabled. Of the first week trips 325 had the CCC engaged at least once during the trip, while 916 trips were driven completely in manual mode. Similarly, of the second week trips 480 had ACC engaged at least once during the trip, while 938 were driven completely in manual mode.

There were 155 more trips taken with ACC engaged as compared to the number of trips with CCC engaged. This represents a 47 percent increase in the number of trips in which ACC was used over CCC. Part of this difference is due to a bias in the amount of time for ACC enabled trips. (An effort is made to make the time equal for both cruise-control modes, but it is not always possible, so generally there is a bias toward having more time with ACC enabled.) However, because the number of manual-only trips are roughly the same for both time periods, the influence of this difference is probably small. More likely, the increase in ACC trips is due to two other reasons: a) the novelty effect of ACC (Drivers want to try the new technology even if they are not regular users of CCC.), and b) in driving situations where drivers would not normally use CCC, they will use ACC because of its added convenience of headway control.

This difference is also shown in the number of miles driven in the three different modes. For the study to date, a total of 26,225 miles were driven by the 35 valid test drivers. Of this total, 15,656 miles were driven in manual mode (distance not engaged). These miles are divided equally between the first week with CCC enabled (7,856 miles) and the second week with ACC enabled (7,800 miles). However, the distance engaged miles show an 89 percent increase in the number of miles driven with ACC engaged (6,915 miles) versus CCC engaged (3,653 miles).

Table 11 shows the same information as Table 10 except the numbers have been normalized by the total number of drivers (the notation "Trips/Drivers" means trips per driver). The table shows that the average driver takes 76 trips and travels 749 total miles during the two-week test period. Of the total miles, 447 were driven in manual mode and 302 were in a cruise-control-engaged mode.

Table 11. Normalized summary of distance and time, all trips

No. of Drivers: 35	All Trips	CCC Off	CCC Used	ACC Off	ACC Used
Trips/Driver	76.0	26.2	9.3	26.8	13.7
Distance/Driver	749.3	98.6	230.3	90.8	329.7
Dist. Not Eng./Driver	447.3	98.6	125.9	90.8	132.1
Dist. Eng./Driver	302.0	0.0	104.4	0.0	197.6
Duration/Driver	20.7	4.2	5.2	4.0	7.4

Table 12 shows a summary of the number of cruise-control button pushes that the average driver made during the two week test period. Not surprisingly, the number of times a typical driver simply turned the cruise control system on is greater for the ACC enabled period (19.6) than it is for the CCC enabled period (13.6). This increase (44 percent) is in line with the corresponding increase in the number of ACC versus CCC trips shown in Table 11.

Table 12 also shows the number of Set- and Resume-button hits per driver. Drivers use these buttons to change the vehicle control mode from manual to cruise engaged. However, these counts can be misleading when used this way because there are conditions when the driver can request the cruise to engage but, due to other reasons, like forward velocity being below the cutoff threshold, the cruise system (CCC and ACC) will not engage. For a more accurate account of the number of time the driver successfully engaged the system see the Engaged/Driver counts in Table 13.

Table 12. Summary of cruise-control buttons activations

No. of Drivers: 35	All Trips	CCC Off	CCC Used	ACC Off	ACC Used
Ccc-AccOn/Driver	33.2	NA	13.6	NA	19.6
Set/Driver	45.8	NA	20.0	NA	25.8
Coast/Driver	85.6	NA	42.3	NA	43.3
Resume/Driver	27.3	NA	10.6	NA	16.7
Accel/Driver	81.0	NA	28.6	NA	52.5
Cancel/Driver	11.1	NA	5.0	NA	5.9

Table 12 also shows the number of Coast, Accel, and Cancel button pushes per driver. For All Trips drivers tend to use both Coast and Accel buttons equally (85.6 Coast button hits versus 8 1 .O Accel button hits per driver). However, the distribution of usage in CCC and ACC driving is quite different for the two buttons. The Coast button is used equally in both CCC Used and ACC Used modes (42.3 and 43.3, respectively). Whereas, the Accel button is used approximately 84 percent more in the ACC Used trips

(28.6 for CCC Used and 52.5 for ACC Used). A clear explanation for this difference is difficult to discern. However, it may by attributable to drivers choosing to increase their set speed to take advantage of and challenge the headway control functionality of the ACC system.

Table 13 shows the number of brake applications per mile for the first 35 valid drivers. For All Trips there has been 2.4 brake applications per mile. For the trips when CCC and ACC were engaged this rate drops to 1.4 and 1.3, respectively. The number of downshifts per driver is applicable only when the ACC system is engaged. On average there were 40.0 downshifts per driver. The ACC control algorithm commands a transmission downshift when it has determined that the maximum available amount of deceleration is necessary.

Table 13. Summary of some driver / system control and status variables

No. of Drivers: 35	All Trips	CCC Off	CCC Used	ACC Off	ACC Used
Brake/mile	2.4	5.3	1.4	5.6	1.3
DownShift/Driver	40.0	NA	NA	NA	40.0
Engaged/Driver	64.1	NA	26.0	NA	38.1
Concern/Driver	2.1	0.1	0.3	0.0	1.7
Vgt50/Driver	208.9	39.3	60.0	30.6	79.0

The number of times the system was engaged per driver is shown in Table 13. If these counts are normalized by the number of miles engaged for the two cruise-control modes, then the average CCC engagement lasted for 4.0 miles while the average ACC engagement was 5.2 miles (a 30 percent increase). The table also shows the number of Concern button hits per driver and the number of times the vehicle speed transitioned above 50 mph (Vgt50) per driver for the four different trip categories. Not surprisingly, the trips when CCC and ACC were engaged show a significantly higher rate of transitions above the 50 mph threshold as compared to trips without any CCC or ACC engagement.

The final table (Table 14) in this section describes the number of brake interventions and near encounters per mile for manual driving during the first week (Manl), manual driving during the second week (Man2), CCC engaged driving and ACC engaged driving. (The definition of a near encounter and a brake intervention can be found in Table 6 (“Logical derived channels”). The data show a higher rate of near encounters per mile (0.049 versus 0.060; 22 percent increase) and brake interventions per mile (0.105 versus 0.120; 14 percent increase) when comparing the first and second week manual driving, respectively. However, when comparing CCC engaged near encounters per mile (0.034) to ACC engaged near encounters per mile (0.033) the rates are virtually identical. This is also true for CCC brake interventions per mile (0.054) and ACC brake interventions per mile (0.057).

Table 14. Summary of brake-interventions and near-encounters

No. of Drivers: 35	All Trips	CCC Off	CCC Used	ACC Off	ACC Used
ManlBiLMile	0.105	0.09 1	0.115	NA	NA
ManlNe/Mile	0.049	0.049	0.048	NA	NA
CccBi/Mile	0.054	NA	0.054	NA	NA
CccNe/Mile	0.034	NA	0.034	NA	NA
Man2BiLMile	0.120	NA	NA	0.108	0.128
Man2NeMile	0.060	NA	NA	0.065	0.056
AccBi/Mile	0.057	NA	NA	NA	0.057
AccNe/Mile	0.033	NA	NA	NA	0.033

The results and findings presented next in section 4 are based on the amount and types of driving described and characterized in this section.

4. INTERIM RESULTS AND FINDINGS

This section presents interim results from the FOT, in terms of both objective data (in Section 4.1) as compiled mostly in the form of histograms, and subjective results (in Section 4.2) as obtained from questionnaires. Preliminary findings are derived from these interim results by processing them, examining them, and interpreting their meaning. Section 4.3 addresses possible interpretations concerning societal issues by commenting on safety, traffic, and fuel flow.

4.1 Results and Findings From Quantitative Data

This discussion of the quantitative results is organized around trying to answer the following five questions:

1. How does ACC driving differ from manual or CCC driving if we consider all trips that were taken?
2. How do driving conditions influence driver choice among manual, CCC, and ACC modes of control?
3. How does driver age influence:
   1) the time gap between the ACC vehicle and the preceding vehicle, and
   2) the choice of control mode (ACC, MAN, or CCC)?
4. How do results for individuals differ from the aggregated results?
5. How well does this ACC system perform its functions?

Questions 1, 3, and 4 are associated with the operational issues concerning the nature of the speed and headway-keeping behavior of drivers (see section 1.1). Question 2 pertains to operational issues concerning when, where, and how drivers will use ACC. Question 5 addresses the performance of the current state-of-the-art ACC system.

The answers presented here are based upon information transmitted to UMTRI from the test vehicles via cellular phone at the end of each trip (where a trip is from ignition on to ignition off). This information is in the form of histograms for logical (two-level, yes/no) variables and for floating-point ("continuous" digital scale) variables as described in Section 3.5.

The notion of using the counts in each bin of the histograms to obtain information approximating probabilities plays a key role in understanding how the quantitative data have been processed/examined to respond to the questions posed here. In order to interpret these histograms it is convenient to think of them as if they were conditional probability density functions, since the count in each particular “bin” of the histogram (where a bin covers a small portion of the total range of the selected variable) divided by the total count summed over all of the bins in the histogram expresses the likelihood, or the probability, that the value of the variable at any moment falls within that particular bin. (The idea is cumbersome to state but simple to visualize once it is understood. Further material defining the ideas involved is presented in Appendix B.)

Appendix B explains how the histogram data has been processed to approximate the probability of certain events. These events and the associated probability symbols are of two types: (1) P(A|B) — the conditional probability of event A (i.e., set A is true) given that event B is true, and (2) Pd(A|B) — a conditional probability density function for the variable A. In this case, Pd(A|B) is the total result of computing P(Ai|A) for each of the Ai bins constituting A when B is true.

Putting aside abstract considerations, the point is that counts in the histograms have been used to estimate the chance / likelihood of sets and subsets of data chosen to aid in developing answers to the questions posed.

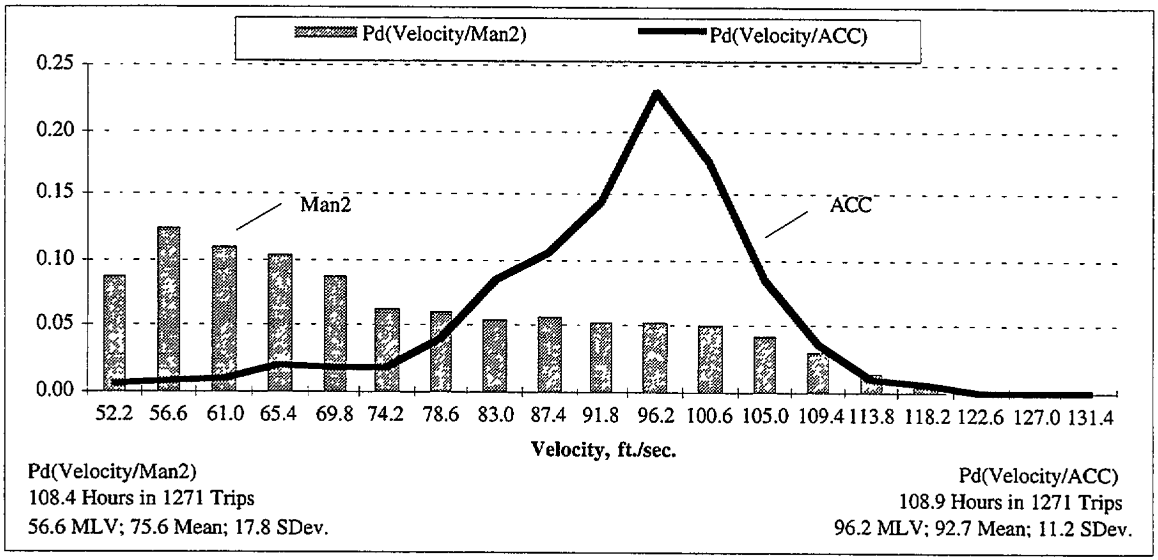
4.1.1 How does ACC driving differ from MAN or CCC driving?

This first question is intended for addressing the field test data at the broadest level. That is, when we look at all the data together, what are the macro characteristics of the driving activity appearing under each of the three forms of control? To address this question, consider applying the P(A|B) operator to the histograms for velocity and range obtained during manual, CCC, and ACC driving using the aggregated results for all drivers and all trips. We will consider further disaggregation (subsetting of the data) in later sections.

ACC versus Manual Results -Aggregated Data on Velocity

We can compare ACC versus manual modes of control by considering the data gathered during the second week with each driver, when only the ACC or manual modes of control were available. For this discussion, we will let ACC represent the set of results for ACC driving and let manual represent the set of results for manual driving. To compare ACC driving with manual driving, we will compare the approximate probability density functions corresponding to the velocity V by examining Pd(V|ACC) and Pd(V|MAN) as given in Figure 20.

This figure (and much of the other data representations in this report) covers speeds 35 mph and above because cruise-control systems are typically built with a lower bound on velocity near 35 mph. Thus, both the manual and ACC data have been restricted to this same range for purposes of comparison. The figure clearly indicates that ACC driving is only likely at highway speeds while manual driving is biased toward low speeds but is otherwise broadly distributed across the range.



Pd(Velocity/Man2)
108.4 Hours in 1271 Trips
56.6 MLV; 75.6 Mean; 17.8 SDev.

Pd(Velocity/ACC)
108.9 Hours in 1271 Trips
96.2 MLV; 92.7 Mean; 11.2 SDev.

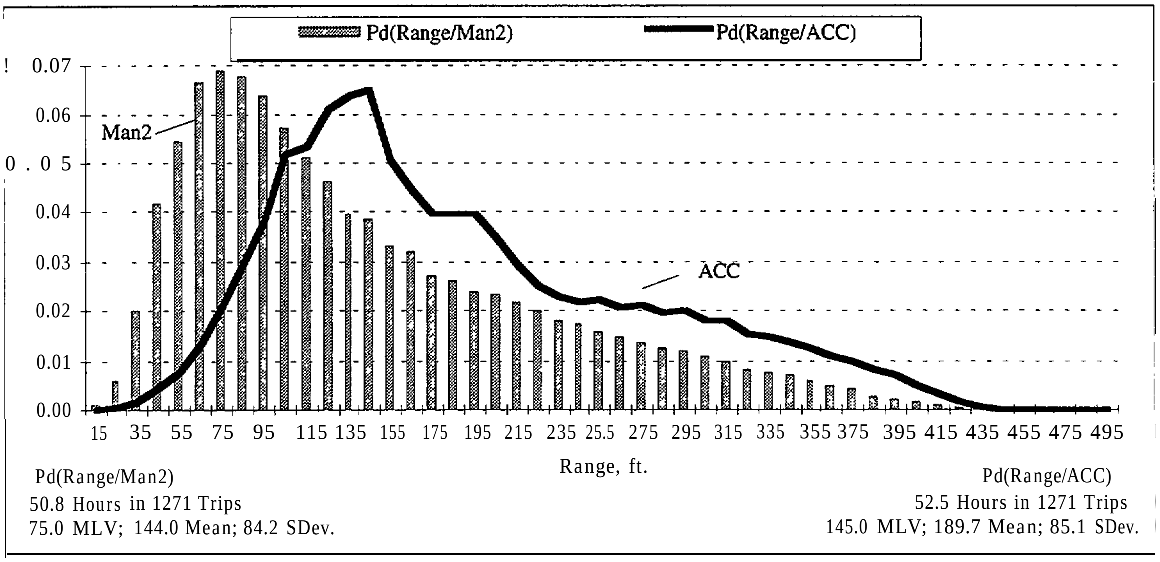
(MLV means Most Likely Value)

Figure 20. Probability density of velocity in ACC versus manual

Perhaps these results are what one might expect. They are interesting mainly because they prompt a following question that recognizes the contextual basis for driver choice in selecting the control mode to be used, namely: When do drivers choose to use ACC? It is quite apparent that any presentation of the fully-aggregated data will show that ACC driving differs from that of manual driving in a similar manner that manual freeway driving differs from manual driving on, say, an urban arterial network. To the extent that driving on limited access freeways is safer per mile of travel than is all driving, one would hypothesize that ACC operation will be safer than all manual driving, even if all the micro factors of longitudinal control with ACC versus manual systems were identical. Although these matters will be reexamined later, even the most casual look at the full data set makes it clear that drivers choose to use this ACC system predominantly in the higher-speed driving environments (which, in turn, tend to emphasize limited access highways in the data).

ACC versus Manual Results -Aggregated Data on Range & Time Gap

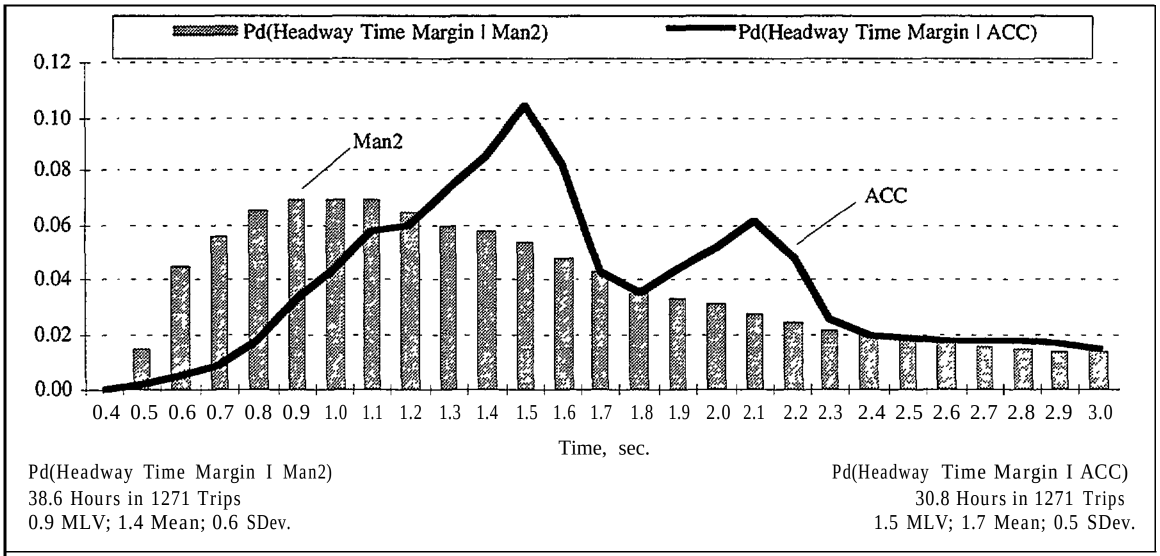
With regard to range, Figure 21 shows that ACC driving is characterized by longer ranges than those associated with manual driving. The figure is based on all drivers and all trips over 0.1 miles during the second week. Manual driving is characterized by fairly high likelihood of short headway range while ACC driving is characterized by little chance that headway range will be less than 65 ft. To the extent that short headway range represents a risky situation with respect to rear-end crashes, ACC driving could be said to pose lower levels of this particular form of risk than does manual driving.



MLV means Most Likely Value)

Figure 2 1. Probability density of range in ACC versus manual

A second look at the headway contrasts is provided in Figure 22. Here we see all of the ACC versus manual driving data presented in terms of the headway time gap, whereby the range, R, has been divided by host vehicle's velocity, V. While the ACC histogram now reveals predominant spikes near the time gap selections of 1.4 and 2.1 seconds, the overall appearance still shows that ACC operation involves longer headway clearances than does manual operation (above 35 mph).



Pd(Headway Time Margin I Man2)
38.6 Hours in 1271 Trips
0.9 MLV; 1.4 Mean; 0.6 SDev.

Pd(Headway Time Margin I ACC)
30.8 Hours in 1271 Trips
1.5 MLV; 1.7 Mean; 0.5 SDev.

(MLV means Most Likely Value)

Figure 22. Probability density of headway time margin in ACC versus manual

There appear to be two reasons why ACC driving has longer headways than manual driving, namely:

1) The ACC controller operates the vehicle at longer time gaps than drivers employ under manual control (even though the driver can choose from among ACC headway times of 1.0, 1.4 , or 2.0 seconds).
2) Drivers choose the manual mode of control under the conditions of road type and traffic density that more or less necessitate close-headway operations.

To support the first point, it is helpful to examine and compare the data shown in Figure 23 and Figure 24 that have been specially gathered and presented to make two-variable histograms involving range and range-rate values measured at the same time. The data used in these histograms are normalized (divided by) the velocity of the preceding vehicle, V,. The quantity R/V, has the units of time and represents the time gap between the ACC vehicle and the preceding vehicle when steady following prevails, with $V=V_p$. Figure 23 shows the results when ACC is in use. We see that the time gap is very well controlled, with peaks near the headway time settings of 1 .O, 1.4, and 2.0 seconds. In addition the likelihood of operation in the near comer of the diagram defined by short time gaps and large, negative, closing rates is very small. The profile of ACC driving is dominated by the highly likely narrowly distributed, peaks associated with the controller's objectives. In contrast, Figure 24 shows that manual driving is more broadly distributed across range values. Further, the likelihood of operating at short time gaps and substantial negative range rate is much larger than it is for ACC driving.

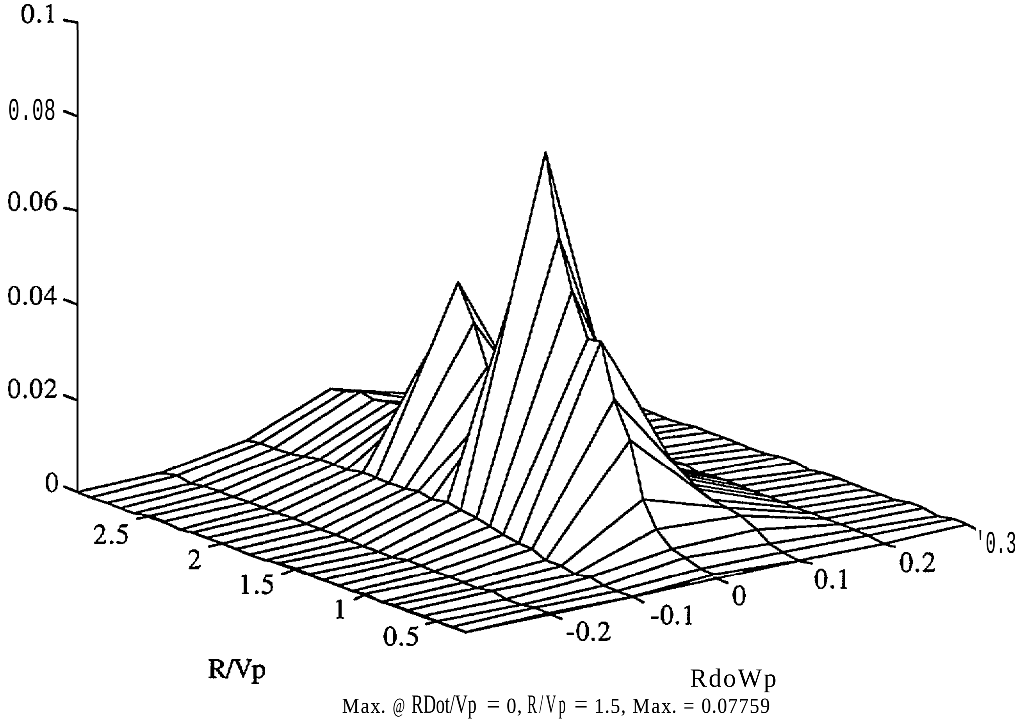


Figure 23. Probability density of normalized range and range rate in ACC driving

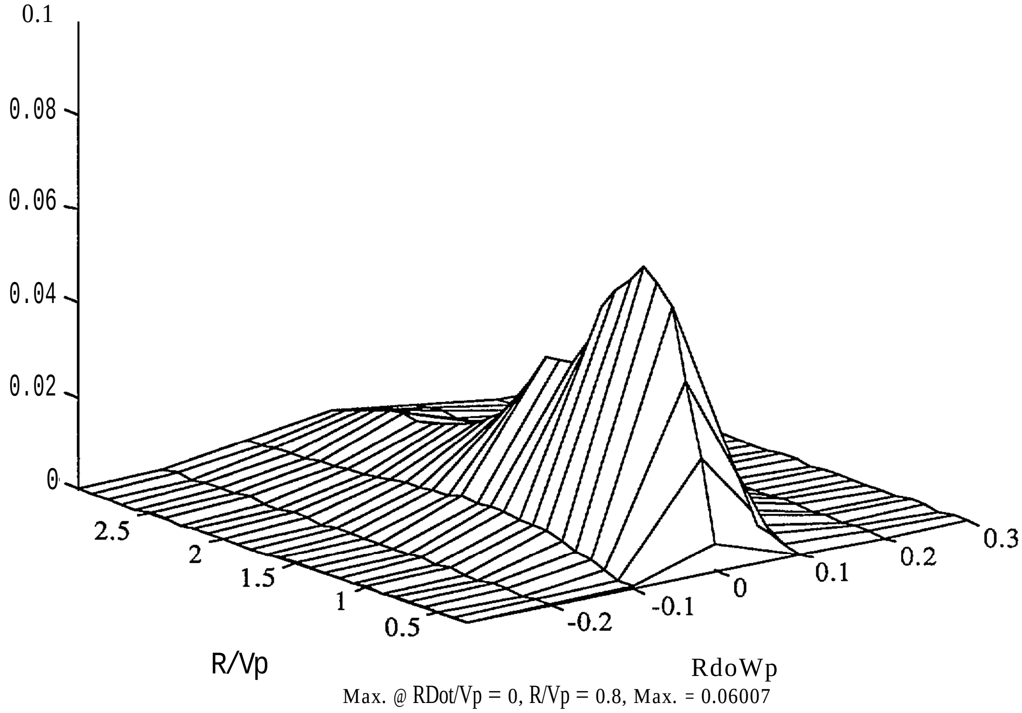


Figure 24. Probability density of normalized range and range rate in manual driving

Results similar to these have been obtained previously in the FOCAS project [5]. However, in that case, driving was restricted to quite uniform operating conditions with each driver operating both manually and with ACC over the same sections of freeway at approximately the same level of traffic. The data presented in Figure 23 and Figure 24, by contrast, were obtained in the wide open, naturalistic driving context by which each driver/participant went wherever they wanted, by whatever route, in whatever traffic as prevailed during the trips they chose to take. Notwithstanding these uncontrolled conditions, however, the FOT data are strikingly similar to those obtained when the driving environment was confined to the specific freeway test loop employed in the FOCAS study.

The second point concerning drivers choice of control mode will be addressed in more detail in the next section, but it is not surprising to find that people prefer to drive manually rather than trust a controller when it appears that braking may be needed. In addition, the FOT drivers have been carefully instructed to perform as the supervisor of ACC driving, being always prepared to brake when braking is needed. Accordingly, the system transitions to the manual control state whenever a headway-compromising conflict emerges. This in turn causes any short headway experience immediately following an ACC disengagement event to be registered as MAN data, as soon as brake pedal movement, for example, causes the brake switch to make. This means that data are recorded as manual driving whenever the driver has become uncomfortable with, and taken supervisory action in response to, an emerging headway conflict using the ACC system.

ACC versus Manual Results -Aggregated Data on Regions of Proximity

For purposes of examining different types of driving situations (regimes), the range-versus range rate space has been divided into the five regions shown labeled in Figure 25 as “closing”, “following”, “separating”, “near”, and “cut-in”. Definitions of these regions are presented in mathematical terms in Table 15. From a pragmatic point of view the boundaries between these regions have been chosen to separate different types of driving regimes. A prominent feature on Figure 25 is the parabola that has been chosen to separate short range conflict situations from the operations appearing at longer range. This parabola intercepts the range axis at a point that corresponds to a time gap of 0.5 seconds. The shape of the parabola corresponds to a deceleration of 0.1 g. The region below this boundary is divided into “near” and “cut-in” regions depending upon whether range rate (RDot) is negative (R is decreasing) or positive (R is increasing). Above the parabola the space is divided into three regions that also depend upon range rate. If range rate is between -5 ft/sec and +5 ft/sec, the subject vehicle is deemed to be following the preceding vehicle with little difference in relative velocity (range rate). The region to the left of following is called closing because in this region the subject vehicle is overtaking the preceding vehicle. The upper right region is called separating because the preceding vehicle is going faster than the subject vehicle thereby causing the vehicles to separate. Clearly, since measures of R and RDot are collected only when the sensor sees a valid target ahead, none of the five regions is satisfied when no valid target exists. The aggregated data taken from manual and ACC driving show that valid targets are detected (and thus tallied as occupying one of the five regions) approximately 52% of the time, regardless of the type of driving.

