U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

www.nhtsa.dot.gov
nhtsa
people saving people

DOT HS 809 886 **May 2005**

Automotive Collision Avoidance System Field Operational Test

Final Program Report

Technical Report Documentation Page

1. Report No.
DOT HS 809 886

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Automotive Collision Avoidance System Field Operational Test (ACAS FOT)
Final Program Report

5. Report Date
March 2005

6. Performing Organizational Code
General Motors Corporation

7. Author(s)

8. Performing Organization Report No.

9. Performing Organization Name and Address
General Motors Corporation
Research and Development Center
30500 Mound Road
Warren, MI 48090

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTNH22-99-H-07019

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
Office of Impaired Driving and Occupant Protection
400 Seventh Street, S.W.
Washington, DC 20590

13. Type of Report and Period Covered
Final Program Report

14. Sponsoring Agency Code

15. Supplementary Notes
See also the following report: *Automotive Collision Avoidance System Field Operational Test Methodology and Results*

16. Abstract

The Automotive Collision Avoidance System field operational test (or ACAS FOT) program was led by General Motors (GM) under a cooperative agreement with the U.S. Department of Transportation. This report summarizes the activities of the entire program, with an emphasis on efforts that occurred after the last program Annual Report. The ACAS system consisted of Adaptive Cruise Control (ACC) and Forward Collision Warning (FCW) systems that were developed and integrated by GM and Delphi Corporation in preparation for the FOT conducted by the University of Michigan Transportation Research Institute. The FOT involved exposing a fleet of 11 ACAS-equipped Buick LeSabre cars to 12 months of naturalistic driving (137,000 miles of driving were accumulated). The 96 test participants were lay drivers from southeastern Michigan who drove these cars as their personal vehicles for several weeks. Data gathered included over 300 data signals, including video samples of the forward driving scene and driver's face. ACC was found to be benign from a traffic safety perspective. Both ACC and FCW reduced the occurrence of short (e.g., <1 sec) headways, with the ACC reductions being substantially more marked and robust across driving conditions. While incidents were found during manual driving in which the FCW may have contributed to a timely driver response to an emerging rear-end crash conflict, the frequency or magnitude of such conflicts were unaffected by FCW presence. Questionnaire, interview, and focus group data indicated that ACC was widely accepted, whereas FCW acceptance was mixed. These data have suggested numerous methods for reducing the occurrence of FCW false alarms that should lead to broader FCW customer acceptability.

17. Key Words
Forward crash warning, adaptive cruise control, crash avoidance, crash warning, FCW, ACC, ACAS, longitudinal control, rear-end crash, driver assistance systems

18. Distribution Statement
Unrestricted

19. Security Classif. (of this report)
None

20. Security Classif. (of this page)
None

21. No. of Pages
107

22. Price

Form DOT F 1700.7 (8-72) Per FORM PRO/Delrina 04/04/94 Reproduction of completed page authorized

Table of Contents

List of Figures

List of Tables

Acronyms

Acronym	Definition
ABS	Antilock Braking System
ACAS	Automotive Collision Avoidance System
ACC	Adaptive Cruise Control
APL	Applied Physics Laboratory, John Hopkins University
CAN	Controller Area Network
CCC	Conventional Cruise Control
CIPS	Closest In-Path Stationary Object
CIPV	Closest In-Path Vehicle
CNF	Consensus-Based Fusion
COF	Confidence-Based Fusion
CW	Collision Warning
DAS	Data Acquisition System
DCS	Delphi Chassis Systems
DES	Delphi Electronics & Safety
DF	Data Fusion
DGPS	Differential Global Positioning System
DVI	Driver Vehicle Interface
EDV	Engineering Development Vehicles
FCW	Forward Collision Warning
FLR	Forward Looking Radar
FMCW	Frequency Modulated Continuous Wave (radar)
FOT	Field Operational Test
FOV	Field of View
GM	General Motors
GPS	Global Positioning System
HUD	Head-Up Display
IBC	Intelligent Brake Control
NHTSA	National Highway Traffic Safety Administration
POV	Principal Other Vehicle
R&D	Research & Development
RCAP	Radar Collision…
RD	Radar Processor
RDP	Radar Data Processor
RDP	Radar Data Processor
RKE	Remote Keyless Entry
SMCC	Stepper Motor Cruise Control
SV	Subject Vehicle
TASIM	Threat Assessment Simulation Tool

Acronym	Definition
TCS	Traction Control
TS	Target Selection
UMTRI	University of Michigan Transportation Research Institute

1.0. Executive Summary

The Automotive Collision Avoidance System Field Operational Test (ACAS FOT) project was conducted as a Cooperative Agreement initiative between the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) and General Motors Corporation (GM). The goal of the ACAS FOT project was to further the science and understanding of Forward Collision Warning (FCW) and Adaptive Cruise Control (ACC) systems by conducting an extensive FOT with lay drivers.

The FOT was designed to address numerous issues dealing with the use and deployment of FCW and ACC systems. These issues revolved around two major areas of interest. First, what are the potential implications of these systems from a traffic safety perspective? Second, what are the implications of these systems from a driver acceptance perspective?

As the team leader for this project, GM was responsible for program management, overall integration of the various subcomponents and their associated software, threat assessment functions, and activities associated with predictions of vehicle location and road geometry. Delco Electronics & Safety (DES)[1] was responsible for the forward-looking radar (FLR) system, the ACC system, the vision and scene tracking systems, the target selection system, and the driver vehicle interface (DVI) system that included a head-up display (HUD), which was used to display ACC- and FCW-related information. HRL Laboratories[2] was responsible for the data fusion (DF) system designed for the purpose of accurately determining forward road geometry. Delphi Chassis Systems (DCS) was responsible for developing the intelligent brake control subsystem for the ACC system. Finally, the University of Michigan Transportation Research Institute (UMTRI) was responsible for the design and implementation of the data acquisition system (DAS), as well as the design and conduct of the formal FOT. Both UMTRI and GM were responsible for conducting the analysis of the FOT data.

The ACAS FOT program began in June 1999, and was completed in November 2004. It was organized into two phases. Phase I ran from June 1999 to December 2001. In this phase, the various ACAS subsystems were selected and developed using five Engineering Development vehicles. Once satisfactory performance was achieved, these subsystems were then integrated into a single prototype vehicle.

Phase II of the ACAS FOT program began in January of 2002 and was completed in November of 2004. In this phase, lessons learned from the prototype vehicle were used to install the ACAS system into two pilot phase vehicles with FOT-deployment-level packaging. Further improvements were then made to the system and these two vehicles along with 11 deployment vehicles were then built-up for a total of 13 deployment vehicles available for the FOT.

The advanced ACAS system that was developed and evaluated in this project consisted of two subsystems that were integrated for the specific needs of this program. These consisted of an FCW system and an ACC system, both using an FLR. These two systems were developed, integrated and ultimately packaged in the 13 Buick LeSabre 2002 model year deployment vehicles. These vehicles were then given to 96 test subjects who, after receiving training on the ACAS system, drove these vehicles as their own personal cars for three or four weeks. The 96 lay drivers chosen for this experiment were randomly selected from three age groups balanced for gender. During the first week of each subject's use, the ACAS features were not available to the drivers. During the subsequent weeks, the ACAS features were available. A robust data acquisition system was employed to capture a wealth of data from each driver's use of the ACAS cars. These data included a myriad of signals

---

[1] Formerly Delphi-Delco Electronic Systems.

[2] Formerly Hughes Research Laboratory.

from the host car’s J1939 data bus as well as visual images of the road ahead, and the driver’s face. Radar tracks of cars, stationary objects, and other “targets” ahead were detected by the radar. Altogether some 1.4 terabytes of information were collected which were available for analyses. Interviews, questionnaires, and focus groups were also employed to capture the test participants’ subjective evaluations of their driving experience with the ACAS system.

When the FOT began in March 2003, the initial acceptance response of the ACAS system was much less positive than was reported by participants during earlier pilot testing. This dissatisfaction was based on what drivers considered to be “nuisance alerts” (or false alarms). About half of the alerts were due to stationary objects along the roadside being detected by the radar and erroneously classified as “threats” to the host vehicle. Many other alerts occurred under conditions that drivers felt did not warrant an alert.

To address this situation, a three-phased approach was implemented. First, in order to ensure sufficient information was garnered from the original algorithm (called Algorithm A), a total of 15 drivers drove with this original set of software. While this testing was underway, an improved algorithm was quickly developed and installed on the ACAS vehicles for a second set of 15 drivers (called Algorithm B). This software included several improvements over Algorithm A and also eliminated all alerts from stationary objects that the radar had never before seen moving during the approach (e.g., a roadside sign). Algorithm B still issued alerts to stationary objects that the radar had previously seen moving during an approach, such as when a lead vehicle came to a stop. Finally, a very ambitious set of software was developed (called Algorithm C) which restored alerts from “never before seen moving” stationary objects and added a host of features to further reduce the number of nuisance alerts. The remaining 66 test subjects drove their vehicles with Algorithm C as the operating software.

It is important to emphasize that the FCW and ACC subsystems examined could potentially reduce the incidence of rear-end crashes, as well as the harm caused by such crashes, primarily in two ways. First, these systems could reduce the amount of tailgating behavior, that is, the amount of time drivers spend following a vehicle ahead at short time headways under “steady-state” driving conditions. A lengthening of headway times during car following can provide the driver with additional time to respond should an unexpected rear-end crash scenario unfold. Second, the FCW system may at times (e.g., when the driver is distracted) alert the driver to an approach (or closing) conflict earlier than the driver would have detected such a conflict. These approach conflicts, as well as tailgating behavior, can ultimately lead to a rear-end crash.

Results indicated that both the FCW and ACC subsystems reduced the incidence of tailgating behavior relative to manual driving without the support of these systems. Overall, the incidence of less than 1-second time headways were 26 percent with FCW system support, and 30 percent without FCW system support. A more detailed examination indicated that this effect was restricted to daytime driving and freeway driving conditions. More notably, the incidence of less than 1-second time headways was three times lower during ACC relative to manual driving. This may in part explain why drivers’ ratings of whether the system increased their driving safety were more positive for ACC than corresponding ratings for FCW. The more dramatic effects of ACC on tailgating behavior are in all likelihood a direct result of the system preventing the driver from selecting an ACC gap (or time headway) setting of less than one second following time. The exact source of the FCW headway lengthening effect on tailgating is less clear, but can be potentially attributed to either the FCW tailgating display (or possibly a transfer of training from the ACC system) increasing the driver’s general awareness of their car following behavior.

On the other hand, evidence that the FCW and ACC systems reduced approach conflict behavior was mixed. Approach conflict metrics examined included the frequency of imminent alerts (where "silent" alerts were examined when the ACAS system was not activated), required deceleration to avoid impact and time-to-collision at brake onset, as well as peak conflict measures during approach events. Results indicated that the FCW system did not have a broad effect on reducing approach conflict behavior. Nevertheless, a small number of FCW imminent alert incidents were identified that were judged to have increased driver's awareness of a potential rear-end crash and/or encouraged the driver to brake. Hence, the potential for the FCW system to help the driver avoid rear-end crashes and reduce the harm caused by such crashes was demonstrated.

With respect to ACC, it can be hypothesized that this system has at least the potential to increase approach conflict behavior, either because of the manner in which ACC controls the vehicle in approach situations and/or due to the choices drivers make in allowing ACC control in their assumed supervisory role. However, results indicated that ACC did not negatively impact approach conflict behavior. On the contrary, it appears that ACC may reduce risks associated with lane changes by decreasing passing behavior, and increasing the range at which drivers initiate certain lane-change-and-passing maneuvers on freeways (presumably to avoid ACC braking during passing).

Although results did not indicate any unintended safety consequences of these systems (e.g., no notable increases were observed in secondary task behavior), it should be noted that the increased percent driving time with ACC relative to conventional cruise control (overall, 37 percent versus 20 percent usage) was evident across all driving conditions, with the most notable increase of ACC usage occurring under heavy traffic conditions. In addition, the rare occurrence of events in which the ACC system provided the maximum level of ACC braking (about 0.3 g's) was observed almost exclusively under surface street conditions. However, the rate of these rare events dropped substantially over the course of the three weeks of driving with ACAS enabled. Overall, there is a clear suggestion that drivers strongly preferred intervening with manual braking before the ACC applied its maximum braking authority, suggesting that drivers were not being overly reliant on ACC braking. Finally, a search for drivers who may have been experimenting with ACC and FCW systems failed to yield a single ACC maximum braking incident while experimenting, and suggested that the heightened level of driver attentiveness during this experimentation may serve to mitigate the risks associated with this activity.

Driver acceptance of the FCW system was clearly mixed, and uniformly high for the ACC system. Overall, the older (60 to 70-year-old) drivers tended to be more accepting of these systems. Without a hypothetical system cost, 45 percent and 75 percent of drivers indicated positive purchase interest toward the FCW and ACC systems, respectively. With a $1,000 system cost for each system individually or a $1,600 combined (ACC plus FCW) system cost, positive purchase interest dropped to between 30 percent and 35 percent. The higher purchase interest in ACC may in large part be due to the fact that ACC profoundly reduces the workload and stress associated with the everyday task of car following (e.g., brake apply rates were 25 times lower under freeway conditions than with manual driving), along with the lack of FCW alert "credibility" (discussed below). It should be noted that the ACAS test participants are not fully representative of likely buyers for initial ACC- and FCW-equipped production vehicles.

With respect to FCW, results clearly suggest that further reductions in false alarms (resulting in a higher proportion of "credible" FCW alerts) are needed to ensure widespread FCW system acceptance. Only one-third of the imminent alerts were issued in response to vehicles that remained in the same lane as the driver during the approach. The remaining imminent alerts were issued primarily to roadside stationary objects (such as signs and mailboxes), when the lead vehicle was turning (which can be anticipated by the driver), or during driver-initiated lane changes. The overall impression is that a formidable technical challenge lies ahead in fielding a widely accepted FCW system. Nonetheless, the lessons learned in this project have suggested numerous improvements that will undoubtedly lead to this broader customer acceptability.

From the perspective of executing an FOT, this effort demonstrates the value of conducting multiple preliminary mini-FOTs (prior to the formal FOT) to ensure system performance is commensurate with driver expectations. Furthermore, it should be stressed that drivers' acceptance of systems based on short-term exposures can be very misleading. In hindsight, given the relatively large resource investment of gathering an FOT dataset, a larger allocation of data mining and analysis resources than were planned for in this program is advised.

2.0. Introduction

2.1. Final Report Purpose

The purpose of this final report is twofold. First, it is designed to provide a detailed description of all activities and tasks that have occurred since the last annual report[3], which covered the period of performance from January 1 through December 31, 2003. Second, this final report provides an analysis and discussion of all noteworthy activities, results, and events that occurred during the entire program. Thus, this final report is not designed to be an all-encompassing detailed summary of all program activities and technical content. A listing of associated background reports (such as annual reports) for the interested reader has been included at the end of this document.

2.2. Purpose of ACAS FOT

The Automotive Collision Avoidance System Field Operational Test program was undertaken via a Cooperative Agreement between GM and the U.S. Department of Transportation's National Highway Traffic Safety Administration. The goal of the ACAS FOT was to advance the science of collision warning by conducting an extensive FOT to assess the potential impact of an integrated Forward Collision Warning and Adaptive Cruise Control system on driver safety and acceptance.

The ACAS FOT project sought to address several issues through the execution and analysis of the Field Operational Test. The issues can be grouped into two categories: 1) those relating to driver performance, behavior, and safety; and 2) those relating to driver acceptance.

Driver performance, behavior, and safety issues that were addressed include:

- Are there fewer near crashes, since rear-end collisions were not anticipated?
- Do drivers do less tailgating?
- Are there unintended consequences associated with these systems?
- When do drivers use ACC?

The driver acceptance issues that were addressed include:

- What is driver tolerance for "nuisance" alerts?
- Are some "nuisance" alerts more acceptable than others?
- Are "valid alerts" considered too early or too late?
- Is the interface approach acceptable?
- What settings do drivers prefer and use?
- What is the driver's purchase interest in these systems?

2.3. Partners

Under the Cooperative Agreement, GM, Delco Electronics & Safety, Delphi Chassis Systems, the University of Michigan Transportation Research Institute and HRL Laboratories worked as a team to refine and integrate the required technologies necessary to prepare for and then conduct the FOT. NHTSA, GM, DDE, and DCS each provided funds for the execution of the project. UMTRI was a subcontractor to GM and provided extensive support in the development and execution of the actual FOT, including data collection and subsequent analyses. The Volpe Center (of the U.S. Department

---

[3] Deliverable 43 – ACAS Fourth Annual Report, dated February 2004.

of Transportation's Research and Special Programs Administration) served as the program's Independent Evaluator for NHTSA.

2.4. Project Organization and Responsibilities

GM was the prime organization that led the ACAS FOT team. The GM project manager served as the primary liaison between team members and the Government representative (Contracting Officer's Technical Representative – COTR). Dr. Ronald C. Colgin served as the first GM project manager for this program. He was replaced by Dr. Raymond Kiefer in May 2002, who served as the GM project manager for the remainder of the project. Besides overall program management responsibilities, GM also undertook those tasks dealing with integrating all sensor systems, the threat assessment functions, the "enhanced global positioning system (GPS)" dead reckoning technology, and map database functions. GM was also responsible for integrating the software of all the various components along with the build of the vehicles and the integration of the various ACAS components.

DES responsibilities included the development and integration of the driver vehicle interface (DVI) system with its head-up display (HUD), the ACC system, the radar system, the vision and scene tracking systems, and the target selection algorithm and processing system.

HRL developed the algorithms to fuse the data from the vision system, the radar system, map data, and the host vehicle state sensors (e.g., yaw information) with the goal of accurately determining the geometry of the road ahead of the vehicle. Accurate road geometry estimates are essential for correctly selecting in-path targets for collision warning applications.

DCS was responsible for developing an intelligent brake control subsystem for the ACC system. This was a solenoid-based, closed-loop control system, which was based on DCS's family of antilock braking (ABS) systems. This system performed computer-controlled (or automatic) ACC braking.

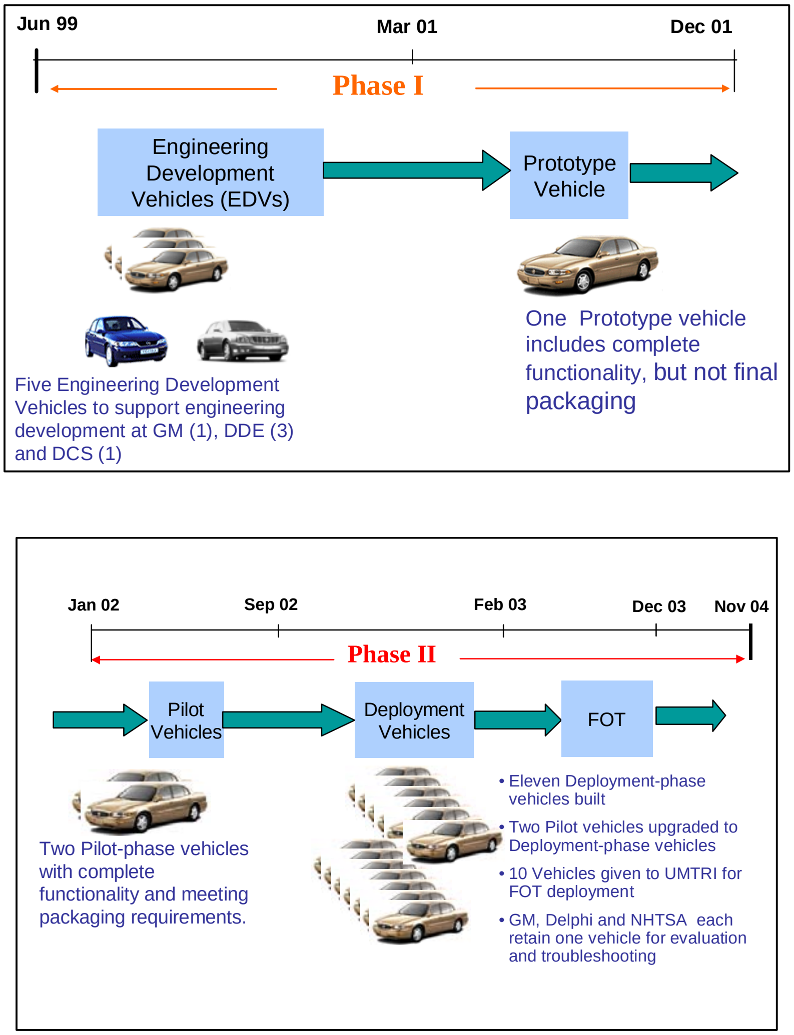
UMTRI had the responsibility of designing and developing the data acquisition system (DAS) along with designing and executing the actual FOT. UMTRI was also tasked (along with GM) with the mission of conducting analyses of all the objective and subjective test data generated by the FOT.

2.5. Schedule

The ACAS FOT program was conducted in two phases, as shown in Figure 1. Phase I of the ACAS FOT program ran from June 1999 through December 2001. During phase I, the required subsystems were selected and refined using five engineering development vehicles. Once satisfactory performance was achieved, these subsystems were then integrated into a single prototype vehicle. This prototype vehicle integrated all the required ACAS systems, but did not have the requisite "deployment" level of packaging desired in order for test subjects to use the vehicles as their personal cars in the actual FOT.

Phase II of the ACAS FOT program ran from January 2002 through November 2004. This phase first used lessons learned from the prototype vehicle to improve the system and to build two pilot vehicles with the functionality and deployment-level packaging configuration required for the FOT. Next, the remaining deployment vehicles were built and the actual FOT was conducted. Finally, the collected data were analyzed and the FOT report and this final program report were prepared.

Phase II was originally designed to end in May 2004. However, at the suggestion of the Government to enhance the FOT, and to allow a more complete analysis of the test data, the performance period was extended through November 2004.



Five Engineering Development Vehicles to support engineering development at GM (1), DDE (3) and DCS (1)

One Prototype vehicle includes complete functionality, but not final packaging

Two Pilot-phase vehicles with complete functionality and meeting packaging requirements.

- Eleven Deployment-phase vehicles built
- Two Pilot vehicles upgraded to Deployment-phase vehicles
- 10 Vehicles given to UMTRI for FOT deployment
- GM, Delphi and NHTSA each retain one vehicle for evaluation and troubleshooting

Figure 1: Program Phase Timelines and Vehicles

2.6. Technical Approach and Field Operational Test Design

The ACAS integrates a radar-based FCW system with an ACC system.

2.6.1. Technical Approach

The FCW system is designed to provide visual and audible warnings to a driver if the system predicts a crash may occur with the rear end of another vehicle in its forward path unless the driver takes immediate action. The system also provides visual cues to help the driver maintain a safe distance when following a vehicle directly ahead. The ACAS uses a forward-looking radar to detect and track objects ahead of the host vehicle. The radar outputs track data to the path and vehicle control functions to support both the ACC and FCW subsystems. The FLR is a narrow-beam, mechanically scanned, frequency-modulated, continuous-wave (FMCW) radar operating at a frequency of 76.5 GHz (mid-band). This radar consists of a single transmit/receive antenna, scan motor, transceiver assembly and radar data processor (RDP).

The ACAS ACC system is an extension of Conventional Cruise Control (CCC). Like cruise control, this feature maintains a set speed when there is no impeding traffic. Unlike CCC, ACC reduces the host vehicle's speed to maintain a driver-selected "time headway" when slower moving traffic impinges upon the path of the host vehicle. "Time headway" refers to the time required for the following vehicle to travel the distance between it and the lead vehicle.

Figure 2 shows a functional breakdown of the ACAS. At the top are four separate functions used to estimate the geometry of the road ahead of the vehicle. Accurate assessment of roadway geometry is very important in order to correctly identify whether a target seen by the radar is in the vehicle's projected path rather than to the side of the road (and not of interest). The current conventional method to determine road geometry ahead is to use only a yaw-rate-based approach. The yaw rate, along with vehicle speed, is used to predict the curvature of the road at the current vehicle location. However, the accuracy of this information in predicting roadway geometry ahead degrades considerably when lane changes are made or when a vehicle transitions between straight and curved segments of a road.

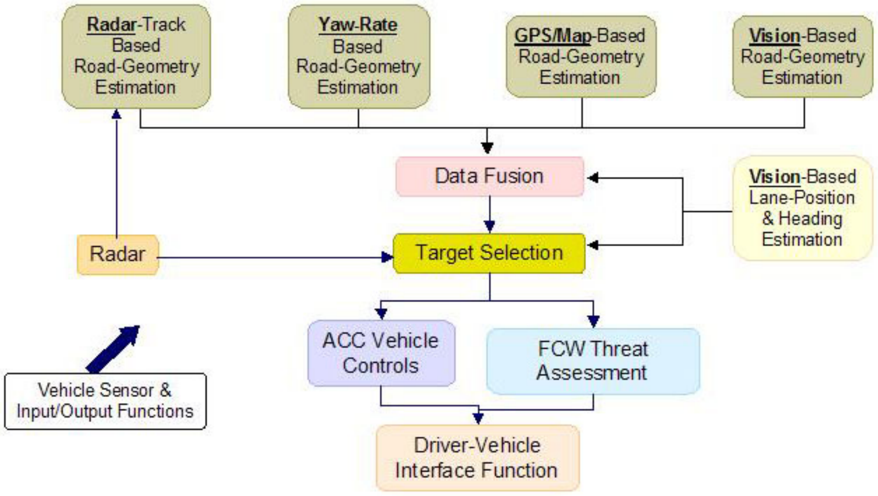


Figure 2: Functional Breakdown of ACAS

To improve upon the yaw-rate-based road geometry estimate, the ACAS employed three other methods to predict changes in the curvature of the road before the vehicle reaches them. The first additional method uses a digital map and a GPS receiver. The vehicle's position and direction of travel reported by the GPS receiver are used to determine the vehicle's position on the digital map. The road geometry indicated by the map is then used to predict the road geometry ahead of the vehicle.

A second additional method for estimating roadway geometry uses a forward-looking video camera placed near the rear-view mirror. A vision system then finds the lane markings in the video images and uses them to estimate the road geometry ahead.

A third additional method for estimating the road geometry uses the tracks of other vehicles ahead as they are detected by the radar. These tracks are analyzed to determine if there is a pattern in the paths of the other vehicles, which can be used to help estimate geometry of the road ahead.

The results of these four road geometry estimates are then combined by the DF function to produce an optimized estimate of the road geometry ahead of the vehicle. This road geometry estimate produced by the DF function is then used by the target selection function to determine which objects detected by the radar are actually in the predicted path of the vehicle.

Once this is known, the closest in-path movable target (i.e., moving or previously seen moving by the radar) is used by the ACC to control the speed of the vehicle. In the ACAS vehicles, the ACC can control both the throttle and the brakes, with the maximum braking authority of the ACC system set at 0.3g's.

The closest in-path movable and stationary targets are both used by the Threat Assessment function to control the FCW output (via the DVI) to the driver.

The DVI function includes control of the HUD. This display shows the vehicle speed, warning icons, setting, and status information. The DVI also includes buttons to control the ACC, the alert timing (sensitivity setting) of the FCW system, the brightness and vertical position of the HUD image on the windshield, and audio alerts provided through a dedicated speaker. The vehicle's radio sound system is muted during auditory alerts.

2.6.2. Field Operational Test Design

The original FOT plan called for 78 drivers to use the ACAS-equipped vehicles as their personal vehicles for four weeks each. The drivers were divided into three age groups and balanced for gender. All drivers were to use the vehicle without the ACAS features for the first week. Most drivers were then to drive the vehicles with the ACAS features turned on for the remaining three weeks.

However, the subjective results from the first few drivers in the actual FOT were significantly less positive than the responses from the drivers in the previous pilot testing in which drivers' exposure to the ACAS was considerably shorter (see *ACAS FOT Deliverable 43 - Fourth Annual Report*). Rather than proceeding with the remaining subjects using the same algorithm, it was quickly decided to improve the algorithm by attempting to reduce the number of "nuisance alerts" (or false alarms) by the FCW system, since drivers reported this as the primary cause of dissatisfaction. This necessitated a change in the original test plan.

The approach to addressing this unanticipated issue included three steps. First, while improved algorithms were being developed, several more subjects continued to experience the original algorithm (called Algorithm A) in order to gather data from a significant number of subjects. A total of 15 drivers used Algorithm A. Second, an updated version of Algorithm A (called Algorithm B) was created by quickly implementing low-risk changes. This version substantially reduced the number of unnecessary alerts. It included several improvements that had been identified and tested after the Algorithm A software had been frozen for the FOT, and it also eliminated all alerts from "never before seen moving" stationary objects, which constituted about half of the alerts issued. A total of fifteen drivers used Algorithm B. Finally, while subjects were using Algorithm B, a more ambitious set of updates were created, tested, and implemented (called Algorithm C). This version restored alerts from "never before seen moving" stationary objects and also incorporated new changes to reduce the number of nuisance alerts from both stopped and moving objects. A total of 66 subjects used Algorithm C.

The resulting final experimental design is shown in Figure 3.

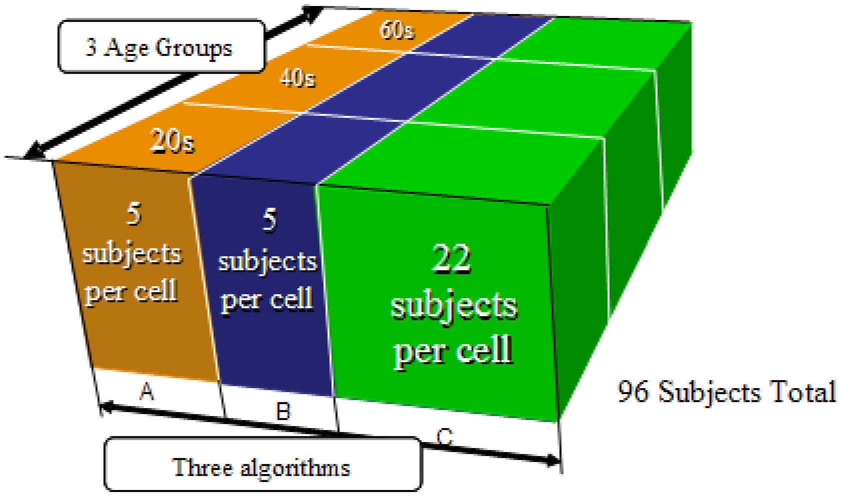


Figure 3: Revised FOT Plan

2.7. Funding and Cost Sharing

The estimated cost of this project was $35.1 million over the original 59-month period of performance. Of this, phase I was estimated to cost $19.7 million and phase II $15.4 million.

As this Cooperative Agreement was established as a Cost-Share Program, the Government was to provide $10.9 million in funding for phase I and $10.5 million in phase II. For its share, GM and its team members were to fund $8.7 million in phase I and approximately $4.9 million in phase II.

Cost-sharing ratios within the various tasks and subtasks varied from a 50/50 ratio (Government / GM) for system development and system integration tasks, to an 80/20 ratio for the build task of the fleet test vehicles and the conduct of the actual FOT (with one small task paid 100 percent by the Government). Program management costs were set at a 50/50 cost-share ratio.

Due to the mix of tasks in each phase, the final cost share ratios that resulted were as follows: Phase I had a 54.8/45.2 cost-share ratio whereas phase II had a 69.9/30.1 cost-share ratio. The overall program cost-share ratio was 61.6/38.4.

In response to a Government suggestion, the actual conduct of the FOT was extended for two additional months. Additionally, the program's period of performance was extended through November 2004 to allow additional time for data analysis. Both of these actions were accomplished with no budget increase to this project.

3.0. Detailed Description of All Activities and Tasks Since Last Annual Report

3.1. GM Activities and Tasks (January – November 2004)

3.1.1. Extension of the Field Operational Test

It was decided in the fall of 2003 that additional test subjects would be required to provide sufficient test data. To accomplish this, the FOT, which was to have ended in December 2003, was extended two months to accommodate an additional 12 driver test subjects. FOT data collection was thus concluded in February 2004.

3.1.2. Data Analysis by GM

Since the UMTRI administered the FOT of the project and had prior experience with such projects, UMTRI was given the task of data collection and database development. In an effort to avoid duplicate work and share common tools, GM used the UMTRI database design while maintaining its own development format of the data. The development format was valuable for simulations and examination of specific events utilizing tools established during the development phase of the project. However, this format is not an ideal tool for aggregate analysis of the ACAS FOT data, so both the database and development formats of data have been maintained.

The procedure for collecting and disseminating the data was as follows. After the subjects returned the vehicles to an UMTRI garage (at the end of their ACAS experience), UMTRI copied the data from the DAS (located in the vehicle’s trunk) to a server located at UMTRI. UMTRI then imported the new data into the ACAS FOT database. An external hard disk drive (containing data for approximately ten drivers) was then used to transport the data to the GM server (as well as to the Volpe Center and DES). This became part of GM’s copy of the ACAS FOT database. The hardware on which the GM copy of the database resides was an HP ProLiant ML530 Generation 2 server. The server was dedicated to the task of housing and analyzing the data set and was equipped with the following features:

- Microsoft Windows 2000 Server operating system
- Microsoft SQL Server 2000 database management software
- Two Intel 2.8 GHz Xeon processors with 512 KB L2 cache
- 4 GB of PC1600 ECC SDRAM
- 146-gigabyte RAID1 system drive
- 1.4-terabyte RAID5 data drive
- Seven 64-BIT/100 MHz PCI-X slots (two slots used)

The GM ACAS FOT evaluation team then conducted analyses on both the subjective and the objective test data. These analyses included an examination of conflict metrics, relationships between subjective and objective data, focus group data, potential indicators of driver distraction, and continued exploration of algorithm improvements.

