U.S. Department
of Transportation
**National Highway
Traffic Safety
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DOT HS 809 600

May 2003

Automotive Collision Avoidance System Field Operational Test

ACAS /FOT Third Annual Report

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Technical Report Documentation Page

1. Report No. DOT HS 809 600	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Automotive Collision Avoidance System Field Operational Test Third Annual Report		5. Report Date May 2003 6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No.
9. Performing Organization Name and Address General Motors Corporation 30500 Mound Road Warren, MI 48090-9055	Delphi-Delco Electronic Systems One Corporate Center Kokomo, IN 46904	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 U.S. Department of Transportation 400 Seventh Street, S.W. Washington, DC 20590		13. Type of Report and Period Covered Annual Report January – December 2002 14. Sponsoring Agency Code

15. Supplementary Notes

This project was carried out by a team lead by General Motors Corporation, North American Operations. Other major team members included: Delphi-Delco Electronic Systems, Delphi-Chassis, HRL Laboratories, HE Microwave and UMTRI.

16. Abstract

In June of 1999, the National Highway Traffic Safety Administration entered into a cooperative research agreement with General Motors to advance the state-of-the-art of rear-end collision warning technology and conduct a field operational test of a fleet of passenger vehicles outfitted with a prototype rear-end collision warning system and adaptive cruise control.

The goal of the research program was to demonstrate the state-of-the-art of rear-end collision warning systems and measure system performance and effectiveness using lay drivers driving on public roads in the United States.

The five-year program consists of a 2 1/2 year development phase during which refinement of component technologies will continue and be integrated into a prototype test vehicle. In the three-year period of the second program phase, a fleet of ten vehicles will be constructed and outfitted with rear-end collision warning and adaptive cruise control systems and given to volunteer drivers to drive over a period of several weeks. Data collected from on-board vehicle instrumentation will be analyzed and used to estimate potential safety benefits, obtain information on the driving experiences of the volunteer drivers and their acceptance of this next-generation safety technology. The operational test will last approximately one year.

This document reports on the activities and results from the end of the first program year of Phase II of this research project.

17. Key Words Collision avoidance, crash avoidance, collision warning, rear-end collisions, forward collision warning, human factors, head-up display	18. Distribution Statement This document is available to the public from the National Technical Information Service, Springfield, VA 22161 http//:www.ntis.gov

19. Security Classif. (of this report) None	20. Security Classif. (of this page) None	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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EXECUTIVE SUMMARY

The Automotive Collision Avoidance System Field Operational Test (ACAS/FOT) is a cooperative agreement between General Motors and the U.S. Department of Transportation National Highway Transportation Administration. The goal of the ACAS/FOT is to advance the science of collision warning by conducting an extensive Field Operational Test (FOT) to assess the impact of an integrated Forward Collision Warning (FCW) and Adaptive Cruise Control (ACC) system. Under the agreement, General Motors and Delphi-Electronics Systems (DDE) are working as a team to refine and integrate the required technologies necessary to conduct the FOT. The U.S. DOT, General Motors, DDE and Delphi-Chassis Systems (DCS) are each providing funds for the execution of the project.

The ACAS FCW system is designed to provide visual and audible warnings to a driver if it detects an imminent crash with the rear end of another vehicle. It also provides visual cues to help the driver maintain a safe distance when following other vehicles. The ACAS ACC system is a driving comfort and convenience feature that maintains a set speed when there is no impeding traffic, and that will reduce the speed to maintain a selected time headway when slower moving traffic impinges upon the path of the vehicle.

During the field operational test, lay drivers will use vehicles equipped with the ACAS functions as their personal vehicles, unrestricted and unsupervised, for four weeks each. Extensive subjective and quantitative data will be collected to help determine driver acceptance and the impact of the system on driving safety.

Summary of Phase 1

Phase 1 of the ACAS/FOT program ran from June 1999 through December 2001. During Phase 1 the technical approach for the ACAS system was implemented and integrated into a Prototype vehicle. Previous projects had determined that a major limitation on the performance of ACC and FCW systems was errors in selecting which vehicles were in the path of the host vehicles. The errors were found particularly when the curvature of the road was changing, such as at the transition from straight to curved or from curved to straight road segments. Therefore, much of the technical effort in the ACAS/FOT program addresses this problem. Figure 4 shows a functional breakdown of the ACAS system. At the top are four separate functions used to estimate the geometry of the road ahead of the vehicle.

Results of these road geometry estimates are combined by the Data Fusion function to produce a best estimate of the road geometry ahead of the vehicle. The road geometry estimate produced by the Data Fusion function is used by the Target Selection process to determine which objects detected by the radar are in the path of the vehicle.

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. The maximum braking authority of the ACC is 0.3g.