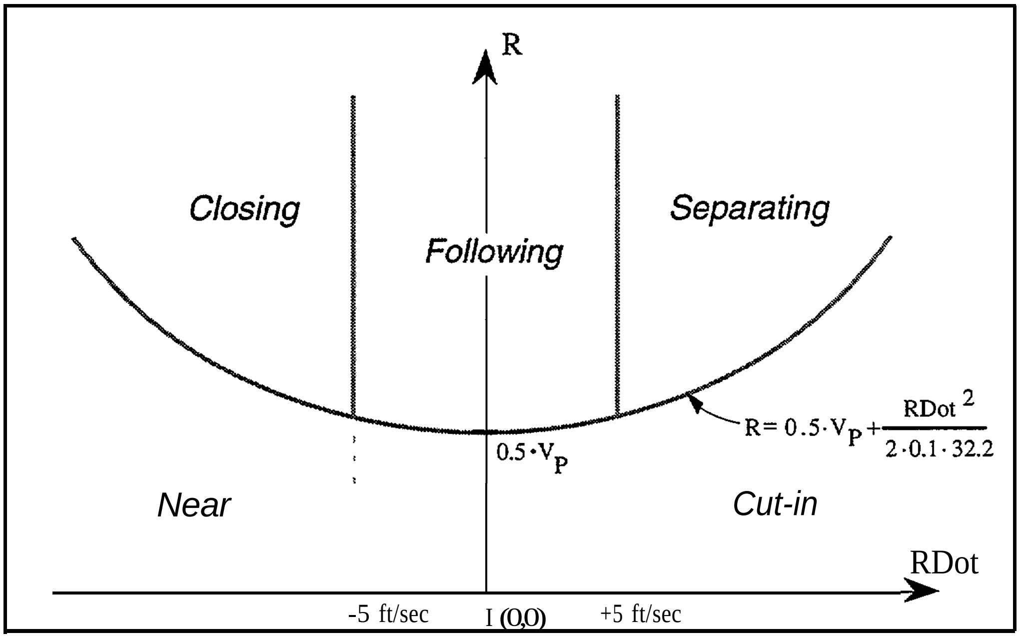


Figure 25. Driving situation (regimes) in the range-range rate space

Table 15. Definitions of driving regimes

$$R_b = 0.5 \cdot V_p + \frac{\mathrm{RDot}^2}{2 \cdot 0.1 \cdot 32.2} \ \mathrm{ft}$$

$$\mathrm{RDot} - b = -5 \ \mathrm{ft}/\mathrm{sec}$$

$$\mathrm{RDot} + b = +5 \ \mathrm{ft}/\mathrm{sec}$$

$$\mathrm{Near} \equiv [R \le R_b \ \text{ AND } \ \mathrm{RDot} \le 0]$$

$$\mathrm{Cutin} \equiv [R \le R_b \ \text{ AND } \ \mathrm{RDot} > 0]$$

$$\mathrm{Closing} \equiv [R > R_b \ \text{ AND } \ \mathrm{RDot} \le \mathrm{RDot} - b]$$

$$\mathrm{Following} \equiv [R > R_b \ \text{ AND } \ \mathrm{RDot} - b < \mathrm{RDot} < \mathrm{RDot} + b]$$

$$\mathrm{Separating} \equiv [R > R_b \ \text{ AND } \ \mathrm{RDot} \ge \mathrm{RDot} + b]$$

The logical histogram of these tallies in Figure 26 express the probability of vehicle operation in each of the five regions discussed above, for manual and ACC modes of driving. Examination of the figure indicates that the great bulk of the time (with a valid target ahead) is spent at relatively long range, in either the closing, following, or separating regions of operation. The probability of operating in the near or cut-in regions is of the order of a few percent.

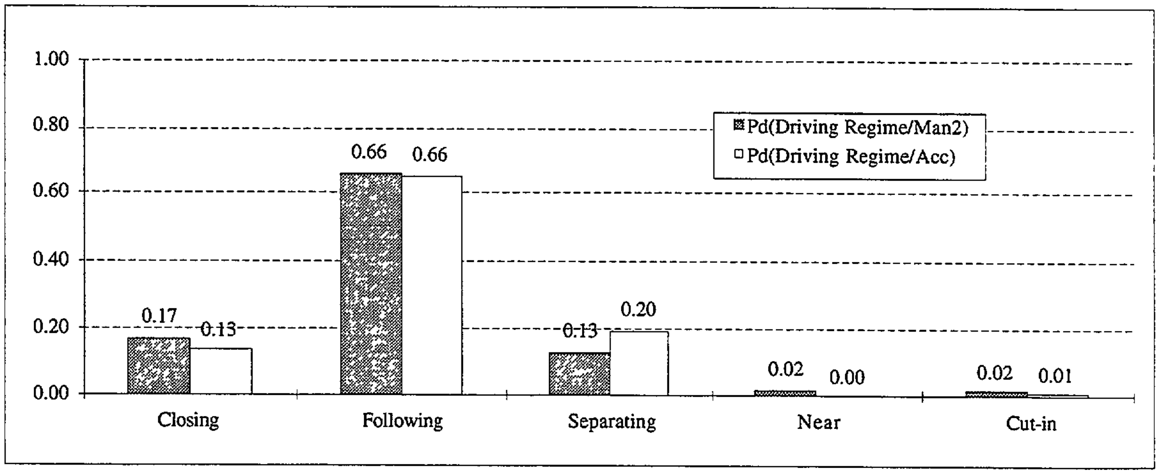


Figure 26. Probability density of operating within various driving regimes (2nd week)

Substantial differences between ACC and manual driving are noted in the near and the separating regions. Clearly, Figure 26 shows that the near region is generally avoided in either the manual or ACC control modes, but even more so with ACC since the system, by design, seeks time gaps that are substantially larger than the 0.5 second value at which the near-region's parabola reaches its minimum. A detailed look at these contrasting data indicates that of the total time spent in the near region during the second week of each subject's use of the vehicle, the ACC controller was engaged 1/8th of the time and the manual mode was in operation 7/8ths of the time.

Regarding the separating region, we note that since the ACC system does not aggressively chase vehicles that are going faster than itself, there is a relatively high probability of sustaining a positive RDot and dwelling in the separating region for substantial periods of time as a faster vehicle gradually recedes at long range. If we compute the conditional probabilities of ACC and manual control, given the separating region of operation, we find that the manual mode prevailed with a 0.38 probability and the ACC mode prevailed with a 0.62 probability.

The characteristics of the controller also explain why the likelihood of operating in the cut-in region is similar for both modes of control since vehicles that cut-in after a pass (by far the most common type of cut-in scenario) are going faster than either the ACC or the manually-controlled vehicle. Apparently, cut-in activity, overall, occurs with approximately the same frequency in either mode of control. More study of this issue is needed, however, with the aid of detailed examination of the transitions from one region to the next. Although it is recognized that merge or cut-in activity at entrance and exit ramps can influence the occurrence of either the near or the cut-in region operations, the overall frequency of such transients is thought to be so low as not to have significantly registered in the breakdown of data in Figure 26.

CCC versus Manual Results -Aggregated Data on Regions of Proximity

Shown in Figure 27, conventional cruise control (CCC) is compared with manual operation (during the first week of driving) in terms of the distribution among the five R versus RDot regions. The results show, again, that near and cut-in regions are only infrequently entered and that the majority of the operational time is spent at longer range in the closing, following, and separating regions. Interestingly, when compared with the ACC results shown earlier, the CCC mode of operation has a much higher occurrence in the separating region and substantially less time spent following (within the +/- 5 ft/sec window about zero RDot.) One would hypothesize on this result that drivers choose a higher value of set speed, given the traffic, when operating ACC than when operating in the CCC mode.

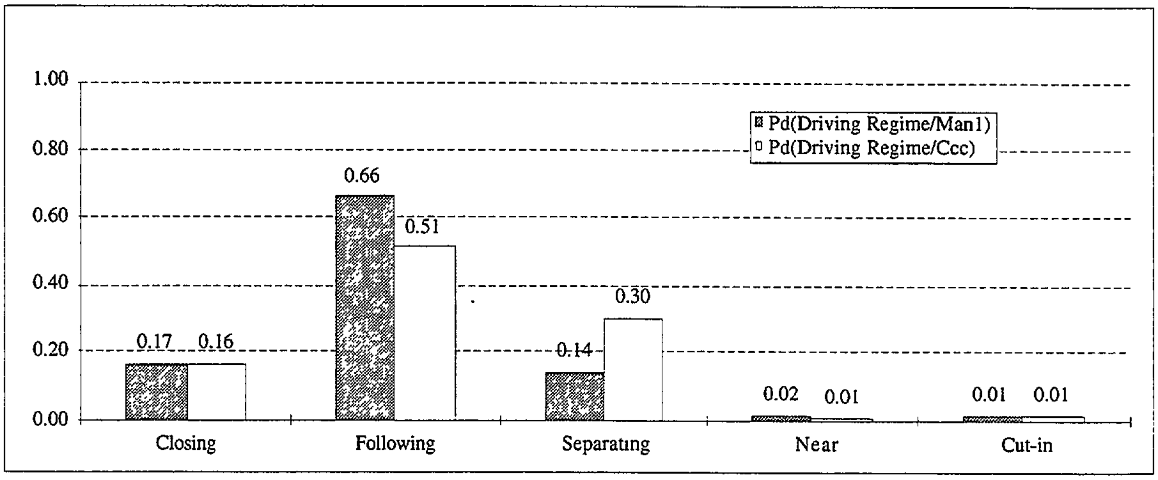
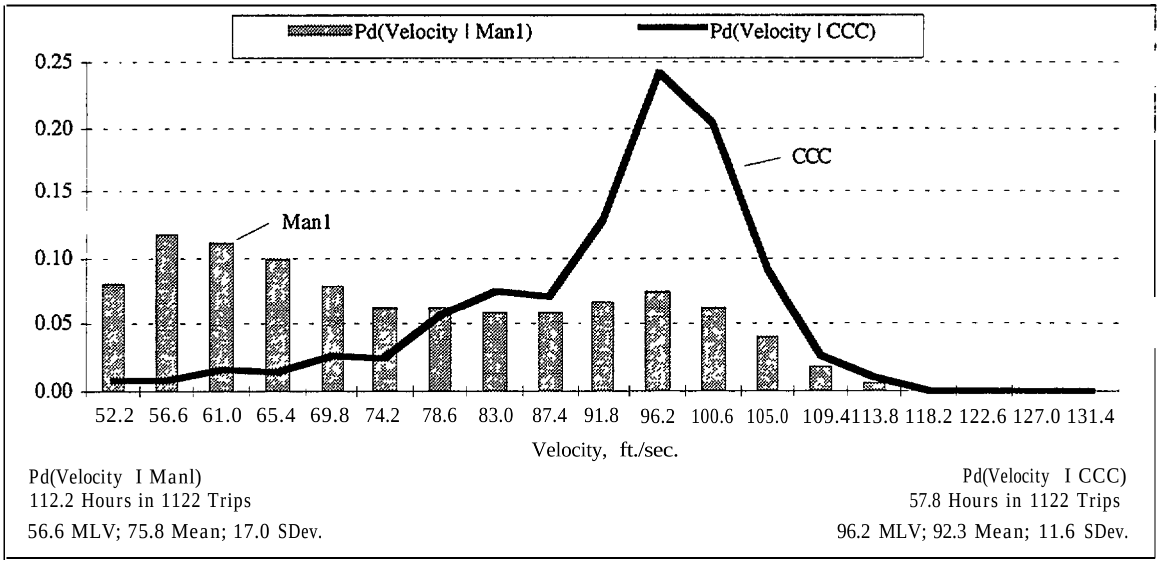


Figure 27. Probability density of operating within various driving regimes (1st week)

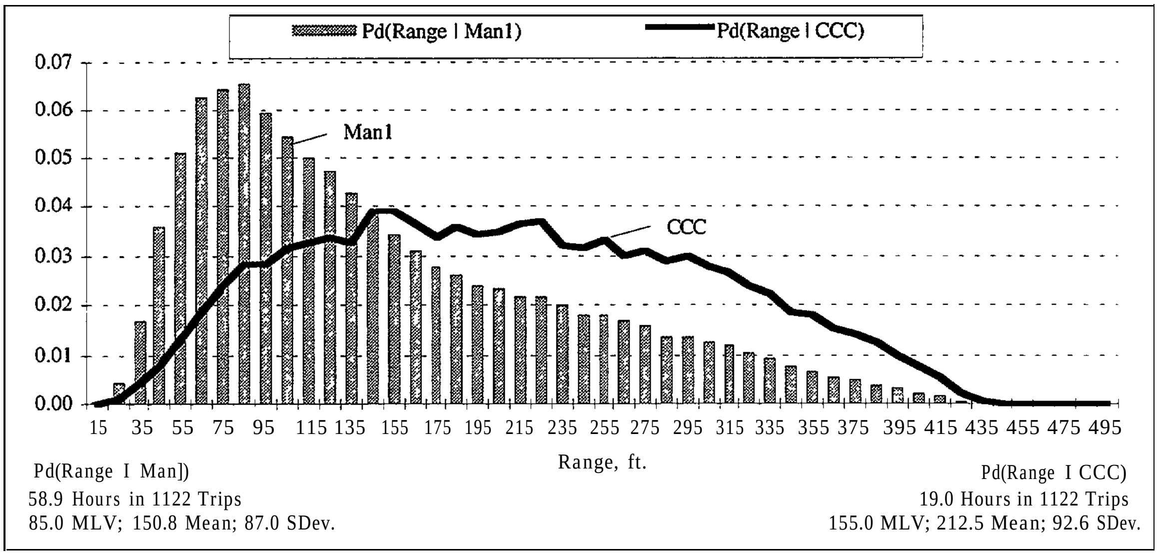
CCC versus Manual Results — Aggregated Data on Speed and Headway

Shown in Figure 28, Figure 29, and Figure 30 are corresponding comparisons between CCC and manual operations, as gathered from first-week data in terms of the velocity, range, and time-gap histograms. The velocity data in Figure 28 show that manual operation spreads down into the lower-speed regime while CCC is clearly used in high-speed environments. The range data in Figure 29 show that while the CCC operation does extend down into very short headway values, it does not compete with the downward bias in headway distributions that characterize manual driving. Indeed, CCC range values are rather flatly distributed, while manual values are sharply concentrated toward the left. Figure 30 shows that when range is normalized with the host vehicle velocity, V, the contrast between manual and CCC headways, expressed at time gaps, is less pronounced. This result further confirms that drivers are more attentive to time gaps than to distance, per se, and that the large skew toward short headway range values seen in the MAN1 data in Figure 29 is explained largely by the low speeds prevalent in much of the manual driving.



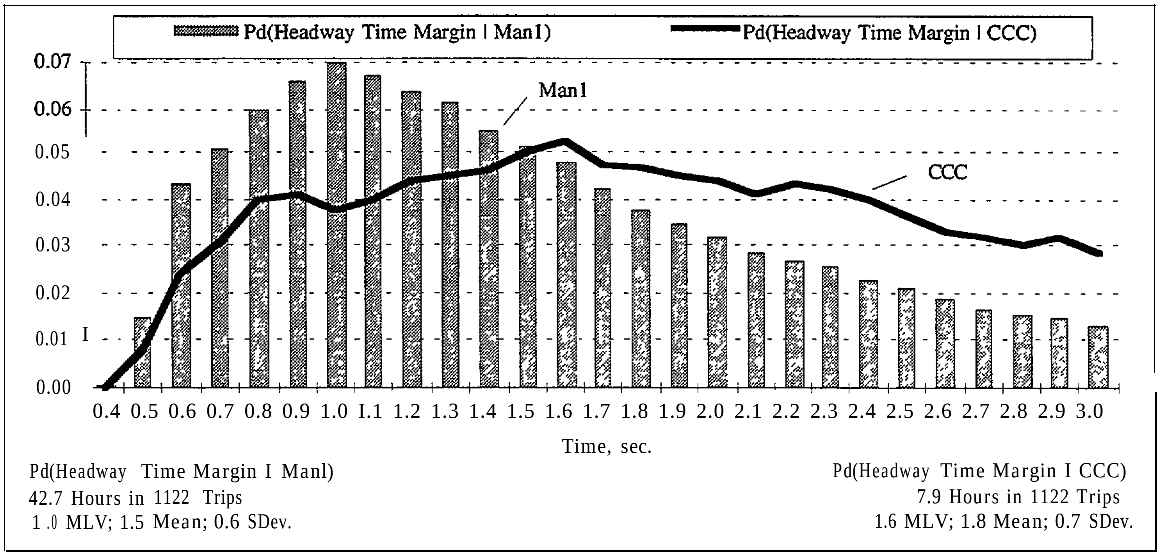
(MLV means Most Likely Value)

Figure 28. Probability density of velocity in manual versus CCC



(MLV means Most Likely Value)

Figure 29. Probability density of range in manual versus CCC



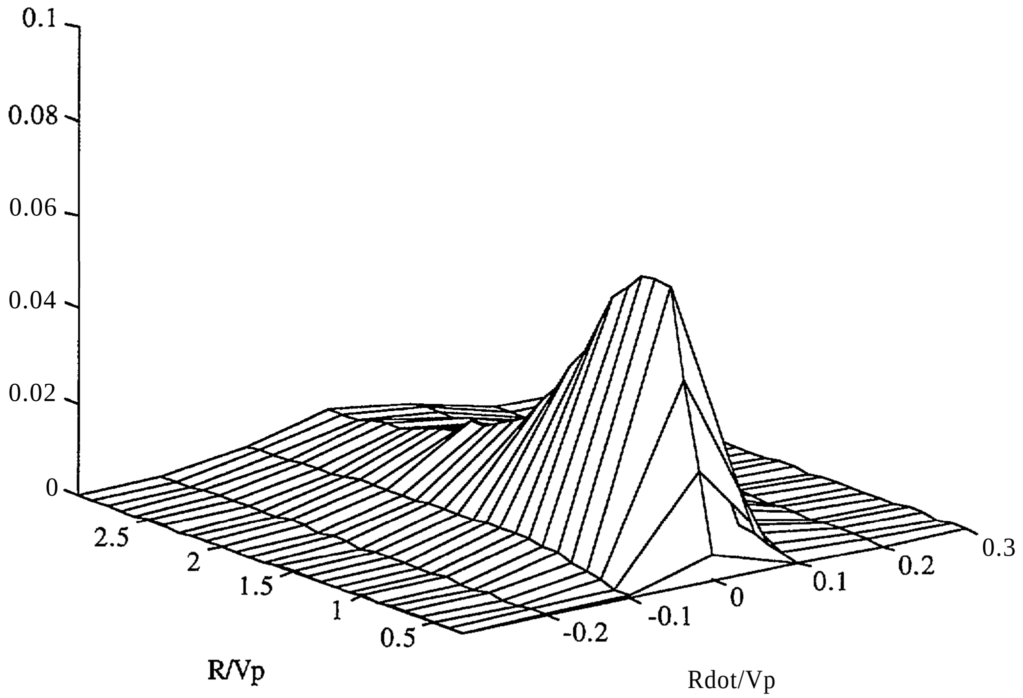
Pd(Headway Time Margin I Manl)
42.7 Hours in 1122 Trips
1 .0 MLV; 1.5 Mean; 0.6 SDev.

Pd(Headway Time Margin I CCC)
7.9 Hours in 1122 Trips
1.6 MLV; 1.8 Mean; 0.7 SDev.

(MLV means Most Likely Value)

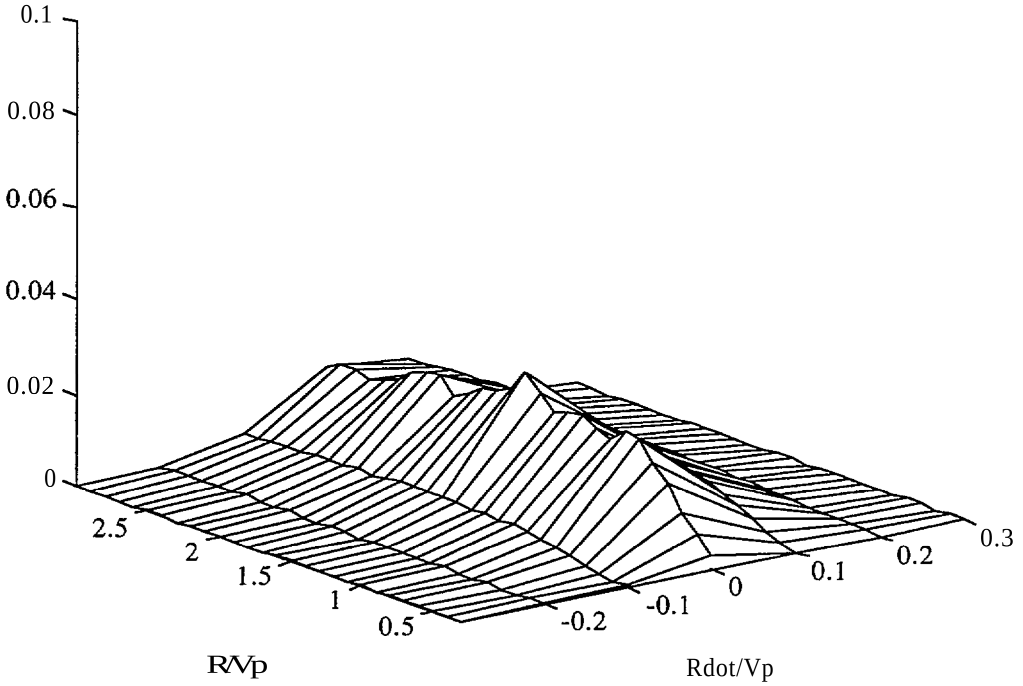
Figure 30. Probability density of headway time margin in manual versus CCC

Figure 3 1 and Figure 32 present two-dimensional, normalized, histograms of range and range-rate contrasting the manual and CCC results aggregated across all first-week driving. The CCC histogram spreads out over a very wide span of range values, but otherwise exhibits very nearly the same content in the critical-near corner (i.e., the negative RDot/V_p regime, with short values of R/V_p) of the diagram as does the manual result. Clearly, CCC operations are as “headway-blind” a means of longitudinal control as one could envision.



Max. @ RDot/Vp = 0, R/Vp = 0.7, Max. = 0.05993

Figure 3 1. Probability density of normalized range and range rate in manual driving



Max. @ RDot/Vp = 0, R/Vp = 1.6, Max. = 0.02847

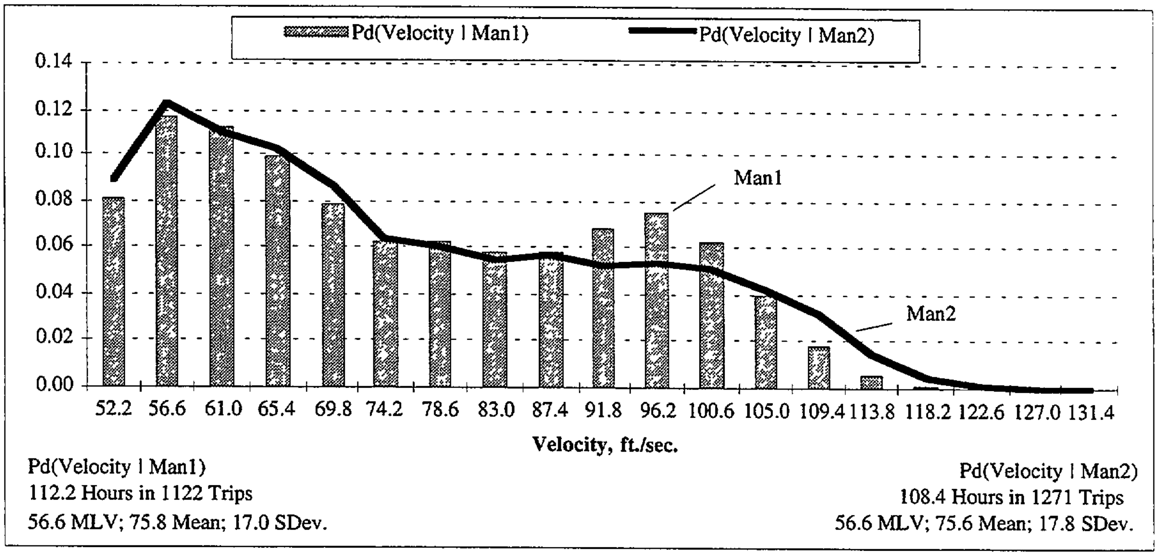
Figure 32. Probability density of normalized range and range rate in CCC driving

Manual Driving Only, Comparing Velocity and Headway Results From Week One versus Week Two

Because it is useful to compare ACC operations (which occurred only in the second week) with CCC operations (which occurred only in the first week), it was deemed valuable to compare the manual data gathered during each of the two respective weeks as a cross-check for nominal similarity of driving conditions. Thus, aggregated (that is, essentially all) MAN1 and aggregated MAN2 data are considered here as one (albeit not fully conclusive) illustration of the similarity. The comparison also supports later a combination of both weeks of manual data into one set, simply to improve its statistical power.

Shown in Figure 33 is a histogram of velocity covered under MAN1 and MAN2 episodes of driving. The figure shows very great similarity in the speed distributions (above 35 mph) covered driving manually during the two weeks, although the second week did appear to involve a modestly higher incidence of second-week operation at the high end of the velocity spectrum.

Shown in Figure 34 is a histogram of the time gap, again showing a high degree of similarity in the headway distributions between the two weeks. We conclude on a preliminary basis, at least, that manual operation during both weeks was quite the same and thus there is some degree of encouragement that comparison of the first- and second-week experiences with control in either the CCC or ACC modes will pertain to more or less comparable types of driving.

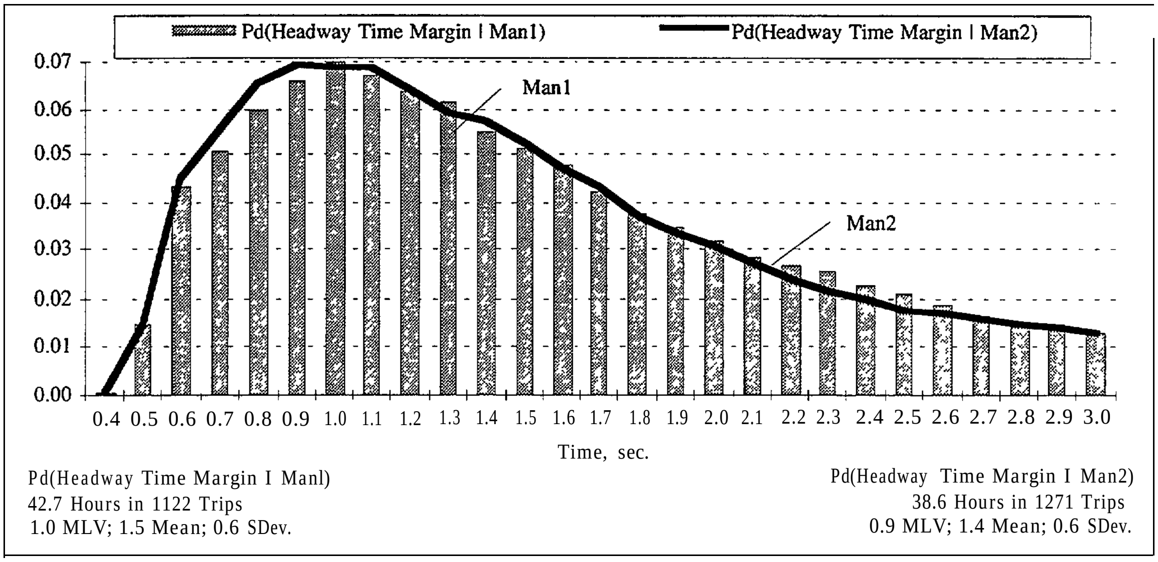


Pd(Velocity | Man1)
112.2 Hours in 1122 Trips
56.6 MLV; 75.8 Mean; 17.0 SDev.

Pd(Velocity | Man2)
108.4 Hours in 1271 Trips
56.6 MLV; 75.6 Mean; 17.8 SDev.