3.2. Delco Activities and Tasks (January – November 2004)

The tasks assigned to DES for the above time period consisted of continuing to provide support as required for the ongoing FOT.

DES repaired two radar units for anomalous behavior, and provided GM with guidance about the proper procedure for conducting checks on radar blockage events.

3.3. University of Michigan Transportation Research Institute (January – November 2004)

The UMTRI was selected by GM as the primary organization to process and analyze the objective and subjective data collected during the FOT. Their executive summary of the FOT results (also contained in the FOT report) is provided in Section 4.5. The FOT report meticulously documents the methodology and results of the FOT. It should be noted that the FOT report was prepared to complement the reporting done by the Independent Evaluator (The Volpe Center).

For the first two months of this reporting period (January - February 2004), UMTRI was fully engaged in concluding the FOT activities. Data collection was completed in mid-February, following which the focus of UMTRI efforts moved entirely to that of database management, data analysis, and FOT report preparation.

Database management involved the completion of the quality checks and database enhancements (by deriving additional variables and data fields). The FOT database was finalized for use in data analysis by early April and was delivered by the end of June to GM, DES, and Volpe Center. Data analysis activities were pursued throughout the reporting period, with substantial activity occurring from April through June. Preparation of the UMTRI FOT report to GM was accomplished from April through November, with GM/UMTRI face-to-face and teleconferencing meetings occurring frequently as a means of ensuring project focus.

3.4. The Volpe Center (January – November 2004)

The NHTSA selected the Volpe Center to conduct an independent evaluation of potential safety benefits and user acceptance of the ACAS system. It was to conduct this evaluation using data collected by GM (through UMTRI) during the FOT. During the FOT, UMTRI provided the Volpe Center with test data via the same procedure it used to transfer data to GM, i.e., via shipping the external hard disk drive to Volpe Center for downloading of data.

4.0. Analysis and Discussion of All Noteworthy Activities, Results and Events

The remainder of this final report is focused on what the ACAS FOT team believes are the key accomplishments of the program along with important insights, findings and conclusions.

The ACAS FOT project was organized into five major tasks, most of which include several major subtasks. The major tasks were:

Task A – Systems Integration
Task B – Subsystem Development (Hardware)
Task C – Subsystem Processing Development (Software)
Task D – Fleet Vehicle Build
Task E – Field Operational Test

This section of the report will address the key aspects and highlights of each of these task areas.

4.1. Systems Integration (Task A)

The Systems Integration Task (Task A) consisted of the following subtasks, which were performed by GM. These subtasks are discussed in this section.

Task A1 - Functional Description
Task A2 - System Architecture/Mechanization
Task A3 - Interface Management
Task A4 - System Verification
Task A5 - Risk Management Plan

4.1.1. Functional Description (Task A1)

4.1.1.1. Goals, Purpose and Background

The purpose of the Functional Description subtask was to:

1. Capture the system functional requirements;
2. Allocate system functional requirements to subsystems and components.

The approach for this task was based on the real-time system specification approach of Hatley and Pirbhai (1988). Following this approach, system requirements, architecture and specification models were developed using the process model (Data Context Diagram and Data Flow Diagram) and the control model (Control Context Diagram and Control Flow Diagram).

4.1.1.2. Intermediate and Final Results

The following is a description of the controls, displays, and operating modes that were defined for the ACC and FCW systems.

4.1.1.3. System Functional Description

The ACC provides operating modes similar to conventional cruise control with the following additional features:

1. For the purposes of the FOT, the ACC was commanded to operate like a conventional cruise control for the first week of each driver’s use of the ACAS vehicle.
2. When active, the ACC has two modes, maintaining the set speed and maintaining the selected headway.
3. When maintaining headway, the system is capable of slowing the vehicle to pace a moving lead vehicle that is traveling slower than the set speed.
4. Once the ACC subsystem slows the host vehicle below the minimum cruise speed (20 mph), a message indicates that the driver should take full control of the vehicle. Once this message is displayed, the system will not command the host vehicle to accelerate until the driver manually accelerates above the minimum set speed and then initiates the resume function or the set speed function.

The primary driver interface to engage and operate the ACC function consists of the standard production cruise controls and a headway selection switch. Using this interface, the driver is provided with the following capabilities:

1. Turn the ACC on and off
2. Set the desired cruise speed (set speed)
3. Increase set speed by fixed steps
4. Decrease set speed by fixed steps
5. Accelerate to a new set speed
6. Coast (decelerate) to a new set speed
7. Resume a previously set speed
8. Set the desired headway (headway adjustment)

Additionally, the accelerator pedal may be used to override the ACC system. As in standard cruise control, manual braking causes the system to go to the standby mode. When the ACC is first turned on at the end of the first week for each driver, the initial headway setting is set to the maximum gap setting (2 seconds), however, after that it remembers the last setting selected by the driver even if it was in the previous ignition cycle.

The primary ACC display is a HUD that presents the following information:

1. Current Speed
2. ACC Engaged/Disengaged state
3. Set Speed while ACC is engaged
4. Tracking/Not Tracking a Lead Vehicle while ACC is engaged
5. ACC headway setting while ACC is engaged

When only conventional cruise control is available, only the current vehicle speed is displayed on the HUD.

For the purposes of the FOT, the FCW had enabled and disabled modes. The FCW was disabled when only conventional cruise control was available in the vehicle. When the FCW was enabled, the driver was not able to disable the FCW but was allowed to adjust the sensitivity of the FCW function. The sensitivity adjustment does not permit the FCW function to be disabled by the vehicle operator. The button to control the sensitivity of the FCW was the same button as that used to adjust headway when ACC is engaged.

4.1.1.4. Cruise Control Modes-Adaptive Cruise Control Enabled

The cruise control behaves like a standard cruise control system until the adaptive features are enabled. Figure 4 shows the states and transitions for the cruise control when the adaptive features are enabled.

Table 1 describes the various ACC modes.

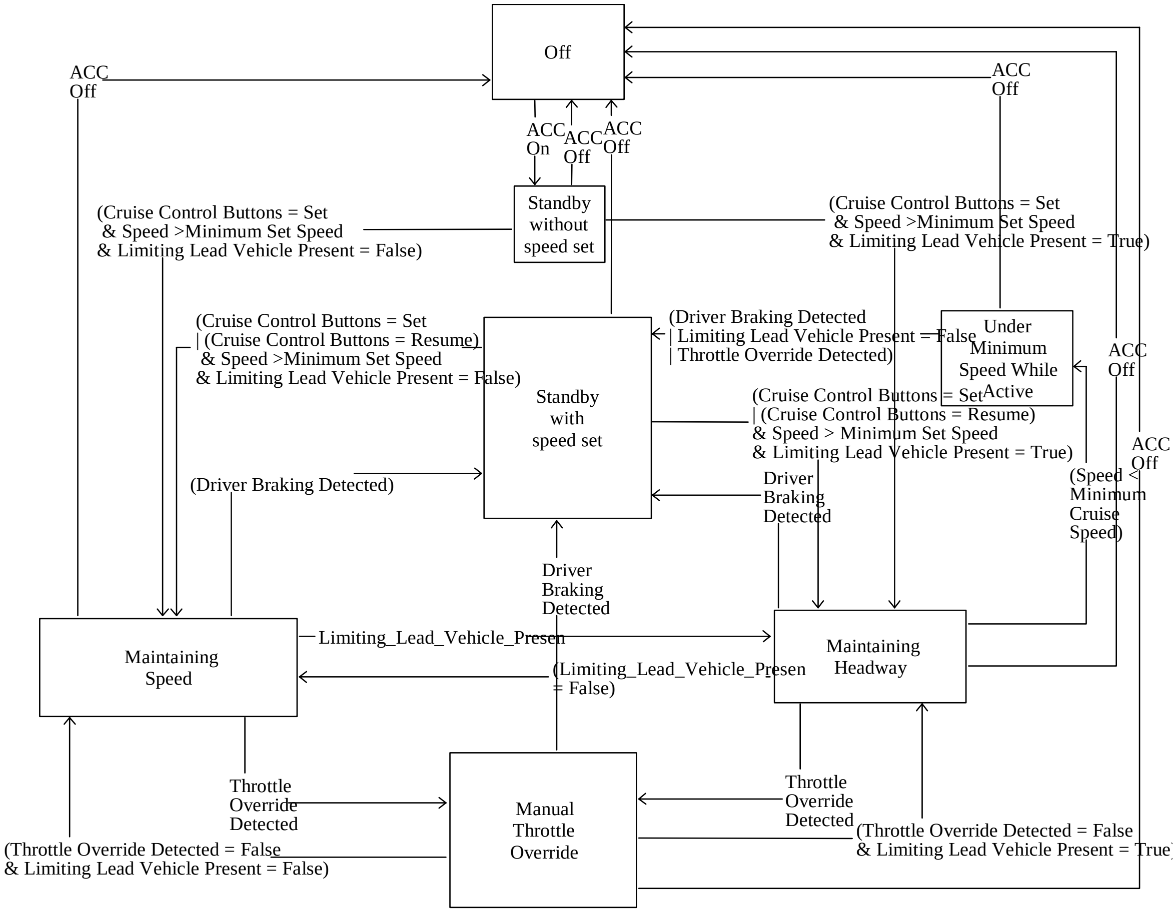


Figure 4: ACC Controls

Table 1 - Adaptive Cruise Control Modes

Mode	Description
ACC Off	The ACC system is not functional. This state is entered whenever the ignition is on and the ACC is turned off.
Standby without speed set	The system is waiting to take control of the throttle and brakes. This state is entered when the ignition is turned on and the ACC is turned on. From this state, assertion of the set button after the vehicle has reached the minimum set speed will activate the system.
Standby with speed set	The system is waiting to take control of the throttle and brakes. A set speed has been established previously. Assertion of the set or resume buttons after the vehicle has reached the minimum set speed will activate the system.
Maintaining Speed	In this mode, the ACC system attempts to reach and hold a specified speed. While in this mode, the set speed can be increased or decreased by pressing the RESUME/ACCEL or SET/COAST buttons. Also, in this mode, the desired headway can be adjusted by pressing the GAP/WARN button. Changes in desired headway impact ACC behavior only if a lead vehicle is detected.
Maintaining Headway	In this mode, the ACC system attempts to reach and hold a specified headway. While in this mode, the set speed can be increased or decreased by pressing the RESUME/ACCEL or SET/COAST buttons. Also, in this mode, the desired headway can be adjusted by pressing the GAP/WARN button.
Manual Throttle Override	In this mode, the driver is pushing on the throttle to force the vehicle to go faster than the cruise control function would command.
Under Minimum Speed While Active	In this mode, the ACC has reduced the vehicle speed below a minimum cruise speed because a slow vehicle is ahead. When this state is entered, the driver is given a message to take control of the vehicle. Once this happens, the ACC will not cause the vehicle to accelerate but will continue to brake if the lead vehicle continues to decelerate.

4.1.1.5. System Process Model

System requirement, architecture, and specification models were developed using the process model (Data Context Diagram and Data Flow Diagram) and the control model (Control Context Diagram and Control Flow Diagram). Figure 5 summarizes the data flow model. The following paragraphs briefly describe the functional breakdown of the system.

The **Vehicle Sensor and I/O Interface** functions include filters for the vehicle kinematics sensors to provide engineering units and to reduce noise in these measurements.

The **Radar Auto-Alignment and Blockage Detection** function evaluates the radar returns to detect when the signal seems to be attenuated by a blocked radome. It also looks at target tracks to produce electronic adjustments of the radar alignment. This function also produces control signals that indicate if the radome is blocked or if the alignment is beyond the range that can be corrected.

The **Target Detection** function processes the radar signals to produce estimates of the range, range rate, acceleration, and extent of objects. It also reports the amplitude of the return from each detection.

The **Multi-Target Tracking** function associates detections in each new sample with previously observed tracks. It reports whether any currently stationary objects were ever observed to be moving and can let a target "coast" if it disappears for a short period of time.

The **Bridge Rejection** function looks at the target tracks to determine if any should be classified as a bridge or overhead sign. Objects classified as bridges or overhead signs will not be used to generate FCW alerts. The **Radar-Track-Based Road-Geometry Estimation** function (also called **Radar Scene Tracking)** evaluates the target tracks to estimate the geometry of the road ahead of the vehicle and the vehicle's relationship to the road.

The **Yaw-Based Road-Geometry Estimation** function predicts the host vehicle's path using yaw-rate sensor input, vehicle speed, and acceleration measurements.

The **GPS/Map-Based Road-Geometry Estimation** function uses a digital map database, a differential GPS receiver, and dead reckoning to determine the current map position of the vehicle. It then extracts information from the database indicating the geometry of the road ahead of the vehicle and the location of significant features (such as intersections) along the road.

The **Vision-Based Road-Geometry Estimation** and **Vision-Based Lane-Position & Heading Estimation** functions determine the geometry of the road ahead of the vehicle and the relationship between the road and the host vehicle. The road-geometry information includes the curvature of the road ahead of the vehicle. The relationship between the vehicle and the road includes the lateral position in the lane, the heading angle, and whether a lane change is occurring.

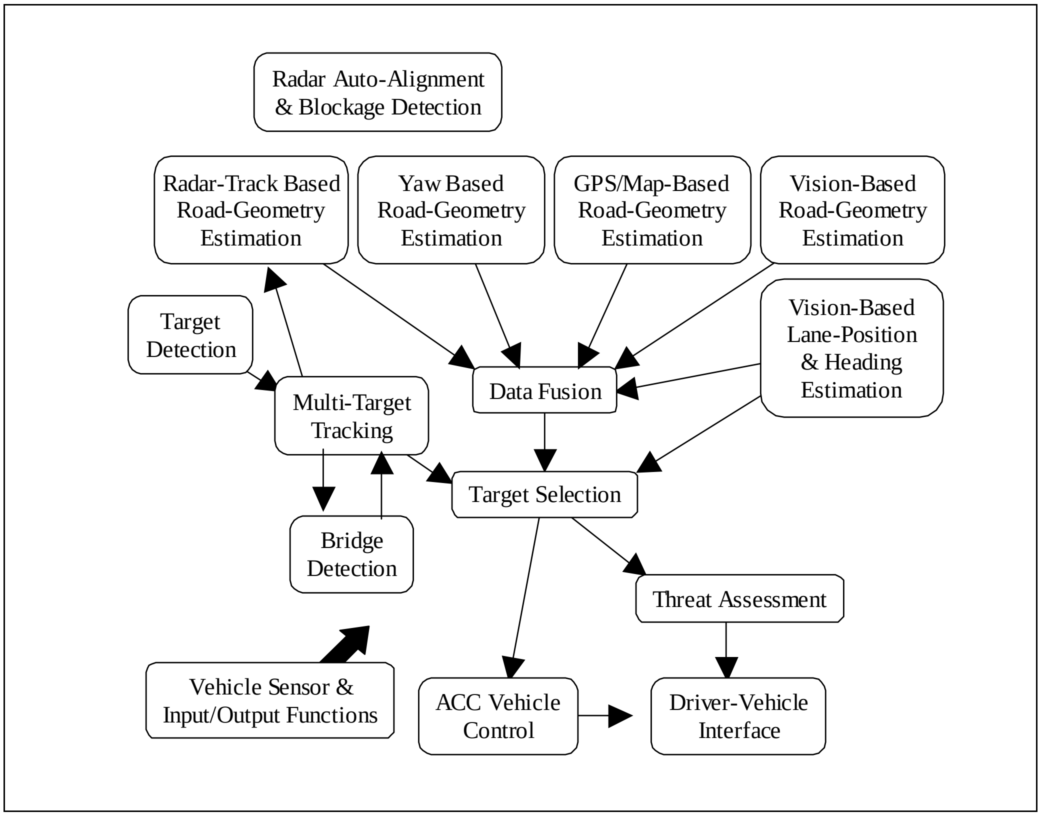


Figure 5: Vehicle System Process Model

The **Data Fusion** function combines the evidence from the entire sensor suite to develop a higher confidence prediction of the host vehicle's path and the geometry of the road ahead.

The **Target Selection** function evaluates the predicted path of the host vehicle and the objects to determine the threatening targets that will be used for ACC control and for FCW threat assessment. The FCW targets are those that are in the host vehicle's path or are predicted to cross the host vehicle's path. They may be moving or stationary. The ACC only looks at targets that are or have been observed to be moving.

The **Threat Assessment** function uses the host vehicle dynamics, the target dynamics, and the expected driver response to determine the warning level. The warning algorithm also depends upon whether the ACC is engaged. In response to stationary targets while ACC is engaged, the warning algorithm is unchanged. In response to moving targets while ACC is engaged, a warning is produced when the maximum braking authority is requested by the ACC.

The **ACC Vehicle Control** function maintains the vehicle's speed or headway when the ACC is engaged. The controls are similar to those of a conventional cruise control system with the addition of a headway setting control. The output includes throttle and brake actuator control signals. In headway maintenance mode, the ACC uses range and range rate data for the target chosen by the Target Selection function.

The **Driver Vehicle Interface** functions control all of the devices that transmit information to the driver. These include audio and visual outputs. The visual display includes a HUD. The information displayed visually includes the status of the ACC (engaged, set speed, and target detected). The information also includes warnings that indicate maintenance is required or that the vehicle is being operated beyond the range of capability of the ACC/FCW systems.

The **Data Acquisition** function is not shown in Figure 5 but acts to collect information from all other functions and collects video data, all for the purpose of post-drive analysis. This function collects and records communications messages from all other subsystems and records video of the forward scene and driver face as well as audio comments from the driver. Through a hardwired digital I/O interface, this function also indicates to the rest of the functions whether adaptive or conventional cruise control should be enabled.

4.1.2. System Architecture/Mechanization (Task A2)

4.1.2.1. Goals, Purpose and Background

The main objectives of the System Architecture/Mechanization subtask were to:

1. Partition the system into subsystems and components;
2. Allocate functional requirements to the subsystems and components;
3. Designate interfaces among the subsystems and components.

Following the structured method of Hatley and Pirbhai (1988), the total vehicle, with all its embedded systems, was considered as one super system. The super system was partitioned into physical boxes that, in their totality, satisfy all the functional requirements. Processes in the requirement model were allocated to slots in the architecture model.

4.1.2.2. Intermediate and Final Results

Table 2 lists the major physical system modules and their primitive functions.

Table 2 - System Modules and Their Primitive Functions

Architecture Module	Function
Host Path Estimation / Target Selection / Radar Control Processor	Yaw-Based Road-Geometry Estimation Target Selection
Main Processor	Vehicle Sensor and Input /Output Functions GPS/Map-Based Road-Geometry Estimation Data Fusion Threat Assessment
ACC/Radar Subsystem	Radar Auto-Alignment and Blockage Detection Target Detection Multi-Target Tracking Bridge Detection ACC Vehicle Control
Vision / Scene Tracking Processor	Radar-Track-Based Road-Geometry Estimation Vision-Based Road-Geometry Estimation Vision-Based Lane Position & Heading Estimation
Driver Vehicle Interface (DVI) Processor	Driver Vehicle Interface
Data Acquisition Subsystem	Data Acquisition

Figure 6 shows the physical architecture, subsystems, and components of the system with connections and buses between the processors. This drawing shows the top-level hardware used in the vehicle. More detailed drawings, including the flow and sources of information from and for each physical box (block) were provided in the *ACAS FOT Deliverable 2 - System Architecture/Mechanization Report*. This report describes the functional interaction between the blocks as well as the internal functions of each block. The main information artery is a high-speed CAN Bus (500k baud) which transfers a large body of communication messages among the subsystems or the components. Additionally, a GM Class 2 Bus provides information linkage from the vehicle-based signals to all subsystems requesting such signals, either directly or indirectly via the CAN Bus. Other harnesses are direct wires.

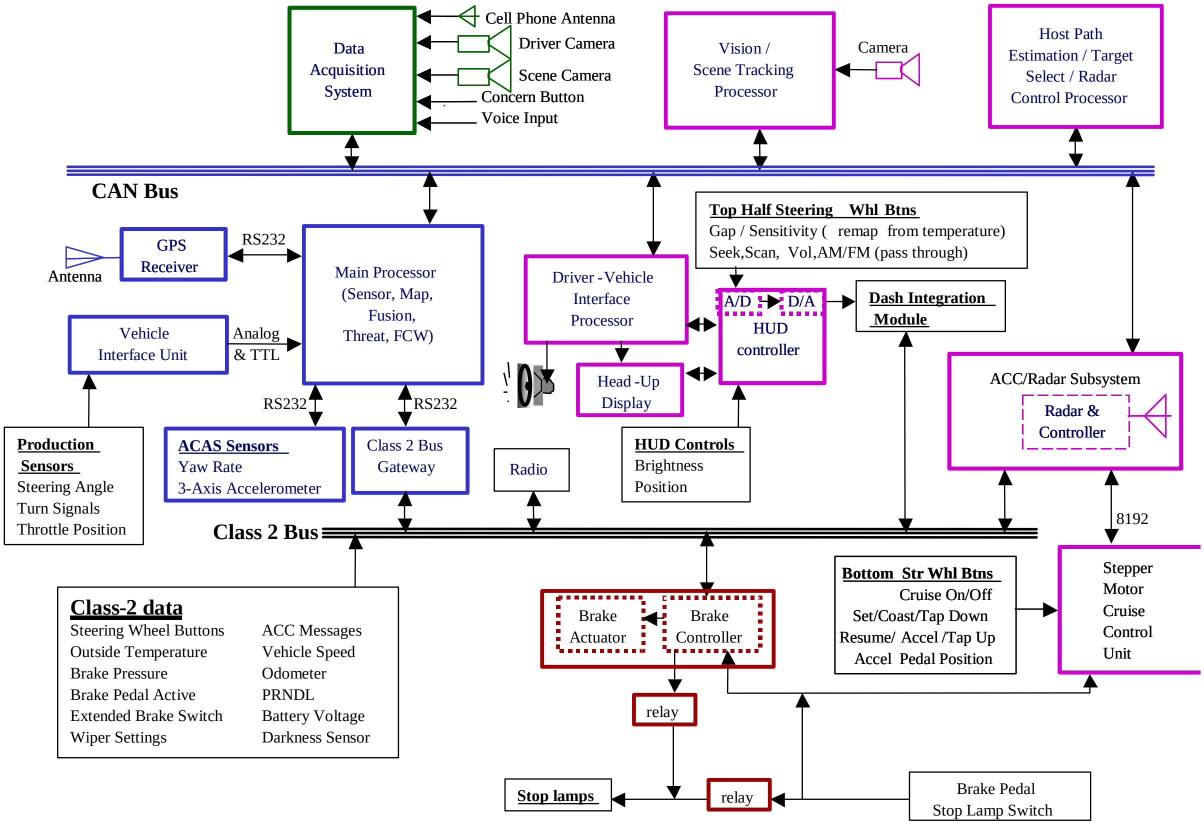


Figure 6: Vehicle System Block Diagram and Mechanization

4.1.3. Interface Management (Task A3)

4.1.3.1. Goals, Purpose and Background

The main objective of the Interface Management task was to ensure that independently developed subsystems or components satisfied the prescribed requirements and operated according to the specifications and in adherence with the communication protocol when connected as a system.

To ensure subsystem interface compatibility and traceability, a systematic approach was followed. First, the interface signals between each hardware block in the block diagram (Figure 6) were labeled. Then, every signal source, destination, bit structure, and other relevant information was tabulated. This approach allowed:

1. Developing a complete record of all signals among different subsystems or components;
2. Mapping a one-to-one correspondence between each input signal (to a block) and its source;
3. Implementing changes with minimal effort.

4.1.3.2. Intermediate and Final Results

The *Initial Interface Control Document* was generated in March 2000. The document included four sections:

1. Introduction
2. Vehicle System Block Diagram and Mechanization Drawing
3. CAN Bus Message Definitions
4. Class 2 Bus Message Definitions

Originally, a total of 43 different eight-byte CAN Bus message types were defined. The definition of each message included the number of bits for each variable contained in the message, the number format, its units, range, resolution, and accuracy. After numerous revisions, the final system resulted in 47 different eight-byte CAN Bus types consisting of 90 different sets of messages. Many of the additional messages were added to improve FOT system reliability and enhance data collection.

4.1.4. System Verification (Task A4)

4.1.4.1. Goals, Purpose and Background

The overall objective of the ACAS System Verification task was to make sure the system was ready for use by subjects in the FOT. This verification required that the system satisfy certain minimum performance requirements at the component, subsystem, and system level. The System Verification Task included:

1. Definition of the system verification process;
2. Supervision of the definition and execution of verification tests at the component and subsystem level;
3. Definition and execution of the verification plan at the system level.

Verification was done on the engineering development, prototype, and deployment vehicles at several levels: component, subsystem, and system. Component-level verification included the operation of the ACAS-specific onboard sensors. These included sensors for vehicle kinematics, environment sensors, and driver activity sensors. Subsystem-level verification included testing the operation of the interfaces between the subsystems and the functionality of each subsystem. The subsystem designers were responsible for definition and execution of the test procedures at the component and subsystem level. System-level verification included subjecting the vehicles to crash and nuisance alert scenarios choreographed and executed on test tracks, and driving the vehicle on public roadways.

The systems engineers were responsible for definition of the test procedures at the system level. The systems engineers executed the system-level tests.

The dynamic scenarios shown in Table 3 were selected for use for system-level verification. Each of these system-level tests was executed on the prototype vehicle under the supervision of a government official. Each test marked with an asterisk in the table was performed on the first two deployment vehicles also known as the pilot vehicles. Subsequent deployment vehicles were not formally tested using these tests but were prepared for the FOT by undergoing at least 100 miles of ordinary driving along with being placed in a minimum of two different imminent alert scenarios.

Table 3 - System-level Verification Test Scenario Descriptions

Test	Scenario Description	Quantitative Collision Alert Test	Qualitative Nuisance Alert Test	Qualitative ACC Test
1*	SV 60 mph to POV Stopped**	X		X
2*	SV 50 mph to POV 10 mph	X		X
3	SV 60 mph to POV Braking Unusually Hard from 60 mph	X		X
4	SV 60 mph to Motorcycle POV Braking Moderately Hard from 60 mph	X		X
5*	SV 50 mph to POV Stopped on Curve	X		X
6*	SV 50 mph to POV 25 mph in a Curve	X		X
7*	SV 60 mph Cut-off by POV 40 mph	X		X
8*	SV 45 mph Changes Lanes and Encounters POV Stopped	X		X
9	SV 60 mph Tailgating POV Braking from 60 mph	X		
10	SV 60 mph Approaches Motorcycle and Truck POVs 20 mph	X		X
11	SV 60 mph Approaches Motorcycle behind Truck POVs 20 mph	X		X
12*	SV 50 mph on Curve to POV Braking Moderately Hard from 50 mph on Curve	X		X
13	SV 65 mph Following POV 60 mph	X		
14	SV 50 mph to POV Braking Unusually Hard from 50 mph	X		X
15*	SV 40 mph to POV Stopping from 40 mph	X		X
16*	SV 45 mph behind 45 mph POV Changing Lanes to Reveal Stopped POV	X		X
17*	SV 50 mph Passing POVs 25 mph Around Curve		X	X
18	SV 60 mph Passing Truck POVs 20 mph in Adjacent Lanes		X	X
19	SV 60 mph following POV 60 mph		X	X
20	SV 50 mph POV 60 mph Cuts in Ahead of SV		X	X
21	SV on Simulated Open Road No Other Traffic		X	X
22*	SV Daytime Public Road Test		X	
23*	SV following POV on Simulated Open Road			X
24*	SV 45 mph POV 45 mph Changes Lanes in front of Accelerating SV			X
25	SV 60 mph changing ACC Headway following POV 60 mph			X
26	SV 50 mph following POV Accelerating from 50 mph			X
27*	SV 50 mph following POV 50 mph Changes Lanes to reveal POV 50 mph			X
28	SV 40 mph passes POV 40 mph			X
29*	SV 50 mph Throttle Override during Automatic Braking			X
30*	SV 50 mph ACC Test with Antilock Braking Activated			X

* indicates deployment vehicle test

** SV refers to Subject (or following) Vehicle, and POV refers to Principal Other (or lead) Vehicle

4.1.4.2. Intermediate and Final Results

The subsystem verification tests for the prototype vehicle were executed between August 2001 and September 2001. Prototype vehicle system-level tests were performed during October 2001. Pilot vehicle testing was performed in the fall of 2002, with the remaining deployment vehicles tested in late 2002 and early 2003.

4.1.5. Risk Management Plan (Task A5)

4.1.5.1. Goals, Purpose and Background

The overall objective of the Risk Management task was to define the hazard analysis and safety risk management program to be implemented by the team in the performance of the ACAS FOT program. The risk management plan was developed using guidelines from MIL Standard 882C and SAE J1789. Safety plan presentations were prepared and presented at meetings in November 1999 and June 2000. In addition, the Safety Engineering team met with the principal engineers working on each subsystem to gather the required information for the safety analysis and hazard mitigation plan. The risk management plan was delivered to NHTSA in February 2001.

During the preliminary safety assessment, each responsible engineer provided information about the functions of the particular system, subsystem or component they were responsible for, and identified the safety impact of those functions. That information was used to generate a preliminary hazard list. This resulted in being able to identify which subsystems or components could be considered safety-critical or safety-related. In general, components were categorized by the ability of the vehicle's driver to take control of the vehicle should one or more of the components fail.

During this development program, testing of individual subsystems and integration of those systems into engineering development vehicles (EDV) and integration into the prototype vehicle and FOT pilot vehicle were completed. At each stage of the process, engineers and program management were alerted to safety-critical or safety-related issues as they were observed.

In addition, the UMTRI was involved in testing the EDV and the FOT vehicles for operator-related functions. During the UMTRI testing all observed deficiencies were flagged and subsequently addressed.

4.1.5.2. Intermediate and Final Results

A list of 27 hazardous conditions that could develop as a result of a failure in the ACC or FCW systems was developed. Some examples of hazards and possible resulting accident scenarios are listed in Table 4.

Table 4 - Sample Hazard List and Potential Accident Scenarios

Hazard	Potential Accident Scenario/Comments
Cannot disengage cruise manually	Driver is in either speed or distance mode and wishes to return to manual operation. Applying brake does not reset system. Turning off switch does not reset system.
ACC brake engages unexpectedly	Worst-case brake application causes rear end collision and startles driver. Driver brake application (manual over-ride) in this situation is counter-intuitive.
ACC brake fails to engage when required	ACC applies brake in distance mode, nothing happens. Driver needs to be warned to take control.
FCW does not identify in-path target (missed detection)	Driver sees target vehicle, but FCW does not identify vehicle and/or change speed to avoid incident and/or warn driver to take control.
Improper threat assessment logic triggers alarm that is not a threat or not perceived by driver to be a threat	Driver slams on brakes when not warranted or driver begins to discount future warnings.

While a number of examples of risk mitigation strategies were identified, preliminary hazard analysis indicated that the ACC and the associated braking system were the areas of most concern. For these particular subsystems, considerable evaluation took place at DES, DCS, and the various supplier partners.

The auto-braking feature that is part of the ACC functionality is a capability that was added to the already existing functions of the traction control system and ABS. Considerable testing and evaluation were performed by DES before the systems were released in the prototype vehicle. Further winter testing took place on the pilot vehicles before production of the FOT deployment vehicles.

From the hazard list made for the system, as shown in Table 4, unrequested braking was identified as a primary concern. In addition to assuring the reliability of the braking subsystem and its diagnostics, one of the mitigation steps that were implemented was a limit on the braking authority and the rate the brakes could be automatically applied (or the jerk rate). This provided time for a following vehicle to react or for the driver of the ACAS vehicle to override the automatic braking.

In addition to the hazard list developed near the beginning of the program, improper display to the driver during ACC activation was also identified to be a potential hazard. In order to prevent the hazard from occurring, a mechanism was added to disable ACC during the failure of any system that might have an impact on the visual display to the driver. With this mechanism, the ACC subsystem was never in control of the vehicle without visual feedback to the driver indicating ACC is engaged.

4.2. Subsystem Development - Hardware (Task B)

Task B focused on development of the ACAS subsystems and had the following subtasks:

Task B1 – Forward Radar
Task B2 – Forward Vision Sensor
Task B3 – Brake Control System
Task B4 – Throttle Control System
Task B5 – Driver Vehicle Interface

4.2.1. Forward Radar (Task B1)

4.2.1.1. Overview of Radar Design and Performance

The FLR detects and tracks objects in the forward area and outputs track data to the path and vehicle control functions to support the ACC and FCW systems. This radar was supplied by DES and is a modified version of the one developed for production (although the design that is actually on production vehicles is one generation after the one used for ACAS). A top-level block diagram of the FLR is shown in Figure 7. Radar parameters are summarized in

Table 5.

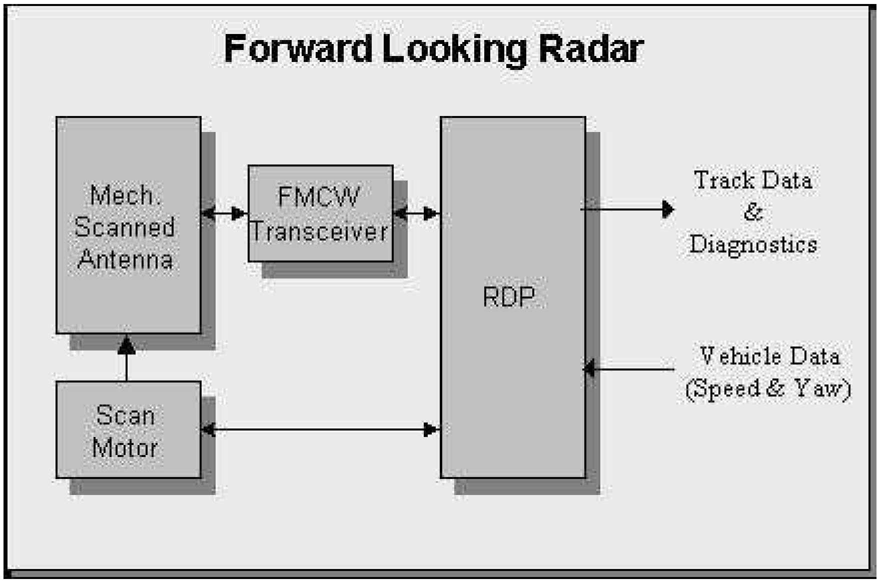


Figure 7: Forward-Looking Radar Block Diagram

The FLR is a narrow-beam, mechanically scanned, frequency-modulated continuous-wave (FMCW) radar operating at a frequency of 76.5 GHz (mid-band). The radar consists of a single transmit/receive antenna, scan motor, transceiver assembly, and radar data processor (RDP).

The radar scans a narrow (1.7 degree) beam over a field of view (FOV) of ±7.5 degrees in azimuth. This permits a minimum radius-of-curvature of 500 meters at a range of 100 meters with substantial margin to accommodate alignment tolerances. Furthermore, the wide FOV supports quick reaction to close range cut-in scenarios (even with the sensor mounted offset from the vehicle centerline). The narrow scanned beam is able to discriminate adjacent-lane vehicles traveling at the same range and range rate out to a range of at least 100 meters.

The RDP performs the radar signal and data processing functions including A/D conversion, FFT filtering, object detection and object tracking. The track file data includes the measured attributes of each detected object including range, range rate, range acceleration, angle and various classification attributes (e.g., stationary, moving, stationary-previously moving, bridge, etc.).

Table 5 – Forward-Looking Radar Parameters

Frequency	76.5 GHz
Waveform	FMCW
RF Bandwidth	184 MHz
Scan Mechanism	Mechanically scanned
Range	
Coverage	1-150 m
Detection Range (10 dBsm)	150 m
Accuracy	± 0.5 m (random), ± 5.0 percent (bias)
Discrimination	5 m (2 m inherent capability, 5 m track merging gate)
Azimuth	
Horizontal Beamwidth	1.7 deg
Coverage	± 7.5 deg
Accuracy	± 0.5 deg
Discrimination	2.0 deg
Range Rate	
Coverage	-64 to +32 m/sec
Stopped Object	Yes
Accuracy	± 0.5 m/sec
Discrimination	3.0 m/sec
Vertical Beamwidth	4.1 deg
Update Rate	10 Hz
Target Acquisition Delay	300 msec (typical)
Target Tracking	15 targets

4.2.2. Forward Vision Sensor (Task B2)

DES was responsible for the forward-vision sensor (FVS).

The goal of the FVS was to improve the accuracy of the target selection process by supplying information about the position and orientation of the host vehicle in the lane of travel, and the shape and location of the lane ahead. The subsystem consists of a forward-looking camera, mounted behind the rear-view mirror, and a remotely located image-processing unit that detects and tracks the lane boundaries and communicates results to other subsystems via the controller area network (CAN) bus.

4.2.2.1. Algorithm Development

Prior to the start of the ACAS FOT program, a number of groups had developed short-range lane tracking systems for lane departure warning and lane keeping. However, little effort had been put forth to apply this technology to FCW systems.

During the development phase of this program, three university teams[4] participated in efforts to extend their existing lane tracking techniques out to a range of about 75 meters. Each was able to demonstrate a system that achieved a 60-meter range with sufficient accuracy much of the time. In parallel, DES's short-range lane tracking system was also improved in a number of ways. The strengths and weaknesses of each approach were reviewed, and a final system was implemented. In addition to the lane tracking functions, algorithms to optimize camera exposure and to estimate camera pitch and pan angles were also developed and employed.

Evaluating the performance of a lane tracking system is inherently difficult because of the difficulty of establishing ground truth against which to measure system accuracy and responsiveness. In order to evaluate the performance of the vision sensor, and to measure improvements in the subsystem, methods had to be invented to evaluate and compare the results of the different approaches. Simply observing results overlaid on video images can be misleading because they frequently do not correctly reflect the effects of vehicle pitching and other phenomenon that can have significant consequences on the estimates reported to other subsystems. As a result of these efforts, a great deal of practical expertise was gained in evaluating lane tracking system performance.

4.2.2.2. Hardware Implementation

The hardware implementation of the vision subsystem was built entirely from off-the-shelf components. A progressive scan (CCD) camera that allowed external control of the shutter speed was selected for the system. This allowed the exposure to be optimized over the primary region of interest, and resulted in images that were crisp and free of interlace artifacts.

The processor unit was based on a single-board Pentium PC with a PC104+ stack to accept the frame grabber and CAN interface cards. An Embedded NT operating system on flash memory enabled turnkey operation, while still allowing fast and easy implementation of feature algorithms. The scene tracking function was also implemented in the same unit.

Reflections from the dashboard or other structures in the car are an important concern for forward-looking vision systems and usually require installation of a light shield. A shroud was designed to house and protect both the vision and forward scene cameras. Though plainly visible by the passenger, the unit was unobtrusive to the driver's field-of-view.

4.2.2.3. Final System Performance

At the onset of the program, the vision system was expected to aid target selection primarily (a) in curve entries and exits, (b) in the presence of wandering within a lane or a driver bias to position themselves to one side of the lane, and (c) during host lane changes. All of these are situations in which yaw-rate, which is typically a good predictor of host path, can be a source of error in the target selection process. Analysis of data collected during the development and validation phases of the FOT has shown that the system was able to successfully meet goals (b) and (c) above. The longer-range performance, desired to reduce false alarms in the curve entry/exit scenarios, fell short of initial expectations. The level of achievement of each of these performance goals is now discussed.

---

[4] University teams: 1) Ohio State University (U. Ozguner/ K. Redmill), 2) University of Michigan – Dearborn (S. Lakshmanan/ K. Kluge), and 3) University of Pennsylvania (C.J. Taylor).

Curve Entry / Curve Exit

Though the long-range systems frequently appeared (in video overlay) to successfully detect, track, and model the lane boundaries out to at least a 40-60 meter range, none was able to reliably *predict* the subtle changes in curvature that can lead to false FCW warnings in curve entry and curve exit situations. The primary reasons for this inability are now discussed.

In some cases, the algorithms may have been overly influenced by more populace near-field markers and distracted by long-range non-markers. At the beginning of a curvature change, for example, most of the extracted lane data still supports the previous constant curvature solution. Even weighted by range distribution, it is difficult for a few distant samples entering the curve to drive the solution. In addition, the reliability of more distant data is generally lower than that of near-field detections, a fact well illustrated by the plot in Figure 8. The graph shows that even under good conditions the amplitude (or contrast) of lane marker features decreases with range. Thus, at longer range the probability of errors being introduced by non-marker features increases significantly. The plot also shows the relatively low contrast of some yellow lane markers. This motivated DES to consider an imager with more near infrared sensitivity for production systems.

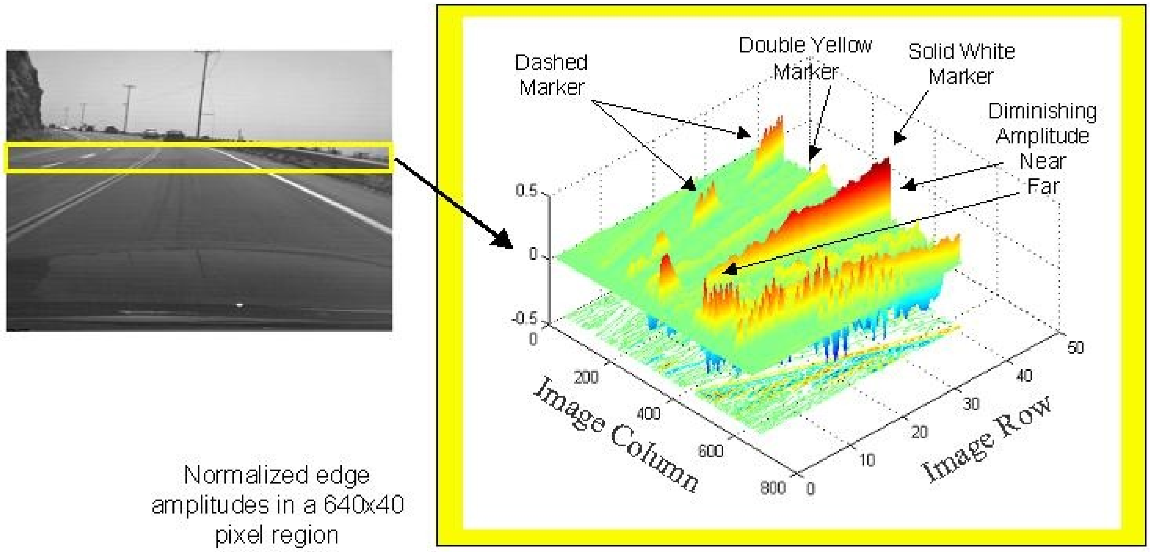


Figure 8: Edge Amplitudes Normalized for Local Illumination.

Vehicle pitching is one of the most significant sources of error for the long-range system. Even on a relatively smooth road, vehicle pitch motion of ±0.5 degrees is typical. The plot in Figure 9 shows the effect of a small pitch error on lane shape for a 500-meter curve. The resulting offset errors become increasingly significant beyond about 30 meters. When filtering is added to the system to reduce these pitch effects, curve preview is also reduced.

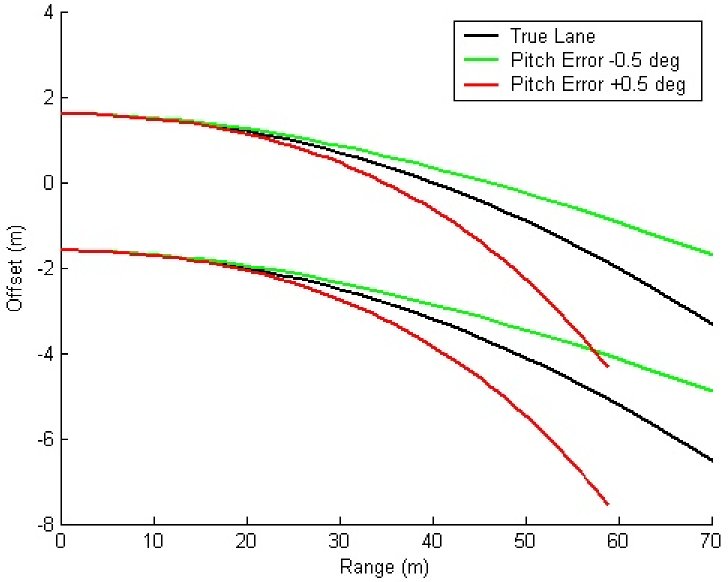


Figure 9: Potential Effects of Vehicle Pitching on Road Shape Estimates.

Ultimately, curve transitions are short-lived, transient events that amount to a very small (albeit important) percentage of the overall driving experience. Comparing the lane shape-describing abilities of vision and yaw rate, it was determined that:

- Yaw rate is quite reliable, and rarely completely wrong, except at very low speed and under the situations described above, and
- Vision, while it may predict an upcoming curve, also has the possibility of tracking non-marker features and producing completely incorrect results in otherwise benign situations.

Thus, the real challenge in taking advantage of a long-range vision system for FCW centers on determining *when* to rely on its estimates. This task could not be fully completed during the development phase of the Program, but remains a focus of ongoing work.

Driver In-Lane Wandering

The second goal of the vision subsystem was to provide accurate host state information, such as lateral position and orientation in lane, and local curvature. Knowledge of these parameters can help reduce false alarms on adjacent lane objects and roadside objects, and during host and target maneuvers.

Analysis of on-road data showed that the accuracy of vision system-supplied lane position and heading information met the stated requirements. Figure 10 shows the results for a short sequence on a straight road. For analysis, yaw rate was used to compute instantaneous curvature and was also post-processed to provide the ground truth for heading shown in the plots. Statistical analysis of the system outputs over longer sequences provides an indication of the accuracy of the sensor. The results are shown in Table 6 and Table 7.

Table 6 - Average Lane Width for a 5-Mile Segment

Source	Lane Width (m)
Vision Sensor	3.48 ± 0.05
Measured	3.5

Table 7 - Estimated Maximum System Resolution (3-sigma values)

	Offset (m)	Heading (deg)	Curvature (1/m)
Resolution	0.07	0.45	3e-4

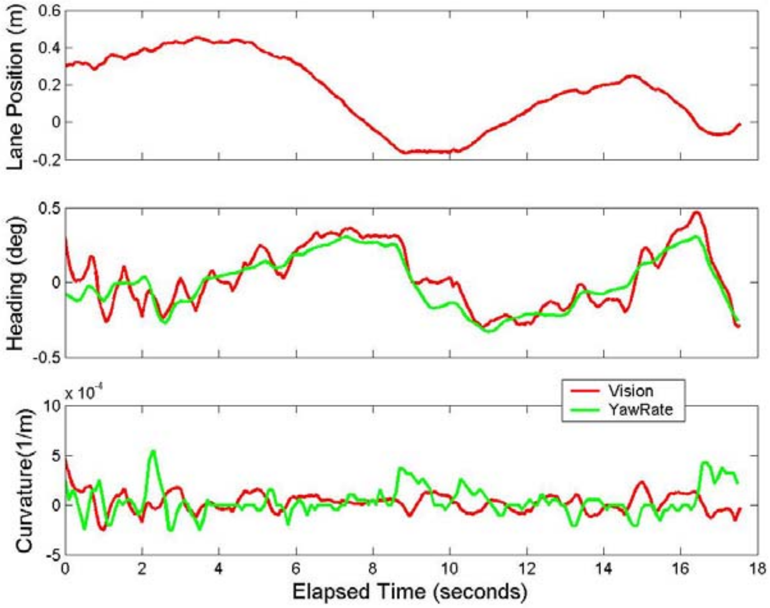


Figure 10: Vision Subsystem Results for a Sequence with Driver In-Lane Wandering on a Straight Road.

ACAS-equipped Vehicle Lane Changes

The third type of situation for which the vision subsystem was expected to provide valuable information was in ACAS-equipped vehicle lane changes. During these events, curvature estimates from yaw-rate measurements can be very inaccurate. In addition, the vehicle can build up a large heading angle in the lane and, for a time, point squarely at (and possibly issue alerts to) roadside or other-lane objects.

As expected, the vision subsystem performed well in these conditions. Lane changes (fast and slow) in the presence of good to fair lane markers were reliably detected and reported. Figure 11 shows vision system results for a series of lane changes on a straight road. During the faster two maneuvers, the yaw-rate-based radius of curvature is as tight as 475 meters, while the vision system reports correctly that the lane is straight.

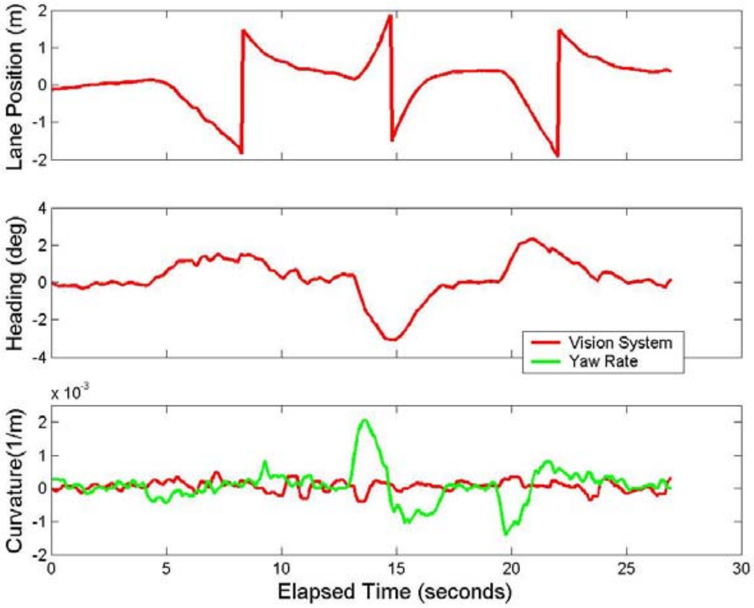


Figure 11: Vision Subsystem Results for a Multiple Lane Change Sequence on a Straight Road.

Since the implementation of this system, camera technology suitable for in-vehicle use has improved dramatically. DES worked with imager manufacturers in order to develop a camera system that met the needs of various forward-vision applications, including lane tracking. A CMOS imager, with a greater response in near infrared wavelengths, now provides better operation over a wider range of conditions than was possible for the ACAS FOT. A major challenge for production has been how to integrate the camera into the vehicle without interfering with a host of other vehicle components and sensors that are typically packaged behind the rear-view mirror. Thus, for production-intent systems, the team has designed a significantly more compact camera and shroud assembly. Also, as previously mentioned, production intent cameras provide greater near infrared response to improve yellow marker detection. These improvements in hardware and others in algorithm functionality make ACAS-style lane tracking a viable subsystem for consideration in future products.

4.2.3. Brake Control System (Task B3)

Delphi Chassis Systems was responsible for providing the production base brake and antilock brake systems (ABS) with the addition of a developmental autobraking feature. The autobraking feature provides automatic braking in response to a deceleration command from the radar unit (RU). Figure 12 shows the hydraulic mechanization of the DBC 7.2 brake system used to provide ABS, dynamic rear proportioning, traction control, vehicle stability control, and automatic braking functionality for the FOT fleet vehicles.

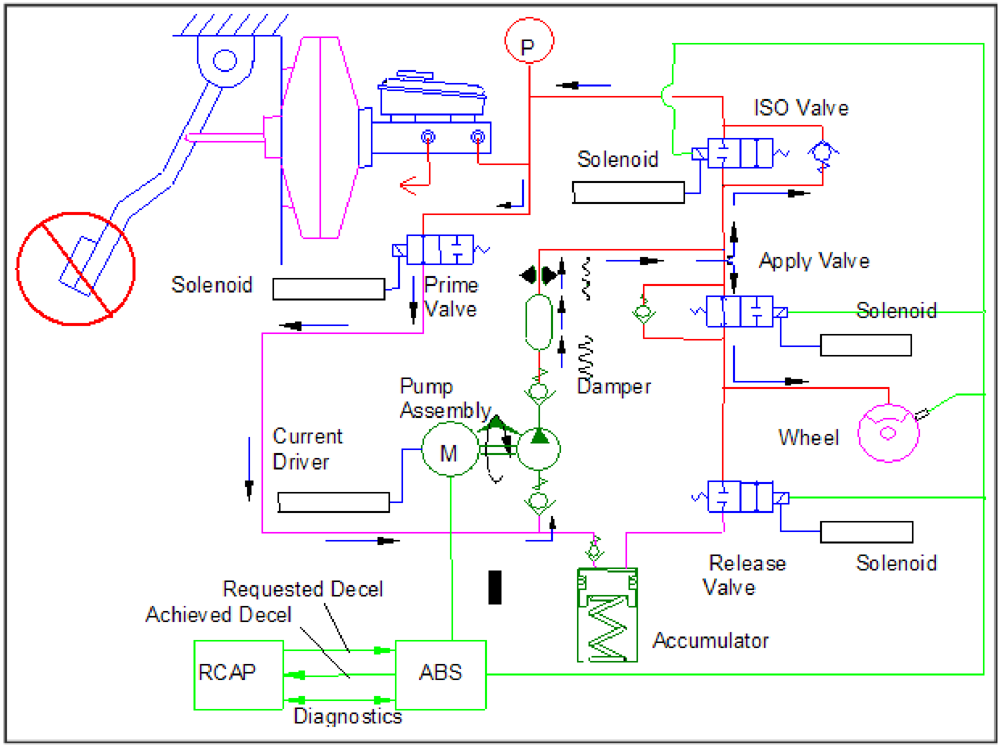


Figure 12: Brake System Hydraulic Mechanization

The brake system functioned with no reported anomalies throughout the FOT study. Subjective performance evaluation of the brake system was deemed favorable. A sample of data from a random autobraking event in an FOT development vehicle is shown in Figure 13.

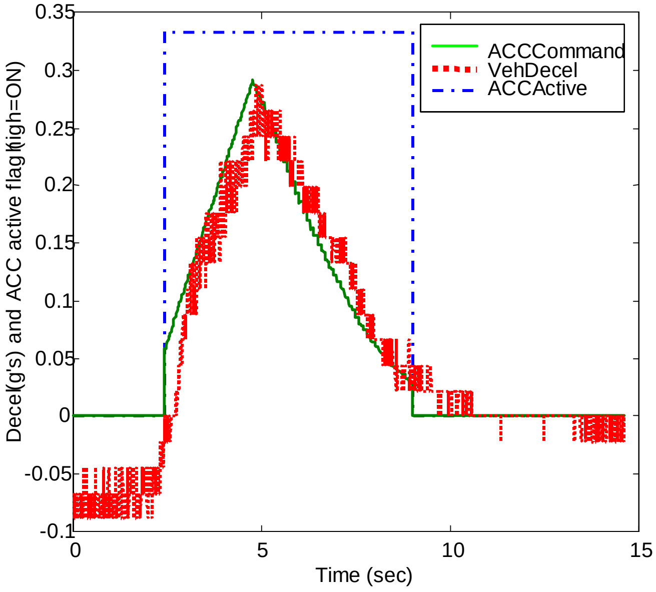


Figure 13: Deceleration Tracking Control During Auto-Braking

Figure 13 shows the automatic braking active flag, a deceleration command, and the achieved deceleration value. Figure 14 shows the wheel brake pressures that correspond to the achieved deceleration value of Figure 13.

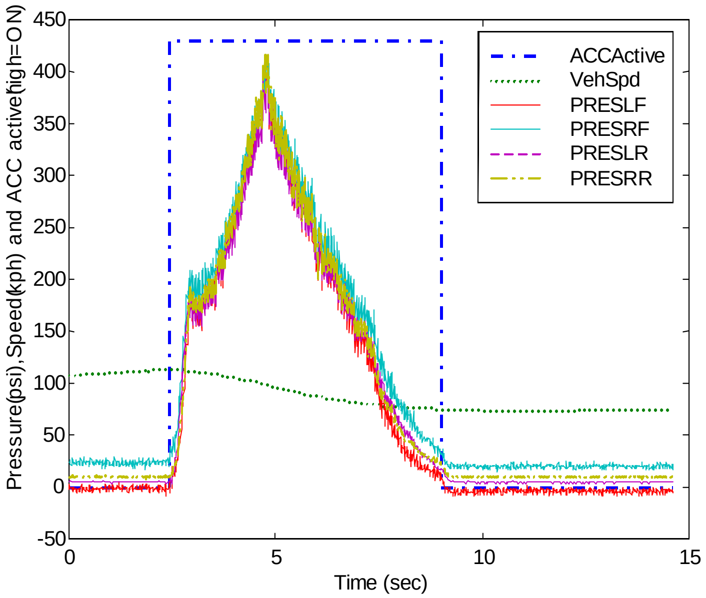


Figure 14: Wheel Pressure Response During Autobraking Event

There are several requirements for an ACC system. Two of those requirements are to achieve smooth deceleration and consistent (predictable) system performance. Figure 14 shows smooth (< 30 psi pressure gradient) wheel pressure responses with pressure gradients less than 20 psi. Consistency in system performance is heavily dependent upon the overall robustness of the autobraking algorithm to variance in temperature and everyday wear-and-tear on brake system components. The real-world data collected from the autobraking system prior to the FOT program consisted of 86 separate test drives which resulted in 3,246 test miles of ACC activation logged, during which 847 automatic braking events were recorded. Extrapolation and simulation were used to predict brake control performance over the typical life of a vehicle (100,000 miles). Using these methods, it was determined that the DBC 7.2 brake system would meet the ACAS FOT requirements over the life of the vehicle.

4.2.4. Throttle Control System (Task B4)

The objectives of the Throttle Control System were to:

1. Provide a throttle control system for the development and deployment vehicles
2. Provide interface requirements to other vehicle systems
3. Provide support to the development and deployment groups

The basic approach to accomplishing this task was to modify the existing throttle control system on the Buick LeSabre. The throttle control in the Buick LeSabre is a stepper motor cruise control (SMCC) designed and built by DES.

DES modified the software of the SMCC and provided replacement printed circuit boards for all of the vehicles. The interface was a serial 8192 link that was compatible with the ACAS ACC systems.

The modifications required were to alter the standard unit to accept input from the ACC system and to report the driver's input without taking any action, with the exception of on/off and safety-related functions.

The initial modifications performed as required and did not need any changes during the program.

4.2.5. Driver Vehicle Interface (Task B5)

The primary objective of the DVI task, performed by DES, was to develop an interface that clearly conveys information from the ACC and FCW systems to the vehicle operator, allows the driver to easily control these systems, and provides a highly acceptable interface approach to the driver. For the FCW system, the warning cues and presentation methodology were selected and developed with the intention of immediately directing the driver's attention to a potential rear-end crash event, while allowing sufficient time to perform some corrective vehicle control action to either completely avoid the event or, at a minimum, to mitigate the crash energy. For the ACC system, sufficient information must be presented to the driver so that the driver is aware of the current status of the system (e.g., cruise control set speed, selected inter-vehicle separation time headway, and whether or not a preceding vehicle has been detected by the system). For both systems, the goal was to present this information in such a fashion as to be easily understandable at a glance by the operator.

The Warning Cue Suite Selection task was completed during the 2001 calendar year and is summarized in the *ACAS FOT Deliverable 11 - Warning Cue Implementation Summary Report*. This section will focus on the activities not currently described in that report.

The primary display interface for the ACAS FOT system was a reconfigurable HUD developed specifically for this project. It projects an image that subtends a 1.5 degrees (vertical) by 3 degrees (horizontal) visual angle. The DVI also includes the audio warning equipment, steering wheel and instrument panel controls, and their associated electronics. The approach to optimizing this interface in the 2002 calendar year was to collect usability information from members of the ACAS FOT program team who had experienced the DVI, use this information to reveal any unanticipated consequences of the design, and then to optimize the DVI using this feedback.

Based on human factors experimentation conducted by DES, a three-stage display sequence (referred to as the "Looming display") was selected for the FCW (see Figure 15). The sequence from left to right of Figure 15 transitions from No Vehicle Detected, Vehicle Detected, Caution Warning, and Imminent Threat. The Imminent icon (far right) flashes at 4 Hz and is accompanied by an audio tone and was based on symbol testing by the GM Structure and Safety Integration Center. The configurations of the HUD that were selected are displayed in Figure 16.

Figure 15: Looming Display

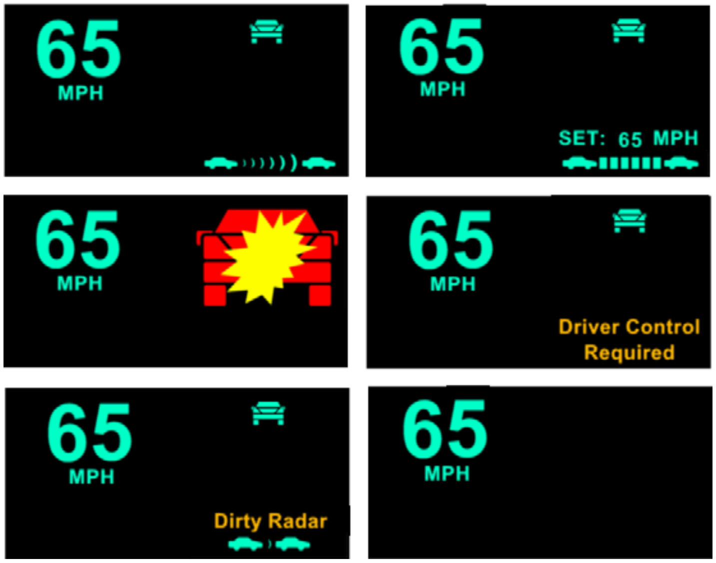


Figure 16: DVI Head-Up Configuration

At the top left of Figure 16, the HUD configuration for FCW is displayed. This figure shows how the display would appear when the vehicle is traveling at 65 mph, a vehicle is detected but not yet classified as a collision threat, the sensitivity setting is at the most cautious setting (setting 6), and the ACC is disengaged or off.

When ACC is engaged, the display would change to the top right panel. The set speed appears on the first line, and below is the ACC gap setting. Blocks rather than radar waves are used to communicate the coupling between lead and host vehicles when ACC is engaged.

The middle left panel shows the display during imminent alerts. Note that the sensitivity setting line (and the message text line) is blanked.

The middle right panel shows the display when the ACC is automatically disengaged (e.g., when the vehicle automatically brakes below a specified speed) and control is required of the driver. This graphic would be accompanied by a pair of 50-ms long 3000-Hz tones, which are also used when messages such as “Dirty Radar” are displayed (lower left panel).

Also note that the lower left panel displays the most aggressive sensitivity setting (setting 1). Drivers could select a single-stage display (i.e., no cautionary alert icons were displayed) by activating this setting.

The lower right panel displays what drivers see when the FCW system is disengaged (e.g., when the vehicle is below 25 mph or during each driver’s first week with the vehicle).

The various messages were programmed into the system and could appear on the message text line:

- A “Dirty Radar” message was displayed when the radome was obstructed, reducing the reliability of the ACC and FCW systems, and needed to be cleaned.
- A “Heavy Rain” message was displayed when the wipers were on high and the temperature was above freezing, reminding the driver that a high level of rainfall can reduce the reliability of the ACC and FCW systems, so caution is required.
- “Slippery” was displayed when the cool temperature indicated that the roads may be slippery and so the FCW algorithm will assume a more cautious driver braking assumption.

- "Sharp Curve" was displayed when the radar was unable to detect what is around the curve so the driver should use caution. "Speed Too Fast" was displayed when the vehicle was traveling at a speed that may mean that insufficient warning time is provided by the FCW system.
- A "Malfunction" was displayed when there was an ACC or FCW system failure. This message appeared in the event of a system malfunction, and similar to the "Driver Control Required" message (Figure 16), would occupy both the message text and sensitivity setting lines.

Because only one message could occupy the HUD at a single moment in time, messages were prioritized as a function of probable duration and importance to the driver. Some of the messages were also accompanied by the pair of tones described above.

To accommodate the new "Gap/Warn" control button, the temperature control button on the steering wheel was removed and steering wheel buttons were rearranged such that the "Gap/Warn" button was located on the upper left side of the steering wheel button. For a more detailed description of the research conducted and specifications of the DVI, refer to the *ACAS FOT Deliverable 11 - Warning Cue Implementation Summary Report*. The block diagram for the DVI electronics is displayed in Figure 17.

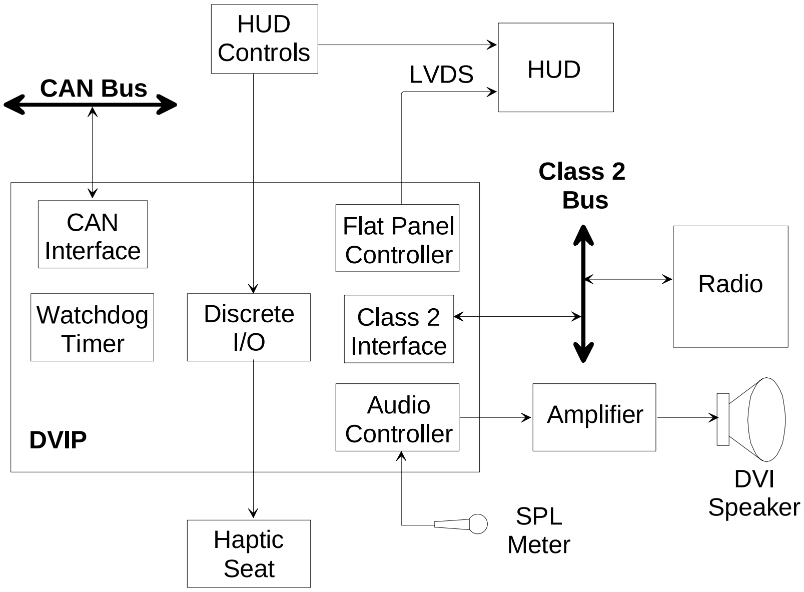


Figure 17: DVI Block Diagram

During 2002, as new information surfaced during the validation of the emerging ACAS fleet of vehicles, the DVI functionality and electronics were further optimized. As the ACAS team gained experience with the interface, minor modifications were made to the FCW display format, DVI software, DVI processor, and HUD hardware design.