(MLV means Most Likely Value)

Figure 33. Probability density of velocity in manual: 1st week versus 2nd week

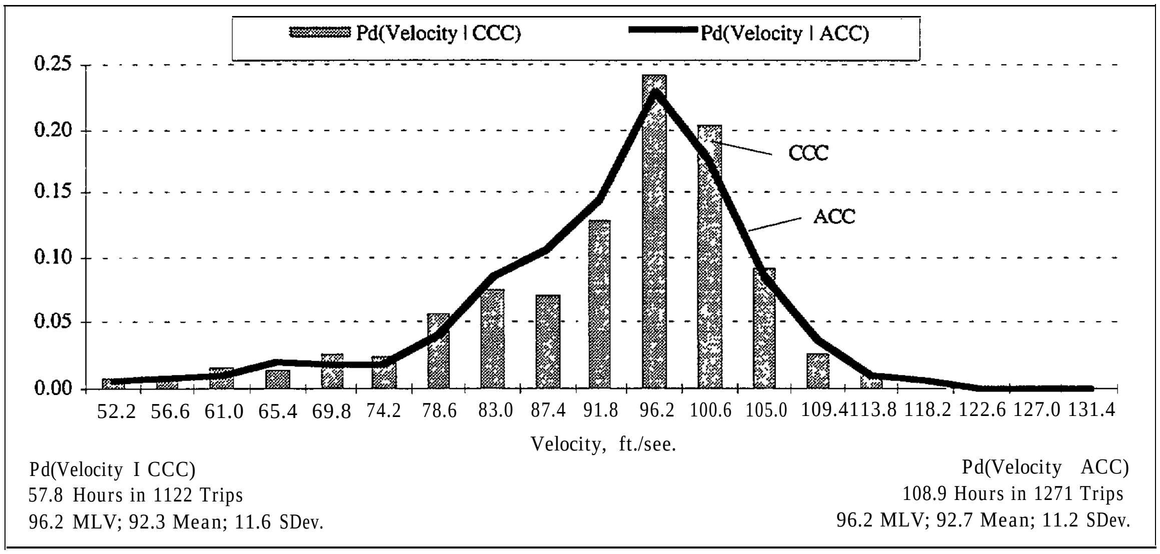


(MLV means Most Likely Value)

Figure 34. Probability density of headway time margin in manual: 1st week versus 2nd week

ACC versus CCC -Aggregated Data on Speed and Headway

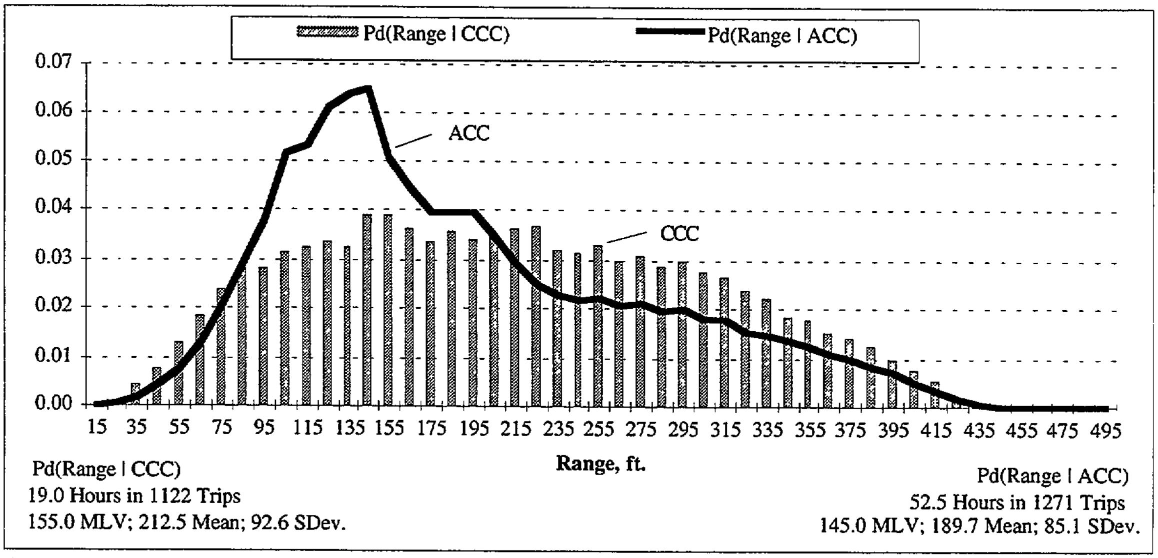
Shown in Figure 35 is a comparison of velocity histograms characterizing ACC and CCC operations. The data suggest that both forms of cruise control were utilized in comparable speed environments, with means being almost identical at 63 mph (92.4 ft./sec.) and with virtually identical distributions.



(MLV means Most Likely Value)

Figure 35. Probability density of velocity in ACC versus CCC

By way of contrast, the range (distance) and headway (time) histograms in Figure 36 and Figure 37 show that the patterns of headway keeping under CCC and ACC modalities differ markedly, as expected. Namely, the ACC controller seeks to modulate headway in the following mode of operation around the driver-selected times of 1.0, 1.4, and 2.0 seconds while the CCC controller is oblivious of headway and simply slews through the range spectrum while either overtaking and separating from vehicles ahead. On the very short end of the headway scale, CCC operations show a substantially higher incidence of time gaps below 0.9 seconds or so. Even though the ACC controller does indeed overshoot its minimum time gap settings depending upon the closure conditions, or braking ahead, the driver does seem to permit CCC to close into substantially shorter distances than are encountered with ACC.

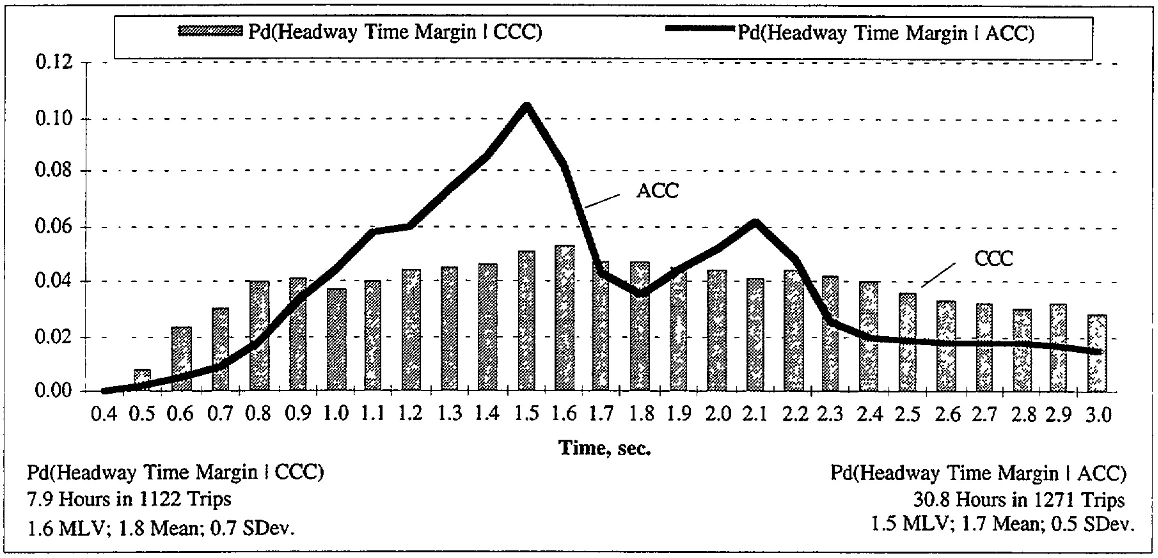


Pd(Range | CCC)
19.0 Hours in 1122 Trips
155.0 MLV; 212.5 Mean; 92.6 SDev.

Pd(Range | ACC)
52.5 Hours in 1271 Trips
145.0 MLV; 189.7 Mean; 85.1 SDev.

(MLV means Most Likely Value)

Figure 36. Probability density of range in ACC versus CCC



(MLV means Most Likely Value)

Figure 37. Probability density of headway time margin in ACC versus CCC

4.1.2 How do driving conditions influence driver choice among manual, CCC, and ACC modes of control?

In this section we address the evidence in the data that driver choice between manual and the available cruise-control mode (CCC in first week, ACC in second week) is determined by the prevailing conditions of the trip. In this sense, the conditions that are candidates for investigation are limited to characteristics that were measured during the field test. And at this particular stage of the project, data describing the roadway itself (surface street, freeway, etc.) or the traffic (density, flow, erratic congestion, etc.) or the ambient weather (rain, snow, etc.) are unavailable, or yet to be analyzed. Later processing of GPS data or manual identification of conditions from video exposure data may serve to enhance the list of available conditions that could be examined.

Nevertheless, it is very clear that drivers are making a conscious choice of control mode, based apparently upon their perceptions of the suitability of the driving environment for each mode and perhaps the value to be derived from operating a selected mode in the prevailing environment. In this section we will present the relationship between certain variables and the choice of control mode for the sake of both a) presenting results that reveal the mode choice as a function of condition variables and b) deducing a means of filtering the full set of data to select just those trips which offer reasonably uniform conditions under which to compare driving under ACC, CCC and manual modes of operation. Put simply, we wish to filter the trip selections so as to avoid comparing, for example, ACC driving at 60 mph on a busy freeway with manual driving at 30 mph on a residential street.

ACC and CCC Mode Choice as a Function of Average Trip Velocity

Shown in Figure 38 is a presentation of the fraction of all first week and second week trips that included the engagement of CCC and ACC modes of control, respectively, as a function of the average trip velocity. For example, at a trip average velocity of 40 mph in the first week, CCC was engaged (at least temporarily) in 60% of the trips. We see in a general sense that the probability of choosing the available cruise-control mode (CCC or ACC) rises more or less steadily with average trip speed and reaches approximately a 90% level of probability when average speed exceeds approximately 55 mph. Of course, this observation seems reasonable since the only trips whose average speed can attain a 55 mph value (from ignition on to ignition off) are those in which the driver operates predominantly on a freeway or another high-speed roadway upon which the CCC or ACC functions offer their premium utility. Later in this section we indicate a selection of 30 mph as the minimum average speed to be used in filtering for trips in which ACC can be compared with the other modes of control.

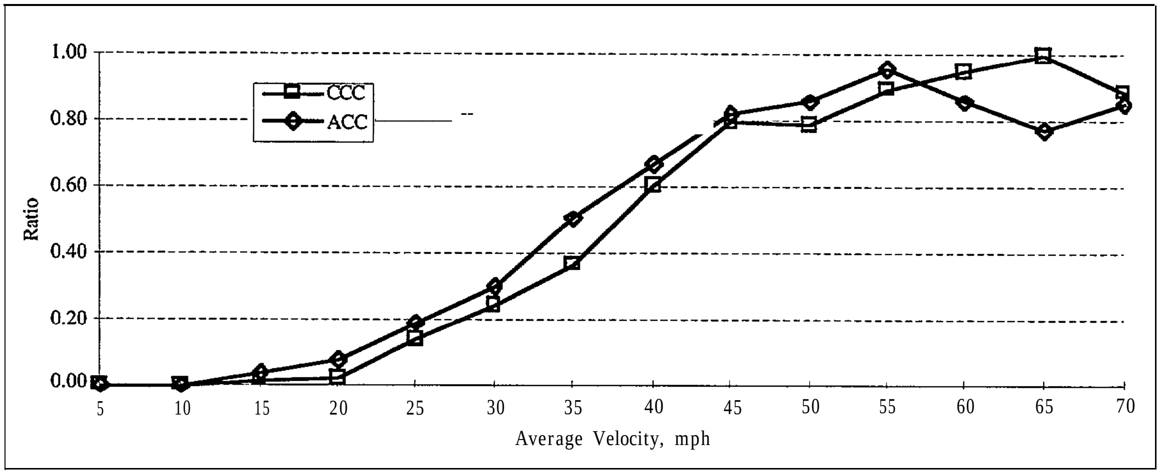


Figure 38. Utility of CCC and ACC as a function of velocity

ACC and CCC Mode Choice as a Function of Trip Length

Shown in Figure 39 is a presentation of the fraction of all first week and second week trips that included the engagement of CCC and ACC modes of control, respectively, as a function of the trip length. For example, at a trip length of 25 miles in the first week, CCC was engaged (at least temporarily) in 62% of the trips. We see in a general sense that the probability of choosing the available cruise-control mode (CCC or ACC) rises strongly up to trip lengths of 15 miles or more and then sustains an elevated probability in the 60 to 100% range. The relative scarcity of trips falling into bins at 50, 55, and 60 mile lengths seems to account for the erratic nature of the data in that zone. The probabilities of CCC selection at 70% and ACC selection at 87% that show up in the "end bins", at 65+ miles, appear to provide a more reliable indicator of the mode choices that were made, asymptotically, on longer trips.

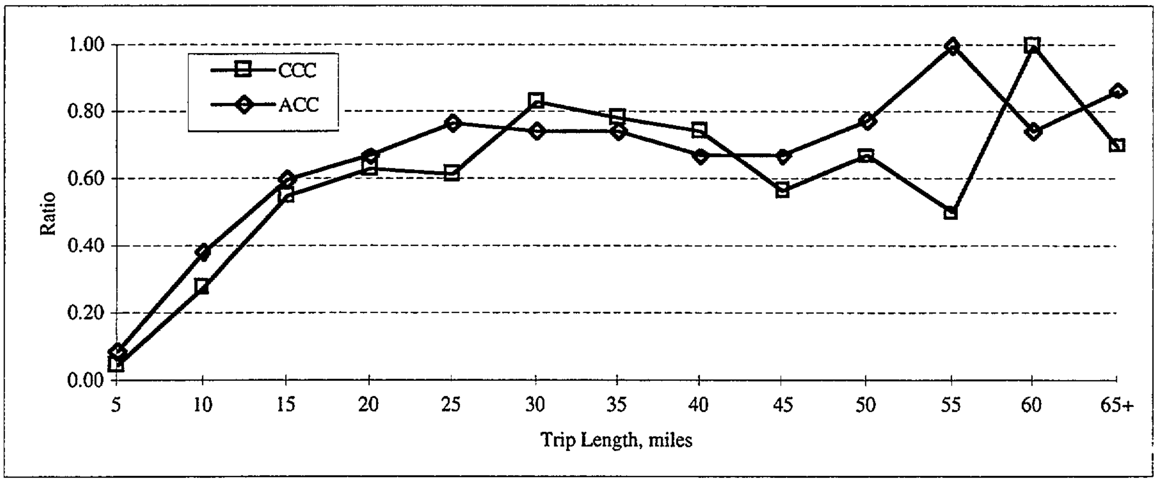


Figure 39. Utility of CCC and ACC as a function of trip length

Another look at the trip length data is shown in Figure 40. This figure presents the average distance actually engaged in the CCC or ACC control modes, respectively, as a function of trip length. This presentation addresses the lurking question, "How valuable is the indication that was shown earlier (for example, in Figure 39) of percent of trips in which the cruise mode was selected at least momentarily during the trip?" The data in Figure 40 show that once a cruise mode has been selected, it typically prevails for half or more of the trip. Thus, incidences of ACC and CCC engagement do not typically occur on a sporadic basis without being retained for a substantial episode of usage. Further, the extent of retained engagement of ACC is generally greater than that of CCC for a given length of trip. This latter observation would seem to be in line with the claim of ACC that, once engaged, it largely frees the driver of the need to intervene, thus yielding more sustained periods of engagement. On the basis of the presented data showing the relationship between trip length and control-mode choice, we have identified 10 miles as the minimum trip length for selecting trips in which ACC can be compared with the other modes of control.

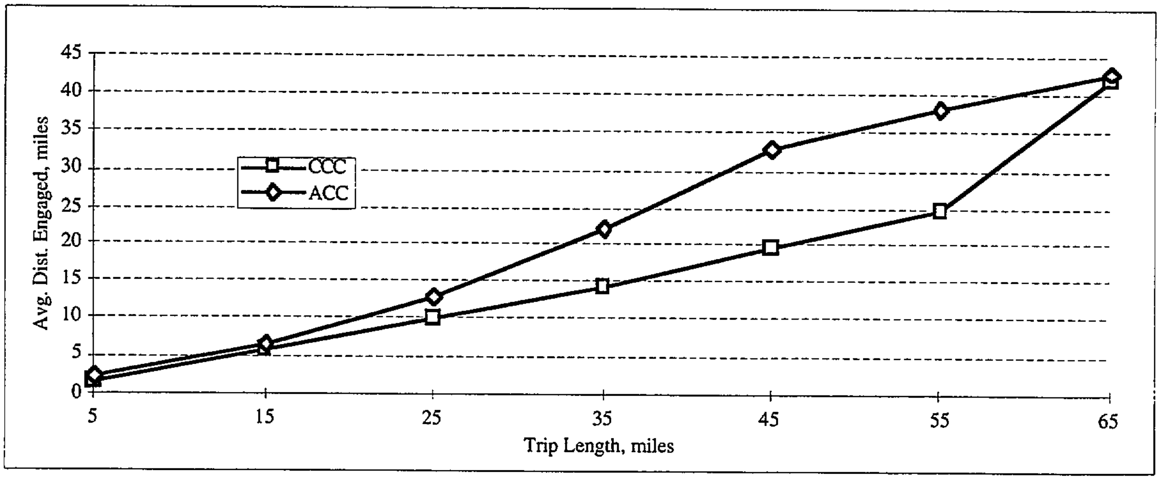


Figure 40. Distance CCC and ACC were engaged as a function of trip length

ACC and CCC Mode Choice as a Function of Time of Day

Figure 41 shows the probability of the driver choosing the CCC(first week) or ACC (second week) mode of control over the manual option at some point during the trip, as a function of time of day. The data show that the most probable times of cruise selection, with either CCC or ACC, are in the early morning and late evening or night. Apparently the daytime travel is so saturated with relatively short manually-driven trips that the incidence of cruise selection is lower in probability overall. Because a rather little amount of data were gathered during the early morning and night hours of the day, it is not currently attractive to filter trip selections on the basis of the time of day.

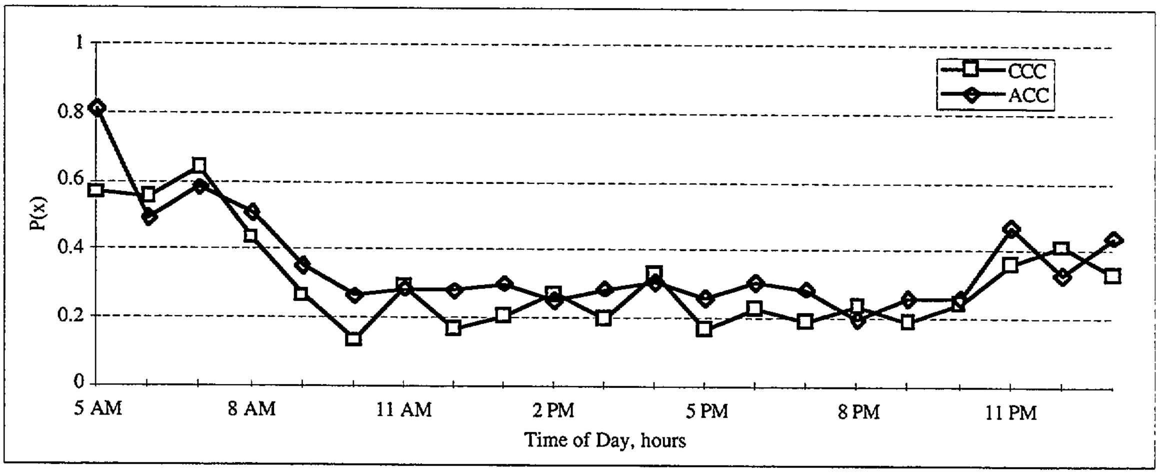


Figure 41. Utility of CCC and ACC as a function of time of day

ACC and CCC Mode Choice as a Function of Day of Week

Figure 42 presents the probability of the driver choice of the CCC or ACC mode over that of manual driving as a function of the day of the week. While, in general, the data all lie in the 20 to 40% band of probability throughout the week, we do note that a greater probability of ACC choice on Wednesdays may have resulted from this novel function first becoming enabled on each vehicle around the middle of the second of week of each person's usage. Thus, Wednesday may only appear as the typical day on which most subjects first had a chance to drive on their own in the ACC mode. The data suggest that it is not currently attractive to filter trip selections for evaluating ACC on the basis of the day of the week.

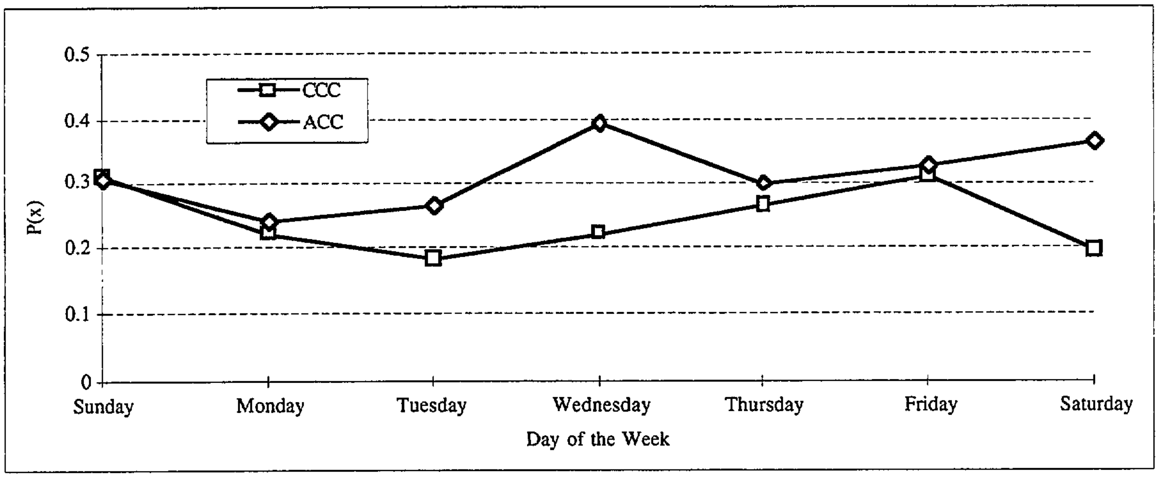
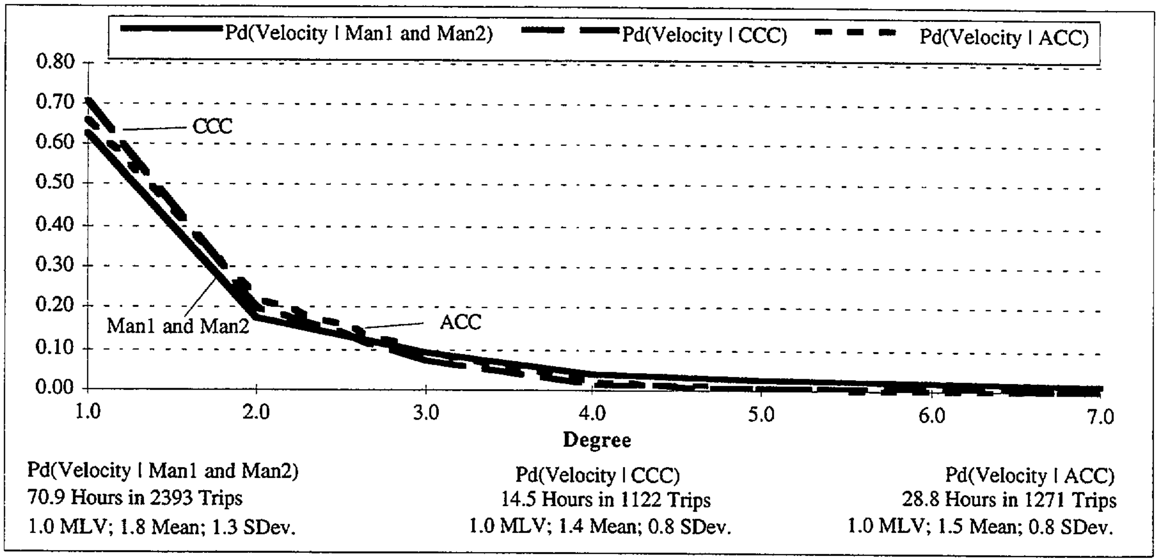


Figure 42. Utility of CCC and ACC as a function of day of the week

ACC and CCC Mode Choice as a Function of Roadway Curvature

One surrogate for identifying the type of road lies in the quantitative data on instantaneous curvature of the roadway (expressed in U.S. highway engineering format as the number of degrees of arc per 100 feet of circumferential distance). These data are obtained on board the test vehicle by a computed scaling of the ratio of yaw rate to velocity. Shown in Figure 43 is the probability density diagram for the "degree of curvature" encountered while operating in each of the three control modes. Assuming that only the manual mode of operation is chosen when driving on city streets and around the tightly curved (higher degree) road segments characteristic of local roads, the data showing a considerably greater extent of manual driving in the 4 and 5 degree curvature regimes seems reasonable. Conversely, the CCC and ACC modes of control are distributed overwhelmingly onto roads of 3 degree curvature (approximately 2,000 ft radius) and less, which characterize limited access highways and other high-speed facilities. Since tighter curvature tends to constrain speed rather naturally, however, a further filtering of trips according to the curvature data is seen as more or less redundant with the choice of average trip speed as a filter variable, as mentioned above.



(MLV means Most Likely Value)

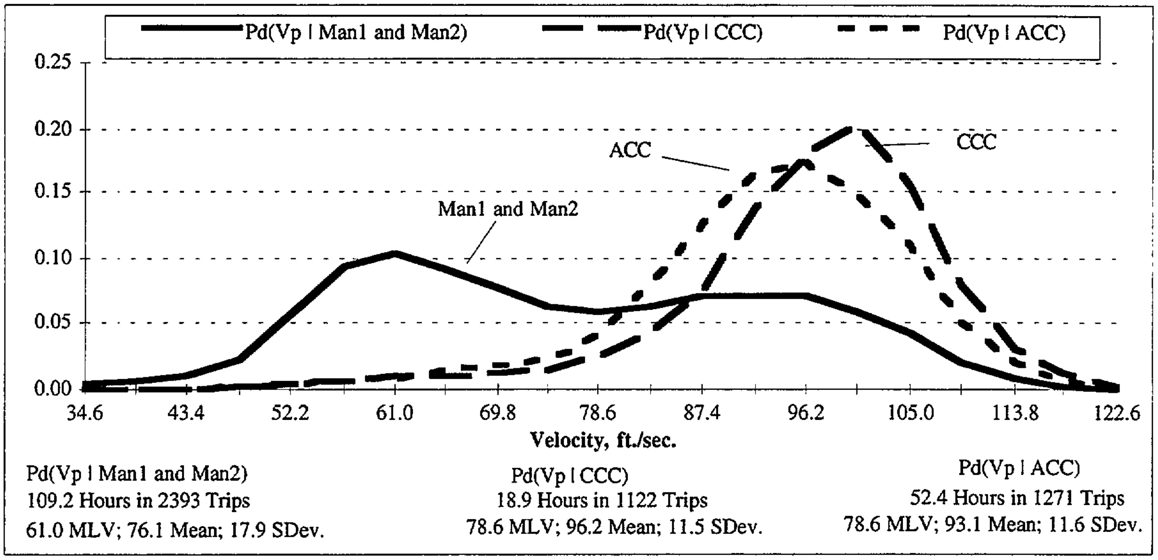
Figure 43. Utility of CCC and ACC as a function of roadway curvature

ACC and CCC Mode Choice as a Function of Preceding Vehicle's Speed and Acceleration

Another interesting exposure variable that is directly or indirectly associated with the choice of control mode is the speed, V_p, of the preceding vehicle. This variable and its derivative were examined as constituting an important aspect of the driving condition, but were not considered as a means of screening trips for the evaluation of ACC.

Although there is a very close connection between the host vehicle speed and the speed of any target vehicle detected ahead, the V_p value and its derivative are considered to be virtually independent of the host speed. Thus the preceding vehicle serves to characterize traffic in the sense of a probe device that, on the average, should approximate the speed selections, and longitudinal accelerations, of others in the traffic stream.

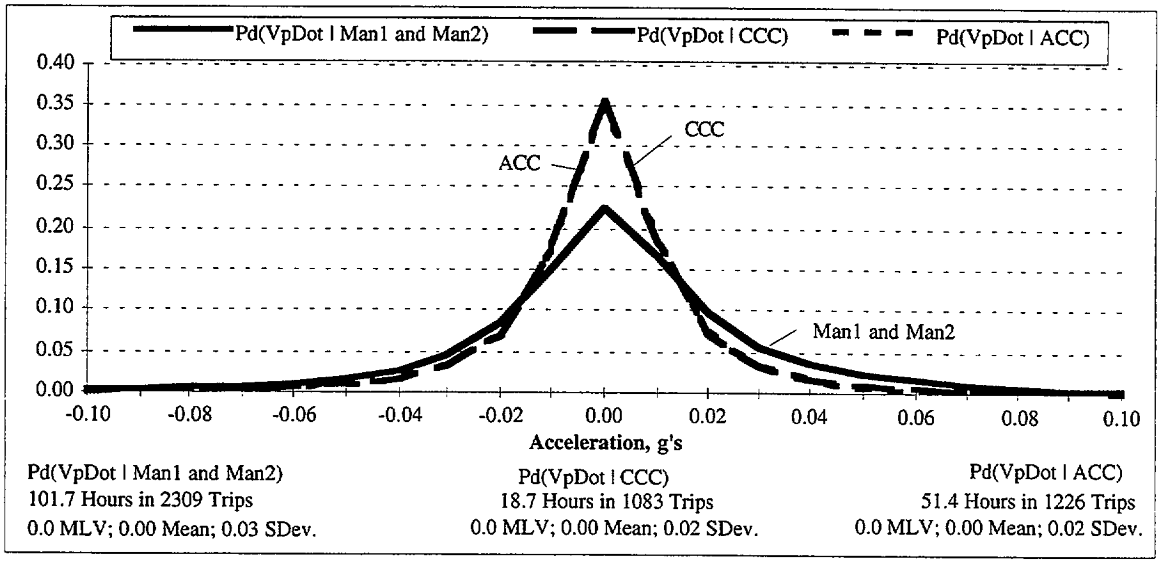
Shown in Figure 44 is the histogram of V_p as seen while the host vehicle was in each of the respective modes of control. We find these speed data to be comparable to those based upon the speed, V, of the host vehicle itself, shown earlier in section 4.1.1.