During extensive on-road testing, it was observed that the three-stage display (amber, red, and flashing red warnings) was overly animated, producing large changes in the display as a function of potentially minor changes in the state variables. It was felt that this "busy" activity could annoy and potentially distract drivers. In particular, the change in display from amber to the first red icon (seen in Figure 15) provided a relatively salient cue to the driver, yet was driven by a relatively arbitrary constraint (half way between imminent and cautionary ranges). A decision was made to remove the red stage, reverting to a two-stage display (amber and flashing red). The human factors experimentation supporting the three-stage display (see *ACAS FOT Deliverable 11 - Warning Cue Implementation Summary Report* revealed little benefit of a three-stage display over a two-stage display. To make the display smoother, so that small changes in the world corresponded to smaller changes in the display, the Cautionary stage was expanded to include varying sized amber icons (see Figure 18). The rationale was that the change from Vehicle Detected to Caution would be less salient, however, as Caution approached Imminent, the driver would receive additional preview that an imminent alert may occur.

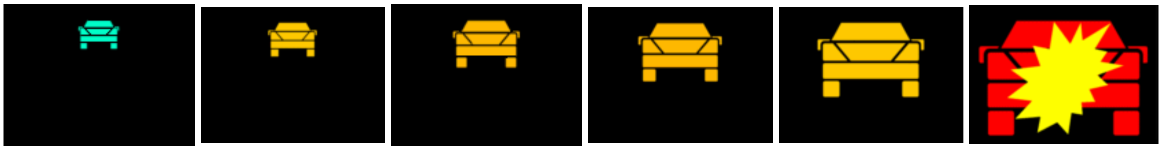


Figure 18: Looming Two-stage Display

After it was observed that participants were reluctant to change the sensitivity and gap settings during Stage 2 testing at UMTRI, a decision was made to allow the DVI to save the setting used at the termination of the previous ignition cycle. Furthermore, the sensitivity and gap settings were separated (i.e., changing one would not change the other) to make it as easy as possible for the driver to independently change in ACC gap and FCW sensitivity settings.

Based on observations that the DVI HUD information messages were overly annoying and likely to be difficult to comprehend by the typical driver, several driver message-related modifications were introduced. The “Speed Too Fast”, “Slippery”, and “Sharp Curve” messages were removed because it was felt they had a high potential of being misunderstood, were unnecessary, and had high potential of annoying the driver. The “Slippery” message was removed also because it was only being driven by a temperature sensor, and therefore had the potential of being inaccurate (e.g., on a cold dry day with no ice on the roads).

To ensure that the remaining messages were understood, they were changed from a one-line to a two-line format. An “ACC/FCW Needs Service” message was also added to indicate when system performance may be degraded by noncritical system malfunctions. The messages were prioritized according to Figure 19.

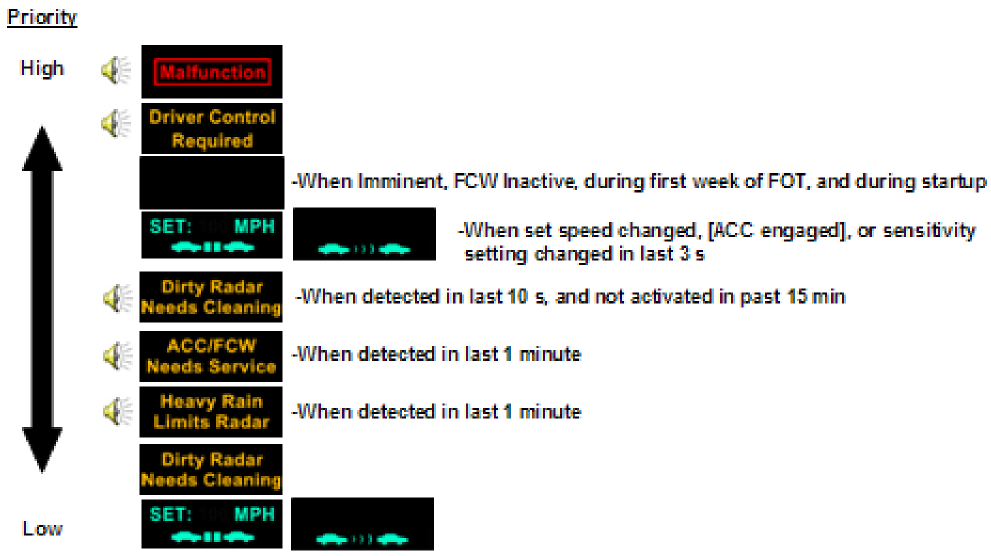


Figure 19: Message Priorities

During Phase II there were no events of DVI system failure and only one change was made to the DVI software. The Threat Assessment algorithm was changed to use the Imminent-Alert (flashing) visual icon to communicate the highest level of tailgating to the driver (see the right-most panels of Figure 15 and Figure 18) for Algorithm C. Whereas Algorithms A and B always associated this icon with the Imminent auditory stimulus, for Algorithm C the DVI was reprogrammed to present this visual icon without audio accompaniment when the highest level of tailgating occurred (with the intention of reducing driver annoyance).

4.3. Subsystem Processing Development - Software (Task C)

The Subsystem Processing Development (Software) task included the following subtasks:

Task C1 - Data Fusion
Task C2 - Tracking and Identification
Task C3 - Threat Assessment algorithm Development

4.3.1. Data Fusion (Task C1)

4.3.1.1. Purpose

The objective of the Data Fusion (DF) task, performed primarily by HRL in collaboration with GM, was to develop and implement a fusion system that evaluates multiple sources of potentially conflicting information to produce improved estimates of the road geometry, host vehicle state, driver distraction and environmental conditions. As shown in Figure 20, the DF system receives its inputs from a variety of subsystems (namely the host vehicle sensors, vision system, GPS/Map system and the Scene Tracker system). The outputs of the DF subsystem are used by the path prediction and target selection systems to identify in-path targets and by the Threat Assessment system to make a collision warning decision based on identified in-path targets. Real-time DF software was developed, tested, and fully interfaced and integrated into the Pilot and Deployment Vehicles.

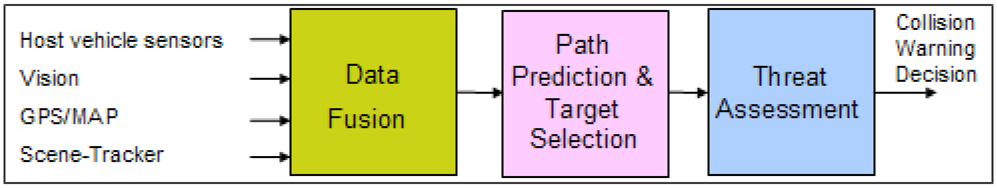


Figure 20: Data Fusion and its Relationship to Other System Tasks

4.3.1.2. Background

The Data Fusion task was divided into five subtasks:

1. **Task C1A: Requirements Definition and Architecture Development**

   The goal of the Requirements Definition and Architecture Development subtask was to develop requirements (performance, interface) and architecture for the DF system. This task was completed on September 16, 1999 with a meeting held at HRL, where HRL presented performance and architecture requirements of the data fusion subsystem, and a preliminary architecture for the data fusion subsystem.

2. **Task C1B: Initial Algorithm Development**

   The goal of the Initial Algorithm Development subtask was to develop algorithms to fuse radar, lane tracking, GPS/Map, and host vehicle sensors to produce a robust estimate of the host lane geometry, host state, driver distraction level, and environment state. This task was completed with a non real-time demonstration of the DF system presented to the NHTSA, GM, and DES on December 4, 2000. In addition, HRL submitted *ACAS FOT Deliverable 12 - Data Fusion Algorithm Simulation Summary Report* to GM on December 14, 2001. This report describes the data fusion algorithms developed in this task and the performance of those algorithms on simulated data.

3. **Task C1C: Real-time Algorithm Development**

   The goal of the Real-time Algorithm Development subtask was to develop real-time versions of the algorithms developed in the Initial Algorithm Development task for integration into the pilot and deployment vehicles. This task was completed on May 1, 2001, with a demonstration of the real-time data fusion algorithm to GM and DES at HRL.

4. **Task C1D: System Integration and Development Support**

   The goal of the System Integration and Development Support subtask was to assist the ACAS FOT team in integrating the real-time data fusion algorithms into the Prototype and Pilot vehicles and to modify and tune the data fusion algorithms as needed. This task was completed with the submission of *ACAS FOT Deliverable 29: Data Fusion Algorithm In-Vehicle Summary Report* to GM on December 20, 2002. This report provides a description of the data fusion algorithms that are implemented in the Prototype, Pilot, and Deployment Vehicles and provides a summary of the performance of these algorithms on collected vehicle data.

5. **Task C1E: System Integration and Development Execution**

   The goal of the System Integration and Development Execution subtask was to provide support to the ACAS FOT team to address any anomalies in the FCW system experienced during the FOT phase of the program.

The DF system was further divided into four main functional subunits: host lane geometry estimation; host state estimation; driver distraction estimation; and environment state estimation. Each of these functional sub-units is described below.

4.3.1.2.1. Host Lane Geometry Estimation

The goal of the Host Lane Geometry Estimation DF functional subunit was to provide an estimate of the host vehicle lane geometry for a distance of up to 100 meters ahead of the vehicle by fusing host lane geometry estimates from the vision subsystem, the map-based subsystem, the scene-tracking subsystem, and the road curvature estimates obtained from the host vehicle dynamics sensors. The host lane geometry estimation system also provided a confidence measure of the estimated host lane geometry and indicated whether it was unable to determine geometry from either the available inputs or based on current conditions.

Road Geometry Model

A fundamental issue in fusing different forms of information about forward lane geometry is the choice of a good road model. HRL investigated several different road models (parabolic, single-clothoid, spline) and initially chose a “higher-order” road model after simulation-based and in-traffic testing.

After gathering in-traffic data and conducting extensive analysis, it was revealed that the conventional single clothoid model outperformed the higher order road model. At near ranges (60 meters or less) both road models performed equally well. At far ranges, however, the performance of the higher order road model was determined solely by the statistics of the far range road estimates, which have a larger variance, whereas the higher performance of the single clothoid model at far ranges was due to both far range and near range estimates. The single clothoid model was judged to be a better road model choice due to lower variance in the far range estimates.

Host Lane Geometry Estimation

The DF subsystem provided an estimate of the forward lane geometry of the current host vehicle lane by fusing forward lane geometry estimates from the vision sensor subsystem, map-based subsystem, scene-tracking subsystem, and curvature estimates based upon vehicle dynamics sensors. Since vehicle motion along the road makes forward road geometry a quantity that varies dynamically with time, a dynamic recursive estimation approach such as the Kalman filter approach appeared to be promising. Kalman filters perform recursive estimation using both a model-based update of state variables and an update of the state estimates using a weighted version of the new measurements. Fusion is often done using Kalman filters as it provides a natural framework of fusing incomplete and inaccurate information from multiple sources and can provide more accuracy and improved robustness to stochastic errors (e.g., sensor noise) by acting as a sort of “low-pass” filter.

The original fusion architecture for the host lane geometry estimation was based on the idea of fusing the subsystem estimates based on their associated confidence measures. However, ground-truth analysis of the subsystem outputs on available real data suggested that, in general, their confidence measures were not adequate for fusion. As a result, the data fusion architecture and software was modified, and several different fusion methods were developed and tested on real driving data. The confidence-based fusion (COF) algorithm (the original approach) used the subsystem confidence measurements for fusion. The disadvantage of this approach is that since confidences are not always correct or reliable, fusing subsystems based on confidence “as is” may make things worse. The consensus-based fusion (CNF) algorithm uses agreement between subsystems to detect “incorrect subsystems” and ignore them. However, it requires at least two subsystems to be in good agreement for the method to work. The disadvantage of this approach is that good “lone” performers will not be fused. An alternate algorithm, and the one that provided the best results, fuses based on both rules and confidences. This approach relies on modifying confidences based on heuristic rules prior to fusion. An example would be to ignore scene-tracker outputs when it is operating in zero or low confidence modes and artificially bump up its confidence otherwise.

In evaluating the performance of the Kalman filter-based fusion algorithm for host lane geometry estimation, it was learned that when there is a transition in the forward road geometry (e.g., a straight-to-curve or curve-to-straight), the Kalman filter-based algorithm had a significant delay in properly estimating the transition. This delay causes errors in the host lane geometry estimation that were significant enough to cause false alarms in the FCW system. Further analysis of the performance of the Kalman filter-based algorithm revealed that, although Kalman filtering is widely used for data fusion, that it was ineffective for host lane geometry estimation. The reasons that the Kalman filter is ineffective for host lane geometry estimation can be summarized as follows:

1. When the road has a (relatively) constant curvature, the input sensor subsystems have already filtered their estimates and while the Kalman filter can further reduce the noise variance (at the cost of some delay), the variance is already sufficiently small. In other words, in constant curvature situations, the performance of the sensor subsystems in estimating host lane geometry is good enough that a simple fusion algorithm will work well.
2. When there is a transition in the forward road geometry, the transition or future is uncorrelated with the past road geometry. Therefore the Kalman filter cannot predict transitions and as a result performs poorly. Tuning of the Kalman filter to improve performance either introduces significant delay (which corresponds to large errors during transitions) or a smaller delay with significant overshoot errors.

Since the sensor subsystems do a good job of host lane estimation in constant curvature sections and do a relatively poor job when there is a road geometry transition, the main value added of data fusion is to improve host lane geometry estimates at the road transitions. The Kalman filter-based approach did not improve host lane geometry estimates at road transitions, and consequently, a new algorithm was needed.

After extensive processing of vehicle data using data fusion, the approach for host lane estimation was changed to a simple zero delay estimator that was referred to as instantaneous data fusion. The method is a type of weighted average estimate. If we have M independent (uncorrelated) estimates, x_i, and the variance of each estimate is σ_i^2, then the minimum variance, unbiased estimator is given by:

$$\tilde{x} = \sum_{i=1}^{N} \frac{x_i}{\sigma_i^2} \Bigg/ \sum_{i=1}^{N} \frac{1}{\sigma_i^2}$$

(Weighted average, with weight proportional to inverse variance.) In our application, the variance/confidence estimates provided by the sensor subsystems are not always good estimates. We address this problem by introducing a set of heuristic rules in which we adjust the weights for each estimate, w_i. Instantaneous data fusion is then defined as:

$$\tilde{x} = \sum_{i=1}^{N} \frac{w_i x_i}{\sigma_i^2} \Bigg/ \sum_{i=1}^{N} \frac{w_i}{\sigma_i^2}$$

Heuristic Rules

As described above, the instantaneous data fusion algorithm for host lane geometry estimation fuses the lane geometry estimates from the different subsystems using a weight for each subsystem that is adjusted based on a set of heuristic rules that are dependent on the driving and road conditions. Based on extensive analysis of collected data from the prototype and pilot vehicles, rules were developed that adjust the weight given to each of the sensor subsystems as a function of host vehicle speed, road shape, road type (paved, unpaved, limited access), and whether the host vehicle is in the midst of a turn. Several techniques were tried to automatically determine rules and optimal weightings, including decision trees, regression trees, and support vector machines. These methods were unable to generalize into small rule sets, and the limitations on how they can transform the subsystems' inputs restricted their applicability unless heuristic transformations of the observables were performed. These limitations, combined with high computational complexity and very large data sets, led to development of heuristic rule weights that were roughly tuned through a limited relaxation method. A detailed description of the heuristic rules that are used was provided in *ACAS FOT Deliverable 29: Data Fusion Algorithm In-Vehicle Summary Report*.

4.3.1.2.2. Host State Estimation

The goal of the host state estimation subsystem was to provide a fused host state estimate along with confidence values by fusing information from vision and scene-tracking systems. The vehicle host state consists of heading (in lane), lane offset, lane width, and a lane change indicator. Originally, the approach for host state estimation was to use a Kalman filter for reasons similar to those discussed above with regard to using a Kalman filter for host lane geometry estimation. However, in the current system, only the vision sensor subsystem provides estimates for heading, lane offset, and lane width. Therefore these values are passed through the data fusion subsystem un-modified.

The scene tracker and vision subsystems both provide lane change indicators, which are fused by the data fusion subsystem. The algorithm developed to fuse the lane change indicator is as follows: if both subsystems indicate a lane change, the data fusion subsystem indicates a lane change with confidence equal to the maximum confidence of the inputs. If the scene tracker and vision subsystems disagree on lane change presence, the lane change indicator of the vision system, and confidence is used because the vision subsystem lane change indicator was deemed more reliable than the scene tracker lane change indicator based on in-traffic testing.

4.3.1.2.3. Driver Distraction Estimation

The goal of the driver distraction estimation subsystem was to estimate driver distraction by monitoring if the driver is performing a secondary task such as adjusting the controls of the entertainment (radio) or climate control (HVAC) systems. The data fusion subsystem provides an estimate of driver distraction by monitoring if the driver is performing a complex secondary task, which occurs when the driver manipulates the turn signal, entertainment or HVAC controls. Domain knowledge of the secondary task is combined with monitoring of the controls in a set of fuzzy rules that provide an estimate of the level of driver distraction. A complete description of the fuzzy rule-based system for estimating driver distraction was provided in *ACAS FOT Deliverable 12 – Data Fusion Algorithm Simulation Summary Report.*

The fuzzy rule-based driver distraction estimation subsystem described above was not implemented in the pilot and deployment vehicles because the necessary inputs (driver manipulation of entertainment and HVAC controls) were either not available or interfaces to the controls were not implemented.

4.3.1.2.4. Environment State Estimation

The goal of the environment state estimation subsystem was to detect and report conditions indicative of slippery road surfaces. Data on road coefficient of friction can be used to modify the expected braking intensity the driver will achieve when responding to an alert, which in turn affects alert timing.

A fuzzy rule-based algorithm was developed to estimate the environment state. Road conditions were defined as dry, dry-icy, wet, or icy. Both the road conditions and their associated confidence levels are derived through a fuzzy rule set that is based first upon the windshield wiper activity; then further refined through the use of outside temperature measurements. A complete description of the fuzzy-rule-based system for estimating environmental state was provided in *ACAS FOT Deliverable 12 – Data Fusion Algorithm Simulation Summary Report*.

In the pilot and deployment vehicles, the environment state estimation subsystem was not part of the data fusion system due to sensor limitations that precluded information fusion. Instead, the threat assessment subsystem made an estimate of the environment state using temperature and windshield wiper activity inputs.

4.3.1.3. Testing, Evaluation, Results, and Conclusions

Testing and validation of the data fusion subsystem was performed by driving the engineering development, prototype, pilot, and deployment vehicles on public roads, or by replaying the data logged on public roads on a bench setup. Most of the testing and performance evaluation was done on the host lane geometry estimation subsystem. As described above, the other three subsystems of the data fusion system were either not implemented or were implemented in a manner that made their functions no longer part of the data fusion system.

The performance of the host lane geometry estimation subsystem is measured in terms of the accuracy of upcoming road geometry predictions. The predicted road geometry is compared against the actual road geometry (ground truth), which is obtained from a tool that extracts true road geometry from the host vehicle yaw-rate measurements. The ground truth algorithm is based on integrating the yaw-rate to determine the actual path driven by the host vehicle, which is assumed to be the same as the true road geometry, except when the vehicle is changing lanes or is stopped. True road geometry from collected vehicle data was used to analyze the road geometry prediction performance of the sensor subsystems and data fusion.

Table 8 and Table 9 show the typical results of host lane geometry estimation. Table 8 represents a typical highway-driving segment and Table 9 represents a mixed set of driving on highway, primary, secondary roads, and unpaved roads. The rows of the tables are the sensor subsystems that are inputs to the data fusion lane geometry estimation algorithm, and the output of the data fusion algorithm. These data show both the older Kalman Filter approach (labeled “Kalman Fus”) and the current instantaneous data fusion method (labeled “Fusion”) for comparison. Road geometry errors are measured as the difference between the predicted road geometry and the ground truth measured at a down range distance equal to the maximum of 30.0 m or a speed-dependent look-ahead distance[5]. (Look-ahead distance equals the product of the look-ahead time, Tlook = 2.5 seconds, and the vehicle speed. For example, the Look-ahead distance equals 72.6 meters at 65 MPH.)

The first information row of the table indicates the percentage of time that the ground truth is available (marked as valid), and specifies the look-ahead time and the driving time. The

---

[5] For almost all roads, the difference error between the ground truth and the predicted road geometry increases with down-range distance. Thus, evaluating the error only at the look-ahead distance has been found effective.

"percentavail" is the percent of time that ground truth is marked as valid and the subsystem has a new measurement estimate. The columns " percenterr > x m" are the percentage of time that ground truth is marked as valid, the subsystem has a new measurement estimate, and the resulting road geometry error at the look-ahead distance is greater than x meters. A 2-meter (2m) error corresponds to approximately a half lane width. A 4-meter error at the look-ahead distance means that the system might misidentify targets in the adjacent lane or road shoulder as threats. Ideally, percenterr > 2m would be zero, but the current sensor subsystems are not able to attain such a high level of performance. The single measure, percenterr > 2m, is felt to best characterize the road geometry estimation performance for a given data set and subsystem. It should be noted that all of the subsystems perform with very low variance on straight roads, and that when comparing results between data sets it is important to note what percentage of time the road is straight. (If most of the road is straight, percenterr > 2m will be small.)

Note that GPS/MAP, Vision, and especially Scene Tracker subsystems, can all potentially have low availability, (percentavail). For example, Scene Tracker is available 20 percent of the time in the L1031_02H data set in Table 9. In this data set there are frequently no other vehicles for the Scene Tracker to track.

Table 8 - Road Geometry Results, Highway

L1004_05H	Ground Truth available 89.6 percent, Tlook = 2.5 sec, 687.7 sec (highway)					
Sensor	**Mean(err)**	**Std(err)**	**percentavail**	**percenterr > 1m**	**percenterr > 2m**	**percenterr > 4m**
Yaw	0.46	0.69	100.00	13.02	2.14	0.00
Map	0.62	1.01	99.23	21.54	6.09	0.66
ScnTrk	0.48	0.69	90.65	11.18	1.97	0.02
Vision	0.71	0.92	89.19	23.64	4.94	0.35
Fusion	0.37	0.54	100.00	6.44	0.63	0.00
Kalman Fus	0.51	0.80	100.00	15.79	4.02	0.00

Table 9 - Road Geometry Results, Mixed Roads

L1031_02H	Ground Truth available 85.9 percent, Tlook = 2.5 sec, 2831.7 sec (Mixed, highway, primary, secondary, unpaved)					
Sensor	**Mean(err)**	**Std(err)**	**percentavail**	**percenterr > 1m**	**percenterr > 2m**	**percenterr > 4m**
Yaw	0.34	0.53	99.93	5.05	1.20	0.11
Map	0.30	0.52	97.01	5.82	1.07	0.12
ScnTrk	0.41	0.61	20.20	7.98	1.57	0.12
Vision	0.53	0.74	64.57	12.82	3.03	0.14
Fusion	0.26	0.44	99.81	3.71	0.60	0.08
Kalman Fus	0.36	0.64	99.93	6.78	2.20	0.20

As can be seen in the tables, the fused host lane estimation algorithm, based on instantaneous fusion, is successful in improving the road geometry estimates over the estimate of the individual subsystems by statistically and heuristically fusing the data. In all cases the fused estimates have lower mean and variance than any of the individual subsystems; additionally fusion improves the percenterr > 2m metric. Note that in these examples the instantaneous fusion algorithm performs better that the Kalman filter-based approach in every performance category, and specifically reduces the percenterr > 2m metric by more than a factor of three.

From the results obtained through testing and performance evaluation of the data fusion system throughout its development, the following three conclusions can be formed:

1. DF provides a significant improvement in host lane geometry estimation. The improvement is a result of being able to exploit information from multiple sensor systems (Vision, GPS/Map, Scene Tracker, and Yaw Rate) to achieve both a more accurate and more robust estimation of road geometry.
2. The conventional single-clothoid road model produces smaller road geometry estimation errors than the higher-order road model on real-vehicle data. On real-vehicle data, it was found that there is a large variance in the far range road geometry estimates. This large variance in the far range estimates adversely affects the higher order road model much more than the single clothoid road model, resulting in poorer overall performance of the higher order road model.
3. The confidence outputs from the various subsystems cannot be directly used by the fusion system. Additional methods and heuristic rules are needed to effectively fuse the correct estimates and ignore the incorrect ones. Special rules and heuristics that can be applied under special conditions will further improve the consensus-based fusion approach.

4.3.2. Tracking and Identification (Task C2)

4.3.2.1. Purpose

The objectives of the Tracking and Identification task were to refine the Path Estimation and Target Identification algorithms, to incorporate Vision-, Scene Tracking-, and GPS-derived information, to integrate these components into the FOT vehicle system, and to support FOT deployment.

Significant progress was made in the ACAS FOT program under Task C2. DES was responsible for the Conventional Target Path Estimation and Target Selection (Task C2A) and radar-based Scene Tracking activities (Task C2B) associated with the Tracking and Identification Task. GM was responsible for the Enhanced GPS approach (Task C2C). This section provides a summary of the noteworthy activities and results that were accomplished under these tasks.

4.3.2.2. Conventional Approach Development (Task C2A)

4.3.2.2.1. Purpose

The objective of Target Selection is to resolve and identify the existence of both stationary and moving "target" vehicles that are in the motion path of the host vehicle. In order to accomplish this, the target selection algorithms must (1) estimate the relative inter-vehicular path motion (range, relative speed, radius of curvature, etc.) between the host vehicle, the roadway ahead of the host, and all of the appropriate targets (roadside objects, in-lane, adjacent-lane, and crossing vehicles, etc.); and (2) predict the mutual intersection of these motion paths. In addition, the target selection algorithms must be robust in the presence of various types of driving behavior (in-lane weaving/drift, lane change maneuvers, etc.) and roadway conditions (straight roads, curved roads, curve entry/exit transitions, intersections, etc.) that are encountered in the real-world environment.

4.3.2.2.2. Algorithm Development

During the first year of the ACAS FOT program, enhancements were made to DES's baseline yaw-rate-based path estimation and target selection algorithms to improve performance during curve transitions and host lane changes. Stationary object false alarms were reduced by (a) refining target selection heuristics and persistency requirements, (b) optimizing target lane position estimation during severe right- and left-hand turns, and (c) rejecting bridge objects. The moving target cut in/cut-out response was improved by dynamically altering the shape of the target selection zone based on target lateral rate, acceleration, and proximity to the host vehicle. An additional analysis and development effort was also undertaken to improve target selection performance at low speeds. The development effort used steering sensor data together with a boresight-based path estimation approach to estimate the host's predicted path at low vehicle speeds.

During the second year of the ACAS FOT program, the path estimation and target selection algorithms were modified to incorporate fusion-based host and road state information. As explained in Section 4.3.1, the fused state information was provided by the DF subsystem (Task C1), and was derived from the following four complementary road geometry estimation approaches:

1. Vision-Based Lane Tracking (Task B2)
2. Yaw-Rate-Based Road and Host State Estimation (Task C2A)
3. Radar-Based Scene Tracking (Task C2B)
4. GPS/Map-Based Road Prediction (Task C2C)

The target selection algorithms were tuned to switch between the yaw-rate-based-only and the state-based fusion approaches based on the continuity of the fused road and host state information, and on the data fusion confidence measures. These target selection improvements were found to provide more robust roadside object discrimination, and to improve target selection performance at long range, during lane-change maneuvers, and during road transitions.

During the third year of the ACAS FOT program, the responsiveness of the target selection algorithms to close range cut-in / cut-out targets was improved by refining heuristics related to target detection status, target proximity to lane edge, and target distance from the edge of the radar sensor's horizontal field of view. In addition, the Target Selection subsystem's responsiveness to aggressive host lane changes was also improved by using the vision-based host state (e.g., heading, lateral lane position, and lane width) to provide more accurate target lane position estimates. During the fourth year of the ACAS FOT program, data collected from the preliminary trials of the pilot test vehicles was analyzed, and key issues and areas of possible improvement were identified. As a result of the analysis, additional heuristics and discriminants were added to the target selection process to reduce the incidence of stationary-object false alarms.

4.3.2.2.3. Subsystem Integration and Testing

The Target Path Estimation and Target Selection algorithms were integrated into a custom Radar Collision Avoidance Processor (RCAP). The RCAP unit has a Motorola 68332 processor and various onboard serial, A/D, and CAN interfaces.

4.3.2.2.4. Data Collection and Analysis Tool Upgrades

During the ACAS FOT program, DES developed a suite of laptop-computer-based data collection and playback tools. DES's data collection tools had a similar purpose to those developed by GM in that they were designed to evaluate real-time system performance while performing on-road vehicle testing. The tools also provided a mechanism to perform in-depth ACC/FCW system data analysis and quantify system performance. The data collection tools were used to digitize live video and store it to disk synchronous with digital system data, provide a graphical visualization of the roadway scene, and allow for synchronous replay of video and system data for analysis and re-simulation.

4.3.2.2.5. Algorithm Iteration and Refinement

The tuning and refinement of the target selection and path estimation algorithms was performed during an iterative test-and-validation process. The test-and-validation activities were performed on DES's real-time system bench, and on both the prototype and pilot test vehicles. GM, DES, and UMTRI performed extensive track and open road tests on freeways, city streets, and rural roads in order to collect a robust suite of test data. Target Selection subsystem performance and overall ACC and FCW system performance were evaluated. Key areas of improvement and problematic scenarios were identified and corrected. Required changes to lower-level subsystems to help improve target selection were identified. Those algorithms and interfaces were subsequently improved, and the collected data were rerun on the real-time bench to verify the improvements.

4.3.2.2.6. Performance Assessment

Over the course of the ACAS FOT program, the ACAS system's "stationary in-path target" false alarm rates were significantly reduced due to (a) improvements in the GPS/Map subsystem's road geometry estimates, (b) a reduction in the Data Fusion subsystem's road geometry errors and road prediction lag, and (c) refinements made to the Target Selection subsystem's path estimation algorithms and heuristics. Similarly, the "moving in-path target" false alarm rates were also significantly reduced due to (a) improvements made to the Data Fusion subsystem's road geometry estimation, (b) refinements made to the Target Selection subsystem processing, and (c) enhancements made to the Threat Assessment algorithms.

Many of the remaining errors in selecting "moving in-path targets" can be attributed to (a) target position uncertainties caused by radar target scintillation and horizontal field-of-view effects, and (b) the inherent limit to the accuracy of the radar target edge information. In addition, most of the remaining errors in selecting "stationary in-path targets" can be attributed to (a) nonvehicular off-road clutter (e.g., curbs, trees, poles, guardrails, etc.) detected during curve entry and exit transitions, and (b) overhead signs and bridges that were not rejected by the ACAS radar's bridge discrimination logic. A more detailed description of these issues is provided below.

4.3.2.2.7. Radar Scintillation

Radar target scintillation effects can cause a target's reported position to shift due to the dynamically changing aspect view of the target (e.g., while traveling on a curved road, during a target lane change maneuver, or during a target turnout). These scintillation effects can increase the target position uncertainty and generate noisy and inaccurate target lateral rates. This effect is compounded for large trucks and trailers, which, due to their large size and numerous reflective corners, can experience very large centroid shifts.

4.3.2.2.8. Proximity to Edge of Radar Horizontal Field of View

At short range, most adjacent lane targets and many cut-out targets do not lie fully within the 15-degree horizontal field –of view (HVOF) of the ACAS radar. Consequently, the centroids reported by the radar for these targets may not be representative of the actual target centroid. This causes two primary problems. First, the centroid position error makes it difficult to reliably determine if the target falls within the host vehicle's path. In addition, the centroid position error also generates a false lateral velocity when the host vehicle is overtaking an adjacent lane target vehicle, or an in-lane vehicle is cutting out of the host lane as it moves outside of the radar horizontal field of view. In the later case of a cut-out target, the target's centroid appears to ride the HFOV in toward the host, falsely indicating that the target is cutting into, rather than out of, the host's path. Algorithmic solutions mitigate most of these effects, but some false alarms result from these effects.

4.3.2.2.9. Radar Target Edge Information

Radar target edge information is inherently inaccurate. It is typically derived from knowledge of the radar's antenna beam pattern coupled with the target's power characteristics and angular profile, rather than the physical edges of the target. As a result, it is difficult to use target width to reliably discriminate between valid vehicular objects and false targets (e.g., poles, trees, etc.).

4.3.2.2.10. Overhead Objects

The ACAS radar detects stationary as well as moving objects. Given that overhead stopped objects are detected along with valid roadway stopped objects, the ACAS radar sensor applies a specialized bridge rejection algorithm to classify stopped objects as either overhead (bridges) or valid scene targets. The bridge rejection algorithm consists of a combination of geometric, statistical, and contextual discriminants to provide a probability that an object is an overhead object verses roadway object. In an attempt to further reduce the stationary false alarm rates due to overhead objects, additional target detection confidence measures were added to the target selection algorithms. These confidence measures were based on target detection status and variance in target angle and width measurements.