(MLV means Most Likely Value)

Figure 44. Histogram of preceding vehicle's velocity in various control modes

Of more interest, however, is the corresponding histogram, in Figure 45, showing the acceleration behavior, VpDot, for the preceding vehicle. This variable is of special pertinence to the task of headway keeping since it reveals the nature of disturbances that act to either shorten the headway gap or open it up. We see, for example, that preceding vehicles encountered during manual driving exceed a deceleration level of -0.05g approximately 5 times more frequently (i.e., comparing the included areas under the respective histograms to the left of -0.05g) than do vehicles encountered while driving under either ACC or CCC control. Clearly, the $V_p$dot condition posed by the traffic level and road type constitutes another of the many factors judged by drivers when they choose the appropriate mode of control. And, of course, it is well recognized that the freeway environment, and other high-speed roads, are generally characterized by very low levels of longitudinal acceleration. When they become congested such that more harsh stopping and starting transients prevail, the driver will have typically abandoned either of the cruise modes in favor of manual operation (although, of course, neither of the cruise modes is available below 30 mph, anyway.)



(MLV means Most Likely Value)

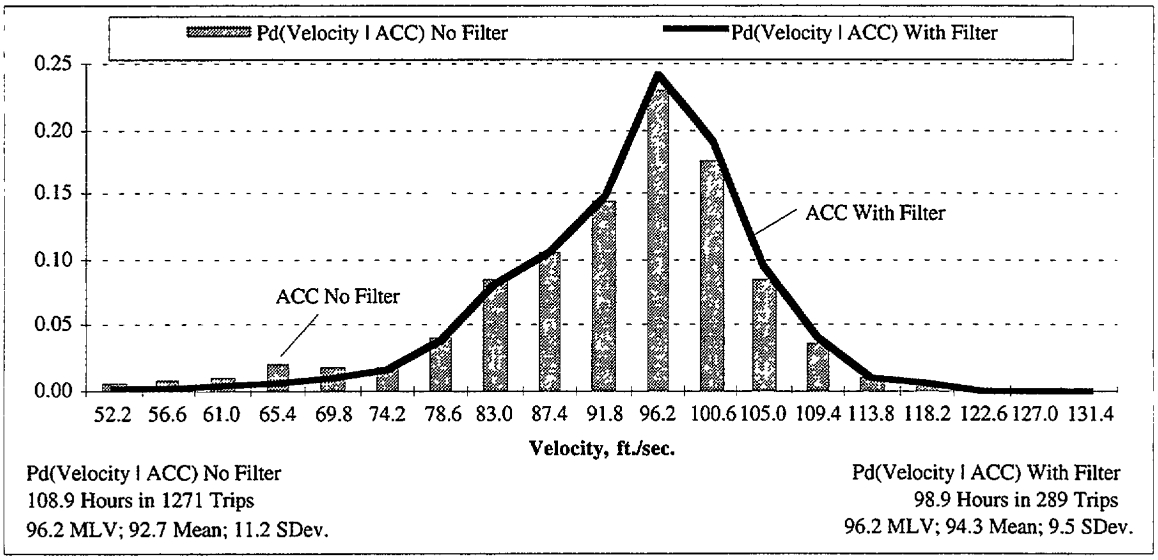
Figure 45. Histogram of preceding vehicle's acceleration in various control modes

4.1.3 What is the Influence of a Trip Filter on Basic Results?

In order to compare ACC operations with manual driving under nominally comparable conditions, trips were sub-selected to include only those whose average velocity exceeded 30 mph and whose trip length exceeded 10 miles. This screening filter retains a mere 22% of all the manual-only trips, but approximately 63% of the manual driving time. In ACC driving, only 28% of the ACC trips made it through the filter, but they represent 91% of all the ACC driving time. Even by these crude measures, then, we confirm that the filter removes much of the driving data in order to retain only those trips whose operating conditions are like those seen in most of the ACC driving. Thus, the short, relatively low-speed trips that were very numerous have provided rather little that can be used in studying the driver's experience with ACC. Note, also, that the large number of ACC trips that were removed by the filter, without significantly reducing the total amount of ACC driving time, reveals that our subjects were frequently trying to use ACC in very brief episodes, presumably as a curiosity while they were on a brief stretch of freeway or other road facility.

ACC Operations With and Without a Trip Filter

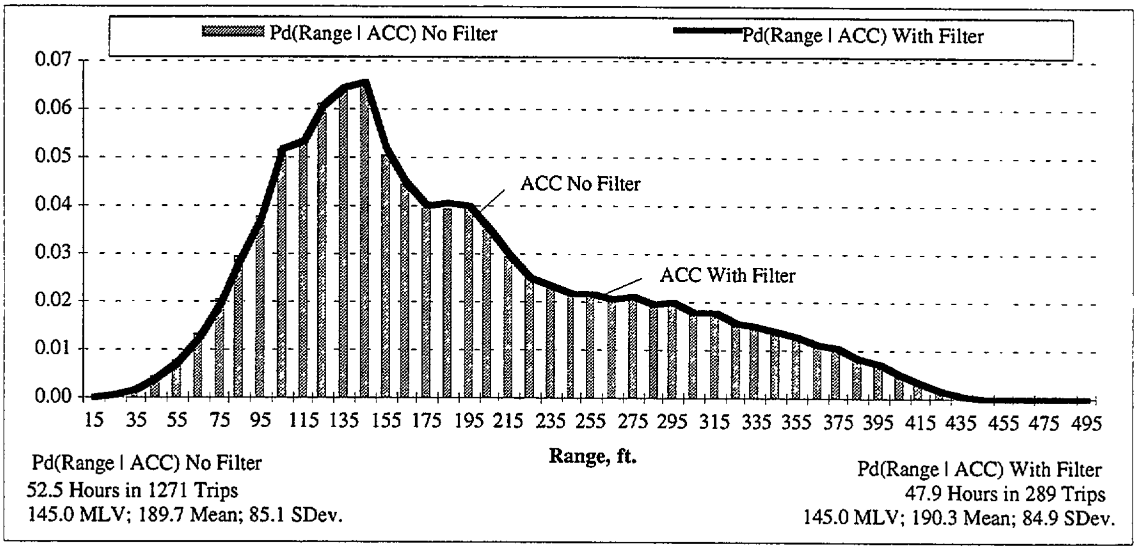
Shown in Figure 46 is the velocity histogram for ACC operations with and without the trip filter. Such charts are useful for assessing the impact of the selected trip filter, itself. The gray bars show all the ACC data (i.e., without filtering according to trip characteristics) while the solid line depicts the distribution from only the longer (>10 miles) and faster (>30 mph average speed) trips. These results indicate that the filtered trips are rather representative of the velocity distributions occurring in all ACC trips, albeit clipping out most of the narrow "tail" to the left, which pertains to driving below approximately 70 ft/sec.



(MLV means Most Likely Value)

Figure 46. Velocity histogram for ACC, with and without trip filter

Figure 47 compares the distance, or range, histograms for ACC operation in all the trips (gray bars) versus the filtered trips (solid line). Again, the filtered ACC trips appear virtually indistinguishable from the unfiltered ones. Dividing range by velocity to examine the headway times, we see in Figure 48 that the two graphs are still almost indistinguishable from one another. Of course, a simple reflection on the nature of this ACC controller would suggest that range-related histograms, which are compiled only while ACC is continuously engaged, should be largely insensitive to the trip conditions since the controller does indeed control that variable with substantial precision (see Section 4.1.6).



(MLV means Most Likely Value)

Figure 47. Range histogram for ACC, with and without trip filter

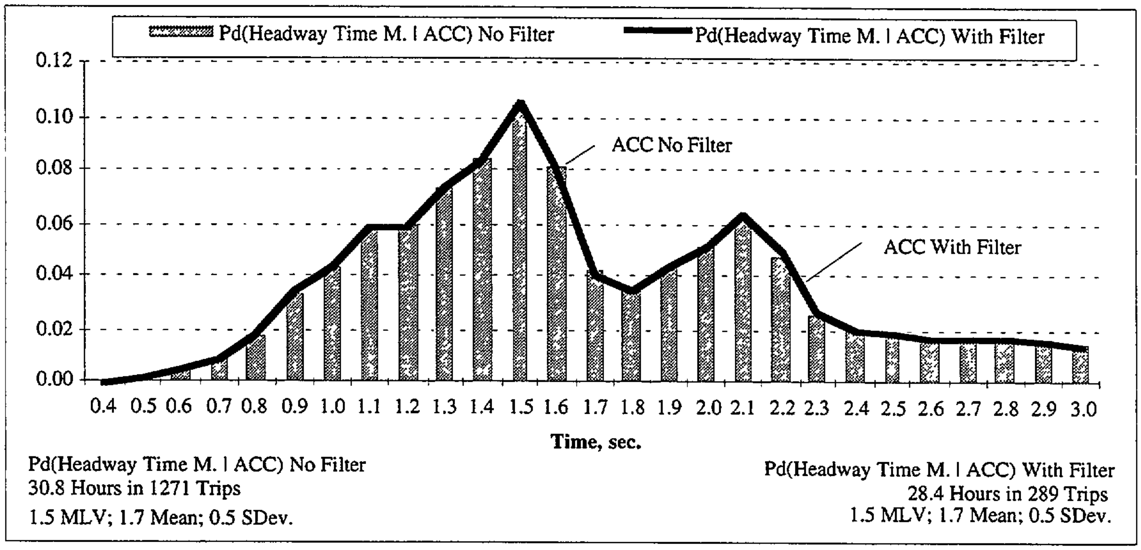


Figure 48. Headway Time Margin histogram for ACC, with and without trip filter

Manual Operations With and Without a Trip Filter

Shown in Figure 49 are the unfiltered (gray bars) versus the filtered (solid line) velocity histograms for manual driving. In this case, as intended, the filter serves to remove trips characterized by lower speed operation—conditions in which ACC usage has been seen to be very infrequent. Together with the observation, above, that the filtered trips do a good job of representing virtually all ACC operations, the data in Figure 49 further confirm the reasonableness of this simple filter approach since the filtered manual control trips show an upward shift in their velocity histogram.

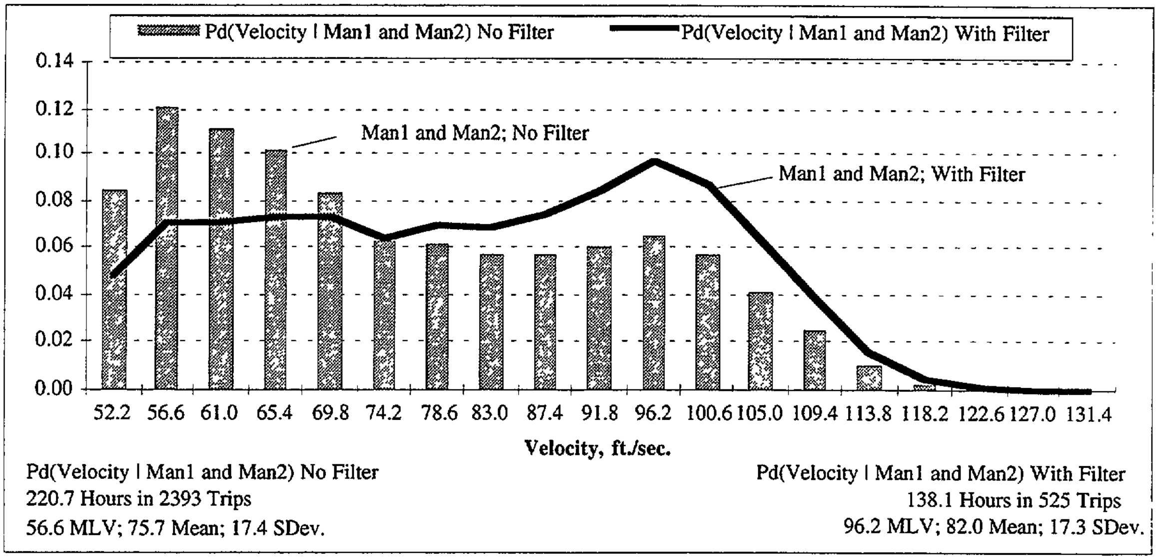
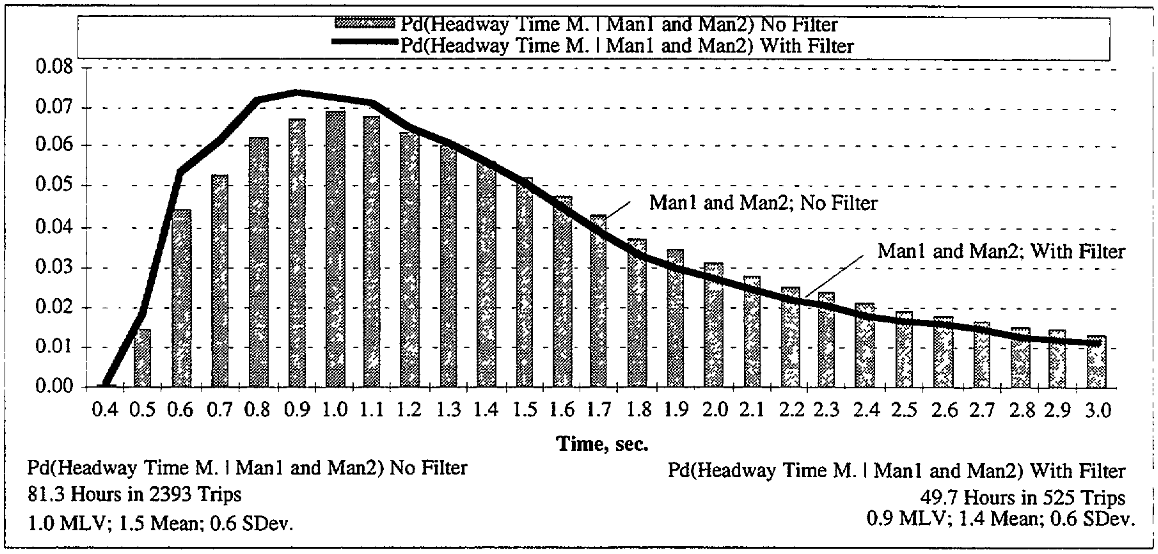


Figure 49. Velocity histogram for manual, with and without trip filter

Shown in Figure 50 are the unfiltered and filtered histograms for headway time in the manual mode of operation. Although a rather small redistribution of the results was affected by the trip filter, the direction of the change due to trip filtering can simply be called a puzzle at this point. That is, further investigation is needed to determine if a downward trend in headway time typically accompanies increasing speed in manual driving (as implied by the data which were filtered for speed and trip length.) More attention to this issue will be given as the project proceeds.



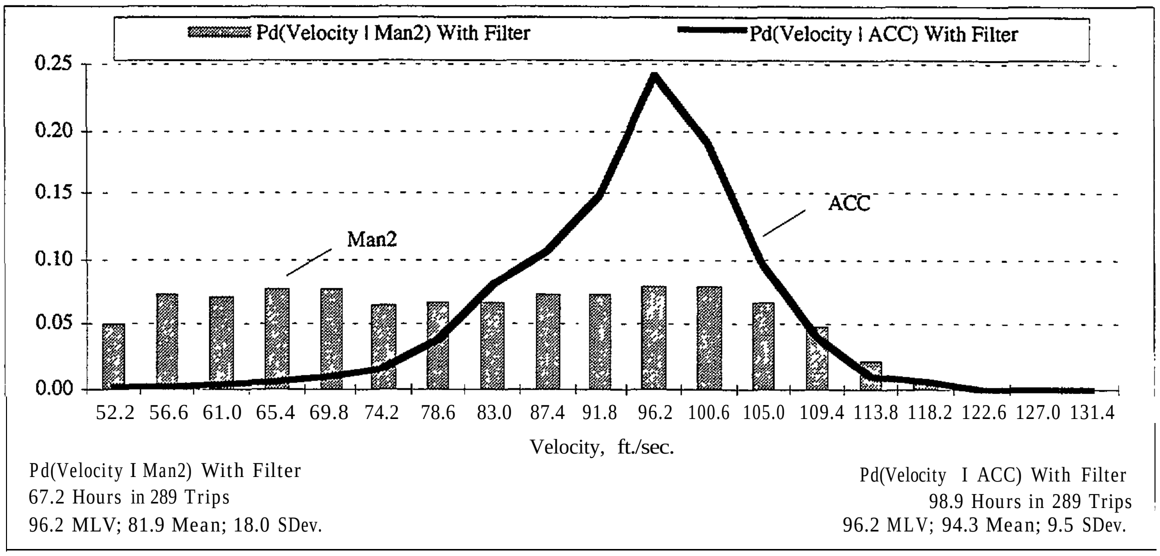
(MLV means Most Likely Value)

Figure 50. Headway Time Margin histogram for manual, with and without trip filter

In the remainder of this section, the trip filter described above will be employed to compare manual and ACC operations.

Manual versus ACC Operations Velocity Data Using the Trip Filter

Shown in Figure 5 1 is a comparison of the velocity histograms obtained during manual versus ACC driving from the filtered trips, only. The data are rather similar to those shown earlier, in section 4.1.1, for all trips (Figure 20, in particular) except that both the manual and ACC data show a reduced presence of low-speed (below 70 ft/sec) operation. The data, as filtered for only longer and higher-speed trips, suggest that ACC is used as a speed controller over a rather narrow range of speeds whose most likely value is around 94 ft/sec (64 mph).



Pd(Velocity I Man2) With Filter
67.2 Hours in 289 Trips
96.2 MLV; 81.9 Mean; 18.0 SDev.

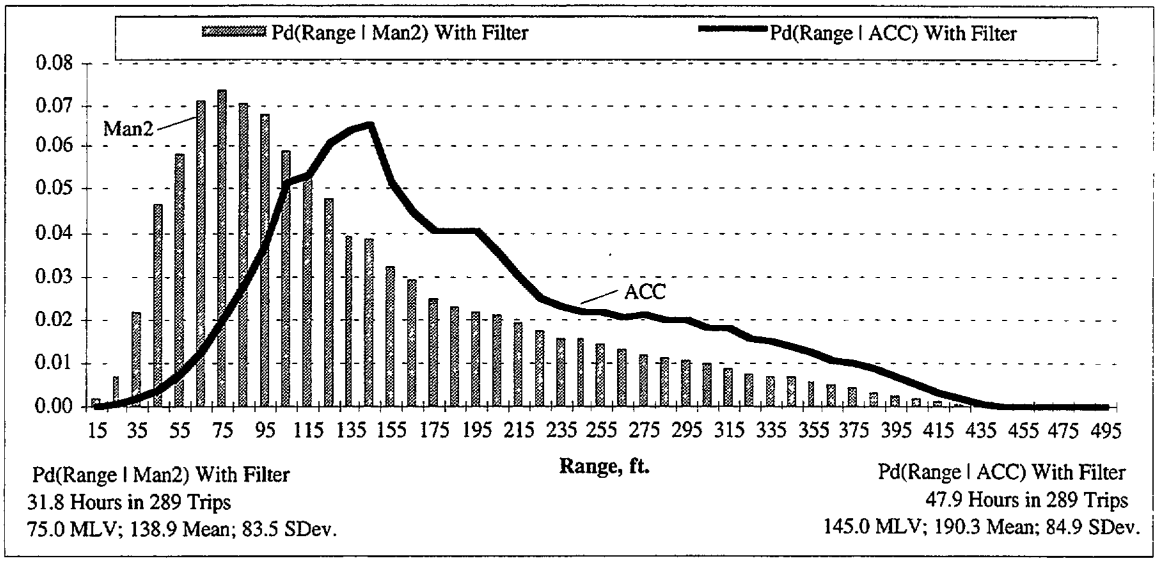
Pd(Velocity I ACC) With Filter
98.9 Hours in 289 Trips
96.2 MLV; 94.3 Mean; 9.5 SDev.

(MLV means Most Likely Value)

Figure 5 1. Probability density of velocity in ACC versus manual, with trip filter

Manual *versus ACC Operations Range Data Using the Trip Filter*

The range data obtained by trip-filtering on manual and ACC operations are shown in Figure 52. Although again the results appear very much like those that were shown comparing ACC versus manual driving from all trips in section 4.1.1 (see Figure 21), the mean value for manual driving has moved more to the left, toward shorter ranges, with the trip filter employed than did the overall distribution of manual results. Nevertheless, it would be fair to say that a negligible change in the comparison of ACC versus manual range values has occurred due to the trip filter.



(MLV means Most Likely Value)

Figure 52. Probability density of range in ACC versus manual, with trip filter

Normalizing range by velocity to obtain headway time margins in Figure 53, we observe that while the filtered-trip comparisons, ACC versus manual are, again, almost identical to those from all trips, the mean time gap from manual driving has moved about 6% to the left, yielding modestly more contrast between the two modes of control.

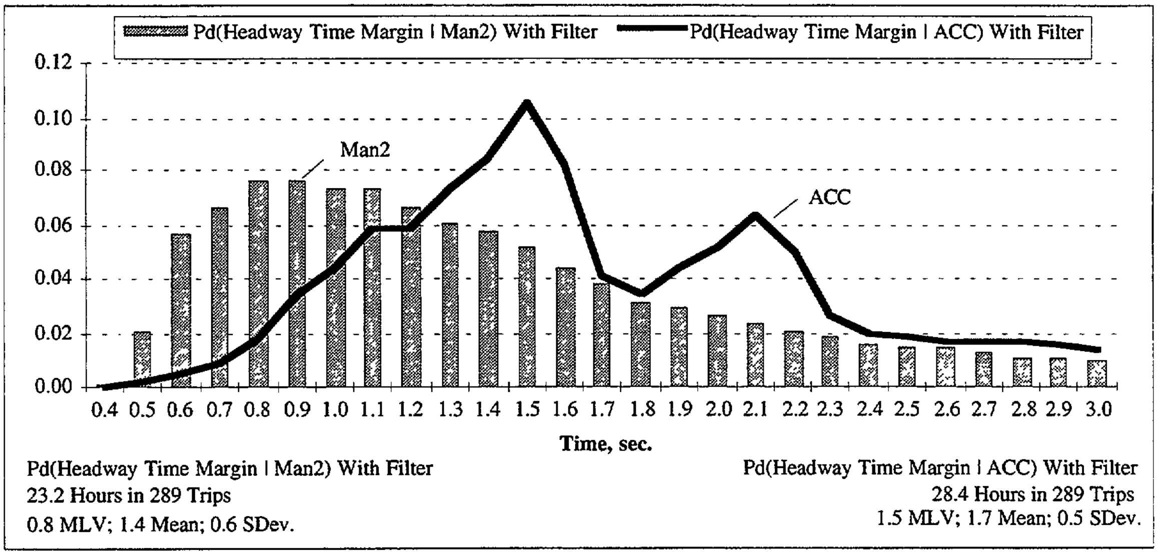
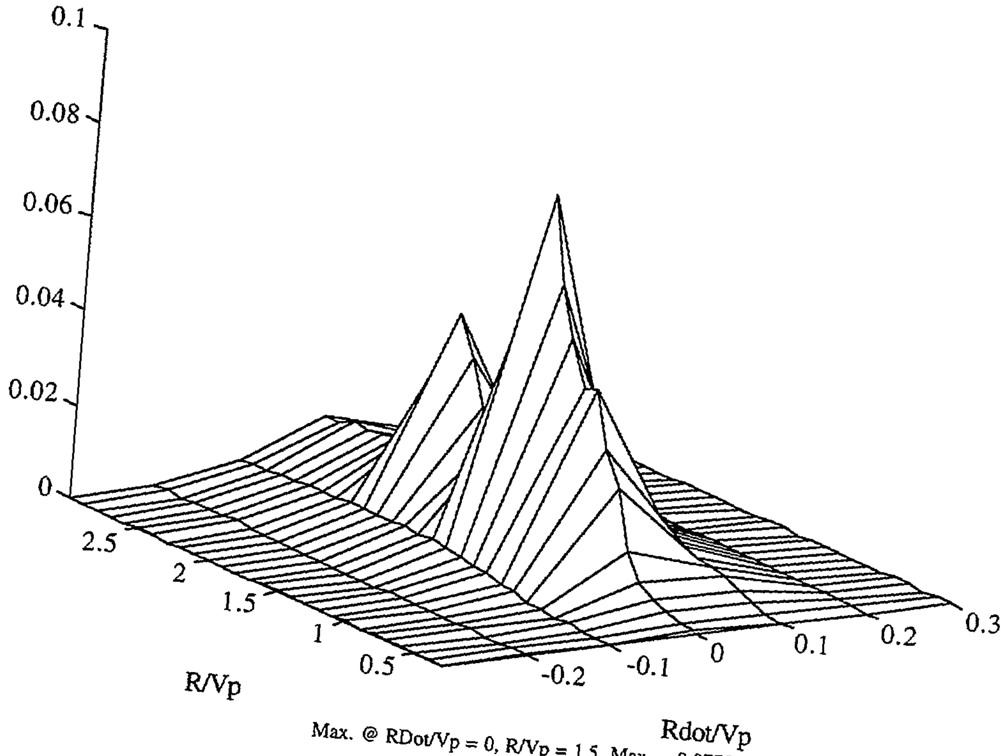


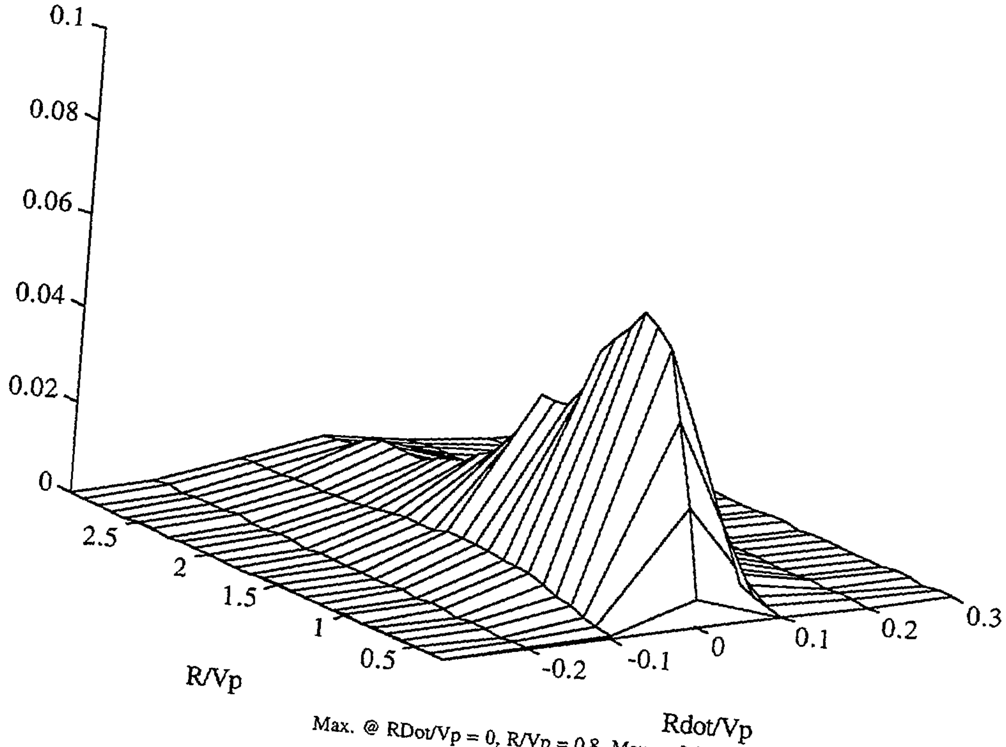
Figure 53. Probability density of headway time margin in ACC versus manual, with trip filter

Figure 54 and Figure 55 illustrate the two-dimensional histograms from ACC and manual driving modes, in the filtered trips, only. These figures are virtually indistinguishable from those shown earlier (Figure 23 and Figure 24) for all trips.



Max. @ RDot/Vp = 0, R/Vp = 1.5, Max. = 0.07779

Figure 54. Probability density of normalized range and range rate in ACC driving, with trip filter



Max. @ RDot/Vp = 0, R/Vp = 0.8, Max. = 0.06128

Figure 55. Probability density of normalized range and range rate in ACC driving, with trip filter

Finally, Figure 56 illustrates the results for five proximity regions defined earlier. The data compare the distributions of total probability of landing each of the five regions, given that a target has been acquired, under ACC and manual operations. These results, obtained from the filtered trips, only, are also virtually indistinguishable from those presented earlier, from all trips.