4.3.2.2.11. Road Geometry Estimation

The DF process (Task C1) compares and correlates multiple and complementary road geometry estimation approaches (e.g., yaw-rate, radar-based scene tracking, GPS-Map, vision-based lane tracking) in an instantaneous data fusion approach. This approach has improved the overall FCW system performance and driven down system false alarm rates during host lane changes, road jogs, and "gentle" road transitions. However, the task of providing reliable road geometry preview during road transitions has been difficult due to the design constraints and real-world issues discussed below.

Yaw-rate-based path estimation provides reliable road geometry estimation performance during constant-curve and straight-road conditions. Moreover, during dynamic road conditions, such as curve entry and exit transitions, the yaw-rate-based approach provides "some" road geometry prediction as the driver begins to adjust his steering angle in anticipation of the curve ahead. However, the yaw-rate-based approach is not sufficient to predict S-curves, long range road transitions, and host lane changes, or to provide robust roadside object discrimination.

The radar-based Scene Tracking approach was developed to address many of these yaw-rate-based limitations. The Scene Tracking approach provides useful long-range road geometry estimates when there are enough moving cars on the road to trace out the road shape ahead of the host. However, on isolated roads, with few or no other moving vehicles, the Scene Tracking approach provides the same performance as yaw rate.

Similarly, the GPS-Map subsystem provides good forward road geometry preview (a) when the received GPS position is accurate and timely, (b) when there is GPS/Map information available in the map database, and (c) when the road segments and shape points stored in the map database are accurate. However, in many instances these conditions are not met, and the road GPS-Map geometry cannot provide adequate preview.

Conversely, the vision-based Lane Tracking subsystem does not provide a long-range road model. However, it does provide accurate host state estimates (e.g., host lateral lane position, lane width, and heading), and good near-range road curvature. While these vision-based host and near road state estimates are useful during host lane changes and turns, they cannot be used to predict road transitions.

4.3.2.2.12. Lessons Learned

Evaluations done by DES indicate that nearly all of the remaining ACAS FOT false alarms due to (a) above-road and off-road clutter (e.g., bridges, signs, poles, guardrails, trees, etc.), and (b) target angle and edge measurement uncertainties due to radar scintillation and radar field-of-view effects - could be eliminated by adding radar-cued, vision-based object-detection-and-classification capability to the ACAS system architecture. While this technology was not mature enough for use at the inception of the ACAS FOT program, advances in algorithms and processing after the system implementation was frozen make such a system much more viable. A vision system can provide more accurate and stable angle, edge, and lateral rate measurements, more precise target classification and an expanded field of view. The more accurate target position and angle rate information can improve the overall system’s performance against close-range cut-in and cut-out targets. In addition, the vision-based classification information can be used to potentially eliminate many of the nonvehicular false alarms and to dramatically increase the system’s overall performance.

4.3.2.3. Scene Tracking Approach Development (Task C2B)

4.3.2.3.1. Purpose

Scene tracking is an enhancement to the conventional path prediction process in which preceding vehicles are classified as being in-lane or not in-lane. The conventional yaw-rate-based road estimation approach cannot reliably predict changes in road curvature ahead of the host, since the road curvature is assumed to be constant. Moreover, the conventional yaw-rate-based approach also assumes that the host is not weaving in lane or changing lanes. In the scene tracking approach the paths of the preceding vehicles are observed in order to estimate the upcoming forward road curvature. This approach assumes that most of the preceding vehicles are staying in their lanes, and that there are reasonable constraints on the rate at which the road curvature can change. In addition to estimating the upcoming road shape, the scene tracking approach also estimates the angular orientation of the host vehicle in its lane, thereby accounting for in-lane weaving or lane changing by the host.

The scene tracking subsystem is charged with providing estimates of the road curvature parameters for a clothoid model which describe the shape of the upcoming road segment, and an estimate of the host's heading angle in the lane. A confidence indication is also provided. These estimates are based on observations of the trajectories of preceding vehicles provided by the forward-looking radar. The scene tracker also requires measurements of the host vehicle's speed and yaw rate.

4.3.2.3.2. Accomplishments

The primary accomplishment of this task was the fully functional real-time scene tracking software which resides in the Vision/Scene Tracking Processor, receives CAN messages from the radar, and transmits to the Data Fusion function CAN messages containing the scene tracker's estimates of host heading angle in lane, the road curvature parameters, and an indication of the confidence in the accuracy of these estimates.

A number of different approaches were investigated, each one intended to be an improvement in areas where earlier approaches were weak. These problem areas included such things as fundamental radar phenomena (occlusion of targets, multipath, multiple returns from a single target, etc.) and their consequent effects on the radar tracker, insufficient target data in the current field of view (FOV), detection and rejection of outlier targets (e.g., lane changers), targets disappearing from the FOV during a host lane change, accounting for differences in transient response to host yaw motions between the yaw rate sensor and the radar tracker, operation at low speeds in urban environments, and dealing with problematic but common road geometries such as on-ramps, off-ramps, and merging lanes of traffic.

At the start of this program, a scene-tracking algorithm existed which will be referred to here as the “original” version. During this program, several other approaches to scene tracking were developed. In all, the various versions can be summarized as:

1. the “original” version, in which target tracking filters estimate target heading angles and target trajectory curvatures at range, allowing estimation of road curvature and host heading angle;
2. the “unified” approach, in which a single variable-dimension Kalman filter estimates the clothoid parameters, host heading angle, and target lateral positions;
3. the “parallel” approach, in which each target has its own Kalman scene-tracking filter, the outputs of which are combined;
4. the “snail tracking flow field” approach, in which stored target position data is used to calculate a flow field that is analyzed; and
5. the “snail tracking unified” approach, in which stored target position data is directly analyzed to form estimates of the desired quantities.

Each version in the sequence was intended to improve performance in some area(s) deemed deficient in earlier versions.

Aside from algorithm development, which mostly was done in the Matlab environment, another significant accomplishment in the scene-tracking task was its migration to a real-time C-language implementation on a processor in a real vehicle. Subsequently, further effort resulted in the porting of this code into the onboard Vision/Scene Tracking hardware.

To some extent, the transition to “snail tracking” approaches alleviated problems associated with the radar phenomena and insufficient data in the FOV. The essence of snail tracking is that, at any time instant, the data available is not only the current data sent by the radar, but also any other recent moving vehicle detections that correspond to locations in front of or near the current location of the host vehicle. In effect, a big image is available showing recent trajectories of many vehicles, some of which may currently be outside of the radar FOV. This is a significant advantage when trying to discern problematic road geometries (off-ramps, etc.), or during host lane changes (when all the targets in front of the host may disappear for a while).

The parallel approaches, such as the “snail tracking flow field” approach, seem to have advantages when pruning outliers from the data under consideration.

The approaches used relied entirely on moving objects and ignored stationary objects. Radar returns from stopped objects also contain significant road shape information that can be of use. Generally, stopped object returns are more numerous and are available more often, however they present a more confusing geometry due to the broad distribution of off-road objects. Future versions of scene tracking could make use of stopped objects to enhance performance.

Earlier ACAS reports have shown the performance of the scene tracker's confidence measure to be high. That is, that the r.m.s. error in predicting the lateral road position at some point down range is smaller for the higher confidence levels than for the lower levels. Because of the accurate confidence measure, the scene tracking estimates were of value to the Data Fusion function. The fusion algorithm made use of the scene tracking estimates in scenarios that are not handled well by the conventional path estimation scheme (e.g., host lane changes and curve entries/exits).

In summary, the scene tracking algorithm makes use of the trajectories traced out by preceding moving vehicles and provides good road geometry estimates to the Data Fusion function, which are accompanied by reliable confidence estimates.

4.3.2.4. GPS/Map-Based Road Geometry Prediction (Task C2C)

The objective of the GPS/Map task was to develop and implement a host vehicle path prediction system capable of aiding a radar-based ACC/FCW system in eliminating irrelevant targets, and to assist in classifying detected objects as in-path or out-of-path. The developed system uses a digitized roadway map database, differential GPS, and dead reckoning. In particular, the objective was to make use of road maps to develop a path prediction method that would continue working during lane changes and curve transitions and to complement a yaw-rate-based path prediction system. In addition, the goal was to provide other map-derived information (for example, road geometry classification, and presence of forks, ramps, intersections, T-junctions, start and end of curves and distances to them) deemed useful in enhancing the performance of the Data Fusion, Target Selection and Threat Assessment subsystems.

4.3.2.4.1. Background

Development of a GPS/Map-based host path prediction algorithm had been undertaken in the 1997-98 timeframe under the auspices of a GM Research & Development (R&D) FCW System development project. This initial attempt at developing such a subsystem yielded satisfactory results for certain road classifications in controlled testing environments. However, several shortcomings were revealed:

- The subsystem data output rate (one update per second) was not sufficient to keep up with the requirements of an FCW application.
- The forward road geometry did not meet the accuracy requirements of an FCW application.
- The technique lacked the ability to estimate confidence in its results.
- The system could not function during periods of GPS outage.

To meet the ACAS FOT requirements, the previously existing system was completely redesigned to provide smoother road geometry transitions, confidence estimates, a road geometry classification scheme, dead reckoning, and auxiliary map-derived information. In addition, accuracy and timeliness were significantly improved to support the FCW requirements.

4.3.2.4.2. Algorithm Development

The process of predicting the forward road geometry of the host vehicle using a digital road map database and vehicle positioning consists of two main steps: first, matching the vehicle position to a road on the map, and second, retrieving information pertaining to the forward path of the host vehicle from the map database. In addition, a measure of confidence in the real-time output is needed to help down-stream subsystems assign proper weight to the retrieved map geometry.

4.3.2.4.3. Map Matching Using GPS and Dead Reckoning

Map matching is achieved by continuously estimating the location of the vehicle on the road using differential GPS (DGPS) and dead reckoning sensors, searching a stored road database for road segments in the vicinity of the vehicle’s location, and matching the vehicle location to a point on a road in the stored roadway map. The map matching methods developed earlier were made more robust by adding logic to overcome the problem of switching back and forth between freeways and frontage roads or ramps due to GPS ambiguities and map errors. Also, methods were developed to detect and accommodate map errors, and avoid the perpetuation of the error in subsequent map matching iterations.

To overcome the shortcoming due to GPS outages, further refinements of the subsystem were undertaken to fill-in periods of GPS outages. When the GPS/Map subsystem determines that the unmodified GPS position and map data are providing inaccurate results, it employs dead reckoning to calculate a modified vehicle position using inertial navigation software functions. Additionally, dead reckoning aids in determining how closely the path of the vehicle is conforming to the map database. This functionality relies on the yaw-rate sensor and vehicle speed, as well as periodic crosschecks with the GPS and map data.

4.3.2.4.4. Predicted Forward Road Geometry

The map-matched vehicle position serves as the primary input to the path prediction module. Path prediction is achieved by continuously tracking the path traversed by the vehicle, predicting the forward path likely to be taken by the host vehicle using heuristics, and retrieving the forward road geometry pertaining to that path from the map. Upcoming road geometry is determined using the following two steps:

1. Twelve interpolated points (that yield 120 meters of forward geometry) along the road on the predicted vehicle path are computed at 10-meter intervals starting at the host vehicle position.
2. The upcoming path of the host vehicle is defined in terms of offset distances from each of the 12 points (spaced 10 meters apart) to the tangent to the road at the current vehicle location on the map.

Heuristics-based spline-fitting approaches were developed to handle map errors, especially in curves and curve transitions, in the upcoming road geometry. This provides smooth transitions in order to compensate for errors in map databases introduced by the native piece-wise linear representation of roads. Additional enhancements were made by developing heuristics to detect and handle severe map errors, thereby improving the accuracy and robustness of the predicted geometry.

4.3.2.4.5. Confidence Estimates

A method for estimating confidence in the predicted path was developed to assist the Data Fusion module in assigning appropriate weight to each path prediction source. The confidence estimate is defined as the radius of a circle of uncertainty around each of the points defining the predicted road geometry. It is derived from a statistical analysis of recorded trip data, and is based on the distribution of errors for a specific road classification.

During the developmental phase, map performance was studied with regard to the discrepancy between the map-derived forward road geometry and “ground truth” (actual driven road geometry recreated during post-processing from logged yaw-rate and vehicle speed). Based on the distribution of errors, a measure of inaccuracy was developed for each road classification. These statistically derived values were used to set the confidence values associated with the predicted road offsets that are output by the map subsystem.

4.3.2.4.6. Map-derived Auxiliary Information

The attributes and the geometries of all the segments that connect to the predicted forward path of the vehicle are examined to determine if they hold additional information regarding road features of interest, namely:

- Presence of and distances to forks, ramps, intersections, T-junctions and tunnels.
- Presence of curves, and distances to start and end of curves from current host vehicle position with its curvature estimation.
- Information related to road class (freeway, ramp, arterial, and local) along with its surface type (paved/unpaved).

4.3.2.4.7. Data Caching

It was determined that the data rate as obtained from the map database using vendor-supplied access functions was not adequate to ensure the timeliness of results required by the target selection process. To overcome the latencies introduced by the map database, a data caching mechanism was designed and implemented, which reduced the database access time by 98 percent.

4.3.2.4.8. Testing, Evaluation, Results, and Conclusions

Testing and validation of this subsystem was performed by (1) driving the GM engineering development vehicle and the prototype test vehicle on public roads, and by (2) testing in the laboratory by replaying the data logged on public roads on a bench setup. Testing was predominantly performed on public roads, because of the variety of road types (freeways, non-limited access roads, rural roads, congested city streets, intersections, paved and unpaved roads), the number of lanes (one or more), and road geometries (straight, curved, S-shaped and curve transitions) that are encountered in everyday driving. These factors made the tests more realistic and applicable to real driving as compared to any predefined course. This type of testing was especially important for this subsystem because its performance is mainly dependent on maps and GPS signal reception. Public road sites are the only way to get map data (of varying quality) and GPS measurements over a variety of locations (normal, and challenging, namely urban canyons, and under bridges, tunnels, and leafy trees).

The performance of this subsystem, in terms of accuracy of upcoming geometry prediction, has been measured by comparing it against the “ground truth” (actual driven road geometry recreated during post-processing from logged yaw rate and vehicle speed). This can be computed from two perspectives – distance-based (at 60-80 meters from host position) or time-based (at 2-3 second headway based on current vehicle speed). The overall performance of this subsystem has been estimated at two different preview distances of 60 meters and 80 meters. The 60 meters preview represents a distance corresponding to 3-second headway at a speed of 45 mph, which is a common speed seen on arterial roads encountered in suburban driving, and is relevant for the FCW part of the ACAS applications. The 80 meters preview distance is relevant for the ACC application, as it approximates the distance corresponding to a 2.5-second headway at freeway speeds.

Analysis of trip data showed that map-derived geometry is highly reliable in indicating straight road sections. Curved roads are reliably shown with regard to the direction of curvature, but less reliably with regard to degree of curvature, and transition point between the curved and straight section of road. The method used to account for this characteristic in the maps is to assign high confidence to straight road geometry, and less confidence to curved roads, based on the severity of the curvature. Generally, the downstream applications using map data need to know when the data has a low probability of being accurate. Errors in the predicted geometry are accommodated if the prediction is accompanied by a low confidence rating.

The performance evaluation of this subsystem led to the following conclusions:

1. Differential GPS in conjunction with the map database can provide sufficiently accurate host vehicle positioning except in situations of GPS signal outages. During such times, dead reckoning is essential for proper estimation of host vehicle position.
2. Accuracy and road representation in commercially available maps is currently not uniform in quality. It varies from location to location, and at times is insufficient for map matching as well as for forward geometry prediction, especially on curves and at curve transitions. In the maps available for the ACAS system, curves are represented as piecewise linear segments and the exact locations of curve transitions are not accurately captured.
3. Although this subsystem has difficulty in defining the exact location of the curve transition (as mentioned above), it can easily detect the presence of an upcoming curve transition. The downstream data fusion module can use this signal to reduce its reliance on the yaw-rate sensor for distant forward geometry by limiting its maximum preview distance.
4. For all road classifications, the mean error and its standard deviation are lower at a 60-meter preview distance as compared to an 80-meter preview distance.
5. Map matching and forward geometry predictions are observed to be better when the vehicle is positioned on a straight road section. This is because on straight road sections, the maps have a better quality, the host vehicle heading and orientation within lane is fairly stable, and the forward geometry is less sensitive to exact longitudinal placement of the host vehicle.
6. For transitions from straight to curved roads, errors are due to map quality (start of curves are not adequately captured), and longitudinal placement of the host vehicle on the straight road segment leading up to the curve. Errors are more pronounced for the straight to sharp curve category as compared to the straight to gentle curve road classification.
7. Results are observed to be poorer when the host vehicle is on curved road sections. This is because (1) map matching is difficult on curves due to poorer map quality on curves and vehicle heading is continuously changing as the vehicle negotiates the curve, and (2) small errors in vehicle heading manifest into larger offset errors impacting the quality of the forward geometry. In addition, drivers oversteering or understeering in curves add errors in the longitudinal vehicle placement along the curve because small errors in vehicle heading can result in a vehicle-heading match at an erroneous location on the curve.
8. The combined accuracy of predicted geometry and confidence was evaluated based on the criteria of one-half of a lane width (1.8 meters) at a 60-meter distance ahead of the vehicle. Generally, over 90 percent of the offset predictions at 60 meters ahead of the vehicle had less than 1.8 meters of lateral error when confidence in the prediction was high. For curve transitions at 60 meters distance, approximately 80 percent of the offset predictions had less

than 1.8 meters of lateral error. The weakest results were for predicting sharp curve transitions at 80 meters ahead, where the accuracy rate was approximately 50 percent.

4.3.3. Threat Assessment Algorithm Development (Task C3)

4.3.3.1. Purpose

The objective of the threat assessment algorithm development task was to develop a threat assessment algorithm with a low false alarm rate and a low missed detection rate, and then implement, test, and verify the algorithm using computer simulation and in-vehicle testing on test tracks and public roads.

4.3.3.2. Background

The threat assessment algorithm uses data supplied by the target selection function, radar, and vehicle sensors to produce an imminent alert to the driver that a collision may occur if the driver does not take immediate action to brake and/or steer the vehicle. The primary challenge in the development was to implement an algorithm with a false alarm rate low enough to be acceptable to drivers while still providing the driver with time/distance to avoid a potential rear-end crash.

The usefulness of the driver alert warning depends on the robustness of the threat assessment algorithm. The algorithm must assess the probability of a collision with a vehicular target that is in the forward path of motion of the host vehicle. This estimation is determined from the host vehicle's and target's velocity and deceleration, the distance between the host vehicle and target, and the expected host vehicle driver's brake-reaction time and braking intensity.

The time of issuing the warning alert could be determined from these parameters if they were deterministic. However, in real-world traffic scenarios, multiple traffic lanes, roadway curvature, multiple vehicles, roadside obstacles, and driver attentiveness and reaction times confound these parameters. Because of these nondeterministic occurrences, modeling techniques were developed to assist in the selection of the algorithm or algorithms with the highest chance of success. Several iterations of algorithm candidates were simulated, analyzed and tested on instrumented vehicles.

4.3.3.3. Work Accomplished During Phase I (until Dec 2001)

Most of the work done to develop the threat assessment algorithm was in the areas of selecting and optimizing internal parameters and heuristics. An additional development requirement was to make the FCW algorithm compatible with ACC operation.

In phase I, the threat assessment algorithm for the FCW function was developed in four distinct stages.

The first stage was to determine mathematically what all the candidate threat assessment algorithms would be. Seven threat assessment algorithms were evaluated. All but one came from various internal programs. One algorithm was furnished to GM by NHTSA. The seven threat assessment algorithms initially evaluated for the program were referred to as:

1. GMR1 (GM Research 1)
2. GMR2 (GM Research 2)
3. CAMP1 (Single-stage alert described in the 1st CAMP Final Report) (Kiefer et al., 1999)
4. CAMP2 (Two-stage alert similar to CAMP1)
5. HW (An algorithm derived from the host vehicle headway to the lead vehicle)

6. TTC (An algorithm derived from the host vehicle time-to-collision to the lead vehicle)
7. NHTSA (An algorithm implemented by the John Hopkins University Applied Physics Laboratory (APL) for NHTSA per NHTSA's requirements; see Brunson, 2002)

In the second stage, the above algorithms were initially analyzed with numerous desktop simulations. The alert range determined by Algorithms 5 and 6 often differed considerably from the others because they did not utilize actual or estimated following or lead vehicle acceleration. It was concluded that not taking vehicle accelerations into account resulted in a probability of miss that was deemed excessive in a number of operational scenarios. For that reason, Algorithms 5 and 6 were dropped from further consideration. Algorithms CAMP1 and CAMP2 were replaced by the inverse time-to-collision CAMP algorithm (Kiefer, et al, 2003).

During this stage, the Threat Assessment Simulation Tool (TASIM), acquired from UC Berkley PATH, was developed to simulate the performance of the FCW system. Detailed mathematical models of sensors and algorithms that are part of the ACAS system were incorporated into TASIM to provide a realistic simulation environment for evaluating the performance of the various threat assessment algorithms that were considered in the program. TASIM enabled quick evaluation of threat assessment for multiple scenarios (algorithms, sensors, vehicles, roadway conditions). It consists of the following tools:

- TASIMSHIFT – the core simulation
- HWYC - the highway compiler
- TAVIS – the GUI and 2D visualization tool
- VENTURI - the 3D visualization tool

VENTURI uses recorded simulation data from TAVIS for playback and provides realistic animation of the simulation. TASIM was developed by California PATH, University of California, Berkeley, using system model descriptions and algorithms provided by the ACAS FOT team members. A graphical sketch of the TASIM tool is shown in Figure 21.

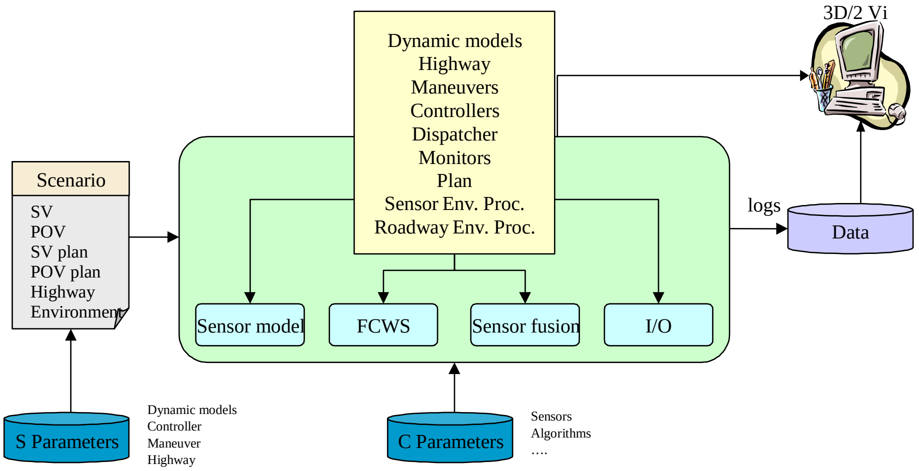


Figure 21: The TASIM Tool

During this stage, numerous simulations were developed using TASIM to evaluate the performance of the remaining threat assessments: GMR1, GMR2, CAMP, and NHTSA. The results of those simulations are documented in *ACAS FOT Deliverables 14 and 15: Threat Assessment Simulation Summary Report*. Based on the results of this study, the GMR2 and NHTSA algorithms performed better than the GMR1 and CAMP algorithms in a majority of the tests. The performance of the GMR2 and NHTSA algorithms were similar in a majority of tests and performed as expected. There were insufficient resources available to properly document, support, and rigorously check the newly developed CAMP algorithm, due to program timing issues and the risk associated in switching algorithms during this stage of the program. Therefore, the promising CAMP approach was dropped from further investigation.

In the third stage, the three remaining threat assessment algorithms, GMR1, GMR2, and NHTSA algorithms, were implemented in the GM EDV. An initial verification plan was prepared and submitted to NHTSA for testing the CW system. During this phase, GM focused efforts on supporting Algorithm GMR2. Data supporting the NHTSA algorithm was given to the Applied Research Laboratory (APL) for review by them and by NHTSA. Due to the better performance of the GMR2 algorithm over GMR1, the GMR1 algorithm was also dropped from further consideration.

In stage four, GMR2 and the NHTSA algorithms were implemented in the prototype vehicle. The NHTSA algorithm was provided to GM by APL as a callable subroutine. The Verification Plan was revised in the final deliverable (refer to *ACAS FOT Deliverable 3: ACAS FOT System Verification Plan*. Verification was performed on the prototype vehicle using the procedures in the *Verification Plan* from October 6 to October 30, 2001. The data collected during the tests were provided to Volpe Center throughout the verification period. All verification tests were observed by a NHTSA designated witness. At the conclusion of the tests, *ACAS FOT Deliverable 16: Prototype Vehicle Verification Test Data and Report* was submitted to NHTSA.

In addition to verifying the proper operation of the FCW function, the Verification Plan also included tests for the ACC function.

4.3.3.4. GMR2 Threat Assessment Algorithm

Most of the work done to develop GMR2 was in the areas of selecting and optimizing internal parameters and heuristics. Many parts of the algorithm are deemed proprietary, and consequently, will only be discussed in general terms. An additional requirement of the development of the FCW algorithm was to make it compatible with ACC operation. The ACC/FCW alert scheme is shown in Table 10.

Table 10 - ACC/FCW Alert Scheme

Alerts Generated	ACC Off	ACC On
Moving Vehicles Closest Movable Vehicle (CIPV) ACC follows the CIPV	X	
Stationary Objects Closest In-Path Stationary Object (CIPS)	X	X
Maximum Deceleration Requested (from ACC Controller)		X

A movable object (presumably a vehicle) is defined as an object that is currently moving or was once observed by the radar to be moving. It should be pointed out that the ACC system does not automatically brake to stationary objects unless they were previously observed to be moving.

However, the ACC system does alert the driver if an in-path stationary object is detected. So a vehicle tracked as a moving object that then stops will cause automatic braking if ACC is engaged. Also, the ACC system alerts the driver if the maximum ACC deceleration of 0.3 g is being requested by the ACC controller.

The ACC maximum deceleration alert and the FCW imminent alert are presented to the driver in an identical fashion. In either case, the driver may need to take control of the vehicle and either brake or steer the vehicle in order to avoid colliding with the vehicle ahead.

Figure 22 identifies the terms used in the basic GMR2 algorithm.

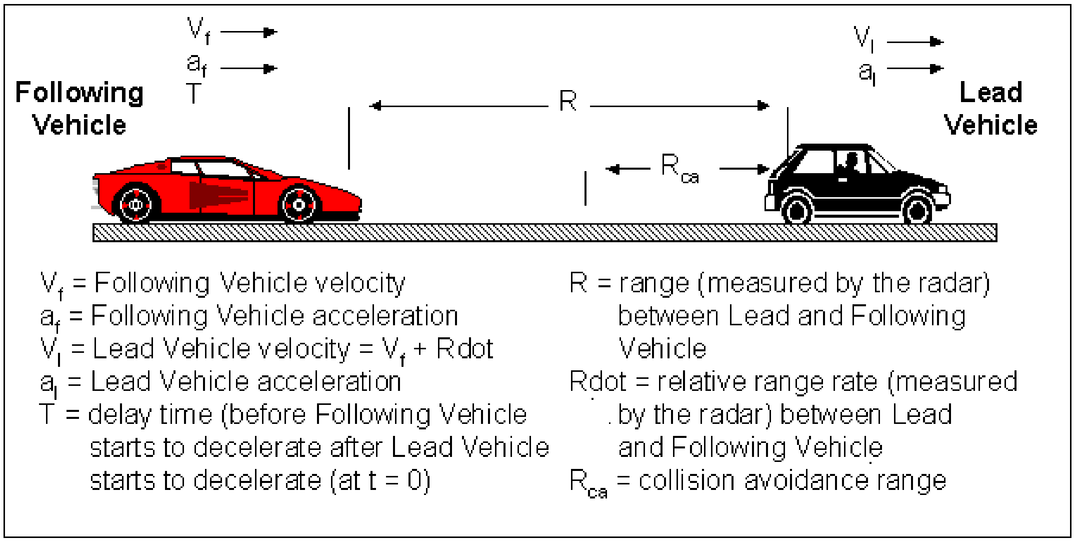


Figure 22: Definition of Threat Assessment Algorithm Terms

The collision avoidance range, R_{ca} is the closest predicted possible range that the driver can make the decision to stop (or steer), assuming the normal equations of motion, and still avoid a collision for parameters V_f, V_l, a_f, a_l, T. These parameters may be measured, assumed or a combination of measured or assumed values. The collision avoidance range is computed as

$$R_{ca} = f(V_f, V_l, a_f, a_l, T),$$

where

V_f is a speed measurement from vehicle sensors

$$V_l = V_f + Rdot$$

$$a_f = f(V_f, V_l, LongAccel)$$

$$a_l = f(LongAccel, a_{rdr})$$

a_{rdr} = Relative acceleration between lead and following vehicles measured by the radar

T = f(human reaction time, brake pressure buildup time, system latency).

LongAccel is the current host vehicle acceleration (while a_f is the expected host vehicle acceleration after the driver's reaction time), a_{rdr} is the relative acceleration between the host vehicle and the lead vehicle, and the other variables are those explained in Figure 22.

The threat assessment algorithm was designed to drive a graded (or staged) FCW display. The equations for the alert onset range R_0 for cautionary alerts is given by

$$R_0 = \max[R_{ca} + (V_f - V_l)\tau, \quad V_f T_g],$$

where τ and T_g are constants in units of time that depend on the driver selectable sensitivity levels. R_0 represents the distance at which there is either a specified time headway determined by T_g or a specified time to an imminent alert determined by τ. The alert level (AL) is a number between 0 and 100 that is output to the DVI. AL is an indicator of the potential for a rear-end collision, and is used to drive the gradient display. The AL is calculated using R_{ca} and R_0 as

AL = 0, for $R > R_0$

AL = $100\left[1 - \frac{(R - R_{ca})}{(R_0 - R_{ca}}\right]$ for $R_0 > R > R_{ca}$

AL = 100, for $R \le R_{ca}$.

The AL is calculated for both the closest in-path vehicle (CIPV) and closest in-path stationary object (CIPS) (CIPV_AL and CIPS_AL). If both types of targets are present, the maximum of the two is used as the output of the alert level:

AL output = max[CIPV_AL, CIPS_AL]

During Phase I, several improvements were made to the threat assessment algorithm to reduce the number of nuisance alerts. The following is a summary of the work accomplished in phase I to improve the threat assessment algorithm.

Algorithm Inhibit Based on Vehicle Speed

The threat assessment algorithm was modified to include a speed-based inhibit feature. This was done to make the algorithm active only when the vehicle speed is greater than or equal to 25 mph and inhibit the algorithm when the vehicle speed drops below 20 mph.

Algorithm Range Cut Off

The threat assessment algorithm was modified to only process the CIPV target if its range is within 100 meters and to only process the CIPS target if its range is within 80 meters.

Imminent Alert Suppression Based on Persistency for Stationary Targets

In order to reduce the nuisance due to alerts from road side clutter such as signs and mailboxes (for example, when the vehicle travels on a curve or makes lane excursions), the threat assessment algorithm was modified to suppress the imminent alert for a short (constant) time before providing the imminent alert for CIPS targets.

Algorithm Inhibit Based on Brake Switch

The threat assessment algorithm was modified to inhibit alerts based on brake switch activation.

Imminent Alert Suppression for Coasting Targets

The threat assessment algorithm was modified to suppress the imminent alert caused by coasting radar targets. Coasting radar targets are recently seen targets whose position is estimated because they were not seen in the current scan.

Imminent Alert Suppression for Host Vehicle Flying Pass

It was observed that the threat assessment algorithm would issue an alert when the host vehicle is making a flying pass (accelerating before lane change to pass a lead vehicle). The threat assessment algorithm was modified to suppress the imminent alert due to the CIPV target by identifying this passing scenario.

Alert Warning Range Adjustment Based on Road Condition

Based on vehicle wiper setting and outside temperature sensor information, three road conditions were identified – Road Condition Dry, Road Condition Wet-Warm, and Road Condition Wet-Cold. The alert ranges were automatically adjusted based on the detected conditions.

The initial design and implementation of the threat assessment algorithm was completed by the fourth quarter of 2001. The threat assessment algorithm was implemented in GM's engineering development vehicle and then in the prototype vehicle. The threat assessment algorithm was tested during the verification tests of the prototype vehicle described in *ACAS FOT Deliverable 27 – ACAS FOT Phase I Interim Report*.

4.3.3.5. Work Accomplished During Phase II

During 2002, the main emphasis was on further testing, validating and fine-tuning the algorithm. As a result of this testing and post-processing the data from the Pilot FOT Stage 2, a number of issues with the algorithm were identified and addressed. False alarms under certain conditions were observed, and although the frequencies of these incidents were considered relatively low, improvements were made in the algorithm to minimize/eliminate these cases. The following is the summary of the work accomplished in 2002 to improve the threat assessment algorithm.

Imminent Alert Persistency Based on Yaw Rate for Stationary Targets

In order to further reduce nuisance alerts from roadside clutter, the threat assessment algorithm was modified to require a persistency that depends on the yaw rate before providing the imminent alert to CIPS targets.

3-Second Filter for Cautionary Alerts

Under tailgating conditions, it was observed that the car icon was changing its size very frequently and therefore could become a distraction to the driver. To address this issue, a 3-second filter was implemented in displaying the car icon. To be able to move to the next larger size icon than the current one, the condition has to sustain for 3 seconds, and then the size of the icon is enlarged. When the size of the icon needs to be reduced, the filter is bypassed. This implementation minimized the sporadic changes in the size of the icon under the tailgating warning conditions.

Imminent Alert Delay on Brake Release

The auditory and visual collision warnings to the driver are suppressed as soon as the driver actuates the brakes, due to the underlying assumption that the driver is already aware of the situation ahead of the vehicle. Subsequently, under certain conditions the driver may release the brakes if the perceived threat condition disappears. However, the threat condition may still persist from the system point of view. Thus, under some conditions, as soon as the brake is released the imminent warning will come on, which may be a nuisance to the driver, since the driver is likely to already be aware of the situation. To overcome this problem, the threat condition has to persist beyond a delay period following brake release before the imminent warning is activated again.

Algorithm Modification for Low-Speed, Low-Range-Rate Alerts

The threat assessment algorithm considers many factors in different situations for generating the driver warning. It was observed that at low vehicle speeds (20 mph to 35 mph) and low closing rates (10 mph or lower) the warning was judged to be activated too early. The algorithm was modified to slightly delay alerts in this condition.

Alert Range Adjustment Based on Slippery Road Condition

An additional condition, Road Condition Slippery, was identified when the ABS or traction control becomes active. The alert ranges were automatically adjusted based on the detected slippery road condition for the next several minutes of travel.

4.3.3.6. Work Accomplished During 2003

Most of the work during 2003 was to:

- study the data collected during the Pilot Stages of the FOT;
- identify opportunities for improvement;
- implement those improvements; and
- test that the improvements had the desired effect through simulations and in-vehicle testing on closed tracks and public roads.

The version used during Pilot FOT Stages 2.5 and 3 was designated Algorithm A. This version was used by the first 15 subjects in the FOT. Based on the subjective results from the first few FOT subjects, a plan was implemented to introduce an improved threat assessment algorithm into the vehicles used during the FOT. Two new versions of the threat assessment algorithm were created. Algorithm B eliminated alerts from “never before seen moving” stopped objects, incorporated enhancements to reduce nuisance alerts from turning lead vehicles and in passing situations, and increased the time that imminent alerts are suppressed after the driver releases the brakes. The following is the summary of the work accomplished in 2003 to further improve the threat assessment algorithm. This improvement was named Algorithm C.

Imminent Alert Suppression Based on Identifying Turning Lead Vehicle

Imminent alerts were observed to occur in scenarios where the host vehicle approaches the closest in-path vehicle, which is starting to turn to leave the predicted path of the host vehicle. An alert driver normally anticipates this situation, and does not normally need to take an evasive action (braking or steering) because the driver is able to predict that the lead vehicle will be out of their predicted path before their vehicle reaches that point. However, under certain range, range rate and speed conditions the threat assessment algorithm generates an imminent warning to the driver in this lead vehicle turning scenario. The algorithm was modified to detect that situation with the intent of not issuing an imminent warning to the driver in this scenario.

Imminent Alert Delay on Host Vehicle Flying Pass

The auditory and visual imminent warning to the driver is suppressed when it identifies that the host vehicle is accelerating to make a flying pass, which suggests that the driver is aware of the situation. Subsequently, under certain conditions the driver may release the acceleration before starting to turn and under those conditions, as soon as the acceleration is released the imminent warning will come on. This may be a nuisance to the driver since they may be already aware of the situation. To overcome this problem, a delay was introduced between the moment a flying pass situation is identified and a new imminent warning is issued. The threat condition has to persist beyond this delay period before the imminent warning is activated again.

Imminent Alert Suppression for Moving Targets Based on Lateral Movement of Host

One of the nuisance alert scenarios is when the host vehicle is predicted to be moving laterally away from a CIPS target. This situation is common when the host vehicle is about to make a curve-entry or lane excursion. In such situations, under certain range, range rate and speed conditions the threat assessment algorithm generates an imminent warning to the driver. The algorithm has been modified to detect that situation and not issue an imminent warning to the driver.

Imminent Alert Delay for Stationary Targets on Host Vehicle Acceleration

The algorithm was modified to suppress imminent alerts due to a CIPS when it is identified that the host vehicle is accelerating beyond a certain threshold, suggesting that the driver is aware of the situation. Subsequently, under certain conditions the driver may release the acceleration and under some conditions, as soon as the acceleration is released the imminent warning will come on. This may be a nuisance to the driver since the driver may already be aware of the situation. To overcome this problem, a delay has been introduced between the moment a host vehicle acceleration situation is identified and a new imminent warning. The threat condition has to persist beyond this delay period before the imminent warning is activated again.

Imminent Alert Delay for Stationary Targets Based on Target Width

In order to reduce nuisance alerts due to CIPS targets from roadside clutter, characteristics such as width of target radar signatures were analyzed to recognize characteristics of stationary objects that could not be stopped in-path vehicles. Based on such identification, imminent alerts from certain types of CIPS targets were suppressed in order to reduce nuisance alerts to stationary targets.

Imminent Alert Delay for Stationary Targets Based on Learned Database

In order to reduce nuisance alerts due to CIPS targets from roadside clutter, an algorithm was developed for learning, building and using a database of stationary objects. Using such a database, if a CIPS target was identified in the database, imminent alerts from such a CIPS target would be suppressed in order to reduce nuisance alerts. This modification was made to reduce repetitive nuisance alerts from the same stationary object.

Algorithm Modification for Tailgating Situation

The algorithm was adjusted so that extreme tailgating situations could generate the visual imminent crash icon without an accompanying auditory alert in order to reduce potential driver annoyance issues.

Results of Algorithm Improvements

To summarize, the algorithm was improved by reducing lead-vehicle braking anticipation, increasing the time alerts are suppressed after braking and increasing the persistency requirement for stopped objects. For low-speed maneuvering situations, the driver reaction time used in the algorithm was reduced based on identifying situations when the driver may be alert, based on vehicle sensor information.

The number of alerts per 100 miles driven by the subjects that used Algorithm B was 32 percent of that experienced by the subjects who used Algorithm A. The rate for the subjects who used Algorithm C was 25 percent of that experienced by the subjects who used Algorithm A.

The threat assessment algorithm Development (Task C3) was completed during 2003 and no further modifications were made in 2004 to Algorithm C.

4.4. Fleet Vehicle Build (Task D)

4.4.1. Purpose

The Phase II Fleet Vehicle Build task objective was to build, test, and validate two pilot vehicles, to upgrade the pilot vehicles to deployment vehicles, and to build eleven more deployment vehicles. Ten of these deployment vehicles were to be used by UMTRI for the FOT, and one each was to be given to NHTSA, GM and DES. The vehicles for NHTSA, GM, and DES were shared with UMTRI so they could have ten vehicles in the field with subjects and one spare throughout most of the data collection phase.

4.4.2. Approach

Since the functionality of the system was validated rigorously during the prototype vehicle phase of the program, the main thrust of this task was to “productionize” the system. The vehicles were to be handed over to lay subjects for four weeks each and would be driven unaccompanied under naturalistic driving conditions. This required that the ACAS packaging be transparent to the drivers so that they perceived the vehicle as a regular production car similar to one they might purchase, rather than a special test vehicle. This was intended to mitigate any bias in how the subjects drove and handled the vehicles.

Two other important issues involved the space that the ACAS equipment required in the vehicle. First, the design of the vehicle modifications needed to be such that there were no intrusions in the cabin area, especially around the driver. Additionally, the subject needed to have reasonable cargo area to accomplish daily tasks. Finally, any modifications to the exterior of the vehicle should not attract the attention of others as well as that of the driver.

To begin, two pilot vehicles were built. The main emphasis was to integrate the functions by using common hardware as much as possible to minimize the space requirements while preserving functionality and performance. In the prototype vehicle, GM used a number of processors to implement various functions. The rationale was to develop and debug individual functions conveniently and not be limited by the performance or the hardware of the computers. In the pilot vehicle all the functions developed by GM were integrated into a single computer. This was feasible for the following two reasons. First, all the functions were already developed and verified, and the performance and hardware requirements were known at the time. As a result of this integration, some of the functions could communicate via software calls rather than over the CAN Bus. Secondly, computer technology progressed during this time such that new systems were available that met the requirements of all the individual components.

A single computer located in the trunk of the vehicle handled the following functions for which GM was responsible:

- Sensor processing
- GPS/Map processing
- Data Fusion processing
- Threat Assessment processing
- FCW processing

Other GM responsible subsystems located in the trunk of the vehicle were the GPS unit, vehicle interface unit, Class 2 bus gateway unit, and a power sequencer.

DES integrated the functions that they were responsible for into five hardware systems: (1) Forward-Looking Radar, (2) Vision and Radar Scene Tracking, (3) Radar Control, Host Path Estimation, and Target Selection, (4) DVI, and (5) the Throttle Controller. Items 2, 3, and 4 were in the trunk. Items 1 and 5 were in the engine compartment.

The DVI processing resided in a single computer packaged with an audio amplifier and a HUD controller and was also located in the trunk.

The final major unit located in the trunk was the data acquisition system designed and implemented by UMTRI. This was the only unit that needed to be accessed during the FOT. When each subject finished using the vehicle, the data was offloaded manually by connecting the data acquisition unit to a land-based computer network.

All the ACAS systems installed in the trunk of the vehicle were mounted on a metal chassis and enclosed in a metal box that was placed in the front end of the trunk, under the back shelf of the passenger compartment (Figure 23). This enclosure is secured to the floor, occupies minimal amount of trunk space, was locked to be tamperproof, and was on rollers for easy access and maintenance. Additionally, there is a second, smaller locked access door in order to connect the data acquisition system to a land-based computer network.

4.4.2.1. Driver Vehicle Interface Modifications

The interior of the vehicle is more important from the subjects’ point of view. There are only a few modifications relative to the production version of the vehicle. First, there are the DVI modifications. The first modification involves the steering wheel. The temperature control button was changed to a “GAP” setting button (Figure 24). The GAP setting adjusts the timing of the FCW warnings or the headway GAP (or time) in ACC, depending on the system mode.

Figure 23: ACAS Subsystems Located in the Trunk

Figure 24: Steering Wheel Controls

The ACAS output to the driver was achieved through two separate means. The primary means was by the HUD (Figure 25). The HUD was custom-made but fits in place of the production HUD. There was no perceived difference from the packaging point of view, but the ACAS HUD achieves higher brightness and higher resolution relative to the production HUD. The HUD intensity and position adjustment controls in the vehicle are the same as in the production vehicle. The secondary means of output is by an audio tone, which is generated by its own amplifier and speaker system.

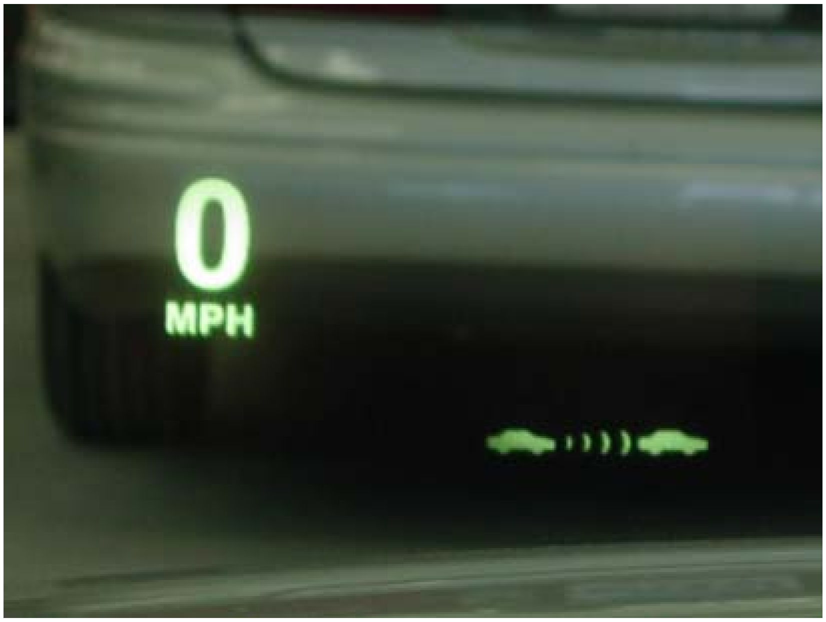


Figure 25: Example of the Head-Up Display

There were two forward-looking cameras mounted on a bracket behind the rear-view mirror (Figure 26). A shroud (not shown) that eliminates tampering as well as reflections from the windshield covered the complete mechanism.

Figure 26: Forward-Looking Cameras

Another camera is mounted on the A-pillar on the driver side, and was aimed at the face of the driver (Figure 27). This camera included infrared illuminators so the driver's face was visible at night. This camera also had a built-in housing to eliminate tampering.

Figure 27: Driver Face Camera

4.4.2.2. Exterior Vehicle Modifications

The exterior of the vehicle was also modified. The most visible modification was the GPS antenna mounted on the roof, centrally located, above the windshield (Figure 28). This antenna, supplied by an aftermarket manufacturer, was much smaller in footprint than the original antenna provided by the GPS receiver manufacturer. The gray color of the antenna did not match the body color of the vehicle.

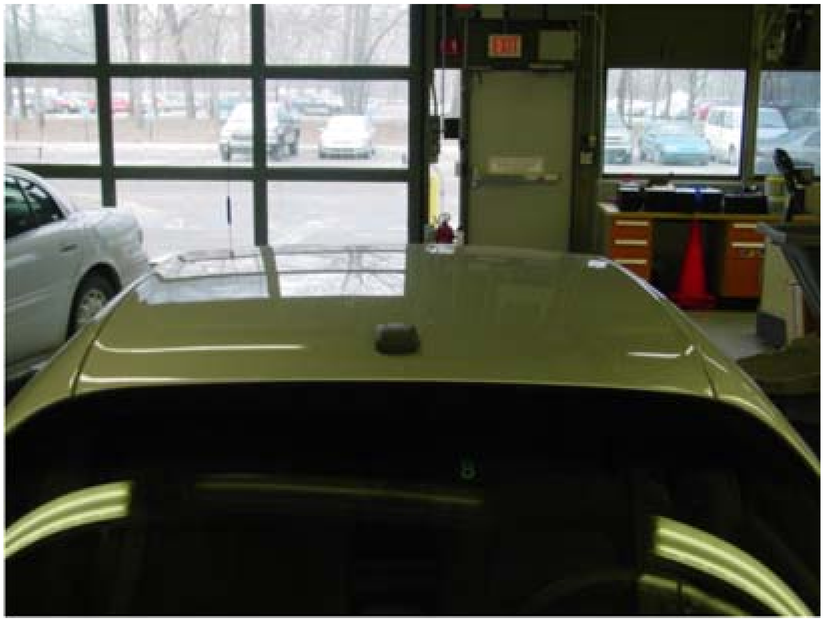


Figure 28: GPS Antenna on Roof of Vehicle

The second exterior modification was in the grill of the vehicle. The radar was mounted behind the grill and had to transmit and receive through the grill (Figure 29). To accomplish this, a small window was carved out of the grill and was covered with a special material that is transparent to radar waves. The original, centrally located, Buick emblem was moved to the side, but was still on the grill. A cellular telephone antenna was also attached to the rear window, in addition to a similar antenna used by OnStar on the production vehicle.

Figure 29: Radar with Front Grill Removed

4.4.2.3. Engine Compartment Modifications

Lastly, modifications were made under the hood of the vehicle. A heavy-duty alternator was installed in place of the original production alternator in order to provide the additional power needed by the ACAS system. Also, a new brake actuator and controller were installed under the hood to provide the electronic braking function needed by the ACC system. These replaced the production brake actuator and controller and were transparent to the driver.

Overall, a complex system was integrated into the production vehicle without these modifications being intrusive or intimidating to either the driver or the occupants. The most notable impact of this integration effort was the small reduction in the space originally available in the trunk.

4.4.3. Summary of Accomplishments Prior to January 2002

Phase I of the program consisted of designing, building, testing, and validating a number of engineering development vehicles and a prototype vehicle. The purpose of designing and building engineering development vehicles was to implement and investigate various candidate technologies that might potentially end up on the deployment vehicles. Each partner was responsible for one or more engineering development vehicle. A competing technology could be investigated by a partner or different partners but had to utilize a different approach. For example, the goal and purpose of building the GM engineering development vehicle (EDV) was to develop, design, implement, and investigate a number of technologies that would potentially be available on the ACAS FOT deployment vehicles. These technologies were evaluated on this vehicle and went through a down selection process with other technologies being investigated by partners in the program. The basic technologies focused on the GM EDV were:

- Threat assessment
- GPS/Map-based path prediction
- Evaluating the performance of an Assistware map database learning system

- Human factors for the FCW display

DES worked on a number of development vehicles. Two vehicles were dedicated to optimizing the ACC function. Another function developed by DES was the vision system for road geometry prediction and determining the heading of the vehicle within the roadway. Also, scene tracking was investigated and developed on these vehicles. DES designed the DVI on a dedicated EDV. This work entailed designing a completely new HUD system to be used on the deployment vehicles. DCS developed an electronically controlled brake system that was required for the ACC function. This included a pre-production controller and a brake actuator that were modified for integration into the LeSabre. This brake system was first integrated into a brake mule vehicle and then later put on the pilot vehicle.

The GM EDV was a 2000 model year Buick LeSabre that was significantly modified to accommodate all the instrumentation required to investigate the intended technologies. GM's approach in building this vehicle consisted of two major steps.

Step 1: Defining the Architecture - This important step consisted of analyzing various architectures and configurations, and determining the best approach for this task. Important factors in this determination were:

1. Simplicity and ease of implementation
2. Compatibility with our partners' architectures
3. Ease of debugging the system
4. Ease of collecting data

Step 2: Implementing the Architecture in the Laboratory – Even if a test vehicle is well designed and built, it is still a very cumbersome and challenging environment in which to debug an electronic system. For this reason, in Step 2, the pertinent vehicle architecture was implemented in the laboratory. The configuration that was intended for the vehicle was implemented on a bench with the identical computers and communications scheme. However, integrating the vehicle sensors on the bench system was not possible in a laboratory environment.

The goal and purpose of building the prototype vehicle was to integrate all the technologies developed, evaluated, and selected by the partners in the program into a single vehicle. The prototype vehicle had the full functionality as required to support the ACAS FOT. It was a precursor to the two pilot vehicles. The pilot vehicles have the same functionality as the prototype vehicle; however, the hardware partitioning of functions, hardware form factors, and the packaging and layout in the pilot vehicles was different. Functionality of the prototype vehicle, with improved packaging, carried over to the pilot vehicles and finally to the deployment vehicles.

The prototype vehicle was the last major milestone before freezing the functional aspects of the system. However, there were some minor modifications to the system configuration during the pilot vehicle phase. The prototype vehicle was still a development vehicle in the sense that all the subsystems that were verified in a number of different development vehicles were integrated into a single vehicle. This required significant collaborative effort among the partners to complete.

Since the build of the prototype vehicle was a result of the effort of various ACAS FOT partners, the task was accomplished at various sites. DCS in Brighton, Michigan, installed the brake system. DES in Malibu, California, installed the throttle control and ACC system. DES in Kokomo, Indiana, installed the DVI. GM Research & Development Center built the vehicle infrastructure and installed the remainder of the systems in the vehicle as well as performing the systems integrator function.

The approach was similar to that undertaken in the GM EDV. However, bench development in the laboratory was limited because this vehicle had an ACC function. The vehicle architecture was still implemented on the bench but without the ACC function. The emphasis was on integration rather than development of individual subsystems. In addition, the vehicle contained UMTRI's full-featured data acquisition system, which was installed after the validation tests. GM's data acquisition system developed for the GM EDV was used throughout the development and validation of the Prototype vehicle.

The software system was designed such that most of the software components of the prototype vehicle had been installed and tested on the GM EDV. The exceptions were:

- Road geometry from the Vision System
- Road geometry from Radar Scene Tracking
- DVI with the HUD
- ACC
- Throttle control for ACC
- Brake control for ACC

The architecture of the prototype vehicle integrated the functions of the GM EDV with the partners' EDVs. The major differences compared to the GM EDV were the additions of the ACC system (which involves throttle and brake control) and the DVI (mainly due to the use of the HUD). The path prediction function was enhanced by use of vision and scene tracking, which are additional inputs to the data fusion unit. In addition, the functional mapping of tasks to hardware was unlike the GM EDV because each partner delivered one or more of the functions already implemented in various EDVs.

4.4.4. Work Accomplished in 2002

The architecture of Pilot and Deployment Vehicles were defined during this phase of the program. This architecture, shown in Figure 30, was implemented and installed into the vehicles as described earlier in Section 4.4.2. The architecture was a streamlined version of the prototype vehicle design. In addition, a number of vehicle modifications were made to assist the installation.

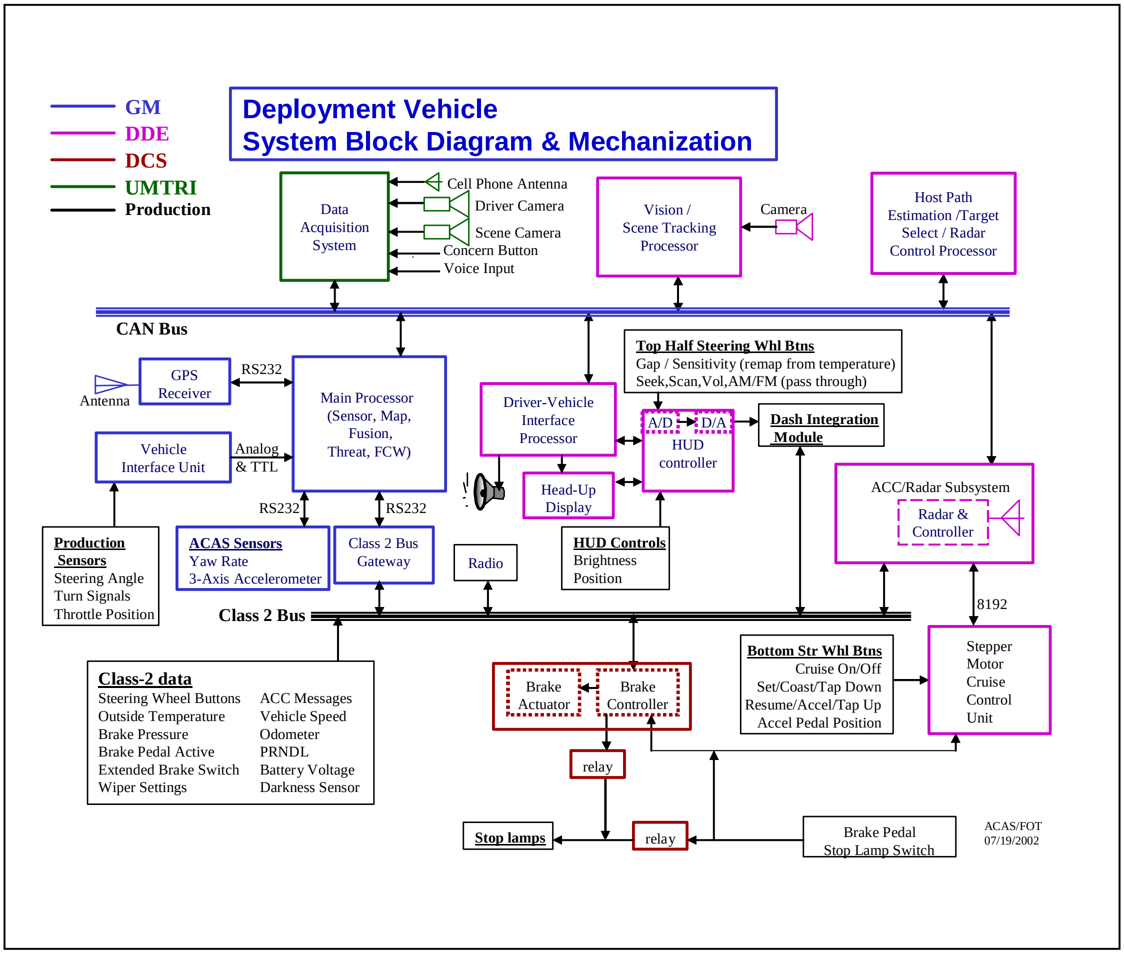


Figure 30: Architecture of Pilot and Deployment Vehicles

There are two major data communication buses in the system. The Class 2 bus is a production data communication medium where vehicle-related data is exchanged. This is part of the production vehicle and there are a number of points in the vehicle to tap into this bus. In this project, vehicle dynamics and various vehicle-related data that is available on this bus are accessed. This eliminated the need to duplicate a number of sensors and also provided access to data related to the state of the vehicle. In addition, data communications between the brake controller and ACC/Radar Subsystem was achieved through this data bus to implement the ACC function.

The CAN bus shown is an add-on and is part of the ACAS system architecture. This high-speed (500 Kbaud) communications bus forms the backbone of the ACAS system. Most elements of the system exchange information through this bus. The central subsystem is the main processor. All the vehicle sensor information is accessed and handled by this processor. As mentioned, some of the sensors consist of production sensors that already exist on the vehicle, which are accessed through the Class 2 Gateway. Others are ACAS add-on sensors that are directly interfaced to this processor. A Vehicle Interface Unit is used to interface some of the vehicle production sensors to the main processor (those whose values are not available on the Class 2 bus). The GPS receiver communicates its information over an RS232 serial bus to the main processor. The main processor contains the map database of the Midwestern United States, which is matched to the coordinates provided by the GPS system for road curvature determination. The data fusion algorithm runs on this processor using information provided by other subsystems. Finally, threat assessment and FCW algorithms are executed in this processor.

The vision and scene tracking processor was interfaced to a forward-looking camera. Vision algorithms determined the lane marker position and curvature ahead on the roadway, and the heading of the vehicle within the lane. This processor also received the radar data to execute the scene tracking algorithm, which is one of the input components of the DF.

Another processor performed the host path estimation, target selection, and radar control functions. At power-up, the processor sends a special set of commands to the radar for configuration. During normal operation, the processor performs two different algorithms. First, based on the data fusion output, it computes the host path. Second, the processor selects the target to be operated on based on the estimated path and radar target information.

The DVI processor receives data from the main processor regarding FCW and ACC, and displays this information on the HUD. Also, it displays the status of the system as well as speed of the vehicle on the HUD. This processor generates the graphics for the HUD and also directly controls the speaker that is used for presenting feedback to the driver. The processor mutes the radio via the Class 2 bus during auditory warnings to the driver.

The ACC radar subsystem communicates both through the Class 2 bus and the CAN bus. There is a controller embedded in the radar that sends commands to the SMCC, to control the throttle and the brake controller based on the algorithm running within the subsystem.

The final subsystem is the data acquisition system that is interfaced to the system through the CAN bus. It monitors the bus and grabs data that is of relevance for permanent storage. This subsystem is also interfaced to two cameras (for recording road and driver face views), a cellular telephone (for communicating with the base station), and a microphone with a concern button (for recording voice input from the driver).

4.4.5. Work Accomplished in 2003

Prior to January 2003, ten of the deployment vehicles had been built. The last two vehicles were built during 2003.

Once the vehicles were built, the effort under this task was to identify and address assembly and fabrication problems that were having a significant impact on reliability. Some of the items that were corrected are now discussed.

Both the main processor and the DVI control processor had problems with cold weather starts. Replacing the magnetic hard disks with solid-state flash disks solved the problems in the main processor. Software changes that supported a low level restart of the processor solved the problem in the DVI processor.

The cause of a group of symptoms was identified as a degradation of the electrical insulation between the radar housing and chassis ground. Symptoms included intermittent periods with no targets detected, and periods where targets would be dropped incorrectly. To fix the problem the mount for the radar was modified to better isolate the casing of the radar from the vehicle chassis to prevent ground loops.

There were two modifications to the vehicles to reduce the effect of electromagnetic emissions from the computers installed in the trunk of the vehicles. The remote keyless entry (RKE) system was found to be unreliable at moderate distances from the vehicles. To correct this, the remote keyless entry system was modified so that its antenna would be farther from the computers. The AM/FM radio also suffered from interference from the computers. To fix this problem a standard whip antenna was mounted on the right front fender. This was used to replace the standard LeSabre antenna embedded in the rear window. Figure 31 shows the modifications made to the RKE and AM/FM radio antenna systems.

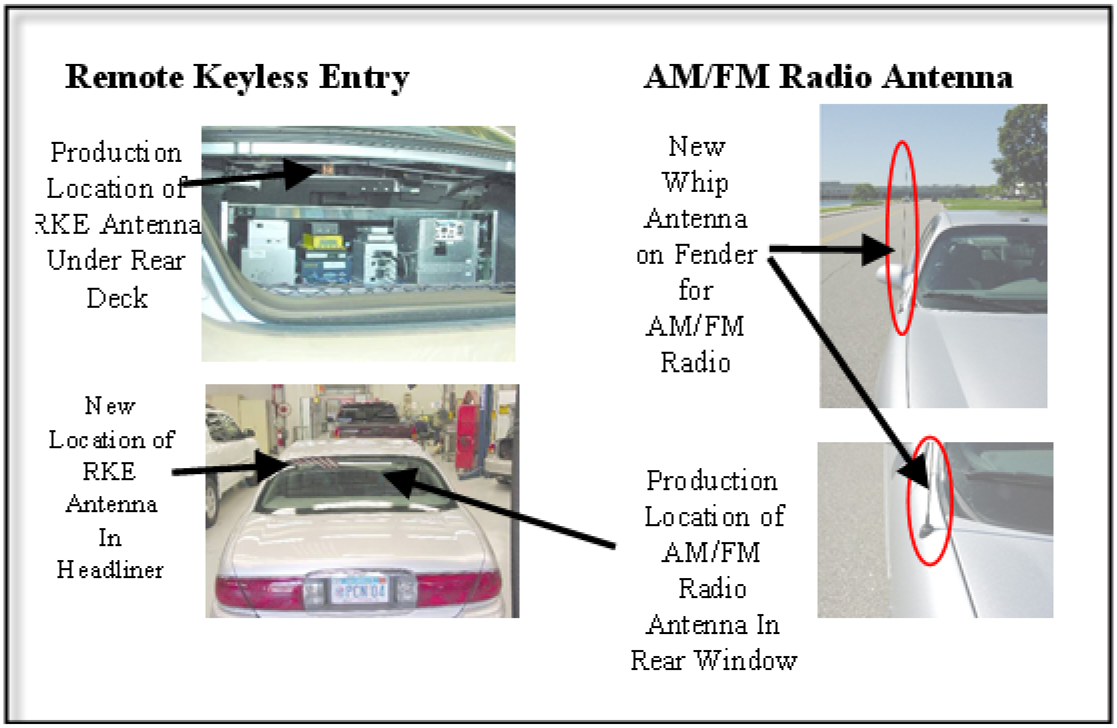


Figure 31: Radio and Remote Keyless Entry Antenna Relocation

The order in which engagement was detected for the switches on the brake pedal was found to be unreliable. This caused situations where the brake controller, ACC, or cruise control modules would report a fault and prevent use of cruise control. The wiring for these switches was modified on all the vehicles to correct this problem.

To address concerns that snow or mud might block the radars during the winter of 2003-2004, methods for automatically cleaning the surface in front of the radar were developed. A prototype was tested and shown to be effective. The required hardware was acquired and installed on several of the FOT vehicles.

The results of field-testing demonstrated that the deployment vehicles functioned in compliance with the technical specifications.

4.5. Field Operational Test (Task E)

The following is the executive summary from the FOT report.

4.5.1. Overview of the ACAS FOT Project and Key Findings

The ACAS FOT has exposed a fleet of ten specially equipped Buick LeSabre passenger cars to 12 months of naturalistic driving by laypersons recruited from the general driving population in southeastern Michigan. The ACAS system that was installed on each car included both an FCW and an ACC system. Both of these systems are supported by a forward-looking radar device, plus several other sensing, actuating, and threat-prediction features.

The goal of the FOT was to examine the suitability of the ACAS system for widespread deployment, from the dual perspectives of driving safety and driver acceptance. Since both aspects of evaluation involve tremendously complex interactions between the driver, vehicle, and roadway/traffic elements of the driving process, the requirement for naturalistic testing was considered appropriate. As expected, given the limited driving exposure involved, no crashes occurred in the FOT.

The FCW system is intended to warn the driver of an emerging conflict that could lead to a rear-end crash. On the one hand, a small set of incidents did occur during the FOT in which the FCW alert may well have helped the driver in avoiding a crash. Each of these involved an initial state of apparent distraction or misjudgment of the situation and culminated in a corrective response by the driver. On the other hand, the majority of alerts were perceived by the driver to have been either unnecessary or something of a nuisance. Accordingly, driver ratings of FCW acceptance were mixed, showing a guarded degree of acceptance of the system.