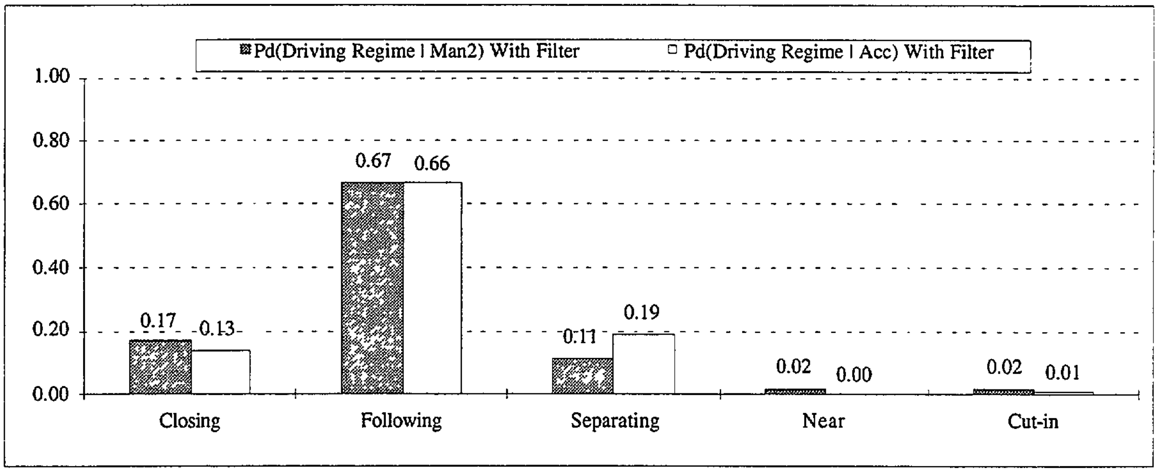


Figure 56. Probability density of operating within various driving regimes (2nd week), with trip filter

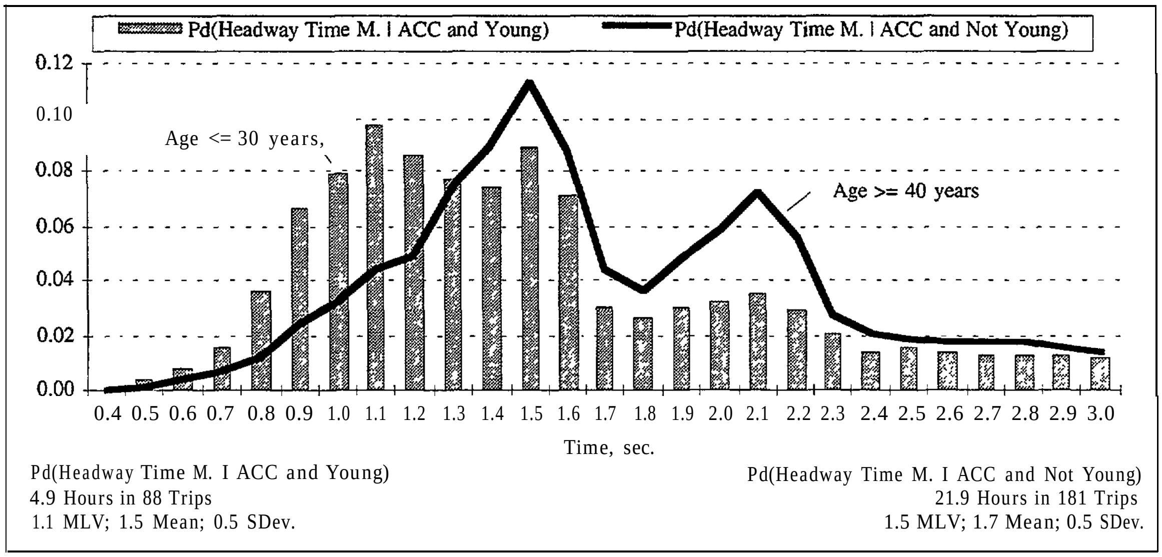
Altogether, these illustrations obtained using the described filtering for only longer and higher-speed trips have shown ACC versus manual comparisons differ from the "all-trip" results only in terms of the speed of manual driving. But since this substantial change in manual speeds in the filtered trips was not also accompanied by a significant change in either manual range values or in headway times, the filtering exercise has not shown itself to have been a needed discrimination mechanism. Nevertheless, the remainder of the results shown in successive sections of this report have employed the trip filter since the logic of its selection seems right (even though it is not possible to show quite what difference it makes). An extension of the exposure concepts and further attempts to identify "biases" in ACC versus manual driving that warrant trip filtering will be pursued during the remaining portion of the project.

4.1.4 How does driver age influence the results?

Previous research into ACC driving has shown that driver age distinctively relates to speed and headway-keeping behavior. Since ACC as an automotive product would be driven by persons across the full spectrum of licensed drivers, it is important that its safe and convenient operation under the age-determined variations in driving style be confirmed.

ACC Driving Young versus Older Drivers

Shown in Figure 57 is the comparison of headway times obtained by young (20-30 yrs.) versus older (>40 yrs.) drivers. The younger drivers (gray bars) apparently choose the 1.0-second headway time as their most popular selection among the three headway selections, with the 1.4-second choice as a close second. The older drivers (solid line) have a tendency to select the two longer headway settings, with the 1.4-second value being most likely. The data confirm that driver usage of ACC distinctly differentiates older from younger age groups, as had been expected from prior work.



(MLV means Most Likely Value)

Figure 57. Probability density of headway time margin in ACC driving, young versus old drivers

Shown in Figure 58 and Figure 59 are the two-dimensional histograms presenting the combined range and range-rate data comparing young ACC drivers with older ACC drivers. The younger drivers in Figure 58 not only come closer to the vehicle ahead, but they approach with higher values of range-rate as well, presumably as a result (to be confirmed later in the study) of having chosen higher set speeds such that higher rates of overtaking occur.

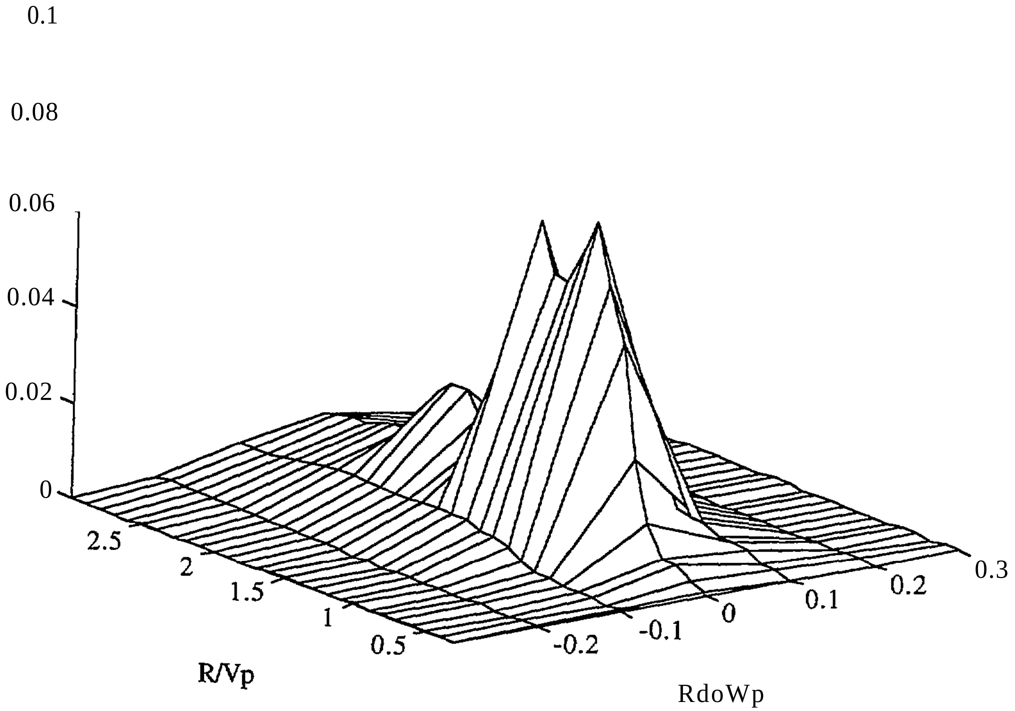


Figure 58. Probability density of normalized range and range rate in ACC driving, young drivers

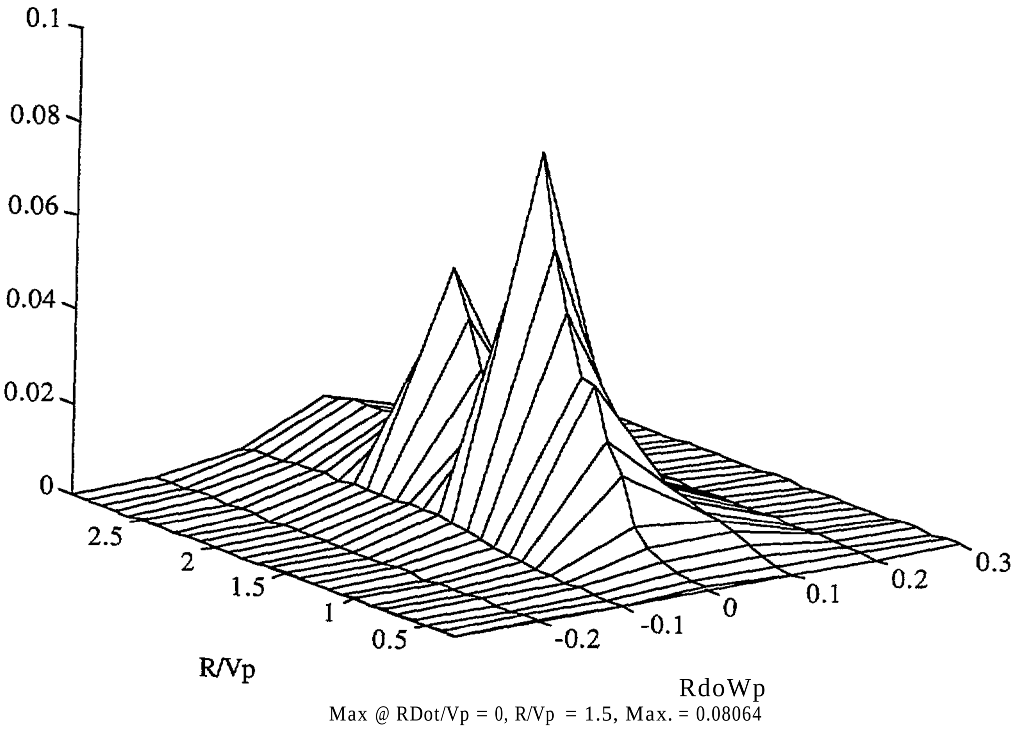


Figure 59. Probability density of normalized range and range rate in ACC driving, old drivers

A comparison of young versus older drivers in terms of the five proximity regions covered during ACC driving may be obtained by examining Figure 60 and Figure 61. The comparison shows that age has only a rather minor influence on the distribution of coverage, overall. Interestingly, however, the younger group shows a greater tendency to occupy the higher-conflict regions of "near" and "closing" than do the older drivers. This is probably because the younger drivers tend to use higher set speed than the older drivers do.

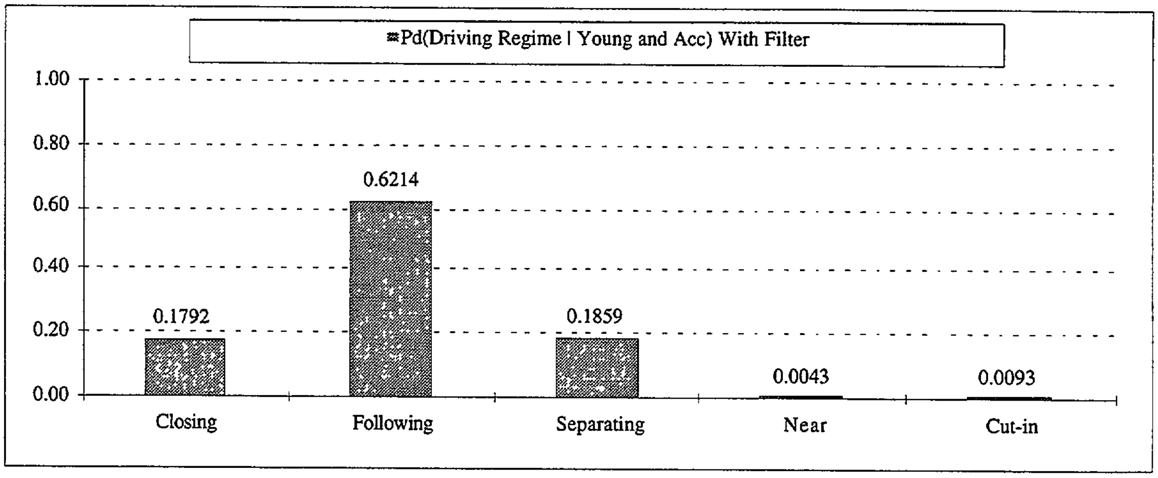


Figure 60. Probability of operating within various driving regime in ACC driving, young drivers

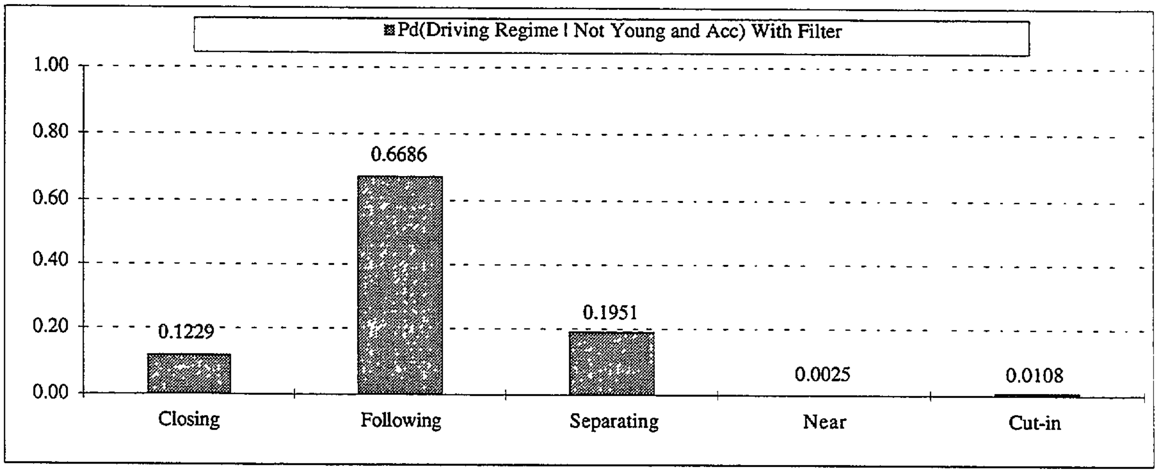
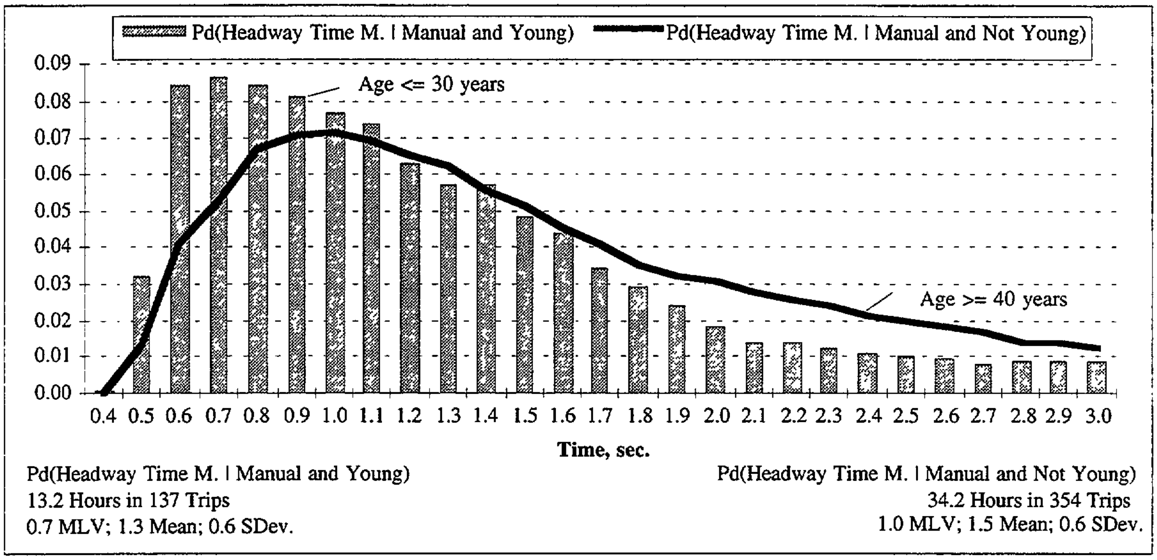


Figure 61. Probability of operating within various driving regime in ACC driving, middle-aged and old drivers

Manual Driving Young versus Older Drivers

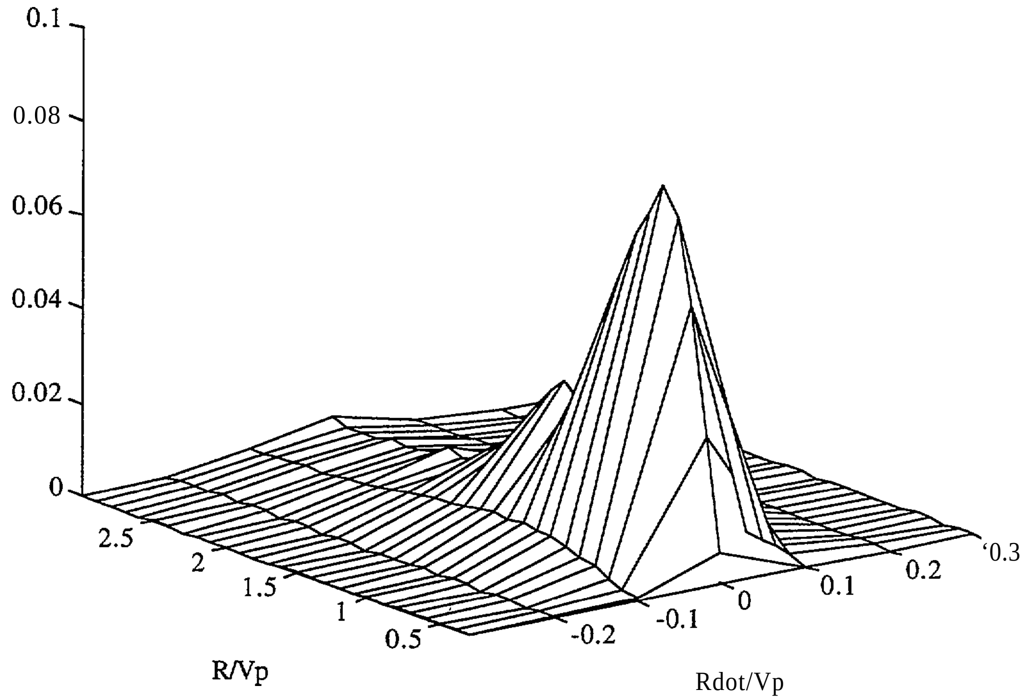
Shown in Figure 62, the headway times for young and older drivers operating in the manual mode are compared. As expected, the young driver (gray bars) show a headway time histogram that is biased more to the left and which includes a large (approximately 40%) probability of operating within a value of 1.0 seconds.



(MLV means Most Likely Value)

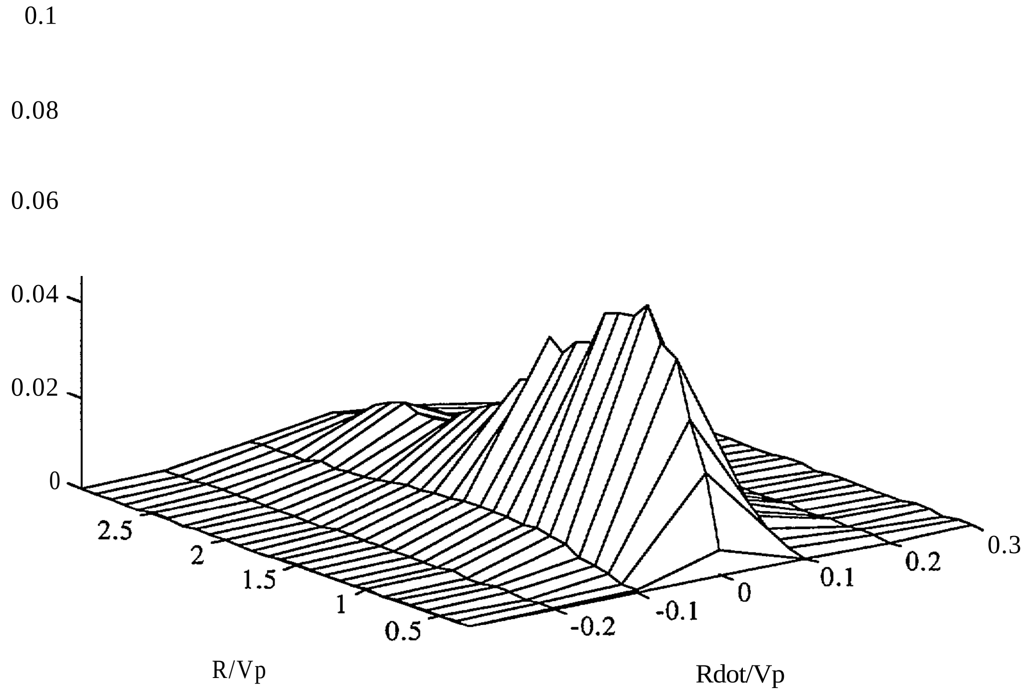
Figure 62. Probability density of headway time margin in manual driving, young versus middle-aged and old drivers

Figure 63 and Figure 64 show two-dimensional R and RDot histograms showing, in turn, young and older drivers operating under manual control. Although the data taken with young drivers is much more concentrated into the short-range end of the spectrum, it must be acknowledged that the older group also shows substantial occupation of both the short-range and negative-RDot portions of the space.



Max. @ RDot/Vp = 0, R/Vp = 0.7, Max. = 0.08047

Figure 63. Probability density of normalized range and range rate in manual driving, young drivers



Max. @ RDot/Vp = 0. R/Vp = 0.8, Max. = 0.05272

Figure 64. Probability density of normalized range and range rate in manual driving, old drivers

Figure 65 and Figure 66 presents a comparison of young versus older driver operations for manual driving across the five proximity regions. We see that while the overall distributions are very similar, the younger group is substantially more likely to occupy the "near" region, but nearly equivalently the "cut-in" region. Although the reader may tend to dismiss the differences in light of the overall small size of the near and cut-in probabilities, we should mention again that these areas are of special interest for their implication of conflicts that could portend near-miss or even rear-end crash possibilities.

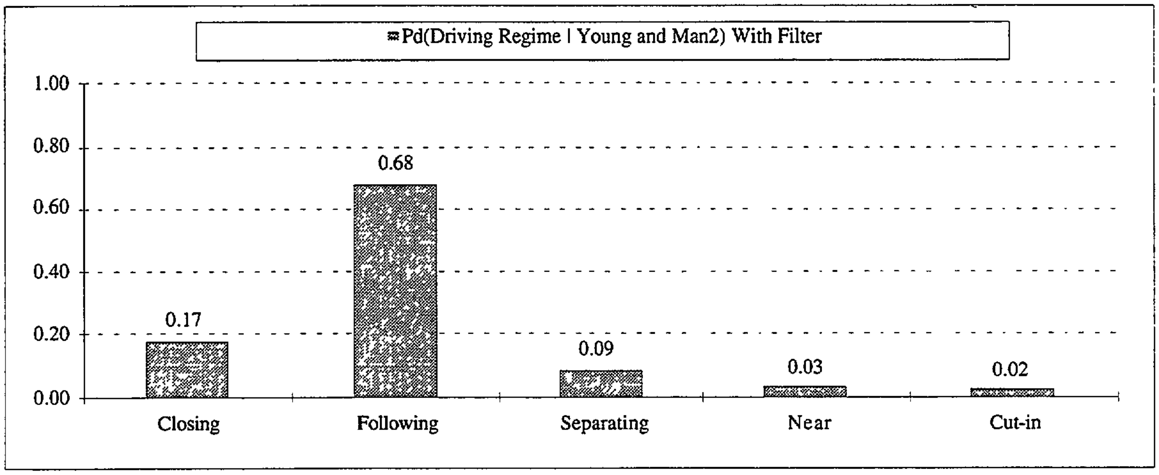


Figure 65. Probability of operating within various driving regime in manual driving, young drivers

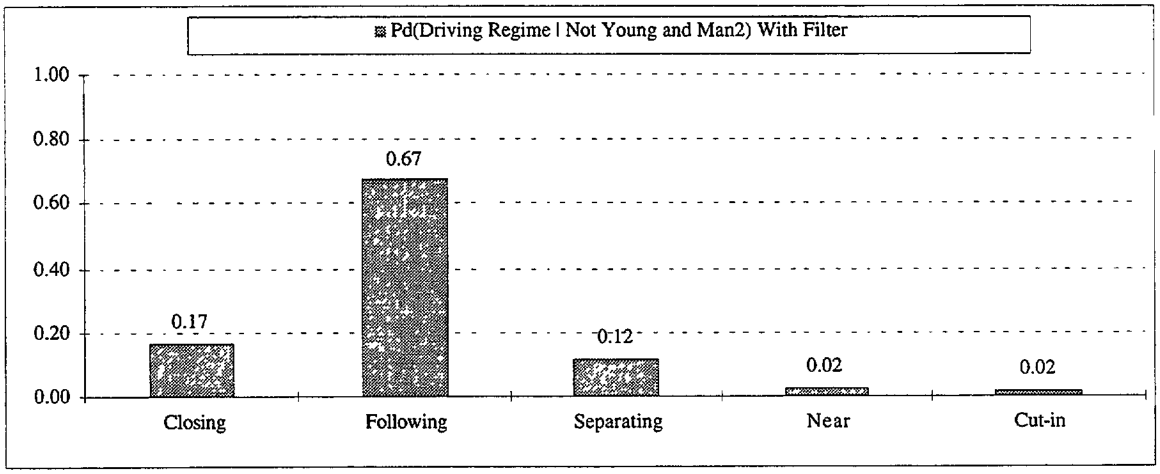


Figure 66. Probability of operating within various driving regime in manual driving, middle-aged and old drivers

ACC versus Manual for Young Drivers and for Older Drivers

By comparing Figure 60 and Figure 65, we see that the tendency for young drivers to be in the near region of the proximity space is greatly reduced. In addition, by comparing Figure 61 and Figure 66, we see also that the tendency for the other drivers (middle-aged and older) to be in the near region is greatly reduced. These results support the proposition that an ACC can provide a safety benefit by reducing the incidence of operation in the near region.

4.1.5 How do results for individuals differ from the aggregated results?

Appendix D provides a set of tables covering all drivers and all variables. Examining certain variables, and comparing them among drivers, can provide an assessment of differences between the individual and the aggregate results. The figures in this section depict the mean value of the variable being discussed, with error bars indicating plus/minus one standard deviation. Each figure is divided into three plots by the three age groups, and each plot groups the drivers by their familiarity with cruise control. The order of the drivers along the x-axis (within the grouping described above) is by their number as it appears under the column "No." in the tables in Appendix D.

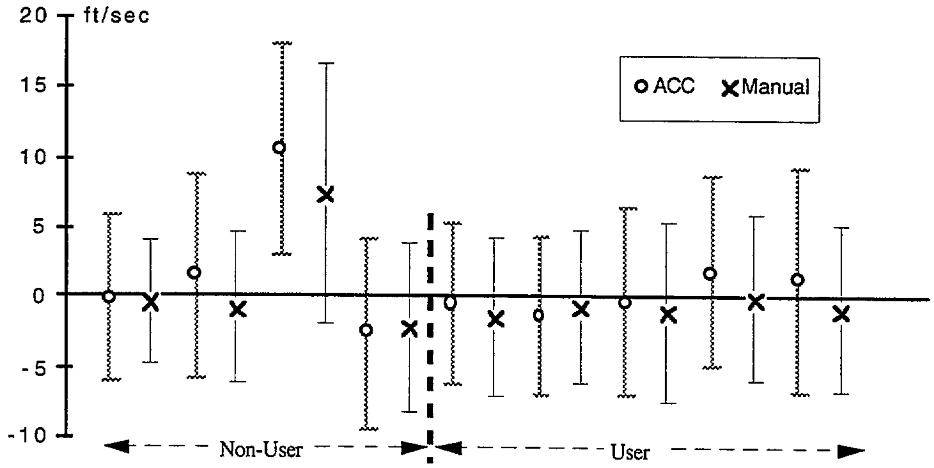
Examination of Relative Velocity (RDot)

The relative velocity RDot is a good indicator for identifying drivers who tend to drive more slowly than the speed of the other vehicles on the same road. This pertains primarily to manual driving but it can be observed in ACC driving as well. Examination of the data presented in Figure 67 shows that driver number 3 in the set of 35 drivers is an example of a slow driver.