The ACC system constitutes an enhancement to conventional cruise control. In addition to controlling speed at the so-called set-speed value selected by the driver, the system also automatically manages the distance to a preceding vehicle. The ACC system performed very well in the field test and received high acceptance ratings by most participants. The consistent performance of the ACC system was seen to be effective in managing almost all conflicts, thereby enabling extended periods of engagement without the need for driver intervention. Although drivers used ACC prudently with respect to many of the details of its operation, an initially high rate of ACC usage on surface roads did give rise to conflicts until drivers adapted their behavior to effectively moderate the risk.

The project was operated under a cooperative agreement with the United States Department of Transportation. GM and DES conducted an extensive program of engineering tests and evaluations throughout the development process, following which the UMTRI executed several stages of pilot testing with lay drivers that led up to the year-long FOT that is reported here. Each vehicle in the FOT fleet was equipped with UMTRI's onboard data acquisition system, yielding a large archival database that has been analyzed to determine the suitability of ACAS in terms of driving safety and driver-acceptance. The database is believed to have long-term value for the study of the driving process.

The scope of the field test was such that 96 individuals who had been recruited from the general driving population completed a prescribed period of naturalistic driving. A total of 81 people drove a total of four weeks and an additional 15 people drove for three weeks during an algorithm-refinement stage of testing (see below). In all cases, the participants were simply asked to use the ACAS vehicle as their personal car.

Participants were sampled in three age bands, with equal numbers of men and women in their 20s, 40s, and 60s. In the first week of driving by any participant, the vehicle operated in a baseline mode corresponding simply to the production version of the 2002 Buick LeSabre. The first week of a person's driving thereby provided a reference data sample against which to evaluate later driving with ACAS enabled. After the baseline period, the vehicle switched over automatically to the ACAS functionality, as anticipated by the driver based upon instructions that were provided by a researcher when the vehicle was picked up.

While testing the first 15 drivers in the FOT, it was determined that changes were needed to better calibrate the FCW algorithm to the context of naturalistic driving and improve FCW system acceptance. In the end, three versions of the FCW algorithm (termed A, B, and C) were subjected to FOT driving. This summary addresses the most mature version of the system (Algorithm C), which was experienced by a total of 66 persons.

The remaining portion of this summary is structured in four parts that expand upon this overview. Firstly, the ACAS functions are briefly reiterated. Secondly, a summary is presented of the test operation, itself, and the general success attained in data collection. Next, the scope of the test exposure is summarized to show how the test miles were distributed across the different factors that strongly influence the resulting data. Finally, for both of the respective FCW and ACC subsystems, the results are discussed in terms of their potential impacts on driver acceptance and driving safety.

4.5.2. Functionality of the ACAS FCW and ACC Systems Evaluated

The FCW and ACC functions both draw upon the same basic sensing and processing elements and employ a HUD that projects images low on the windshield, with a focal plane at the distance of the front bumper, to show the related FCW and ACC information to the driver. Both subsystems also provide the driver with steering-wheel buttons for adjusting the system to personal preference - permitting the driver to vary either the sensitivity level by which a cautionary stage of FCW warning is displayed or the desired gap-setting by which the ACC system controls headway following time. Both subsystems have identical rules for alerting the driver to the threat posed by a stationary object and different rules for alerting to the threat of what is termed a "movable" target (i.e., a moving vehicle or one that was previously seen by radar to have been moving but is currently stopped). The ACC system employs only the movable-target detections when controlling headway to a preceding vehicle. In any case, it is salient to distinguish the FCW alerts that occur during manual driving from the alerts that occur during ACC driving, the former of which constitute the great majority of all alert activity actually experienced during the FOT.

The FCW function provides visual warnings when following within a driver-adjustable headway time, when following very closely (tailgating), or when approaching a vehicle too rapidly (closing). For closing situations, a final imminent alert consists of both a flashing visual display and an auditory warning. In contrast to cautionary alerts, the timing of the imminent alert is not adjustable by the driver.

The ACC function is primarily that of a speed-and-headway controller, once this subsystem has been engaged. The controller modulates speed at or near the driver-adjusted set-speed value and employs the throttle and brakes to manage the driver-adjusted gap, or headway following time, behind the preceding vehicle. The maximum braking authority of the ACC controller is 0.3g. Any headway conflict calling for the full, 0.3g, braking response of the ACC system triggers an imminent alert. Because the ACC system is tuned to provide smooth control that minimizes jerk, the 0.3-g braking level is never applied by means of an abrupt step in deceleration. The lack of tight, instantaneous control over headway is intentional, seeking to ensure both driver comfort and a readiness to take over in the case of a quickly rising threat.

Figure 32 below shows the layout of the HUD. Vehicle speed is at the upper left. System status and the level of FCW sensitivity (or ACC gap-setting, not shown) appear as the car-following icons at the lower right. Vehicle-detected and collision-warning icons are displayed at the upper right. (At times, the HUD displays additional information not shown in the figure, such as ACC set speeds and text alerting the driver to conditions when ACAS is not functioning normally.)

Figure 32. Head-Up Display Configuration

The sequence of icons for the FCW alert is shown in the figure below. On the left, the small blue-green icon representing the back end of a vehicle is displayed when the system determines that there is a vehicle in the host vehicle's path. If the degree of conflict with this obstacle is growing, the icon turns to an amber color and grows in size, providing a looming image to help prompt the driver's response. If the driver does not respond and the host vehicle continues to approach the obstacle, the icon progresses to the imminent-alert icon at the far right. The red vehicle icon flashes with a yellow crash symbol overlaid. When the imminent alert condition involves a closing situation, an audio beeping accompanies the flashing icon. For an extreme tailgating situation, the red and yellow alert icon flashes but no beeping occurs. FCW alerts are suppressed while, and shortly after, the driver applies the brakes. FCW is also not available below a minimum speed of 20 or 25 mph, depending upon whether speed is going down or up, respectively.

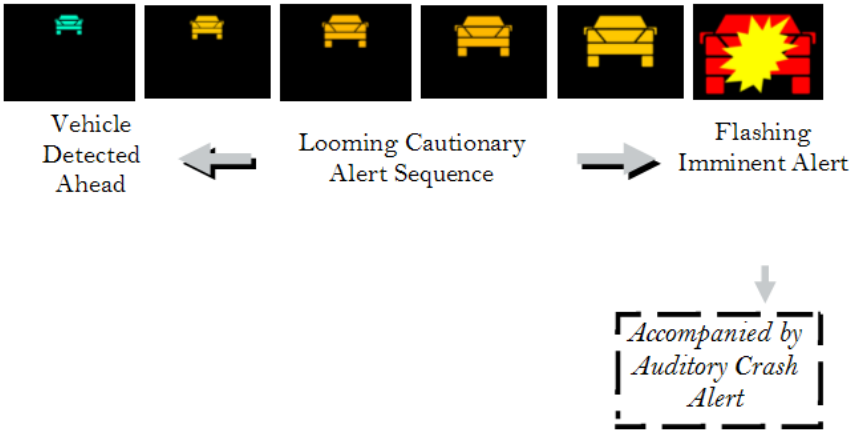


Figure 33. Visual Crash Alert Icons

4.5.3. The Field Operational Test Methodology

The ACAS FOT was broadly successful both in terms of fielding a reliable test vehicle and recovering the desired data. Of the 96 individual drivers who were given an ACAS vehicle and launched as FOT subjects, all successfully completed the multi-week term of the driving assignment. In 13 cases, some problem with a deployed vehicle was resolved by substituting a replacement car for the faulty one in the field.

Measured against the designed scope of the FOT, 94 percent of the intended data was successfully collected and compiled into a relational database. The resulting database of engineering variables is 164 GB in volume and contains up to 400 engineering variables that were sampled at 10-Hz, as well as subjective assessments. The companion set of video files is fully synchronized with the quantitative database.

The video record was derived from forward-looking- and driver's-face-oriented cameras. The forward scene was recorded on a continuous basis at 1 Hz while the driver's face was sampled at 5 Hz for 4 seconds every 5 minutes. When an ACAS-alert event occurred, the forward- and face-oriented cameras were recorded at 10 Hz over an 8-second window that straddled the moment of alert-onset.

Subjective data were collected using several questionnaires as well as an interactive debriefing that was done on the day the car was returned from the field by a participant. The live debriefing involved a replay of approximately a dozen alert events, as seen through the forward- and face-looking cameras. Subjects were asked to rate each of the selected alerts, given their own recollection and observation of the driving circumstances in which the alert occurred. Later, four focus groups were held, each gathering several individuals for a structured discussion and evaluation of their ACAS-driving experience.

4.5.4. Overall Scope of ACAS FOT Exposure

Over the 12-month period of testing, the vehicle fleet covered 137,000 miles. Of that amount, 101,000 miles were traveled with the ACAS system in its Algorithm C configuration from which the principal findings of the FOT have been drawn. The mean trip length was 12 miles, although many trips were shorter than one mile and a few exceeded a hundred miles. The average total distance driven by a subject was 1,500 miles, of which 1,200 miles was in the ACAS-enabled state.

On average, the primary exposure variables were rather well balanced between the baseline and the ACAS-enabled periods. This is an important fact supporting the many FOT analyses in which the baseline data from the first week of driving are used as a reference for evaluating the ACAS data from the subsequent three weeks of driving. Among the various factors of test exposure, the following is worthy of note:

- Males and females traveled almost equal total distances.
- The older age group traveled 38 percent of the total miles, versus 31 percent each for both the younger and middle-aged groups.
- Roughly 50 percent of travel was on freeways, 50 percent on surface roads.
- Roughly 75 percent of travel was in well-lit conditions, 25 percent in dark.
- Roughly 10 percent of travel was with windshield wipers on, 90 percent with wipers off.
- Roughly 40 percent of travel was in sparse traffic, 45 percent in medium traffic, and 15 percent in dense traffic.

The above exposure summary indicates that several significant driving conditions did vary across the FOT. What is not portrayed in these aggregate numbers is that individual drivers tend to differ significantly from one another by the peculiar distributions of the miles that they travel, especially with respect to the road type, traffic density, and the light/dark conditions that prevail. Since the individuals also differ greatly in the total distances they cover, it has been necessary to perform statistical analyses on the objective FOT data in ways that prevent the particular exposure patterns of the high-mileage individuals from unduly skewing the results. In analysis areas where the data are sparse, altogether, some degree of ambiguity from such effects is unavoidable. Where the data volumes are higher, however, other kinds of analysis can remove the undue weighting that otherwise occurs from large differences in total driving exposure.

Of the 101,000 miles traveled in the Algorithm C portion of the FOT, 78,000 miles were traveled during the weeks in which the ACAS system was enabled. The ACAS-enabled miles were distributed such that 63 percent of the driving was under manual control and 37 percent was under ACC control. As suggested above, many aspects of the FOT results are tracked according to the manual versus ACC modes of driving because the outcomes are strongly differentiated by the functional expressions of the system that prevail in each. Since ACC driving is more prevalent in less-conflicted driving conditions, such as freeway environments and light traffic, manual driving (and the FCW function that applies to the manual mode of control) becomes exposed to what is the more conflicted end of the spectrum of traffic densities and road types.

4.5.5. Apparent Driver Experimentation with the System

Most drivers, when asked, acknowledged having experimented with the ACAS system to some degree. While they had been asked to limit their experimentation to the first few days after the ACAS system first became enabled, there were nonetheless instances in which drivers appeared to “probe” the functionality over a longer period, presumably in order to better understand its capabilities and limitations. The data indicate that during the first week of FCW availability, there was a short-lived but substantial jump in the rate of imminent alerts associated with the most obvious forward conflicts—those involving a vehicle ahead in the same lane—that strongly suggests experimentation with the FCW system. In none of these cases did the experimentation seem patently unsafe. Instead, it was often the case that drivers reporting probing the system unsuccessfully by tailgating —a maneuver that will not, in fact, trigger an imminent alert sound.

The ACC system was used on surface streets during the first and second week of its availability in such a way that a distinctly-higher incidence of limit auto-braking by the ACC controller was observed, although this kind of ACC driving activity had greatly subsided by the third week of system usage. In addition, several instances of experimentation were noted when drivers were attempting to demonstrate the functionality to passengers. Drivers reported having had ample opportunity to explore the ranges of FCW and ACC settings such that the rate of variation in setting had also subsided substantially by the third week of system availability.

4.5.6. The Issue of Large Individual Differences

The first principle that connects driver attributes to the FOT results is that differences between individuals tend to have the largest influence among all factors that are identified in the data. This is not to say that important influences of the ACAS system, itself, were not seen in the test data, but rather that such influences are embedded within the tremendous importance of individual effects. Among the factors by which individual drivers affect the FOT data, the principle influences are believed to result from the combination of (1) the relative assertiveness of the person’s driving style, (2) the mileage traveled by the individual during the FOT (especially the corresponding mileage exposures to FCW and ACC functionality), and (3) the distribution of road types and traffic conditions that establish the “conflict potential” of the particular environments within which the individual traveled. Extensive use has been made of statistical techniques to minimize bias in the FOT findings that might derive from the differences that accompany individuals. Nonetheless, such differences have tended to limit the range of findings that can be stated with high statistical confidence.

4.5.7. Introduction to Results from the ACAS FOT

The FOT results are organized and presented below according to the respective FCW and ACC subsystems, using several themes and situational issues that are pertinent to the respective functions that are involved. For each of the subsystems, the summary of FOT results begins by describing the conditions and extent to which the function was manifest to the test drivers and how they interacted with the individual features of the system. While the first level of interaction involved driver adjustment of the ACAS system, the more complex interactions lie in the specific maneuvering activities by which drivers tended to cultivate and/or respond to an ACAS warning or control function. When considering the details of such interaction, potential implications for driving safety and driver acceptance are highlighted.

The principal safety inferences are drawn from analyzing the objective data and the answers that drivers gave when asked about their perceptions of safety. The assessment of driver acceptance comes overwhelmingly from questionnaire responses, although focus-group sessions have added a degree of clarity in seeking to explain the apparent viewpoint lying behind driver responses.

In general, results were deemed worthy of inclusion in this executive summary wherever it is believed that they relate to the long-term potential for FCW and ACC functions as automotive products.

4.5.8. Results Addressing Forward Crash Warning

FCW-related results are presented under 11 different subheadings and then summarized in a brief statement of the key findings.

4.5.8.1. Conditions Under Which FCW Was Experienced

In the 49,000 miles that were driven in the manual mode during the Algorithm-C portion of the field test, some stage of the cautionary alert was present approximately 9 percent of the FCW-available driving time over a speed of 25 mph although only the first three stages of the four looming-image icons were commonly encountered. Noting that drivers could adjust the sensitivity of the cautionary alert even to a lowest setting that suppresses cautionary icons altogether, it is notable that many drivers retained sensitivity settings that yielded cautionary alerts so frequently.

The total rate of exposure to cautionary alerts varied greatly among drivers, with 57 percent of the drivers receiving cautionary icons less than 7.5 percent of the driving time over 25 mph, and 20 percent of drivers receiving them more than 20 percent of the driving time over 25 mph. Cautionary alerts occurred far more frequently when the driver had adjusted the FCW system to higher sensitivity settings. Although this result is also conditioned by the combinations of driving style, traffic environment, and sensitivity settings for the individual. The overwhelming majority of cautionary alerts are associated with following within the driver-adjustable headway time, with less than 2 percent of the cautionary alert time due to closing situations or tailgating.

Overall, imminent FCW alerts were encountered at a rate of 1.1 alerts per 100 miles for drivers using Algorithm C, but the alert rate varies greatly by the manual versus ACC control mode of driving. Thus, the typical FOT participant experienced a total of about 10 imminent alerts, given the average exposure of 1,200 miles of driving during the three weeks that ACAS was enabled. Imminent alerts appeared at a rate of 1.44 per 100 miles in manual driving and 0.38 per 100 miles in ACC driving. The lower alert rate in ACC driving may reflect in part the higher use of ACC in the less-conflicted freeway environments as well as the ability of the ACC controller to manage headway time, further reducing the likelihood of forward conflicts (note that the ACC-related issues are the focus of a later section in this summary). Approximately 40 percent of the imminent-alert events involved a stationary object that did not actually lie in the path of the host vehicle.

Results showed that the imminent alert rate for drivers using Algorithm C:

- varied greatly across individuals, from 0.08/100 miles to 4.34/100 miles;
- was six times higher on surface roads than freeways; and
- was 20 percent higher when freeway traffic was heavy rather than sparse.

Driving scenarios were defined as a means of breaking down imminent alert events according to the relationship between the object triggering the alert and the actual path of the host vehicle. The scenarios included, for example, following behind a vehicle that brakes while remaining in the same lane as the host, approaching a vehicle as a prelude to passing it, approaching a vehicle that is braking to turn out of the host’s lane, and so forth. These scenarios have been, in turn, grouped into categories that provide a useful overview of the distribution of imminent alerts in manual driving. The imminent alerts break down according to the following scenarios:

1. stationary target that is never in the host’s path (36 percent);
2. moving vehicle that is in the same lane as the host at some point in the approach episode, and is in a different lane at other times in the episode (32 percent);
3. moving vehicle that is always in the same lane as the host during the approach episode (27 percent);
4. moving vehicle that is never in the host’s path (3 percent);
5. moving vehicle that crosses more-or-less perpendicular to the host’s path (2 percent); and
6. “other,” including a stopped vehicle in the same lane as the host (less than 1 percent).

Examples of the scenarios in the second item above include a host passing maneuver and, most commonly, a lead vehicle turning left or right. As this breakdown implies, any critique of the FCW function unavoidably encounters the complex temporal/spatial domain of inter-vehicle conflict. That is, the way that vehicles are actually driven in proximity to one another reflects the driver expectations of how each conflict is about to be resolved (and, thus, how much utility might be attributed to an alert, given these expectations).

4.5.8.2. Usage of FCW Sensitivity Settings

Drivers made liberal use of the full range of six FCW sensitivity settings available for varying the extent of presentation of cautionary icons. Approximately the same nominal amount of driving was done in the least-sensitive setting, the two middle ones, and the most sensitive one. Basically the younger drivers preferred low sensitivity settings and the older drivers preferred the high end of the sensitivity range. Women were seen to use the two lowest-sensitivity settings twice as often as men. This, along with ACC utilization rates discussed above, may suggest that men seek more interaction with the system than women.

The FCW sensitivity adjustment was also changed rather frequently from one setting to the next by most participants in the field test, with the typical individual making 30 choices over the three weeks of ACAS-enabled driving. One individual made only 3 changes in adjustment while another changed it 92 times. On average, the sensitivity was adjusted two or three times during every hour of driving.

Such adjustment activity was more than two times as frequent during the first week of ACAS-enabled driving than in the following two weeks, suggesting a period of acclimation to the FCW function and to the preferred adjustment setting. Those who preferred sensitivity values around the top two setting values were about twice as active in varying the sensitivity level as those who preferred the low-sensitivity zone around the bottom two settings. Males were considerably more active in making sensitivity adjustments than were females.

4.5.8.3. Discrimination of Alerts by Moving versus Stationary Lead Vehicles

The majority of imminent FCW alerts were either triggered by stationary, nonvehicular objects, such as signs, mailboxes, and overpasses, or occurred in traffic situations in which the forward conflict with a moving vehicle was ultimately resolved by lateral motions of the vehicles. In most of these situations, drivers generally perceived the alert to be a nuisance and did not rate it as having a positive utility.

There were a minority of the alerts, however, in which the scenario type rendered the alert more compelling for assisting drivers in avoiding rear-end crashes. This group involved the host vehicle approaching a slower vehicle in its lane or one that was decelerating in the same lane such that the host driver needed to apply brakes in order to resolve the developing conflict. These events led to 27 percent of all imminent alerts, and in these alert events, drivers responded with braking 88 percent of the time. These were also rated by drivers as the most useful type of alerts.

Only one case in manual driving was found where an imminent alert was provided for a vehicle that had been stopped in the lane ahead during the entire episode (and had never before been observed by the radar to move). The most common situation in which the FCW could conceivably address a potential stopped-lead-vehicle crash is when the imminent alert sounds while the lead vehicle is still moving but is decelerating. In this stereotypical crash-threat scenario, the lead vehicle often would have been stopped by the time an inattentive driver, without FCW, would have impacted the vehicle. Clearly, this function can be covered without the need to alert on never-before-seen-moving targets, since the target can be detected while still moving.

FOT results make it clear, however, that FCW system effectiveness was compromised by its marginal fidelity in issuing an alert for the rare case of a genuine threat from an in-path, stationary vehicle that has never been observed to have moved. In the FOT, less than 1 percent of all alerts corresponded to this case. The impact of this design requirement on the FCW system performance was that 36 percent of all alerts in the FOT were of the nuisance type that became triggered by nonthreatening, stationary targets. The tradeoff in designing FCW to manage the stationary-target threat is further complicated by the desire to maintain a simple mental model of functionality, (i.e., where it is simpler to conceive the function if the FCW system responds to both moving and stationary vehicles) as another factor impacting driver acceptance of FCW. (On the other hand, if FCW were to be combined with any of the current ACC products that ignore the always-stationary object, the simplest mental model would require that both functions ignore such objects.)

In any case, since drivers became quite aware that FCW alerts often occurred in situations in which braking was not required, they certainly did not brake reflexively to imminent FCW alerts. Braking occurred in 88 percent of shared-lane situations, but only 30 percent of situations in which lane changes or turns constitute the common means of resolving the conflict.

4.5.8.4. Effects of FCW on Following (or Headway-Keeping) Behavior

The ability of FCW to reduce the number and severity of rear-end crashes was examined through the use of surrogate metrics, with emphasis given on identifying changes in driving patterns that occurred with, versus without, ACAS enabled. The influence of FCW on headway time margins was selected as a central portion of such examination because an increase in headway could provide a driver with additional time to react to an event ahead. When ACAS is enabled, headway time is found to increase by statistically significant amounts during periods of quasi-steady-state vehicle following. Across the 66 drivers, the average fraction of time spent following at less than 1-second headway times constituted 30 percent of all vehicle-following time during the baseline week, but only 25.5 percent when ACAS was enabled. Statistically significant reductions in following were seen from headways ranging from 0.4 to 1.6 seconds.

More specifically, significant effects of FCW on headway times were found in two conditions. In daytime conditions, the average percentage of time under 1-second headway was reduced approximately 13 percent (from an average percentile value of 30 percent to approximately 26 percent) under manual driving with FCW available. Second, longer headways were found to occur while driving manually on limited-access roads with FCW available. For this case, the average time under 1-second headway changed with a magnitude similar to that seen in daytime conditions.

Two possible mechanisms that may explain the observed increase in headways with ACAS enabled are (1) an influence of the FCW cautionary alerts, which are predominately headway-based, and/or (2) an increase in driver awareness of headway times when driving. It is possible that the combined exposure to FCW and ACC may have caused some drivers to increase their headway during manual driving with FCW support. The influence of cautionary alerts was studied, and there was a significant effect of ACAS on influencing middle-aged drivers to reduce the frequency of prolonged-following events (i.e., a scenario that is addressed by cautionary alerts). However, this difference was seen to erode over time. Therefore, the observed headway-distance effect appears more likely to be due to a more general awareness of headway fostered by the ACAS system.

4.5.8.5. Effects of FCW on Closing-Type (or Approach) Behavior

ACAS does not appear to change the frequency or the magnitude of approach (or closing-type) conflicts that drivers experience in manual driving, regardless of the conflict metric employed. This is examined in parallel using two data sets: the set of imminent alert events, and a set of 44,827 conflict-study events in which forward conflict metrics exceed a modest threshold. The rate of events in which the imminent alert criterion is satisfied provides a straightforward measure of drivers' experience of forward conflicts. The alert rate was not affected by the availability of ACAS, except for a short-lived jump in alert events when the system first becomes available. This is presumably due to drivers' experimentation with the system. In addition, ACAS does not affect the types of scenarios in which these imminent alert events occur.

The conflict-study events were sampled in a way that was independent of the FCW computations. Results showed that the availability of FCW did not change the rate of such conflict events, nor did it affect the fraction of the events that were identified as same-lane situations. In addition, the peak conflict levels associated with these conflicts were not affected by ACAS. Overall, approach-conflict levels appear unaffected by FCW in the manual driving mode.

Overall, there is no compelling evidence that ACAS influences the way drivers manage the closing-type conflicts with preceding traffic, but instead they appear to adjust their following distances to allow extra distance on limited-access roads, and during daytime.

4.5.8.6. Effects of FCW on Braking Behavior

There was no statistically significant evidence indicating that FCW induced a change in driver-braking response to conflict. Given several metrics for defining and scaling conflicts, driver response-to-conflict during baseline manual driving was compared with responses that occurred following an FCW alert, for commonly scaled conflicts. Although many analyses were conducted to search for such changes, only secondary effects were seen. Results showed no significant changes in either the frequency of driver braking, conflict levels at the time of brake onset, or the time that elapsed from alert onset to brake onset.

When FCW became available, an increase was seen in the magnitude of speed changes that occurred within the first two seconds after alert-level conflicts in manual driving. However, when the larger set of 44,000 events constituting the conflict study set was analyzed, there was no change in the rate of braking, or in the ultimate conflict level.

4.5.8.7. Effect of FCW on Secondary-Task Behavior

One context in which drivers can be said to have interacted with the ACAS-equipped vehicle involved the liberty that they took to indulge in so-called “secondary-task behaviors,” for example, brushing one’s hair, eating, and talking on a cell phone, while driving. A review of video images showed that the rate of secondary-task behaviors during manual driving had only a slight degree of variation over the four-week period, with no statistically significant difference between week 1 (18 percent) and weeks 2 – 4 (19 percent).

Overall, there was no significant relationship observed between the occurrence of FCW alerts and secondary-task behavior, although a slight increase was observed in the first week of ACAS-enabled driving during which drivers appeared to be conversing more frequently with passengers (perhaps regarding the FCW system). Other than the conversations with passengers, which are hypothesized to be associated with the novelty of the ACAS system, the pattern and frequency of other common secondary-task behaviors (e.g., talking on a cell phone) did not change while ACAS was enabled, except for a slight drop in such behaviors that was observed in the final two weeks of exposure.

4.5.8.8. Identification of FCW Alerts with Safety Potential

Several specific events were identified in which an FCW alert appeared to assist drivers. In order to search for such evidence, a set of 65 candidate events was identified for inspection. Candidate events were those in which a driver received an imminent alert and at least one of the following criteria held as well:

1. The driver’s eyes were not on the driving task at the time of the alert,
2. The driver’s face appeared to show a startled expression following the alert,
3. The braking level reached at least 0.4 g within three seconds after the alert, or
4. Drivers chose to steer in response to the alert (indicating a possible urgency in response).

Of the 65 candidate events, 13 were identified where the imminent alert was considered to be valuable because it was associated with one or more of the criteria above. Although the statistics on rear-end crashes suggest that it is very unlikely that all of these events would have precipitated a crash without the FCW system, the events nevertheless demonstrate that the FCW system did have an alerting capability that appears to have assisted at least some drivers in some circumstances.

In contrast, only 1 out of 240 stationary-target alerts was observed to involve a true, in-path vehicular target for which the alert was kinematically justified—and this single event did not qualify among the set of 65 candidates, above. Thus, none of the stationary-target alerts was seen as credible, in the sense of safety-potential as discussed here.

4.5.8.9. Perceived Safety and Driver Acceptance of FCW

In terms of the perceived safety of the FCW system, the results were somewhat mixed. While the majority of drivers acknowledged some safety benefits associated with FCW, most, aside from the majority of older drivers, felt that they themselves did not need the system—yet could think of others who did. There were numerous instances in either debriefing or focus groups where drivers would report that *they* did not need to receive imminent warnings, as they were attentive drivers, but that they could see where the FCW system would be good for *others*. In particular, young and old drivers were frequently mentioned as those that might benefit most, although typically by the opposing age group. The relative infrequency of a true, rear-end crash threat was cited several times in the focus groups as being of concern, as the possibility existed for drivers to become insensitive to imminent alerts if the frequency of false alerts was too high. Nonetheless, a number of drivers in the focus groups stated that the FCW system made them more cognizant of the surrounding traffic conditions—even to the degree that they drove more conservatively than normal in order to avoid imminent alerts or because they recognized that their driving was being examined as part of the study. This was supported by questionnaire results in which the majority of drivers stated that they drove at least as safely with the system as compared with their normal driving behavior. However, when asked if they believed an FCW system would increase their driving safety, approximately one-third either disagreed or were neutral on the matter (mean rating of 4.6 on a 7-point scale). Last, several drivers, mostly from the older group, stated that the system reaffirmed their beliefs in what constitutes "safe" driving. They felt that an infrequent occurrence of imminent alerts meant they must be a good driver. However, there were no strong relationships between objective measures (i.e., frequency of alerts) and the subjective perceptions of FCW system safety.

In terms of the perceptions that were indicative of driver acceptance, most drivers saw some limited benefit in the FCW system, but primarily for drivers other than themselves. Drivers frequently commented that they received more FCW alerts than they believed were necessary and that the additional alerts were deemed to be nuisances or false alarms. This point of view seemed to contribute significantly to the negative ratings of the usefulness of the FCW system. Nevertheless, 45 percent of the FOT subjects indicated that they *probably* or *definitely would* purchase FCW if they were purchasing a new car today.

4.5.8.10. Predicting FCW Acceptance

FCW acceptance differed among drivers due largely to age rather than gender. The majority of age effects were constituted in the dissociations between older drivers' ratings of FCW and their middle-aged and younger counterparts. In general, the obtained age differences resulted in older drivers viewing the FCW system more favorably than either the middle-aged or younger driving groups. Consistent with the value they ascribed to the FCW system, older drivers selected the most-sensitive setting significantly more frequently than did either the younger and middle-aged drivers.

4.5.8.11. Suggested Modifications of the FCW System

The FOT participants had a wide variety of suggestions for improving the FCW system in behalf of driver acceptance. The two statements most frequently associated with FCW system attributes that needed improvement were first, reduce the frequency of nuisance and false alarms, and second, to provide a means to permit the FCW system to be turned off in certain types of traffic conditions.

Some drivers were interested in having the system be more readily adjustable. Some commented that they wanted the freedom to choose from a variety of warning beeps, the colors and types of the icons displayed on the HUD, to turn off the cautionary alerts and perhaps the system altogether, and to adjust for different driving environments (i.e., city versus freeway driving). One suggestion was that the driver might be allowed to indicate to the system what they deemed to be a false alarm after one was experienced, allowing the system to more readily adapt to their personal driving style. Drivers also wanted FCW to work in poor weather conditions, as this is when many thought the concept could be most helpful (the ACAS system warned that its performance is degraded by heavy rain upon use of the highest setting of wipers). Other suggestions included having the system functional at lower speeds (below 25 mph) and having the system detect targets such as pedestrians or deer.

In terms of an objective appraisal of all the FCW data from the FOT, the most compelling change for improving the system, given the current state of the technology, would be the elimination of stationary-target alerts, while still retaining the potential to warn on a “movable” object that may have stopped in the vehicle’s path.

4.5.8.12. Summary of Key FCW Results Pertaining to Driving Safety and Driver Acceptance

Results from analysis of the FCW-related data showed that:

- Driver response to the ACAS FCW system was mixed. Older drivers were more likely to view the system favorably, and middle-aged drivers the least likely. Most drivers saw some limited benefit associated with the FCW system, but typically reported that the benefit would be greater for drivers other than themselves.
- After experiencing the FCW feature for three weeks, most of the FOT subjects were not willing to purchase such a system at a $1,000 cost.
- The most important factor influencing the frequency and conditions in which individual drivers experienced alerts were the individual driver themselves, with the type of road (and therefore, traffic dynamics) being the second most important factor.
- Drivers frequently commented that they received more FCW alerts than they believed were truly necessary, with the additional alerts being deemed as nuisances or false alarms. This seemed to contribute significantly to the negative perceptions of the FCW system.
- The two statements most frequently associated with FCW system attributes that needed improvement were first, reduce the frequency of nuisance and false alarms, and second, to provide a means to permit the FCW system to be turned off in certain types of traffic conditions.
- At least 13 situations were identified where FCW appeared to contribute to the driver’s proper awareness of a potential rear-end crash, and/or the encouragement of an appropriate, firm braking response to the situation.
- The headway distances during periods of vehicle following in manual, daytime driving were also seen to increase on all road types (with no corresponding impact on nighttime driving.)
- No change in the rate or the severity of conflicts were observed when driving with, versus without FCW.
- No consistent set of results suggested that driver braking responses to conflicts was either positively or negatively affected.
- A majority of FCW imminent alerts were either false alerts triggered by objects not on the roadway or alerts occurring in scenarios in which the forward conflict is typically resolved through a divergence in the paths of the two vehicles rather than through braking by the host driver. This aspect of system performance appears to have negatively influenced driver acceptance of FCW.

- The current state of sensor processing leaves FCW operating with much less information than an alert driver has regarding anticipated vehicle movements and the detection of vehicles that are stopped in one's own path. Therefore, the most compelling change for improving the system, given the extent state of the technology, would be the elimination of stationary-target alerts while still retaining the potential to warn on a "movable" object that came to a stop in the vehicle's path.