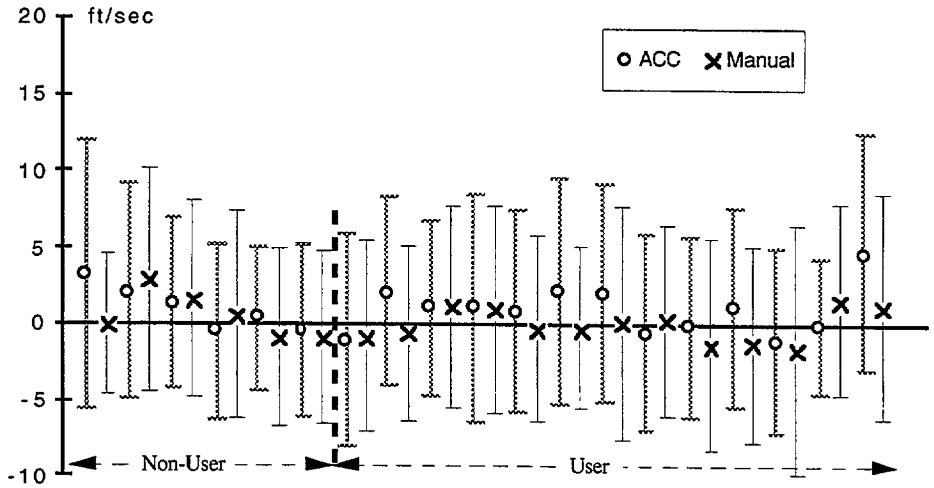
Based on this and past experience, it seems that about 1 in 35 drivers tends to drive at a much slower speed than the speed of the other drivers on the same road. This slow driver is an outlier whose results are different from the other drivers and consequently different from the aggregate of the data for all drivers. The very slow driver does not overtake other vehicles and most of the vehicles picked up by the slow vehicle's sensor are separating from it. In this case the slow driver is an extraordinary 10 ft/sec slower on the average in manual driving and an even larger 14 ft/sec slower on the average in ACC driving. This slow speed in ACC driving is done by selecting a very low set speed. The setting of a low set speed is what a driver can do using CCC to avoid having to brake and use the CCC controls. In ACC it means that the headway controller has almost nothing to do and the vehicle is operating as if it were using CCC.

Examination of the data and logical reasoning indicates that negative range rates do occur but it is difficult and unlikely that a driver can, or will be able to, have an average RDot that is less than -2 ft/sec. This means that it is difficult to travel more than 2 ft/sec. faster than the other vehicles. Even if a driver goes fast and manages to avoid the slower moving vehicles, the driver will encounter other vehicles that are going approximately at the same speed.

RDot in ACC and Manual Driving for Young Drivers



RDot in ACC and Manual Driving for Middle-aged Drivers



RDot in ACC and Manual Driving for Old Drivers

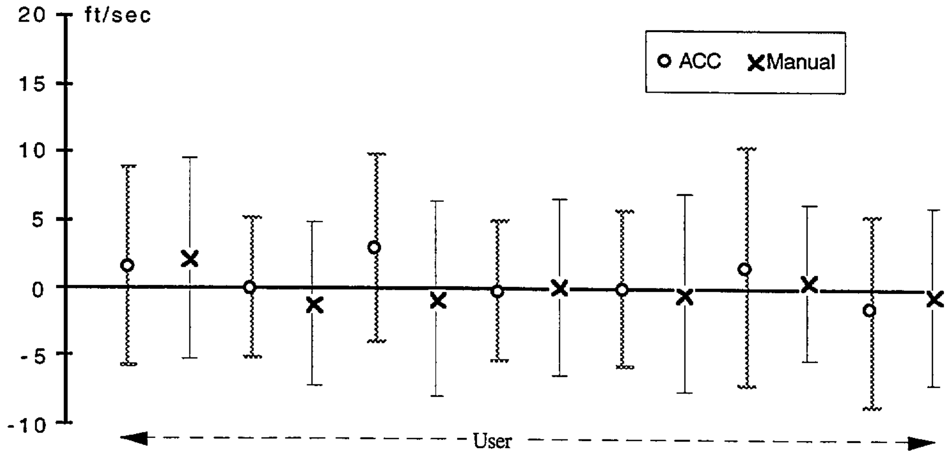


Figure 67. RDot in ACC and manual driving separated by age group

Evidence supporting the proposition that it is not likely that an individual driver will sustain a relative velocity that is negative (closing in on the preceding vehicle) is illustrated in Figure 67 where one can see that the average value of RDot is very close to 0 (except for driver number 3). The RDot average is close to zero and within ±2 ft/sec for nearly all of the drivers that have participated in the FOT so far.

As indicated by the ACC results presented in Figure 67, RDot average for ACC driving is often greater than zero but seldom less than zero (as one might expect given that the ACC system slows the vehicle to the speed of the vehicle ahead).

The conclusion here is that the data for RDot is good for identifying outliers, but aside from this most drivers tend to incur similar levels of RDot Since the RDot aspects of the driving performance of most individual drivers is much like that of the others, the aggregate and individual performances are quite similar with respect to RDot.

Examination of Velocity

The three primary variables used to evaluate headway control are range, range rate (RDot), and velocity. The difference between the velocity of the preceding vehicle and the ACC vehicle is RDot. Nevertheless, RDot tends to be more informative than velocity (V) because RDot takes into account the speed of the preceding vehicle. Examination of the data given in Figure 68 shows that with a few exceptions most drivers tend to use ACC at approximately the same speed somewhere in the range of typical highway speeds.

Driver 3, of course, stands out but not as noticeably as driver 3 did in the examination of RDot. Other drivers also have relatively slow average velocities in manual driving due to the driving environment they encounter in their use of the car, but they keep up with the other cars on the road so that RDot average is approximately near zero.

The one thing that is apparent from the data in Figure 68 is that manual driving for every driver is slower on average than ACC driving. This agrees with the results for the aggregated data (as of course it would have to). In the aggregated data the histograms show that ACC driving is more common at higher speeds and that low speeds are associated with higher likelihood of manual driving.

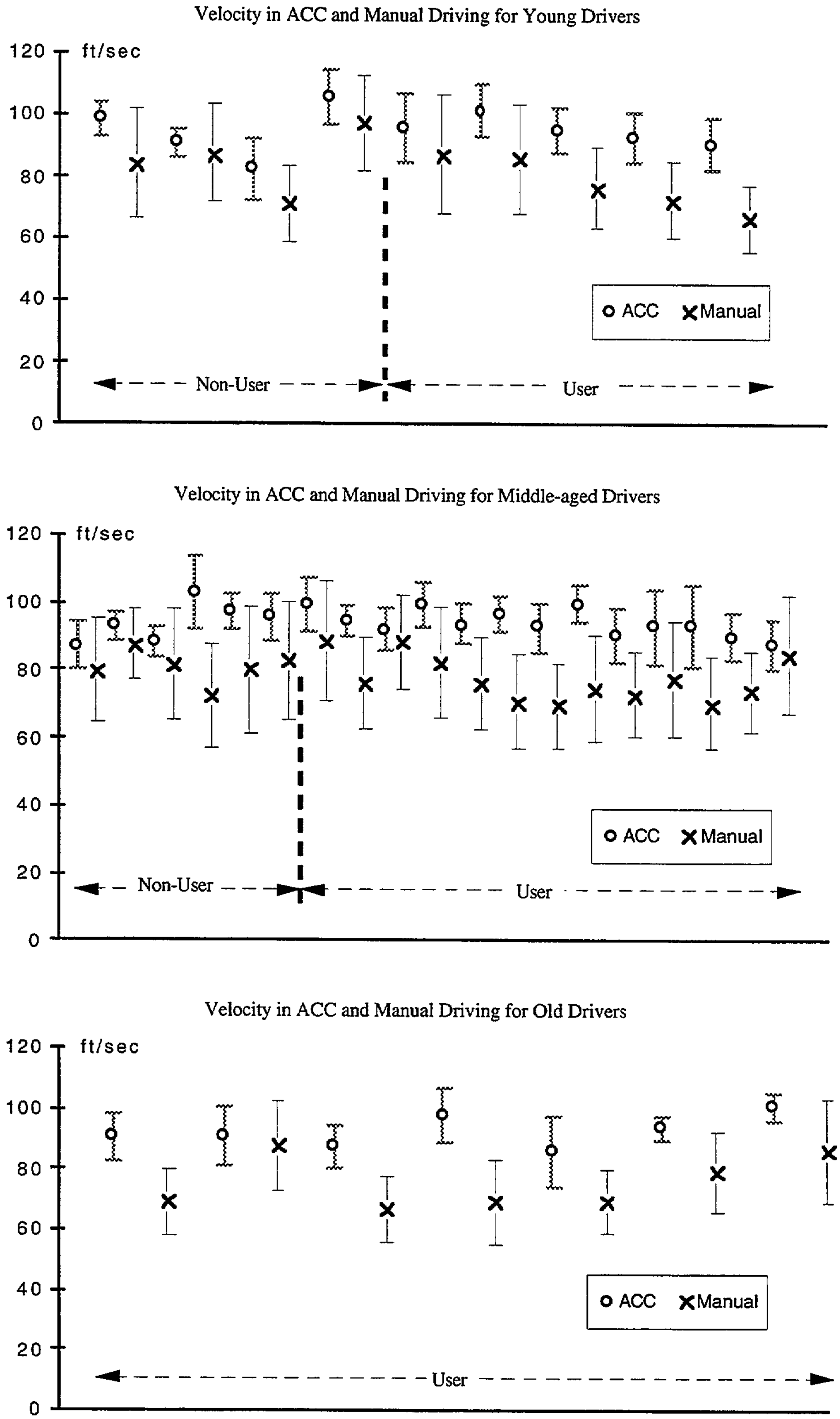


Figure 68. Velocity in ACC and manual driving separated by age group

Examination of Headway Range

Because the subjective results are gathered from each individual, they are in a way like the disaggregated results for the objective data. The opinion of driver 3 counts as much as that of any other driver even though driver 3 may have had very little experience with the headway-control system in operation. With only a few exceptions, the average range during manual driving is less than that attained during ACC driving. See Figure 69. This is in keeping with previous aggregated results. However there is a fairly wide dispersion of the headway ranges that different drivers choose to use. Also the standard deviations in range for all drivers are large, varying from approximately 60 to 100 feet. Different drivers differ considerably in the headway they choose to use.

Examination of Headway Time Margin

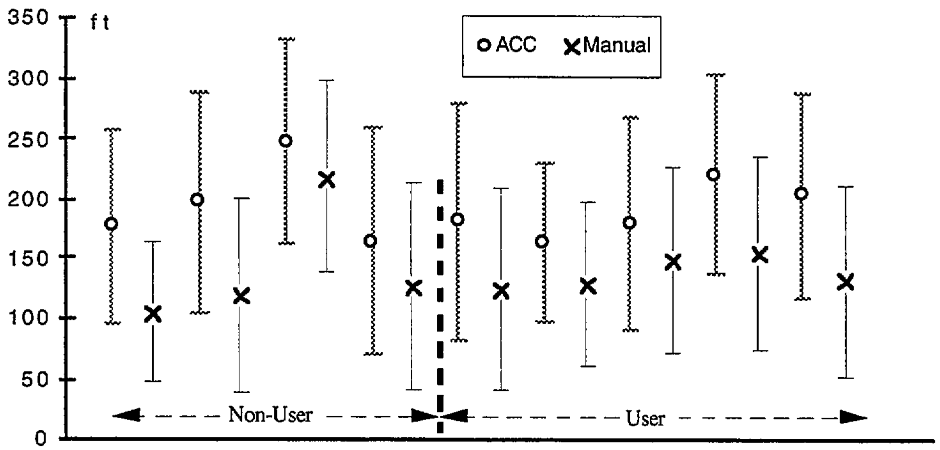
Headway time margin is equal to range divided by velocity (R/V). In a sense, dividing by velocity tends to bring the results for range into a common denominator of time. From a physical standpoint, headway time margin is the time available for the driver to match the deceleration maneuver of the preceding vehicle and still avoid a crash. As can be seen in Figure 70, the younger drivers tend to average short headway time margins just over 1 second with one standard deviation being well below one second. This difference between young and older drivers is discussed in Section 4.1.4.

Further interpretation of the individual driver data for headway time margin can be derived by examining Table 16. This table is extracted from Appendix D which provides a set of tables covering all drivers and all variables. Table 16 indicates that for most drivers the distribution of headway time margin is very skewed. The most likely value (MLV) is approximately one standard deviation below the mean for many drivers when they drive manually. It is interesting to note that only two of the 35 drivers have a MLV over 2 seconds, while 13 drivers have an MLV less than one second.

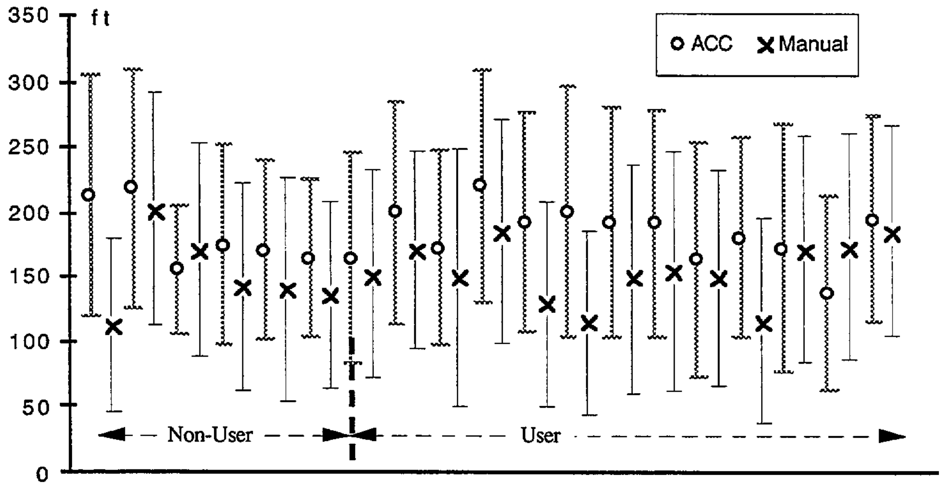
Naturally, the results for ACC driving indicate MLV near the headway times corresponding to the “closer”, unmarked, and “further” headway control buttons available in the driver interface of the ACC system.

Similar to the results for range, but perhaps easier to interpret, headway time margin for each individual is an indicator of that person’s driving style. People with different behavior with respect to headway time margin will have different views as to how headway is to be controlled.

Range in ACC and Manual Driving for Young Drivers



Range in ACC and Manual Driving for Middle-aged Drivers



Range in ACC and Manual Driving for Old Drivers

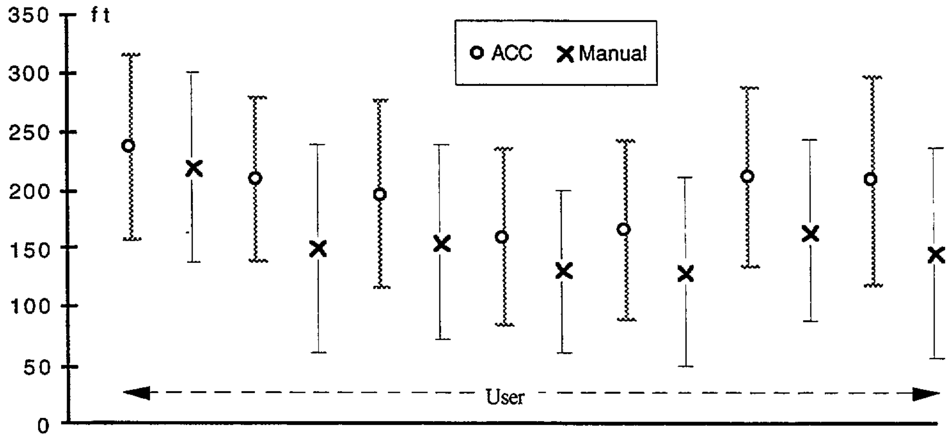
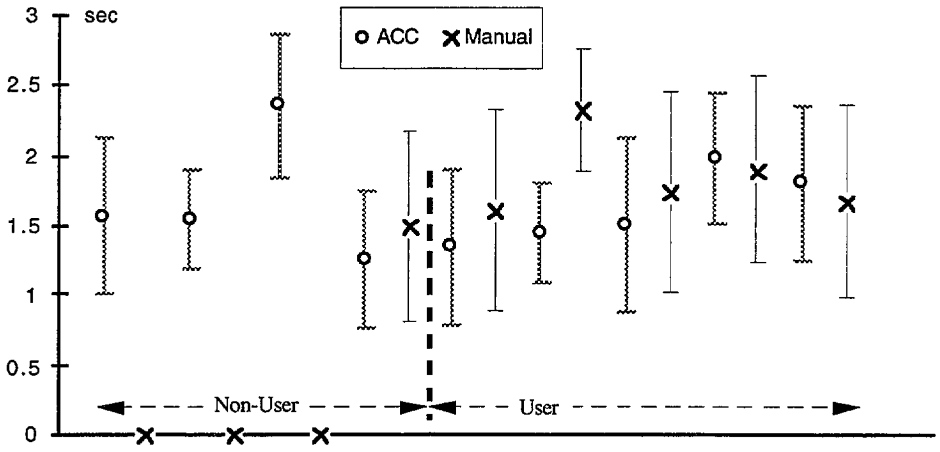
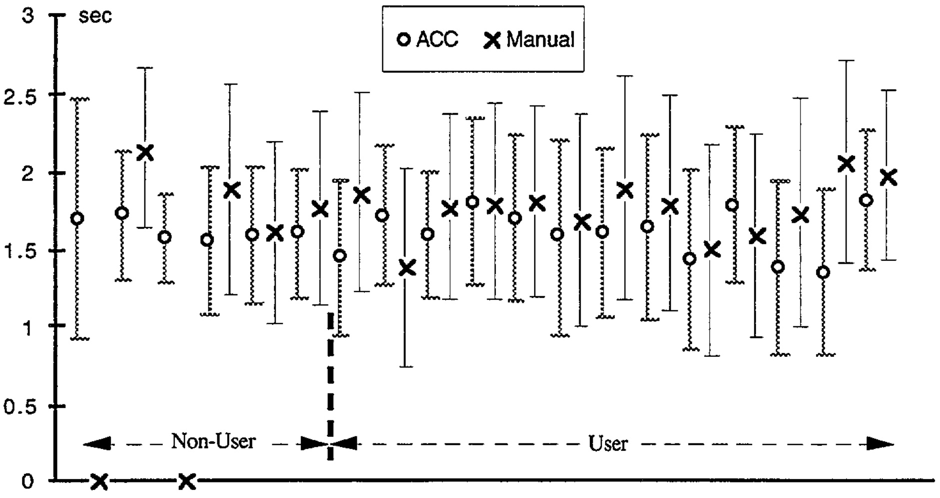


Figure 69. Range in ACC and manual driving separated by age group

Htm in ACC and CCC Driving for Young Drivers



Htm in ACC and CCC Driving for Middle-aged Drivers



Htm in ACC and CCC Driving for Old Drivers

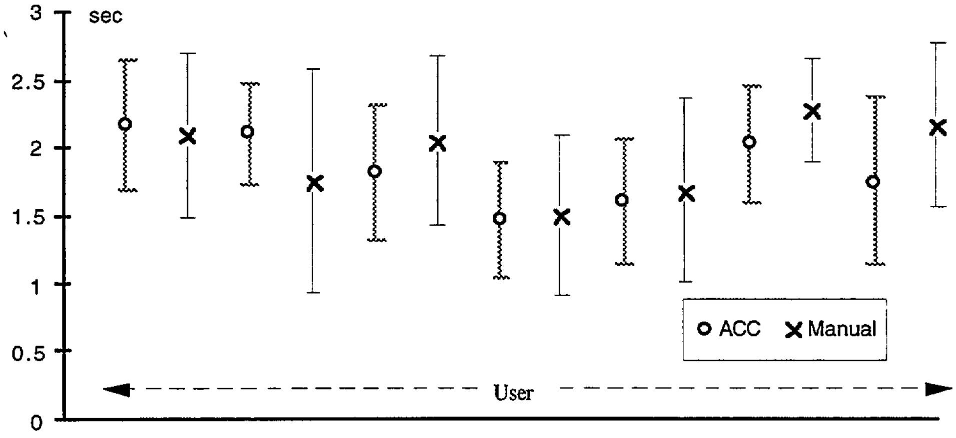


Figure 70. Headway time margin in ACC and manual driving separated by age group

Table 16. Individual driver data of headway time margin

No.	Measure	ID	Age	User	Sex	Mean	StDev	MLV	Trips	Count	Mean	StDev	MLV	Trips	Count
						Manual Driving					***ACC Driving***				
1	Htm	27	20-30	0	F	1.1681443	0.4975232	0.8	5	20731	1.5641183	0.5552279	1.5	5	19227
2	Htm	31	20-30	0	F	1.1743975	0.5500697	0.6	13	71919	1.5386374	0.3606367	1.6	9	2275
3	Htm	38	20-30	0	F	2.3733153	0.4477507	2.5	8	1870	2.359113	0.5164097	3	6	1827
4	Htm	4	20-30	0	M	1.0827788	0.5032789	0.7	27	148670	1.2471877	0.485299	1.1	20	53944
5	Htm	10	20-30	1	F	1.1806717	0.5865881	0.6	24	78310	1.3411504	0.564909	1.1	11	9232
6	Htm	15	20-30	1	F	1.3167459	0.4654576	1.1	7	57799	1.440516	0.3590814	1.5	5	42235
7	Htm	30	20-30	1	F	1.5383257	0.5359594	1.4	15	29886	1.5027409	0.6222135	1.2	9	12478
8	Htm	33	20-30	1	M	1.6638677	0.6086803	1.4	31	53227	1.9761555	0.460899	2	18	27583
9	Htm	37	20-30	1	M	1.4295965	0.6203053	1.2	7	11846	1.7958928	0.5517941	1.6	5	6428
10	Htm	1	40-50	0	F	1.2139962	0.5648585	0.8	10	116524	1.6898156	0.7668481	0.8	5	2278
11	Htm	23	40-50	0	F	1.7302394	0.624849	1.5	14	14372	1.7174224	0.4106176	1.5	6	9683
12	Htm	25	40-50	0	F	1.637643	0.6063775	1.2	7	34896	1.5655613	0.2895653	1.5	3	3046
13	Htm	26	40-50	0	F	1.6196811	0.6163087	1.2	8	25832	1.5490224	0.4837442	1.5	3	23634
14	Htm	29	40-50	0	F	1.4371287	0.6231943	1.3	12	63883	1.5864946	0.4377215	1.5	6	23872
15	Htm	34	40-50	0	M	1.3904135	0.5731566	0.9	29	146612	1.6070911	0.4130346	1.5	14	22366
16	Htm	5	40-50	1	F	1.4387633	0.5962915	1.1	19	76663	1.4441496	0.4970225	1.1	9	9008
17	Htm	6	40-50	1	F	1.8658797	0.5676932	1.4	9	20923	1.7148893	0.4601921	1.5	5	25300
18	Htm	8	40-50	1	F	1.168294	0.5400451	0.8	16	72469	1.5931658	0.4029096	1.5	6	47087
19	Htm	9	40-50	1	F	1.778699	0.637	1.3	29	73710	1.8036171	0.5413188	1.5	17	58196
20	Htm	12	40-50	1	F	1.3405977	0.6294698	1.2	0	36859	1.6933026	0.5347083	1.5	10	22860
21	Htm	21	40-50	1	F	1.2815429	0.5566132	0.8	20	61554	1.5752298	0.6261303	1.1	13	43839
22	Htm	24	40-50	1	F	1.5755169	0.6267019	1.4	8	14169	1.6065556	0.5418142	1.5	6	60240
23	Htm	36	40-50	1	F	1.3199224	0.6279711	0.7	10	24254	1.6368883	0.5975167	1.3	6	34309
24	Htm	3	40-50	1	M	1.5410914	0.6502171	0.8	14	22737	1.4317827	0.5768778	1.1	7	13715
25	Htm	14	40-50	1	M	1.274195	0.5554318	0.9	21	66630	1.7839853	0.5008026	2	13	50890
26	Htm	17	40-50	1	M	1.7039578	0.7254274	1.1	12	5205	1.3755842	0.5628204	0.9	6	11681
27	Htm	22	40-50	1	M	1.6577847	0.5983183	1.6	4	16783	1.3483157	0.5379818	1.1	1	18762
28	Htm	35	40-50	1	M	1.7113351	0.5873117	1.6	13	53268	1.8129628	0.4558271	1.5	5	18831
29	Htm	13	60-70	1	F	2.2296224	0.5123361	2.2	14	22510	2.161881	0.4819218	2.1	9	24190
30	Htm	7	60-70	1	M	1.3757585	0.6166781	0.8	17	193227	2.0997944	0.3650901	2.1	11	92857
31	Htm	11	60-70	1	M	1.6503994	0.5623149	1.3	32	29040	1.8175492	0.4922452	2.1	12	68687
32	Htm	18	60-70	1	M	1.5897008	0.5842963	1.6	11	18817	1.46083	0.4224178	1.5	7	92167
33	Htm	19	60-70	1	M	1.37 11808	0.5370734	1.4	25	30490	1.5975021	0.4603993	1.5	13	40593
34	Htm	20	60-70	1	M	1.7464041	0.5430589	1.7	5	39419	2.0209816	0.4204375	2.1	4	19746
35	Htm	32	60-70	1	M	1.3485503	0.5971186	0.9	9	33734	1.7518723	0.61507	1.3	4	7904

Incidence of Driving in the Near Region of the Proximity Space

The near region is that region of the proximity space that is next to a crash at R = 0 and RDot < 0. Table 17 presents the probability for each driver that that driver will operate in the near region. For ACC driving, the probability of being in the near region is 0.01 or less for all drivers. For manual drivers, there are drivers with a probability of being in the near region exceeding 0.04. In particular these are drivers 2, 5, and 25 as listed in the tables. Examination of Table 16 indicates that these drivers all have headway time margins less than one second. In fact, there appears to be a good correlation between a short MLV for headway time margin and a relatively high probability of operating in the near region (as one might anticipate).

In general the individual data can be used to identify those drivers that have a tendency to drive manually at short headway time and come relatively close to the preceding vehicle. However, for all drivers the use of ACC greatly reduces the likelihood of driving in the near region.

Table 17. Individual driver’s probability for operation in the “Near” region

No.	Measure	ID	Age	User	Sex	Transition	Probability	True	False	Trips	Transition	Probability	True	False	Trips
						Manual Driving					**ACC Driving**				
I	Near	27	20-30	0	F	14	0.011	251	22531	5	17	0.006	166	28471	5
2	Near	31	20-30	0	F	308	0.046	4401	90446	13	1	0.000	2	5001	9
3	Near	38	20-30	0	F	4	0.002	20	9759	8	0	0.000	0	18370	6
4	Near	4	20-30	0	M	305	0.036	7651	203106	27	35	0.010	790	80816	20
5	Near	10	20-30	1	F	211	0.054	6246	108911	24	5	0.002	26	15757	11
6	Near	15	20-30	1	F	78	0.011	758	71072	7	13	0.004	220	59830	5
7	Near	30	20-30	1	F	32	0.006	238	38056	15	4	0.002	48	21376	9
8	Near	33	20-30	1	M	109	0.011	793	71204	31	7	0.000	17	59737	18
9	Near	37	20-30	1	M	30	0.017	266	14991	7	7	0.002	29	14469	5
10	Near	1	40-50	0	F	133	0.029	4196	139898	10	1	0.001	4	6113	5
11	Near	23	40-50	0	F	20	0.004	109	29738	14	10	0.001	25	25474	6
12	Near	25	40-50	0	F	9	0.002	109	52357	7	0	0.000	0	3819	3
13	Near	26	40-50	0	F	23	0.007	229	31804	8	9	0.002	71	33589	3
14	Near	29	40-50	0	F	105	0.025	2328	89915	12	4	0.001	26	32077	6
15	Near	34	40-50	0	M	142	0.008	1574	189779	29	15	0.004	137	31230	14
16	Near	5	40-50	1	F	104	0.010	1106	111697	19	7	0.006	83	13581	9
17	Near	6	40-50	1	F	15	0.002	56	25892	9	2	0.000	5	43474	5
18	Near	8	40-50	1	F	69	0.015	1687	111620	16	6	0.000	32	66272	6
19	Near	9	40-50	1	F	94	0.007	886	122858	29	40	0.003	329	119648	17
20	Near	12	40-50	1	F	80	0.016	815	48828	20	4	0.001	22	39820	10
21	Near	21	40-50	1	F	96	0.020	1253	61484	20	19	0.002	147	94424	13
22	Near	24	40-50	1	F	33	0.021	406	18696	8	28	0.003	323	112285	6
23	Near	36	40-50	1	F	75	0.023	970	41394	10	18	0.003	151	52593	6
24	Near	3	40-50	1	M	84	0.030	1114	36116	14	7	0.007	147	2066 1	7
25	Near	14	40-50	1	M	214	0.063	4552	67502	21	46	0.007	624	85234	13
26	Near	17	40-50	1	M	28	0.030	296	9483	12	8	0.004	68	18721	6
27	Near	22	40-50	1	M	4	0.003	76	28760	4	4	0.004	90	25002	1
28	Near	35	40-50	1	M	42	0.003	260	95125	13	9	0.001	43	36999	5
29	Near	13	60-70	1	F	47	0.004	217	48614	14	56	0.006	306	53020	9
30	Near	7	60-70	1	M	242	0.019	55 15	280208	17	20	0.002	248	136203	11
31	Near	11	60-70	1	M	44	0.011	407	37859	32	17	0.001	115	115837	12
32	Near	18	60-70	1	M	31	0.011	259	22930	11	64	0.003	372	128533	7
33	Near	19	60-70	1	M	64	0.025	1014	39830	25	17	0.002	150	59928	13
34	Near	20	60-70	1	M	30	0.004	198	55999	5	14	0.002	76	45734	4
35	Near	32	60-70	1	M	89	0.031	1577	49389	9	3	0.000	6	14003	4

4.1.6 How well does this ACC system perform its functions?

The ACC system is a controller that closes an inner loop on vehicle velocity and, when a target vehicle is detected ahead, also commands velocity in such a way as to close an additional outer loop on range. When operating in the headway control mode of ACC engagement, the commanded speed, Vc, is computed to satisfy the linear range versus range-rate relationship lying on the so-called *dynamics line* described earlier in section 2. We can examine the nominal performance of the ACC controller by considering how close the vehicle response matches that which would lie precisely on the dynamics line. Response, in this context, is characterized by instantaneous "errors" such that the range value lies a measured distance above or below the line and such that velocity corresponds to a range rate that is to the right or the left of the line.

Quality of the ACC System as a Velocity Controller

When there is no target vehicle ahead, the speed control performance of the test vehicle is simply determined by the OEM cruise-control system provided with the Chrysler Concorde. When the ACC system operates in the headway-control mode, however, we are interested to determine its velocity-control performance as the system modulates throttle and transmission shift commands to converge toward the selected nominal headway condition. The quality of velocity control during headway-constrained operations is presented in Figure 71 in terms of the velocity error (Vc - V), shown in the black bars. For comparison, the figure also shows the (Vc - V) measure in gray for the speed-control mode of ACC operations, when there is no target within range.

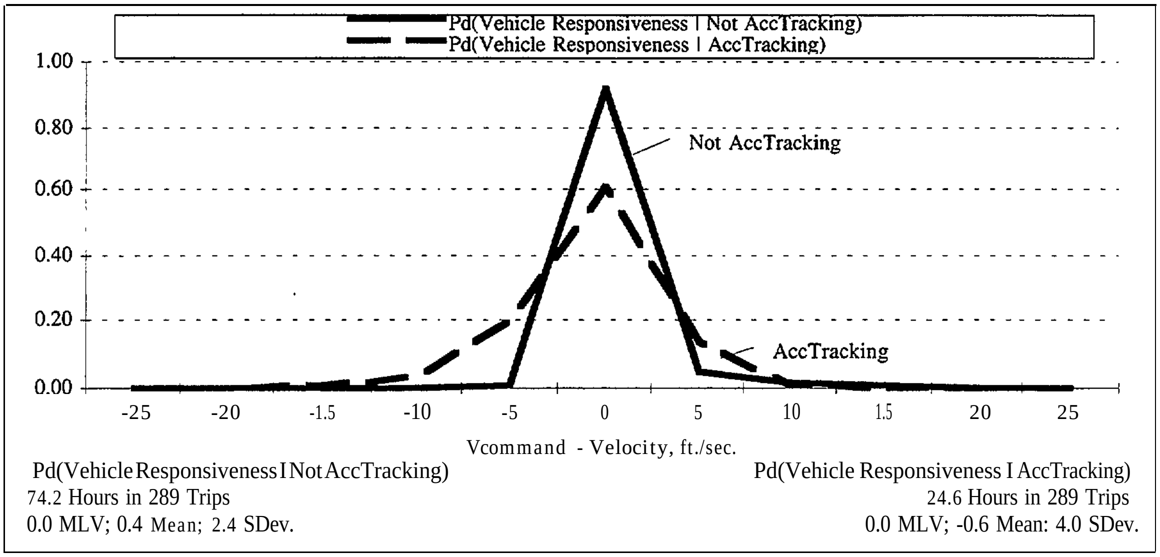


Figure 7 1. Vehicle responsiveness in headway mode versus speed-control mode

We see that the speed error is controlled around the zero value (i.e., within +/- 2.5 ft/sec of the commanded speed) approximately 92% of the time when in the simple speed-control mode and only about 61% of the time when in the headway ("ACC Tracking") mode of control. The ACC headway controller appears to spend approximately 39% of the time outside of this band, with some skew toward negative-polarity (i.e., approaching-type) errors when overtaking another vehicle. Clearly, the occurrence of cut-in, approach from higher speed, and braking-ahead transients serves to cultivate instantaneous velocity errors that look rather substantial, although the subjective reactions of the driver-participants do not imply that these variations are problematical.

Quality of the ACC System as a Range Controller

The quality of the range control is expressed in terms of the difference between the instantaneous range value, R, and the corresponding range value lying directly on the dynamics line, for the prevailing value of RDot. Shown in Figure 72, the probability density diagram of "Tracking Error" is presented between the values of -30 ft and +30 ft of distance error, bracketed by so-called *end bins* which reveal the respective probabilities of values at or below -35 ft and at or above +35 ft.

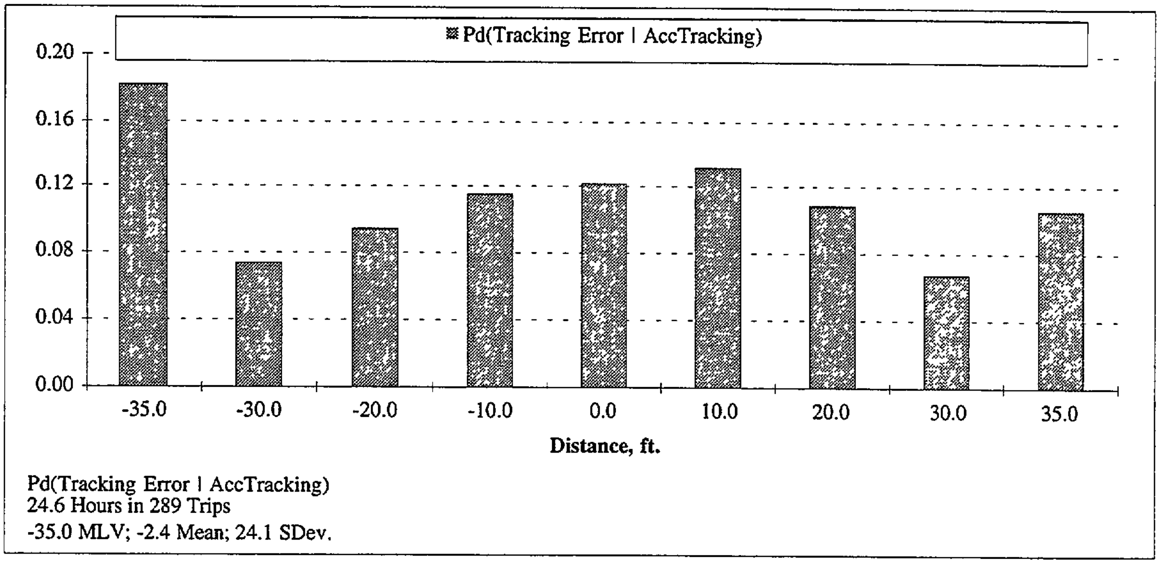


Figure 72. Probability density of range tracking error

It may at first seem surprising that 18% of the time the tracking errors are at or below -35 feet. Indeed, the general pattern of the data from +10 feet through -30 ft suggests that the left-side end bin contains negative distance errors that are substantially larger than -35 feet. If these errors were occurring while range rate was near zero, they would amount to wholesale undershoots of the driver-selected value of headway time, implying a good deal of headway conflict. But the fundamental dynamics of the problem are such that large negative values in tracking error will occur early in the process of closing on a slower-moving vehicle from long range. In such transients, the R-versus-RDot trajectory will drop substantially below the dynamics line after it first crosses it, especially if the overtaking velocity is initially large—for example -10 mph and greater. As the vehicle slows down, the tracking error subsides and often goes to zero before reaching the zero RDot condition. Thus, it is possible in a given closing transient to swing through instantaneous tracking errors as large as, say, 70 feet below the dynamics line and still arrive at RDot=0 with no undershoot of the target headway value.

The figure also shows that substantial positive values of tracking error occur, including some from the not-infrequent case when others cut-in at a positive value of RDot and subscribe growing values of positive distance until the system falls out of the headway control mode and proceeds toward its set speed.

Further study of the performance of the ACC system as a controller require processing of time history data. However, the results in the next section (section 4.2) indicate that drivers are comfortable with the performance of this system. Perhaps this is because the system controls headway-time margin (R/V) with little overshoot. An example time history for headway-time margin is shown in Figure 73. (This figure is from one of the characterization tests described in Appendix A.) Examination of the figure shows that the ACC vehicle closes in on the preceding vehicle in a smooth manner with almost no hunting or oscillation.

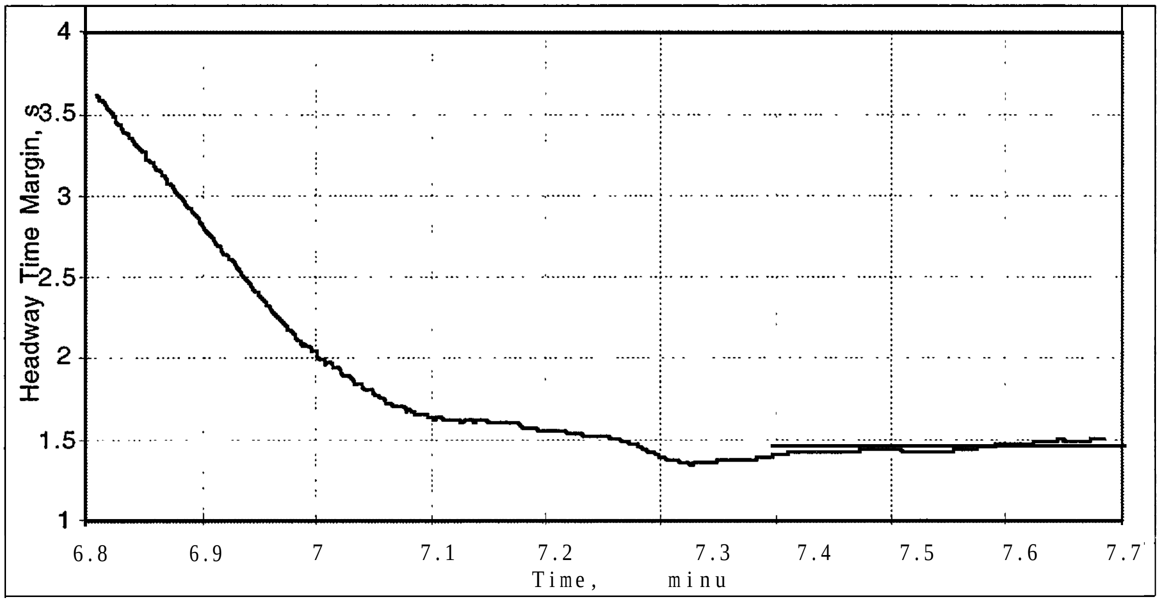


Figure 73. Headway-time margin data recorded in a characterization test

4.2 Results and Findings from Subjective Data

The subjective results and findings presented here pertain to operational issues concerning (1) the levels of comfort, convenience, and safety drivers associate with ACC, (2) driver concerns with ACC operation, and (3) the driver's ability to adapt to different driving situations while using ACC (see section 1.1).

The recovery of subjective results was completed when a participant returned the research vehicle to UMTRI. Subjective data in the form of a questionnaire was obtained from each participant. In addition, each participant was de-briefed by a researcher in order to gauge the participant's reaction to the research vehicle, ACC system, and experimental protocol. At this time participants were reminded that focus groups will be held, and an attempt was made to schedule the participant's attendance at the first available focus group. Participants in the field test were not required to attend focus groups, but their attendance was urged. The focus group setting also provided for open and earnest discussion among participants, permitting them to share ideas and concerns related to ACC.

Log books, which had been given to each participant to record significant events, were retrieved when the research vehicle was returned. A researcher examined the comments made in the log book as the participant completed the questionnaire. All entries into the log book were discussed with the participants.

4.2.1 Questionnaire Results

The complete list of the questions in the questionnaire is provided in Appendix C. For each question, statistics regarding the participants' answers are provided. This section includes excerpts from the appendix, grouped by topics that the questionnaire addresses.

Comfort and Convenience: In general, participants have rated the ACC system highly with relation to driving comfort. Most participants, 3 1 of 36, reported feeling comfortable using the system in one day or less. The remaining five participants reported feeling comfortable using the system after a few days (see questions 1 and 2 in Table 18). However, participants reported that they would become more comfortable with the system were they given additional time to use it (see question 4 in Table 18). The ACC system was also favorably rated on several other dimensions (see questions 6 through 10 in Table 18). When asked to rank the three possible modes of operation on the basis of comfort participants ranked the use of ACC first, followed by conventional cruise control and manual control (see question 11 in Table 18). Similar results were observed when participants were asked to rank the three modes of operation on the basis of convenience (see two items of question 11 in Table 18).

Table 18. Summary of comfort and convenience questions

Question	**Answer**	
1. How comfortable did you feel driving the car using the ACC system?	**Rating** **Mean**	1 to 7 (most comf.) 6.0 (s = 1.6)
2. How long did it take you to be comfortable using the ACC system?	15 after an hour or less 16 after first day 5 after a few days (none needed more) (none were never comfortable)	
4. How likely is it that you would have become more comfortable using the ACC system given more time?	**Rating** **Mean**	1 to 7 (most likely) 5.2 (s = 2.3)
6. How comfortable were you using the ACC system in the rain or snow? *(Note: 3 never experienced rain or snow)*	**Rating** **Mean**	1 to 7 (most comf.) 5.2 (s = 1.5)
7. How comfortable were you using conventional cruise control in the ram or snow?	**Rating** **Mean**	1 to 7 (mostcomf.) 5.1 (s = 1.6)
8. How comfortable were you using the ACC system on hilly roads?	**Rating** **Mean**	1 to 7 (most comf.) 5.6 (s = 1.5)
9. How comfortable were you using the ACC system on winding roads?	**Rating** **Mean**	1 to 7 (most comf.) 5.5 (s = 1.6)
10. How comfortable would you feel if your child, spouse, parents or other loved ones drove a vehicle equipped with ACC?	**Rating** **Mean**	1 to 7 (most comf.) 6.0 (s = 1.5)
11. Compare three operation modes (Manual, Conventional Cruise, ACC) for comfort	**Rank** **Mean**	1 to 3 (least comfort) 2.8 (Manual, s=.5) 2.0 (Conv. Cruise, s=.5 1.2 (ACC, s=.5)
Compare three operation modes (Manual, Conventional Cruise, ACC) for convenience	**Rank** **Mean**	1 to 3 (least convenient **2.9** (Manual, s=.4) 1.9 (Conv. Cruise, s=.4 1.2 (ACC, s=.5)

Safety: With regards to safety, participants have reported the ACC system to be safe to use (see Question 28 in Table 19), and that use of the system may actually increase driving safety (see Question 29 in Table 19). When asked to rank the three possible modes of operation on the basis of safety participants ranked the use of manual control first, followed closely by ACC (see Question 11 in Table 19). Participants also reported driving most cautiously when using ACC relative to conventional cruise control and manual control (see Question 14 in Table 19), without experiencing “unsafe” following distances (see Question 25 in Table 19). In addition, very few system failures were reported (see Questions 34 and 35 in Table 19). Finally, participants reported being both aware and responsive to surrounding traffic when using the ACC system (see Questions 18 and 19 in Table 19).

Table 19. Summary of safety questions

Question	Answer	
11. Compare three operation modes (Manual, Conventional Cruise, ACC)	**Rank**	1 to 3 (least safety)
	Mean	1.5 (Manual, s=.8)
		2.6 (Conv. Cruise, s=.6)
		1.8 (ACC, s=.6)
14. Under which mode of operation do you drive most cautiously?	**Rank**	1 to 3 (least cautious)
	Mean	2.1 (Manual, s=1.0)
		2.0 (Conv. Cruise, s=.6)
		1.8 (ACC, s=.9)
18. Driving the ACC system, compared to manual driving, did you find yourself more or less aware of the actions of vehicles around you?	**Rating**	1 to 7 (most aware)
	Mean	5.8 (s = 1.3)
19. Driving the ACC system, compared to manual driving, did you find yourself more or less responsive to actions of vehicles around you?	**Rating**	1 to 7 (most responsive)
	Mean	5.3 (s = 1.5)
25. How often, if ever, did you experience “unsafe” following distances when using the ACC system?	**Rating**	1 to 7 (least frequent)
	Mean	6.3 (s = 1.0)
28. How safe did you feel using the ACC system?	**Rating**	1 to 7 (very safe)
	Mean	6.4 (s = .9)
29. Do you think ACC is going to increase driving safety?	**Rating**	1 to 7 (strongly agree)
	Mean	5.8 (s = 1.3)
34. While using the ACC system, how often, if ever, did the system fail to detect a preceding vehicle?	**Rating**	1 to 7 (never)
	Mean	6.2 (s = 1.0)
35. While using the ACC system, how often, if ever, did the system produce false alarms (i.e., detect a vehicle when none existed)?	**Rating**	1 to 7 (never)
	Mean	6.4 (s = .7)

Willingness to Purchase: When asked to provide an overall ranking of the three modes of operation for personal use, participants ranked ACC first with conventional cruise control and manual control following a distant second and third (see Question 38 in Table 20). Participants also reported being very willing to purchase an ACC system in their next new car (see Question 39 in Table 20), but were frequently reluctant to provide an amount they would be willing to pay (see Question 40 in Table 20). Participants were also willing to rent an ACC equipped vehicle (see Question 41 in Table 20).

Table 20. Summary of questions regarding willingness to purchase

Question	Answer	
38. Rank, in order of preference, the following modes of operation for personal use	**Rank** **Mean**	1 to 3 (least desirable) 2.5 (Manual, s=.8) 2.2 (Conv. Cruise, s=.7) 1.4 (ACC, s=.6)
39. Would you be willing buy an ACC system in your next new vehicle?	**Rating** **Mean**	1 to 7 (very willing) 6.5 (s = .9)
40. Approximately how much would you be willing to spend for this feature in a new vehicle?	**Rating** **Mean**	$410 (s = $333)
41. Would you be willing to rent a vehicle equipped with an ACC system when you travel?	**Rating** **Mean**	1 to 7 (very willing) 6.7 (s = .7)

<u>Comparison with an Objective Measure</u>: Participants were asked to compare the modes of operation in which they drove the fastest (see Question 12 in Table 21). The result of the ranking for conventional cruise control and ACC use were identical. Interestingly, the objective measure of mean velocity for the two different control modes was nearly identical (with a conventional cruise control mean of 92.62 ft/sec and an ACC mean of 92.90 ft/sec).

Table 21. Summary of questions regarding comparison with an objective measure

Question	Answer	
12. In general, under what mode of operation did you feel like you drove fastest?	**Rank** **Mean**	1 to 3 (slowest) 1.4 (Manual, s=.6) 2.3 (Conv. Cruise, s=.7) 2.3 (ACC, s=.7)

<u>4.2.2 Log: Entries and Participant Debriefing</u>

Upon return of the research vehicles, the log books were reviewed and participants were debriefed after they completed the questionnaire. The issues discussed in the debriefing were largely the result of comments written by the participants in the log books (some very detailed), as well as comments written in the margins of the questionnaire. All entries into the log books, comments written into the questionnaire margins, and notes made by the researcher during the debriefing are being transcribed for future evaluation.

4.2.3 Focus Group

Three sessions of focus group have been held to date, with a total of 15 participants in attendance. These sessions are video taped, as well as audio taped, and transcriptions are being prepared. In each of the three sessions the same 17 questions have been asked. While the responses vary considerably, the overall response to having experienced the ACC system has been very favorable. Because of the limited number of participants to date in the focus group sessions, no detailed summary is provided here. However, current indications are that additional useful information on driver views and experience will be obtained when the responses to the following 17 questions are considered.

Ql : In what situations was adaptive cruise control most useful?
  - Consider traffic density, road type, and weather conditions.
  - What features of adaptive cruise control did you find most beneficial?

Q2: When was the adaptive cruise control system least useful?
  - Consider traffic density, road type, and weather conditions
  - What additional features would you like to have with adaptive cruise control?

Q3: How convenient did you find using adaptive cruise control?
  - Was it difficult to learn to operate?

Q4: How similar to your own driving behavior do you think the adaptive cruise control system operated?
  - If the system was different, how did it differ from your driving behavior?

Q5: Did you feel comfortable with the headway distances available for use?
  - Should they have been longer or shorter?
  - Should there have been more levels?

Q6: Where the controls and display for the ACC system easy to use and easy to see.
  - Were there other types of information you would like displayed?
  - Where else might you place the controls/display?

Q7: What impact did adaptive cruise control have on your sense of comfort?
  - Consider traffic density, road type, and weather conditions

Q8: Did the system ever make you feel too comfortable?
  - Did you feel that you might fall asleep easily?

Q9: Did the system ever track false targets (i.e. cars in adjacent lanes)?
  - Briefly explain the conditions under which this occurred.

Q10: Did the system ever track phantom targets (i.e. vehicles that did not exist)?
  - Briefly explain the conditions under which this occurred.

Q11: Was there ever a situation when you didn't understand whether or not the system was working properly?
  - Briefly explain.
  - If so, what was your strategy?

Q12: What do you think of the adaptive cruise control system's rate of acceleration:
  - when passing?
  - when closing a gap?

Q13: What do you think of the adaptive cruise control system's rate of deceleration:
  - in response to slower moving vehicles?
  - in response to "cut-ins"?

Q14: When a difference in vehicle speeds required you to use the brake, was it difficult to learn when braking was required?
  - Would an audible tone (warning) be useful?

Q15: What impact did adaptive cruise control have on your sense of safety?
  - Consider traffic density, road type, and weather conditions
  - Did you feel more or less safe driving with ACC as compared to manual driving?

Q16: When driving with ACC engaged, were you ever disturbed by an event involving a stopped vehicle -- and the fact that the ACC system does not respond to stopped objects?
  - Do you feel the system should respond to stopped objects

Q17: Would a greater degree of ACC deceleration, using the brake system, have been helpful for dealing with a wider range of traffic situations?

4.3 Implications of Results for the Traffic System as a Whole

In this section, test results are examined for their preliminary (and fairly obvious) implications on the performance of the traffic system as a whole. The questions of system safety, traffic throughput, and fuel usage are addressed. This information provides a starting point for an expanded evaluation of ACC.

Implications for Safety

Although the overall Field Operational Test is configured to emphasize safety-related questions, the data processing to date can only give limited address to this subject.

First, the subjective responses by the driver/participants, reported in section 4.2, strongly suggest that from the drivers' perceptions of safety, no significant new risks were posed by the ACC system tested here. Or, stating it more rigorously, the perceptions acquired here during a limited, novelty-laden, phase of driving confirm that no significant safety hazards presented themselves. It is recognized, however that subtle but powerful safety issues may emerge only after developing long-term adaptation of driving behavior, a richer matrix of driving conditions, and perhaps the appearance of low-probability traffic conflicts and anomalies.

At this preliminary stage of FOT experience, we note the following properties of the system that might relate to safety (more details regarding these observations are provided later in this section):

- no crashes with ACC engaged
- no reported near-miss events
- no complaints of a proximate-hazard concern
- measured headway time (H_{tm}) with ACC is larger than H_{tm} without ACC
- relatively pleased responses despite an approximate variation of 10% in H_{tm}
- some comments revealing relaxed vigilance
- no significant note of problems encountered with stopped vehicles
- most complained about a sluggish resume acceleration (though it may have some safety implications, it is not a production feature)
- Hindrance (V/V_{sec}) is virtually 1.0 in the current data (people seem to use the system almost exactly like CCC).

Quantitative data do provide some supplemental evidence of safety-related distributions. Shown in Figure 74, for example, the probability distribution of the "DecelAvoid" variable is shown for both manual and ACC-engaged operations for the filtered (i.e., trip length > 10 miles, avg. speed > 30 mph) set of trips. The DecelAvoid measure expresses the minimum value of deceleration needed at any moment to resolve the current headway conflict, whenever a target vehicle is detected ahead. The data show probability distributions dominated by values near zero (actually, below 0.0075 g's). Comparing the probability values for ACC and manual modes of control at this lowest g-level bar, we note that ACC shows a probability of 0.97 compared to 0.935 for manual driving. The remaining probabilities falling at higher g levels (e.g., 1.00 - 0.97 = 0.03 for ACC and 1.00 - 0.935 = 0.065 for manual) make it clear that the combination of driver choice of ACC-suitable conditions and the sustained control activity of the ACC system avail it a much more benign conflict environment than with manual driving.

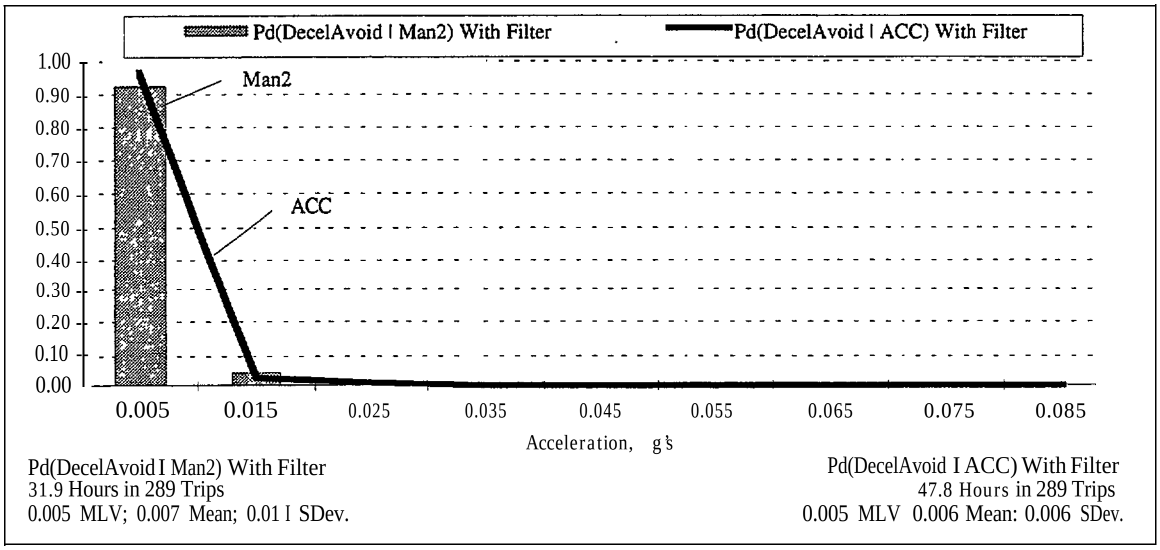
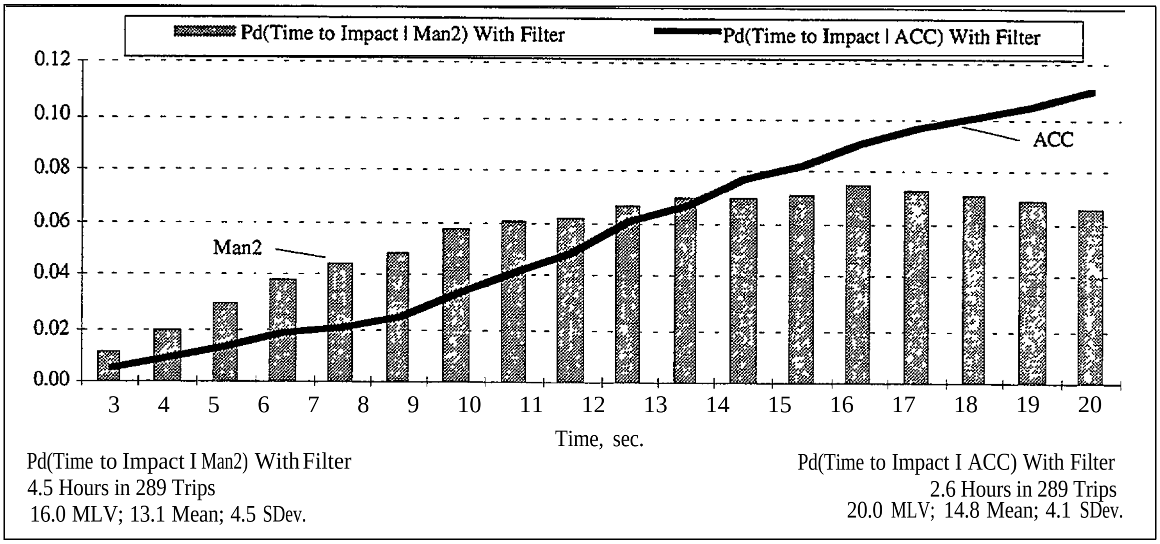


Figure 74. Probability density of Decel-to-Avoid in manual and ACC driving

Moreover, deceleration levels above approximately 0.05 g's appear in much less than one-half of one percent of travel time during these higher speed trips. Thus, we see again the remarkably low incidence of elevated deceleration levels appearing normally on freeways. On the one hand, this finding seems to help explain much of the satisfaction that drivers report with an ACC system that is limited to a 0.07g level of authority. At the same time, it speaks a sobering caution for automatic systems designed to deliver much higher levels of deceleration, for example the 1/4-g levels targeted by pending ACC systems in Europe. That is, the occurrence of 1/4-g braking on a freeway is so rare that its automatic actuation must be done only when warranted by a very high confidence level that the rare, but necessary, response is indeed called for.