4.5.9. Results Addressing Adaptive Cruise Control

ACC-related results are presented under 13 different subheadings and then summarized in a brief statement of the key findings.

4.5.9.1. Conditions under which ACC was Experienced

The ACC function is, of course, manifest when the driver engages it. Thus the ACC driving experience always traces to the conscious choice made by FOT drivers to turn the system on, given their judgment of the suitability of ACC engagement under the prevailing driving conditions.

The percentage of driving distance over which ACC is engaged is termed the utilization level. It was seen that ACC was used in 37 percent of the total distance driven with ACAS enabled, compared to a 20 percent utilization of CCC during the baseline week of driving. ACC was used more frequently than CCC in all driving conditions, including all the variations in road type, traffic density, and day/night illumination, as well as the wet/dry condition that is deduced by whether the wipers are on or off. On interstate highways, ACC was used in 60 percent of the total distance compared to 37 percent with CCC. The largest differences seen between CCC and ACC utilization rates occurred under dense traffic conditions and on surface streets, as follows:

- ACC was used at 3.5 times the rate of CCC under dense traffic conditions. Presumably because ACC has the remarkable ability to manage headway, thereby relieving the driver of much of the stress imposed by this task, it is perhaps not surprising that ACC would be employed at a higher rate under dense traffic conditions. Since dense traffic also poses the higher likelihood of unstable flow, however, braking interventions lasting 2 seconds or more were employed by the ACC driver three and a half times more frequently than under the medium traffic condition. Thus, the higher rate of ACC use in dense traffic appears to pose a greater requirement upon the driver's readiness to intervene. On the other hand, the data suggest that drivers were attentive to the greater demand for intervention.
- ACC was also used at 2.1 times the rate of CCC in the surface-road environment that tends to pose more intense and more frequent conflicts requiring a driver response. Nevertheless, drivers appeared to be adapting their ACC utilization choices as time went on, since the ACC utilization rate on surface roads declined by a quarter over the three weeks of ACAS usage.

Older males used ACC a third more than the younger or middle-aged males, and older females used ACC at more than twice the rate of younger or middle-aged females. Since older drivers, as a total group, also accumulated approximately 15 percent greater travel mileage, the ACC driving data represents a significantly greater expression of older-driver patterns of behavior. Males in the younger and middle-aged groups used ACC at least 50 percent more than females of the same age, although female usage of ACC was about 10 percent above that of males in the older-age group. While older drivers tended to select lower set-speeds and longer gap-settings with ACC relative to their younger counterparts, they experienced higher alert rates with ACC engaged.

As a final observation on ACC usage conditions, approximately 2 percent of ACC driving mileage was traveled on curves whose radii were tight enough to reduce the active range of the radar to less than 100 meters. On the one hand, this constraint does suggest a diminished lead-time for providing both the headway control and alert functions during ACC driving. On the other hand, tight-radius geometries tend to appear only on lower-speed roads such that the effects of the diminished range of the ACC radar on curves appear to be largely compensated by the more moderate speeds.

4.5.9.2. Usage of ACC Set-Speed and Headway-Gap Settings

The ACC system affords a means for adjusting both the cruise set-speed and the preferred time-gap setting to accord with driver preferences under the prevailing road and traffic conditions. Since the ACC system also controls for headway, however, drivers often left the cruise speed set at a level that was above the speed of traffic, thereby depending upon the headway controller to find the speed that is achievable under the prevailing conditions. One notable feature in the ACC set-speed data is that the maximum-adjustable speed, 80 mph, was among the three most-likely values selected by drivers under ACC control, whereas that value was selected one-tenth as much under CCC control. In both ACC and CCC driving, the average set speed values selected over all driving by an individual driver varied widely, from about 50 mph to 78 mph.

The ACC gap setting was adjusted over the whole available range of values in almost the same pattern as was seen in FCW sensitivity adjustments. Of the six values of gap-setting corresponding to headway times of 1.0 seconds to 2.0 seconds in 0.2-second increments, the shortest and longest were almost equally popular, but among different age segments of the driver sample. The younger group was much more likely to prefer the 1.0-second setting and the older group was substantially more likely to prefer the 2.0-second setting. The value of 1.4 second was the next most popular after those two extreme values. The selected gaps tended to be shorter on freeways than on surface roads, with wipers off rather than on, and in dark rather than lighted conditions. This suggests that drivers adjusted the gap settings in response to conditions, although the dark/light contrast seems counter intuitive.

The ACC gap setting was changed much less frequently by most participants than was the FCW sensitivity level. The typical individual changed the ACC gap setting only on the order of two or three times during the three weeks of ACAS-enabled driving. Males altered the ACC gap setting about twice as frequently as females.

4.5.9.3. Rate and Conditions Surrounding ACC Alerts/Maximum-Deceleration Braking

As indicated earlier, imminent alerts were presented much less frequently during ACC driving than during manual driving. Of the 0.38 alerts per 100 miles cited earlier for ACC driving, the breakdown by conflict scenario is as follows:

- Moving vehicle that is always in the same lane as the host during the approach episode (49 percent)
- Stationary target that is never in the host’s path (42 percent)
- Stationary vehicle that is in the host’s path (6 percent of total)
- Moving vehicle that is in the same lane as the host at some point in the approach episode, and is in a different lane at other times in the episode (2 percent)
- Other (less than 1 percent)

ACC alerts are notable in that those listed under the first and third bullet, above (i.e., 55 percent of the total) match the kinematic profile for which the system was designed, compared to approximately 28 percent for imminent FCW alerts that were generated during manual driving.

The fact that the overall rate of imminent alerts under ACC control is well below that of manual driving is partially explained by the fact that the ACC system is a reliable, continuous controller of the headway variable. Although the rules for generating imminent alerts under manual and ACC driving differ in certain important ways, it is apparent that the great difference in alert rates is primarily the reflection of a relatively conservative strategy for ACC control along with drivers' decisions to employ ACC in generally more benign driving environments.

Another important context for ACC manifesting itself to the driver is in the braking response of its controller. The so-called "auto-braking" response of the ACC system constitutes both a haptic cue to the host driver and a direct action by the controller to address forward conflict. A total of 60 episodes occurred in which the ACC controller reached its nominal 0.3-g deceleration limit, for a rate of approximately once every 200 miles of ACC driving, overall. These incidents showed what appeared to be a distinct novelty effect and took place primarily on surface streets. The rate of limit-auto-braking events in the surface-street environment was approximately once every seventy miles compared to a rate of only once every two thousand miles of ACC driving on freeways. Drivers appeared to have progressively adopted a more cautious approach toward using the full-auto braking capability of ACC on surface streets since the rate of such events dropped by three-quarters over the three weeks of ACAS driving. Similarly, even the more rare but observable incidence of limit auto-braking events on freeways had essentially vanished by the final week of ACAS driving. Extrapolating these data, it would appear that drivers would not tend to depend upon limit auto-braking as a common facet of ACC driving, over the long term.

4.5.9.4. Effects of ACC on Following (Headway-Keeping) Behavior

ACC driving was generally differentiated from manual and CCC control by the interesting phenomenon of more sustained following. In freeway driving, where the opportunity for following another vehicle persists for rather long periods of time, it was seen that drivers stayed behind any given preceding vehicle for approximately twice as long when ACC was engaged as occurred when driving in either of the other two control modes. This result aligns well with a focus-group comment by one participant who said, (ACC) "made me able to relax…and let the thing drive." The evidence for prolonged-following episodes also links to the observation that ACC driving induces the practice of staying in one's own lane. It is recognized that this practice may well be beneficial for both calming traffic and for reducing the prospect of lane-change crashes.

As can be anticipated simply from the ACC system design, ACC driving is transacted at headway times that are substantially longer than those employed in manual driving under the same conditions. In heavy freeway traffic, for example, ACC driving has one third the prevalence of travel at shorter than 1.0-second headway times than does manual driving. As traffic density reduces, the distribution of headway times under ACC control tends to become more like that of the manual and CCC driving modes, although still lacking in the very-short headway values that arise from tailgating behavior in manual driving.

4.5.9.5. Effects of ACC on Approach (or Closing-Type) Conflicts

It had been hypothesized that FOT participants would sometimes apply the throttle manually during ACC driving as a means of encroaching upon the preceding vehicle so that, upon throttle release, the automatic ACC control response would be provoked. Such a technique might be used to probe, and thus learn, the full range of the ACC braking response, up to its deceleration limit of 0.3 g. FOT data showed, however, that although approximately half of the test subjects did, indeed, use the "throttle-override" technique at one time or another to intrude substantially within the selected ACC control gap, no individual ever provoked the full, 0.3 g, braking response of the controller by this means.

Several drivers appeared to have employed this tactic as a means of coercing the preceding driver out of the fast lane of the freeway so that the host driver could pass.

Generalizing on the effects of ACC on approach conflicts, the FOT data were analyzed to reveal the ability of the ACC controller to manage approach-type conflicts with the preceding vehicle under both dense and sparse levels of freeway traffic. Results indicate that ACC driving encounters virtually the same distribution of conflicts as in manual driving under dense traffic but is much less likely than the case of manual driving to encounter conflict when the traffic density level is sparse. It appears that the ACC system provides a strategy of control that is rather conservative relative to common manual-control behavior, especially when the host is approaching another vehicle at a substantial overtaking speed. In such cases, the ACC controller decelerates sooner in the approach transient and generally avoids substantial overshoots in headway time.

4.5.9.6. Effect of ACC on Manual Braking Behavior

ACC driving was examined in order to determine the frequency and severity of manual braking that is applied for intervening upon ACC control. It was seen that the frequency with which the driver applies the service brake is much lower in ACC driving than in either manual or CCC driving under the same driving conditions. Typically, the brake is applied approximately 20 times more frequently per distance traveled in manual driving and 3 times more frequently in CCC driving than when driving under ACC control.

When the driver does apply the brake to intervene upon ACC control, the peak decelerations achieved and the conflict levels prevailing at the moment of brake application were not significantly different from those observed when driver braking occurred in manual driving or as a means of intervening upon CCC control. The fact that the brake was not applied more aggressively when the driver intervened upon ACC control suggests that other drivers following behind the ACC-equipped vehicle encountered little difference in the severity of conflicts posed by ACC braking interventions than were experienced when following either CCC- or manually-controlled vehicles.

Since ACC does not decelerate in response to stationary-type targets, it also was of interest to observe whether drivers would act expeditiously to disengage ACC by means of braking intervention upon encountering an in-path stationary vehicle, under ACC control. Results showed that stationary and very-slow-moving vehicles were encountered only rarely as an obstacle that provoked ACC disengagement by the driver. While no such cases occurred on freeways, a total of 32 events of this kind took place on surface streets. Since rather little total mileage was traveled on surface streets, the rate of such encounters was relatively high—approximately once every 80 miles of ACC engagement on surface roads. Nevertheless, when manual braking was applied to disengage ACC and resolve conflict posed by such targets, the relatively short values of driver brake-reaction times that were observed suggest that drivers had been reasonably attentive to the threat of these obstacles.

4.5.9.7. Effect of ACC on Secondary-Task Behavior

ACC driving was examined relative to that of manual- and CCC-driving, to determine the extent of any difference in secondary-task behaviors. It was observed that the rate of secondary-task behaviors in ACC driving was significantly higher than in CCC driving, but not significantly different from that of manual driving. Since the higher incidence of secondary-task behavior with ACC primarily involved the driver conversing with other occupants of the vehicle, it has been hypothesized that the novelty of the ACC system may have stimulated both the situation of driving with occupants present (in order to demonstrate the novel system) and the prospect of a sustained conversation on the matter. The declining rate of such activity from week-2 through week-4 tends to support this view.

4.5.9.8. Sustained Following/Lane-Dwelling, Passing, and Cut-In Behavior

Because ACC driving involves an approximate doubling of the characteristic time that drivers choose to spend following behind any other specific vehicle, ACC driving is sustained for longer periods of time within the same lane, compared to manual driving. The resulting reduction in passing rates suggests that the ACC driver is substantially less exposed to hazards associated with the lane changing that typically initiates the pull-out-to-pass sequence. The resulting rate of passing other vehicles on freeways under ACC control was about 50 percent of that seen during manual driving and 70 percent of the rate under CCC control.

ACC driving was compared to the other control modes for the specific case of the so-called "flying-pass" maneuver (i.e., an overtaking maneuver that is begun by a driver who is approaching at a significant overtaking-speed from directly behind the vehicle that is to be passed.) When the flying pass was conducted during ACC driving, the lane-change phase of the maneuver was initiated at considerably longer range than under manual or CCC control, thus leaving more clearance to the preceding vehicle at the time of crossing over into the adjacent lane. As a result, the levels of conflict (expressed by time-to-collision) that arise during flying passes in ACC driving are considerably more benign than when driving manually or under CCC control. The practice in ACC driving of pulling out at longer range from the preceding vehicle is believed to reflect the driver's awareness that if the ACC vehicle were to be driven closer before pulling out, the headway controller would activate to slow down the host vehicle. If slowing were to occur while the passing maneuver is underway, it would tend to foil the timing of the maneuver and perhaps provoke conflict with faster-moving traffic in the adjacent lane that is being entered.

The rate of cut-in that occurs ahead of the ACC driver on freeways is intermediate between the rates experienced during manual driving and CCC control. It is clear that the experience of cut-in, for any mode of control, is powerfully influenced both by the headway gap that the host driver maintains and by the nominal traffic density that prevails. The fact that the ACC driver cannot select a gap setting shorter than 1 second does result in a considerably higher cut-in rate than would be experienced at the shorter headways that are commonly sustained under manual control. The higher cut-in rate with ACC is particularly pronounced when driving in dense traffic. Focus-group participants did observe that the longer gap values obtained with ACC certainly would "allow cars to cut in front of you." On the other hand, the limitation of the minimum gap-time to 1 second does act to strongly reduce the extent of short-headway driving, thereby reflecting the design trade-off that was made between driving-safety and driver-acceptance qualities of the system.

4.5.9.9. Identification of ACC Alerts with Compelling Justification

Of 25 moving-target alerts that were produced while under ACC control, 24 of them appeared to have been justified by the presence of a vehicle that impeded travel in the host vehicle's established path. Taking the set of 17 of these cases in which the driver reacted with a brake application lasting two seconds or more, the braking inputs all began within 1.1 seconds of the alert onset. Thus, the moving-target alerts that were presented during ACC driving were deemed to be highly credible as a warrant for brake intervention.

Considering stationary-target alerts, the total of 47 such incidents that were encountered in ACC driving included 6 incidents in which the alert was credible, i.e., a stopped vehicle was indeed in the ACC vehicle's path. These six incidents were all among a total of only 18 stationary-target alerts that were encountered on surface streets and all of them were followed by manual brake interventions within 0.5 seconds of the alert onset. Thus, while stationary targets were the source of a large group of false alerts by the FCW system, overall, they were much more likely to have entailed a genuine threat when appearing as an alert under ACC control, especially on surface streets.

4.5.9.10. Perceived Driving Safety and Driver Acceptance of ACC

The perceived safety of the ACC system was largely favorable. When asked if they believed that an ACC system would increase their driving safety the majority of drivers agreed, with a mean rating of 5.5 on a 7-point scale (where 1= strongly disagree and 7= strongly agree), which is considerably higher than the ratings for FCW. Ratings of perceived safety of ACC were particularly common from older drivers relative to their younger and middle-aged counterparts. As a group, middle-aged drivers were least likely to agree that ACC would increase their driving safety. Several focus-group participants acknowledged that the ACC system increased the following distances that they would typically maintain under manual control and that they tended to drive less aggressively when ACC was engaged. Nonetheless, there were comments made during the focus groups that raised concerns about the possibility of diminished attention to the task of driving while ACC was engaged (even though video review of secondary-task behaviors did not support these concerns). Some comments by participants related to slowness to intervene by using the brake at times and the need to use the accelerator more when attempting a passing maneuver.

Overall, drivers showed a high level of acceptance of the ACC system. Responses to several key ACC acceptance questions showed that only a few drivers rated the ACC system as unacceptable. Over the bulk of the ACC acceptance data, there was clear consensus that ACC was a desirable system. When asked if they would consider purchasing an ACC system if they were buying a new car today, 73 percent of the FOT subjects indicated that they *probably* or *definitely would*. The overall satisfaction with the ACC system received a means score of 6.0 on a 7-point scale (where 1 = very dissatisfied and 7 = very satisfied).

4.5.9.11. Factors Predictive of ACC Acceptance

Differences in ACC acceptance amongst drivers were again largely due to age rather than gender. In general, the age differences resulted in older drivers viewing the ACC system more favorably. This finding was consistent in both the post-drive and take-home questionnaires and was obtained regardless of gender. Attempts to determine how characteristics of individual drivers would seem to serve as practical predictors of driver acceptance of ACC were modestly successful. Driver age, in particular, was more likely to predict ACC system acceptance then was driver gender, education, or income. Overall satisfaction level received a mean value of 6.6 on a 7-point scale among the older-drivers who, as a group, had also exhibited a distinctly higher level of ACC utilization than either of the other two age groups.

4.5.9.12. Suggested Modifications of the ACC System

The only substantive suggestions for improvement of the ACC system related to the available ranges of speed and gap-setting adjustments. Noting that some 8 percent of all ACC mileage was traveled with the ACC set speed adjusted to its 80 mph maximum value, it is not surprising there was feedback from some participants that the 80-mph limit was set too low. Also, noting that approximately one quarter of all ACC mileage was traveled at the shortest-available gap setting and another quarter was traveled at the longest-available gap setting, the prospect of extending upper and lower gap-time limits is likely to be of interest to some (but, of course, not the same) drivers.

Clearly, any decisions to extend either the upper limit on set speed or the lower limit on gap-time must address the apparent safety trade-offs that are implied. With regard to the kind of precautionary information that might be included in an ACC owner's manual, or perhaps in training materials provided to drivers, it seems prudent to counsel strongly against the use of ACC on surface streets, given the high potential for conflicts that are sufficiently severe as to require limit auto-braking responses of the ACC system (which serve as something of a surrogate for conflict severity).

4.5.9.13. Summary of Key ACC Findings Relating to Driving Safety and Driver Acceptance

Results from analysis of the ACC-related data showed that:

- The ACAS ACC system was widely used and favorably regarded by most participants.
- After experiencing the ACC feature for three weeks, most of the FOT subjects seemed genuinely willing to purchase such a system.
- The ability of this ACC controller to provide smooth, effective management of speed and headway over a very broad range of driving conditions is believed to account for its wide utilization and acceptance by FOT drivers.
- ACC driving was basically benign in all of its safety implications for freeway driving.
- The rather popular usage of ACC in dense, but flowing, freeway traffic does result in more cut-in activity ahead of the ACC vehicle due to the somewhat longer headway times that are managed by the system.
- The converse effect of longer headway times, as well as the continuous control action of the ACC system is that ACC driving affords more headway clearance and lower levels of kinematic conflict on an ongoing basis.
- ACC can be kept continuously engaged over long distances on freeways, especially when traffic density is sparse.
- ACC driving on surface streets appears to pose a possible safety concern for the neophyte ACC user who will become exposed to the stronger conflicts that may arise in this environment.
- The fact that drivers adapted within only a three-week test window to significantly contain their exposure to conflict-laden driving conditions, such as surface streets, would seem to bode well for the long-term adoption of prudent practices of ACC supervision by the driver.
- All evidence indicates the FOT drivers managed the ACC system with a rather high state of attentiveness, especially as reflected in short driver braking reaction times and modest levels of deceleration, when braking interventions did occur.
- Although the tested ACC system was capable of automatically decelerating at up to 0.3g, the deliberately retarded delivery of this response by the ACC controller is believed to have been an effective characteristic in discouraging drivers from depending upon it.

5.0. Findings and Conclusions

5.1. FCW Safety and Acceptance

The ACAS FOT program has produced pioneering knowledge regarding FCW system alert rates and false alarm issues, the immense variation of driver's alert experiences, driver potential acceptance of an FCW system, and system performance requirements. It is important to emphasize that the FCW and ACC subsystems examined could potentially reduce the incidence of rear-end crashes, as well as the harm caused by such crashes, in primarily two different ways. First, the system could reduce the amount of tailgating behavior, that is, the amount of time drivers spend at short headways when following a vehicle ahead during "steady state" car following conditions. A lengthening of headway times could provide the driver with additional time to respond should an unexpected rear-end crash scenario unfold. Secondly, the FCW system may at times (e.g., when the driver is distracted) alert the driver to an approach (or closing) conflict earlier than the driver would have detected such a conflict. These approach conflicts, as well as tailgating behavior, can ultimately lead to a rear-end crash.

Results indicated that both the FCW and ACC subsystems reduced the incidence of tailgating behavior relative to manual driving without the support of these systems. Overall, the incidence of cumulative time at less than one-second time headways were 26 percent with FCW system support, and 30 percent without such support. This overall FCW headway lengthening effect was also observed at 0.1 second headway steps starting from cumulative time at less than 1.6 second headways all the way down to cumulative time at less than 0.5 second headways. A more detailed examination indicated that this effect was restricted to daytime driving and freeway driving conditions. The exact source of this FCW headway lengthening effect is somewhat unclear, but can be potentially attributed to the FCW system (or possibly a transfer of training from the ACC system) increasing the driver's general awareness of their car following behavior.

With respect to driver's approach conflict behavior, imminent alert incidents were identified that were judged to have increased driver's awareness of a potential rear-end crash and/or encouraged the driver to brake. Hence, the potential for the FCW system to help the driver avoid rear-end crashes and reduce the harm caused by such crashes was demonstrated. However, evidence that the FCW system had a broad effect on reducing approach conflicts was not observed. Approach conflict metrics examined included the frequency of imminent alerts (where "silent" alerts were examined when the FCW system was not activated), required deceleration to avoid impact and time-to-collision at brake onset, and peak conflict measures during approach events.

Data suggested that drivers may have intentionally provoked imminent alerts, particularly during the first week of driving with the FCW system enabled. However, the risk of this experimentation was felt to be minimized by the heightened level of driver attentiveness during this activity.

Despite the observed potential safety benefits of the FCW system, driver acceptance for this system was clearly mixed. Overall, the older (60-70-year-old) drivers tended to be more satisfied with the system, and tolerant of perceived system deficiencies. Without a hypothetical system cost, 45 percent of drivers indicated positive purchase interest toward the FCW system. With a $1,000 system cost, this number dropped to 30 percent. It should be noted that the ACAS test participants are not considered to be necessarily representative (e.g., from an income level or vehicle ownership perspective) of initial owners of FCW-equipped production vehicles.

Results clearly suggested that reductions in false alarms are needed to ensure robust FCW system acceptance across the driver population. In the process of preparing this system for use in the FOT, substantial efforts were put forth to only issue alerts viewed as "credible" to the driver. Many of these false alarm reduction efforts involved heuristics which using data available to the FCW system to more accurately determine if objects are in the planned path of the driver and if the driver is intentionally closing rapidly on the vehicle ahead (e.g., during a passing maneuver). These efforts produced an order of magnitude reduction in the rate of “nuisance alerts” from the first algorithm implemented in the prototype vehicle to the most advanced algorithm that was ultimately employed in the formal ACAS FOT.

However, despite the considerable efforts put forth, during the conduct of the formal FOT, only one-third of the imminent alerts were issued to objects that remained in the same lane as the driver during the approach to the vehicle ahead. The remaining imminent alerts were issued primarily to roadside stationary objects (such as signs and mailboxes), when the lead vehicle was turning (which can be anticipated by the driver), or during driver-initiated lane changes. Consequently, it is not surprising that drivers were not observed to brake reflexively to the imminent alert.

Comparison of subjective results across algorithms investigated, as well as within the 66 drivers experiencing the final algorithm, failed to provide clear direction as to the extent to which false alarms must be reduced in order to ensure widespread acceptance of the FCW system. The overall impression is that a formidable technical challenge lies ahead in fielding a widely accepted FCW system. Nonetheless, the lessons learned in this project have suggested numerous system improvements that will undoubtedly lead toward this broader customer acceptability. For example, at least for the current state-of-the-art capability, it appears that the requirement levied on the ACAS system to detect “always stationary” vehicles (i.e., vehicles that have never been seen moving by the FCW system) may be ill-advised, based on the high frequency of false alarms to “always stationary” objects (such as signs and mailboxes) relative to the extremely rare occurrence of credible imminent alerts to “always stationary” vehicles.

5.2. ACC Safety and Acceptance

Similar to the FCW system, the ACAS ACC system examined could potentially reduce the incidence of rear-end crashes and harm caused by tailgating behavior. Indeed, the headway controlling function of the system evaluated largely prevents drivers from traveling below one-second headways, since one second corresponds to the minimum ACC gap (or time headway) setting available to the driver. Evidence for a reduction in tailgating behavior was observed at a substantially larger magnitude than with the FCW system. The percent of driving time spent below one-second time headways was reduced by 60 percent to 70 percent across sparse and heavy traffic freeway conditions, respectively. This may in part explain why drivers’ ratings of whether the system increased their driving safety were more positive for ACC than corresponding ratings for FCW. It should be pointed out that although this lengthening of headway times caused by ACC will naturally lead to increased cut-in behavior by other drivers, the warm driver acceptance of ACC suggests that the perceived ACC benefits clearly outweigh this potential annoyance.

The possibility that the ACC system could increase approach conflict behavior was examined. This increase could occur either because of the manner in which ACC controls the vehicle in approach situations and/or due to the choices the driver makes in allowing ACC control in their assumed supervisory role. Hence, much of the ACC analysis focused on whether drivers had a tendency to be overly reliant on the ACC system. Overall, results indicated that ACC did not negatively impact approach conflict behavior. On the contrary, it appears that ACC may actually have had a positive impact on reducing traffic conflict by increasing lane dwelling behavior (which may serve to reduce lane change risks). In addition, it was observed that when approaching a slower vehicle to perform certain lane-change-and-passing maneuvers on freeways, driver’s initiated the lane change at longer ranges with ACC than in manual driving (or with conventional cruise control), presumably to avoid ACC braking.

A video-based analysis was also conducted to explore whether the driver engaged in more secondary tasks (e.g., cell phone conversation, passenger conversation, eating, grooming, smoking) during ACC (as well as FCW) driving. This could occur because the driver workload and perceived stress associated with car following is substantially reduced with ACC. Driver-initiated brake-apply rates under freeway conditions were found to be approximately 25 times lower when ACC was engaged than under manual driving conditions. Nevertheless, results did not provide evidence suggesting an undue increase in secondary task behavior under ACC relative to manual driving (this was also true for the corresponding FCW analysis).

Despite the lack of observed negative safety impacts of ACC driving, several observations are worth noting. First, the increased usage of ACC relative to CCC driving was evident across virtually all driving conditions. ACC control was employed in 37 percent of all driving compared to 20 percent with CCC. The increased use of ACC was particularly evident under heavy traffic conditions that may pose more opportunities for conflict for the ACC driver. Second, although the incidences of ACC reaching the system's 0.3 g maximum deceleration authority were rare, these incidents tended to occur under (the generally more conflicting) surface street conditions. These rare incidents decreased substantially over the drivers' three weeks of ACAS-enabled driving. In addition, a search for drivers experimenting with ACC braking failed to yield any incidents in which ACC braking reached the system's maximum deceleration authority during such activity. Overall, there is a clear suggestion that drivers strongly preferred intervening with manual braking before the ACC applied its maximum braking authority, suggesting that drivers were not overly reliant on ACC braking.

Driver acceptance was uniformly high for the ACC system, and as with the FCW system, a somewhat stronger purchase interest was expressed by older drivers. Without a hypothetical system cost, 75 percent of drivers indicated positive purchase interest for the ACC system. However, with a $1,000 system cost, this number dropped to 35 percent (similar in level to that observed with the FCW system). With a $1,600 system cost for a combined FCW and ACC system (i.e., the ACAS system), 35 percent of drivers indicated positive purchase interest. Once again, although ACAS test participants may not be fully representative of likely buyers for initial ACC-equipped vehicles, these data clearly illustrate the importance of ensuring ACC (and FCW) can be offered to consumers at affordable costs in order to foster deployment of these features.

5.3. Program Plan and Execution

Several lessons relative to future FOT programs can be gleaned from the substantial development effort that led up to the formal FOT. Among these was that the basic approach of incremental system development was sound and necessary. Key to this approach was the building of separate engineering development vehicles, each with a part of the functionality of the final system, prior to integrating all the features into a single vehicle. The need for separate vehicles was important since the development team was spread throughout the country.

The pilot FOTs (where subjects were accompanied on a prescribed route) were more important for the tuning of the system than had been anticipated. The initial drives by lay drivers revealed several shortcomings in the original FCW algorithm that were not apparent when members of the project team drove the vehicles.

Even so, it was found that the short-term system exposures (several hours to several days) used in the pilot FOTs produced more favorable acceptance results than those found with longer-term exposures (i.e., three weeks). The testing of three alternative algorithms with longer-term exposures provided valuable data on whether driver acceptance changed with different alert experiences, and provided ongoing opportunities for algorithm improvements. This pattern of executing multiple preliminary "mini-FOTs" leading up to a final FOT phase with the largest driver sample is highly recommended for future FOTs.

As for the length of exposure for each driver (one baseline week without the features and three weeks with the features), it is difficult at best to predict whether driver behavior and/or acceptance would have changed with further system exposure. Given the FCW acceptance findings, it could be argued that further exposure was probably not warranted (i.e., gathering further data would not have improved FCW acceptance ratings). On the other hand, if the FCW imminent alert rates would have been markedly less than observed here, it may have been even more difficult to assess driver behavior and/or acceptance (due to the small number of alerts experienced by drivers), unless drivers experienced considerably longer exposure to the FCW system. With respect to ACC, there are several trends in the data (e.g., the decline of ACC maximum braking events during surface street driving) that would have been interesting to examine beyond a 3-week exposure. When practical, future FOTs might consider bringing back a subset of FOT drivers (perhaps based on their exhibiting behaviors of interest) to further explore driver behavior and/or acceptance under longer-term system exposure.

Finally, the FOT produced approximately 1.4 terabytes of data. The value of this database has already been demonstrated and documented in this report and the FOT report. Evaluation of this data has produced pioneering knowledge that can be used to substantially improve future FCW and ACC systems, and most notably, to change the FCW algorithms to provide drivers with a higher proportion of "credible" alerts. In hindsight, the program would have benefited from allocating additional resources both during and after the data collection phase to further analyze and interpret this rich, immense set of naturalistic data.

References

Brunson, S.J., E.M. Kyle, N.C. Phamdo, and G.R. Presiotti (2002). *Alert Algorithm Development Program: NHTSA Rear-End Collision Alert Algorithm, Final Report*, Report DOT HS 809 526. National Highway Traffic Safety Administration. Washington, DC.

Hatley, Derek J., and Imtiaz A. Pirbhai (1988). *Strategies for Real-Time System Specification*. New York: Dorset House Publishing Co.

Kiefer, R., D. LeBlanc, M. Palmer, J. Salinger, R. Deering, and M. Shulman (1999). *Development and Validation of Functional Definitions and Evaluation Procedures for Collision Warning/Avoidance Systems*, Report DOT HS 808 964. National Highway Traffic Safety Administration. Washington, DC.

Kiefer, R.J., M.T. Cassar, C.A. Flannagan, D.J. LeBlanc, M.D. Palmer, R.K. Deering, and M. Shulman (2003). *Forward Collision Warning Requirements Project Final Report – Task 1: Refining the CAMP Crash Alert Timing Approach by Examining "Last-Second" Braking and Lane-Change Maneuvers Under Various Kinematic Conditions*. DOT HS 809 574. National Highway Traffic Safety Administration. Washington, DC.

Associated ACAS FOT Reports

Phase I

Deliverable	Name of Document
1	Functional Description Document
2	System Architecture/Mechanization Report
3	System Verification Plan
4	Risk Management Plan
6	FLR Interim Report
7	Lane Tracking System Requirements Summary Report
8	Lane Tracking system Down-Select Summary Report
9	Brake Actuator System Design Summary Report
10	Brake Actuator System Test Summary Report
11	Warning Cue Implementation Summary Report
12	Data Fusion Algorithm Simulation Summary Report
13	Path Prediction/Estimation Summary Report
14	Threat Assessment Simulation Summary Report
15	NHTSA Threat Assessment Simulation Summary Report
16	Prototype Vehicle Verification Test Data and Report
17	FOT Pilot Test Plan
19	FOT Operational Test Plan
24	ACAS FOT First Annual Report
27	ACAS FOT Phase I Interim Report

Phase II

Deliverable	Name of Document
28	FLR Summary Report
29	Data Fusion Algorithm In-Vehicle Summary Report
30	Threat Assessment In-Vehicle Summary Report
31	NHTSA Threat Assessment In-Vehicle Summary Report
35	FOT Final Report
36	ACAS FOT Program Review 6 Briefing & Program Plan Package
37	ACAS FOT Program Review 7 Briefing & Program Plan Package
38	ACAS FOT Third Annual Report
39	ACAS FOT Program Review 8 Briefing & Program Plan Package

DOT HS 809 886
May 2005

U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

www.nhtsa.dot.gov
nhtsa
people saving people