Distributions of time-to-impact computed for manual and ACC driving when targets were detected ahead, are compared in Figure 75. We first see that values below 3 seconds occur less than 1% of the time. Further, manual operations result in almost twice the incidence of times-to-impact that are within 8 seconds. While, again, this contrast results from both the drivers' appraisal of conditions suitable for ACC operation and from the controller's performance within those conditions, the net outcome is that ACC operates with less of the conflict that connotes impact risk.



Pd(Time to Impact I Man2) With Filter
4.5 Hours in 289 Trips
16.0 MLV; 13.1 Mean; 4.5 SDev.

Pd(Time to Impact I ACC) With Filter
2.6 Hours in 289 Trips
20.0 MLV; 14.8 Mean; 4.1 SDev.

Figure 75. Probability density of Time-to-Impact in manual and ACC driving

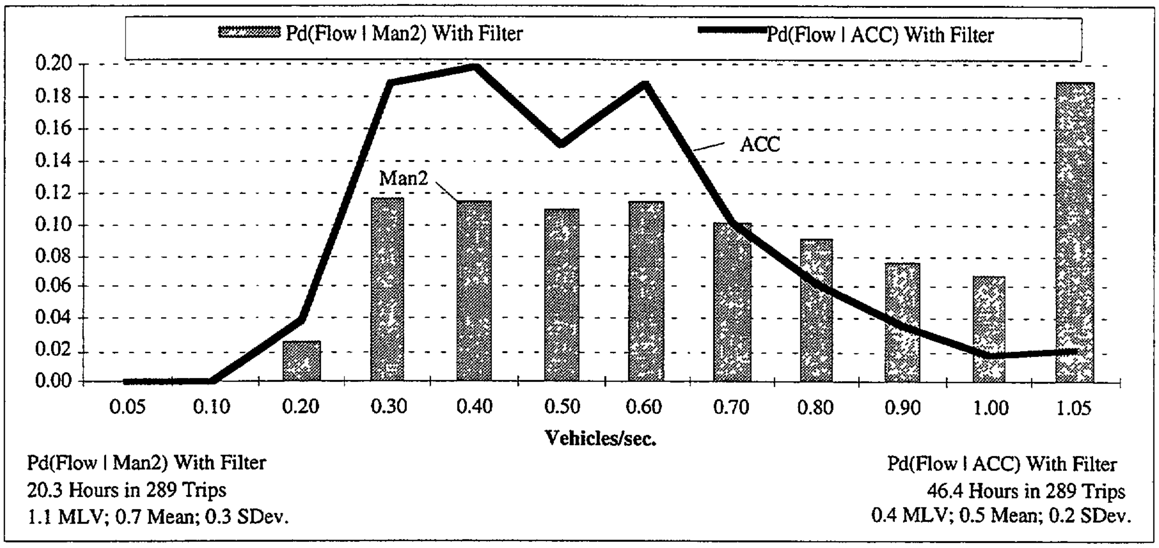
Clearly, much more needs to be done to examine the safety implications of this field operational test. It is expected that more instruction will come from subjects operating the vehicle for 5-week periods and from the careful examination of results in the time domain, as found in the serial stream of data by the detection of transitions in control state.

Implications for Traffic Flow

At any given moment in any local traffic environment of southeastern Michigan, only a single ACC-equipped vehicle is likely to have been present, if any. Thus, no macro detection of traffic during this test could possibly have captured the implications of ACC operation for the traffic flow that may prevail in the future, at high penetrations of ACC vehicles. Accordingly, we must suggest various traffic-impact inferences from piecemeal observations of the immediate experience of the individual equipped vehicle.

In this section, a few differing views of the driving experience are presented as they appear to address some traffic-related variables. In the end, of course, we hope to discern the possible impact of ACC operations on the throughput capacity of freeways at moderate to heavy levels of loading. At the light end of the traffic loading spectrum, the traffic will be expected to move at rated (regulated) speeds, or above, notwithstanding the presence or absence of ACC. At the other, very congested, end of the spectrum, ACC is assumed not to be chosen as a control mode because of the high levels of conflict which seem to induce manual-only operation.

Shown in Figure 76 is the bottom-line illustration of apparent traffic throughput impact, based upon the filtered trips. The figure presents the so-called Flow variable computed continuously within the instrumentation package and stored as the Flow histogram. The Flow variable is defined by the ratio, V/(R + L), where V and R represent the host velocity and range variables addressed many times previously and L represents the nominal length of the passenger car. The Flow measure is expressed as the number of vehicles per second passing a given point on the highway and is computed only when a target vehicle has been detected ahead.



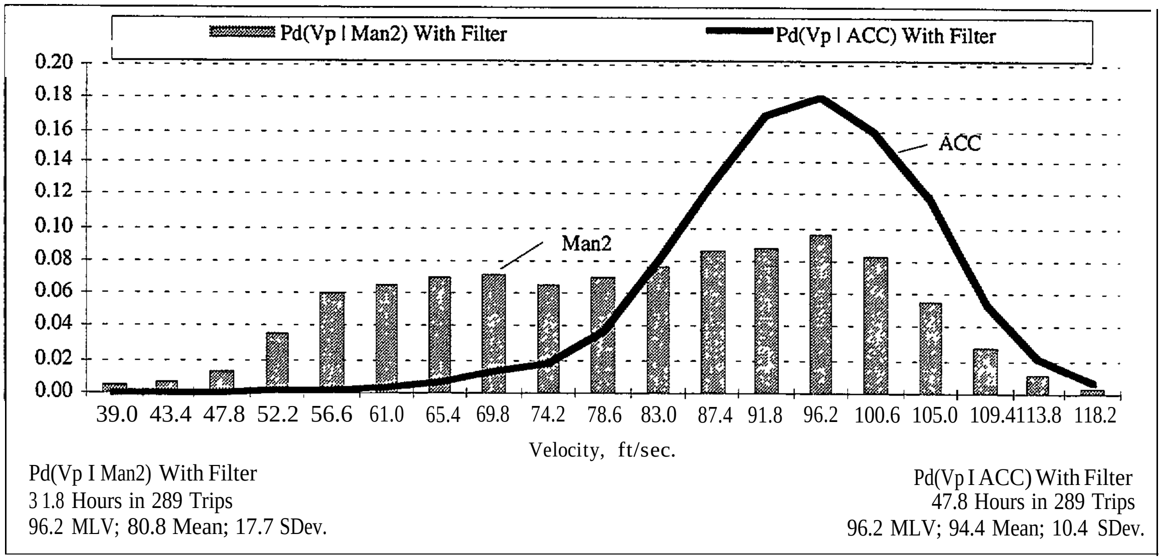
Pd(Flow | Man2) With Filter
20.3 Hours in 289 Trips
1.1 MLV; 0.7 Mean; 0.3 SDev.

Pd(Flow | ACC) With Filter
46.4 Hours in 289 Trips
0.4 MLV; 0.5 Mean; 0.2 SDev.

Figure 76. Probability density of Flow in manual and ACC driving

Figure 76 shows that the ACC system exhibits generally lower values of the Flow variable than are accrued under manual driving. The mean values of Flow under the ACC and manual modes of control are 0.52 and 0.59, respectively. Clearly, most of the contrast between the Flow measures under the two modes of control is attributed to the large (18%) block of manual results lying in the "end bin" at 1.05 vehicles/second and above. This result appears to be due to the short values of headway range that were often employed during manual driving.

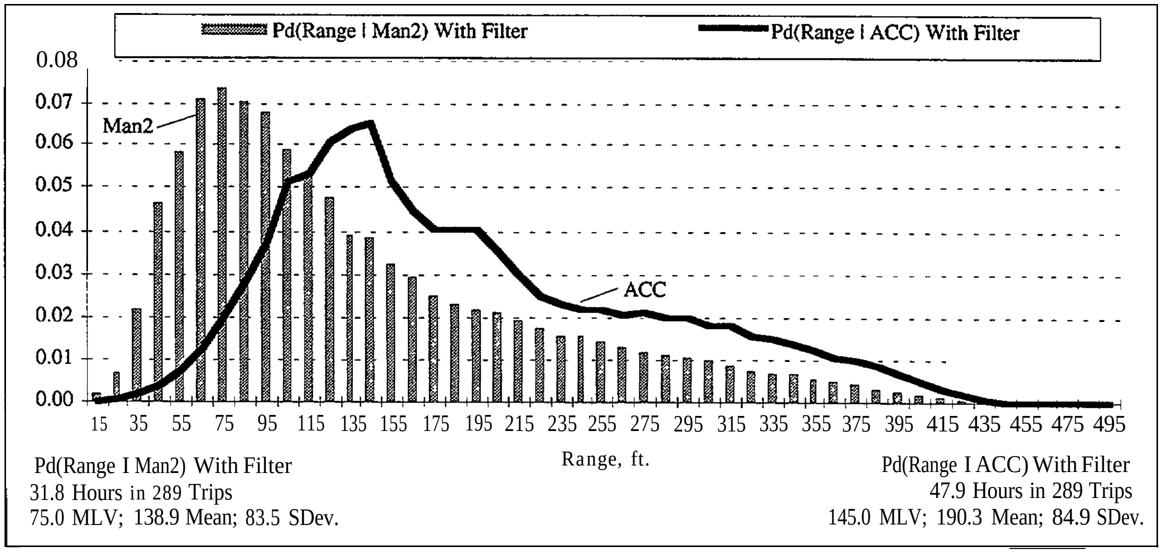
While the data appear at first blush to imply a negative impact of the ACC function on highway capacity, the apparent preference for ACC usage under traffic conditions that are rather free-flowing suggests that no impact on heavier, capacity-determining, traffic flow would be encountered because the system would be turned off. Recapitulating results presented earlier in the report to make this point, Figure 77 shows again that ACC is used almost exclusively when traffic speeds (i.e., Vp values) are higher, above 80 ft/second or so. Thus, it would appear that the longer range values kept during ACC operation, as shown again in Figure 78, are associated with high-speed, relatively free-flowing traffic for which the capacity limitations of the highway are more or less moot.



Pd(Vp I Man2) With Filter
3 1.8 Hours in 289 Trips
96.2 MLV; 80.8 Mean; 17.7 SDev.

Pd(Vp I ACC) With Filter
47.8 Hours in 289 Trips
96.2 MLV; 94.4 Mean; 10.4 SDev.

Figure 77. Probability density of traffic speed (V,) in manual and ACC driving



Pd(Range I Man2) With Filter
31.8 Hours in 289 Trips
75.0 MLV; 138.9 Mean; 83.5 SDev.

Pd(Range I ACC) With Filter
47.9 Hours in 289 Trips
145.0 MLV; 190.3 Mean; 84.9 SDev.

Figure 78. Probability density of Range in manual and ACC driving

Manual driving, on the other hand, includes much more operation at the reduced travel speeds (Figure 77) and shorter range values (Figure 78) that appear commonly in quite congested traffic. Thus, it appears, that the driver/participants in this field test opted to control the vehicle manually in virtually all of the high-conflict situations in which the ultimate capacity of the highway becomes an issue.

As an associated traffic issue, Figure 79 presents the so-called "Hindrance" measure for both conventional cruise (CCC) and ACC operations. This measure expresses the ratio of the host vehicle velocity, V, to the set speed, Vset. With ACC engaged, the ratio of these values indicates how much the prevailing traffic conditions have impeded the driver from continuously sustaining the set speed value due to headway control.

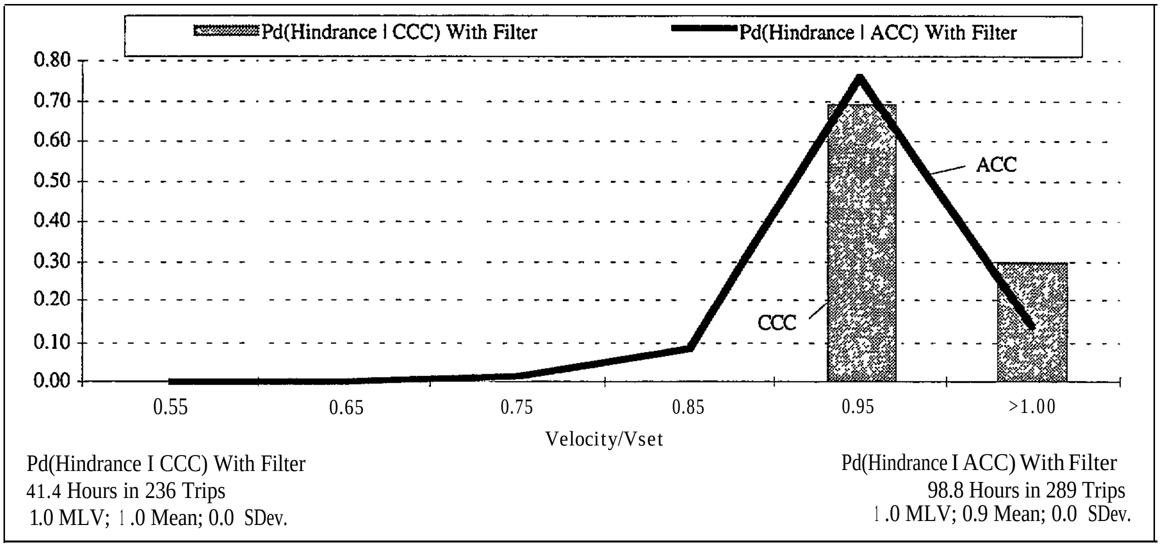


Figure 79. Probability density of Hindrance in manual and ACC driving

We see that the ACC system spends approximately 75% of the time at approximately 95% of its Vset value. This result seems to be partially explained by the testimony of many participants that they tend to select Vset values rather near to the prevailing speed of traffic, thus not significantly falling below Vset even when they encounter a headway-control episode due to a vehicle ahead. Such a pattern of Vset selections is noted to be very nearly mirrored to the learned practice of selecting set speeds with conventional cruise control. That is, CCC is simply unusable in the presence of other traffic unless one adjusts the set speed to virtually match that of nearby traffic.

Considering the CCC data in the figure, the results falling below a hindrance value of 1.0 are something of a puzzle since the system is only a speed controller. Thus, the 68% of all CCC time spent around the hindrance value of 95% can only depict control error of some sort, as if the system has a bias for negative errors relative to the Vset value. Closer examination of this result will be given later in the study.

Implications for Fuel Usage

Shown in Figure 80 is a plot of the longitudinal acceleration histogram for the host vehicle in both the manual and the ACC-engaged conditions. The data show that the ACC system keeps more than 85% of its positive and negative accelerations within 0.01 g's or less, while manual operations result in only about 56% of all travel within the same band. Since the implied speed fluctuations are opposed by speed-squared aerodynamic drag and other nonlinear losses, they imply reduced fuel economy. Accordingly, the preliminary results imply that ACC driving should cause fuel usage to decline relative to manual driving.

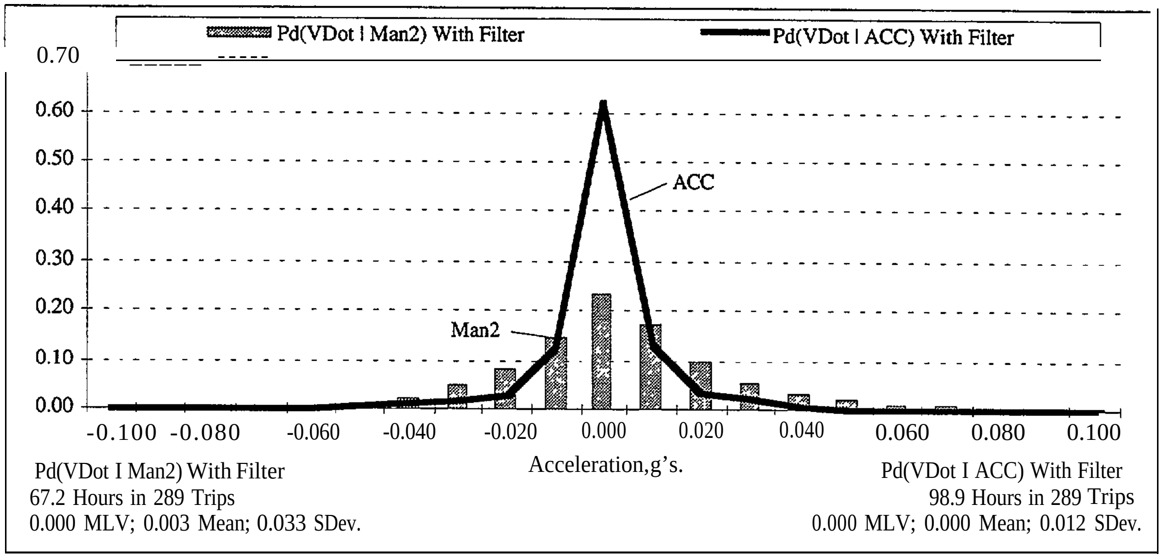


Figure 80. Probability density of Acceleration in manual and ACC driving

5. CONCLUDING STATEMENTS

5.1 Summary of Preliminary findings.

At this stage of the Field Operational Test, all the various systems are performing successfully. The cars run. The sensors work well but they are prototypes that require maintenance and attention, so sensor checking is needed to keep the vehicles in proper working order. The data acquisition system, although complex, with two computers and video, GPS, and cellular phone equipment as well as data storage and processing functions has performed well. The control algorithms, which are quite simple, perform reliably and the drivers indicate that they find the ACC system to be comfortable and convenient to use.

The preliminary results from the initial FOT experience indicate that drivers tend to enjoy driving with ACC. For the most part they find it comfortable and convenient. It seems to reduce stress, particularly on longer trips. The objective data indicate that the ACC system causes drivers to travel at longer clearance gaps than those they use when driving manually. This appears to be not only because the ACC maintains longer headways but also because drivers do not choose to use ACC when they see driving conditions that compel them to use short headways. (This tendency to drive manually when there is competition for gap space on the highway is even more apparent for conventional cruise control.) For ACC, the net effect is that risky driving situations involving short headways are much more likely to occur during manual driving than they are to occur during ACC driving. In addition the ACC system slows the vehicle when a slower preceding vehicle is encountered, thereby drawing the driver’s attention to the forward scene and thereby contributing to the driver’s feeling of comfort and safety.

An interesting finding with respect to driver age is that drivers from different age groups tend to prefer different amounts of clearance time to the preceding vehicle. This ACC system provides the driver with the means for selecting farther, closer, or an intermediate headway clearance. These settings correspond to 2.0, 1 .O, and 1.4 seconds of clearance time, respectively. Given these choices, the younger drivers tended to use 1 .O and 1.4 seconds of headway with almost no use of 2.0 seconds of headway clearance while the older drivers almost never used 1 .O seconds of headway and they have a preference for 1.4 or 2.0 seconds. Apparently an adjustable headway clearance feature will aid in encompassing the preferences of the driving population.

With regard to the difference between ACC driving and manual driving, the preliminary results indicate that:

- Drivers tend to do riskier, more demanding driving at short headway in the manual mode of headway control.
- They use the ACC system when they can travel at highway speeds without frequent interruption.
- Drivers select set speeds at the speed they wish to travel thereby operating much like they would with conventional cruise control when there is not a slower moving preceding vehicle.
- Younger drivers tend to use shorter headway time selections than older drivers do when using ACC. (This fits with the behavior of these age groups when driving manually.)
- The incidence of near approaches to preceding vehicles is much less when ACC is used. (This is because drivers tend to drive closer manually and also because drivers do not tend to use ACC when they anticipate that close headway may be likely.)

The results so far support the following propositions:

- To the extent that remaining further from the preceding vehicle is safety beneficial, ACC driving will be safer than manual driving is now.
- Since drivers do not use ACC when the situation is risky, or when they want to take risks, ACC might not have much influence on the accident record (or traffic flow for that matter).

However, there is the possibility that ACC will provide more uniform headway and speed control and thereby facilitate greater flow at capacity. There is also the possibility that ACC will provide the driver with a deceleration cue that will reduce the incidence of rear-end collisions in which the driver is inattentive.

Drivers find the ACC system easy to use, and they are comfortable using it. They seem to understand what the ACC system does and when they will enjoy using it.

5.2 Anticipated Amount of Information and Its Significance.

The current projection for the total number of drivers participating in the study is 108. This sample size is based upon the following assumptions:

- At least eight vehicles will be fully operational for the duration of the field operational test.
- The turnaround of cars from one participant to the next will not exceed two working days.
- Data collection will continue up to, and including, the first week of September 1997.

On March 18, 1997, data collection for the first 47 drivers is expected to be completed. Of these, 46 drivers are two-week exposures and 1 is a five-week exposure. Beginning with the week of March 9, 1997, and ending the first week in September 1997, and assuming eight operational cars, there are 200 car weeks (25 weeks times eight vehicles). We are currently projecting that at the end of the project there will be data on 14 drivers per combination of age group (20 to 30, 40 to 50, 60 to 70) and cruise-control usage (user, nonuser), balanced for gender, for the two-week exposure group. In the five-week exposure group the projected number of participants is eight in each of the three age groups (balanced for gender). Cruise-control usage is not an independent variable in the five-week exposure group. This would result in a total sample size of 108 drivers (84 drivers with two-week exposures and 24 drivers with five-week exposures).

Later on we will perform further analysis of the expected statistical power of our data. Currently we believe that the number of driver/participants in each cell of our experimental design will be adequate to produce statistically reliable results at the end of the field testing.

Extrapolating from the information for 35 drivers as given in Section 3.6, we will have approximately three times as much information at the end of testing as that used in preparing this report. This means approximately 8,000 trips, 80,000 miles, and 2,200 hours of driving by 108 different people. (These estimates are probably low because there were no five-week participants in the original 35 drivers.)

However, there will be much more information to report since we have just begun to process the data. We have not yet gone into the time history information nor the transition tables. The database on matters related to headway control will be extensive and unique. There will be a CD ROM containing the measured data for each driver and another CD ROM containing the video data for each driver (in total 216 CD ROMs for 108 drivers). In addition, there will be a database of approximately 150 megabytes containing the histograms, transition tables, and other information as transmitted by cellular phone for all drivers. Clearly, a great deal of skill and understanding will be needed to grasp and communicate the meaning of this data. In that regard, this interim report represents a significant step in learning how to process and interpret the data that are now and will be in front of us in the future.

5.3 Where This Is All Going and What Might Be Done Next.

The equipped vehicles will be deployed in operational testing to the maximum extent supportable by the project team. On the one hand, we feel that the histogram-based results reported to date are unlikely to change as more test subjects are added, since driving behaviors and the range of operating conditions have been more or less circumscribed already. On the other hand, the final report is expected to contain a) more statistical power for defining low-probability driving phenomena, b) substantive evidence of the extent of driver adaptation to ACC over four continuous weeks of usage, c) extensive examination of time-domain events (as a complement to the time-independent histogram data), and d) various enhancements of the overall data such as through reverse-geocoded road-type designations and other expansions in the database.

Relative to item (a), above, the remainder of the FOT will involve approximately 2.5 times as much ACC driving exposure as was accrued to date. Thus a large increase in statistical power of the data is pending.

Relative to (b) the engagement of 24 drivers operating the vehicle for five weeks should provide a good opportunity for the novelty effect to subside and for at least suggesting the trends of adaptation, if anything measurable exists. In this regard, it is recognized that a potential relaxation in the driver's vigilance with extended use of ACC is of special interest.

Relative to item (c), it is expected that the process of driver intervention on ACC can be examined in detail beginning with event-identifiers that exist in the so-called transition tables of the dataset. Transitions out of the ACC control mode due to braking or due to activation of the "Cancel" button are all associated with specific time points in the 10Hz-recorded time histories. Extensive study of the mode-transitions is expected to provide a dynamic profile of the driver as an ACC-intervener (i.e., the role by which the driver acts to supervise ACC operation and provide the "outermost loop" of vehicle headway protection.)

Relative to (d), data enhancement to include road-type coding is underway and will be implemented for all travel in southeastern Michigan. Travel outside of that zone will not be reverse geocoded within this study. The road-type coding should help, for example, in isolating manual versus ACC comparisons to freeways, rural two-lane roads, or other defined types of facilities in which significant ACC usage has appeared. Other enhancements may also become attractive such as rebinning of selected histograms and the computation of additional or modified variables derived from measured raw data.

As possible extensions to the field test, it is recognized that a major need exists to explore naturalistic operation of ACC systems that are braking-assisted. In this regard, we note that the worldwide auto industry is tending toward systems having a deceleration authority in the range of 0.2 g's-in contrast to the nominal 0.07 g level of authority that attends our current throttle- and downshift-controlled system. In a complementary NHTSA-sponsored study that is proceeding through the summer and fall of 1997, UMTRI will be conducting preliminary testing of such a braking-assisted ACC package using another 1996 Chrysler Concorde that incorporates a so-called *smart booster* device for brake-by-wire control. Should the pilot testing of this system show it to be suitable for operation by lay drivers in unaccompanied testing, a supplemental phase of ACC field operational testing would seem to be in order.

It may also be attractive to continue employing the current FOT test cars for much longer exposure periods or perhaps under a more focused study of a certain subset of the driving population. The value of any such extensions may become apparent as the remainder of the FOT data are gathered and processed.

6. REFERENCES

1. Slotine, J-J.E., and Li, W. *Applied Nonlinear Control.,* Prentice Hall, Englewood Cliffs, New Jersey, 1991.
2. "Test Definition and Project Plan," delivered to NHTSA as part of the project entitled *Intelligent Cruise Control Field Operational Test,* DTNH22-95-H-07428, The University of Michigan Transportation Research Institute, Ann Arbor, Michigan Feb. 29, 1996.
3. "Operational Test Plan," delivered to NHTSA as part of the project entitled *Intelligent Cruise Control Field Operational Test,* DTNH22-95-H-07428, The University of Michigan Transportation Research Institute, Ann Arbor, Michigan June, 1996.
4. Fancher, P., Bareket, Z., "Evaluating Headway Control Using Range Versus Range-Rate Relationships," *Vehicle System Dynamics,* Vol. 28, No. 8, 1994, pp. 575-596.
5. Fancher, P., Bareket, Z., Sayer, J., Johnson, G., Ervin, R., Mefford, M., "Fostering Development, Evaluation, and Deployment of Forward Crash Avoidance Systems (FOCAS)," Annual Research Report ARR-5-15-95, NHTSA Contract No. DTNH22-94-Y-47016, May 1995.
6. Fancher, P., Sayer, J., Bareket, Z., "A Comparison of Manual Versus Automatic Control of Headway as a Function of Driver Characteristics," 3rd Annual World Congress on Intelligent Transport System, Orlando, FL, October 14-18, 1996.
7. Fancher, P.S., Bareket, Z., Bogard, S., M&Adam, C.C., and Ervin, R.D. "Tests Characterizing Performance of an Adaptive Cruise Control System," Presented at the 1997 International Congress and Exposition Detroit, MI, SAE Paper No. 970458. .