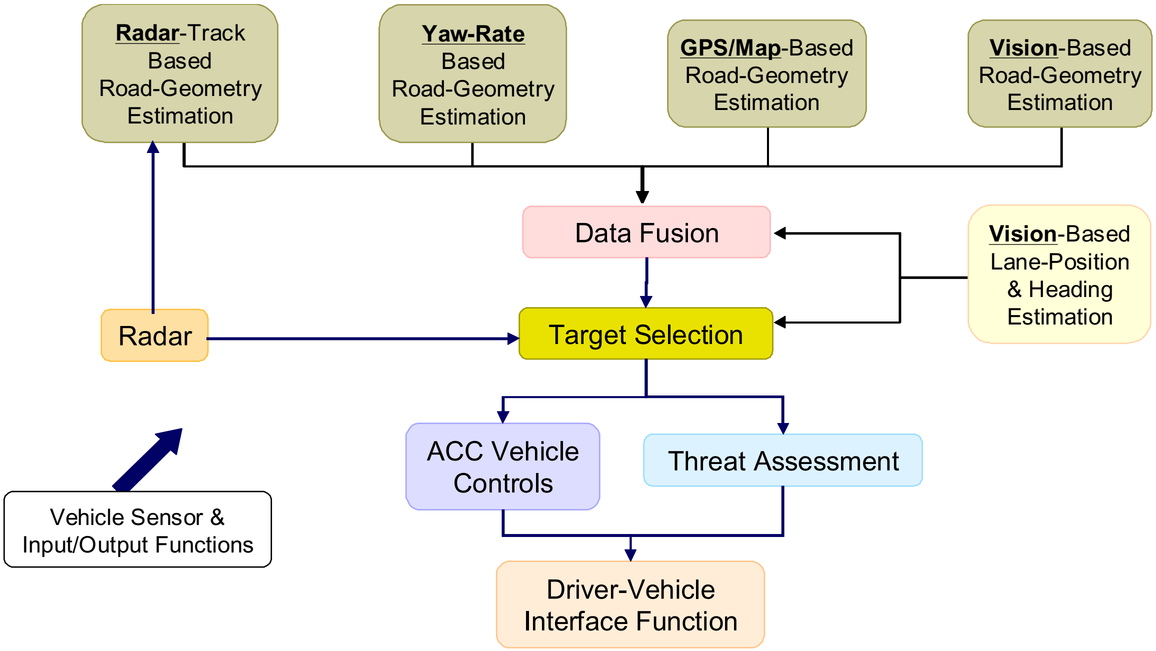


Figure 1: Functional Flow of the ACAS System

All in-path targets are used by the Threat Assessment function to control the FCW output.

The Driver Vehicle Interface (DVI) function includes control of the head-up display. This display shows the vehicle speed, warning icons, and status information. The DVI also includes buttons to control the ACC, the alert timing (sensivity setting) of the FCW, and the brightness and position of the HUD image.

During the Phase 1 of the program the various subsystems were refined using five engineering development vehicles (EDV). The subsystems were then integrated into a single Prototype vehicle. The Prototype vehicle integrated all the required ACAS functionality but without the packaging necessary to look like a production vehicle. Successful completion of verification of the Prototype Vehicle satisfied a major requirement for proceeding with Phase 2 of the ACAS/FOT program.

Summary of Accomplishments during 2002

This report, the ACAS/FOT Third Annual Report covers accomplishments during calendar year 2002, the first year of Phase 2 of the program.

During March and April of 2002 the Prototype Vehicle was used in the Stage 2 Pilot testing. Twelve laypersons, accompanied by a researcher, drove the ACAS Prototype vehicle three times each around a defined 58-mile route for a total of 2045 miles. During and after the drives, extensive quantitative and subjective data was collected.

The test data showed a relatively high rate of imminent alert production during all driving in which the ACAS function was enabled. A detailed breakdown showed that alerts occurred almost exclusively on surface streets and when driving manually, with ACC disengaged. The alerts were split about evenly between moveable targets and stationary targets. The results of this test highlighted the need for refining aspects of ACAS performance, given subjective observations by the drivers, as well as, results from the quantitative data. The general view of the project team was that the overall rate of imminent alert occurrence was at least twice too high for a successful FOT.

A major set of changes ensued, impacting every function shown in Figure 4. These improved the quality of the images on the head-up display, the way information is presented to the driver on the display, improved the feel of the ACC, and reduced the number of alerts from the FCW, particularly while driving on surface streets.

The improvements were incorporated into two Pilot vehicles. These vehicles included the functionality demonstrated in the Prototype vehicle, with the improvements to the hardware and software, along with the added feature that the packaging meets the size and appearance required for the FOT. Verification testing of the Prototype vehicles was completed in October 2002.

During November 2002, the Pilot Vehicles were used to perform another round of trials with laypersons accompanied on the same prescribed route. Six of the laypersons who participated in the Stage 2 Pilot Tests also participated in the Stage 2.5 Pilot Tests. Each subject drove the prescribed route twice, once during the day and once after dark. The purpose of the repeat testing was to confirm that changes to the ACAS design had been accomplished successfully. This was confirmed and the decision was made to proceed early in 2003 into the Stage 3 “FOT dress-rehearsal” test (where subjects will be given the vehicles for several days to use as their personal vehicle) as a final step before launching the formal FOT.

By the end of December 2002, ten of the eleven deployment vehicles had been assembled. During 2003, the last of the deployment vehicles will be assembled and the two prototype vehicles will be brought to the same configuration, providing a total of thirteen vehicles. Ten of these vehicles will be provided to UMTRI for use in the FOT. GM, Delphi, and NHTSA will each receive one of the remaining vehicles for testing.

The full dress rehearsal of the FOT will be executed in 2003. During these tests six subjects will each use the vehicles for several days. Once the data from these six subjects is analyzed, the program will proceed with execution of the FOT, which will end in December 2003. Data analysis and a final report will then be produced during 2004.

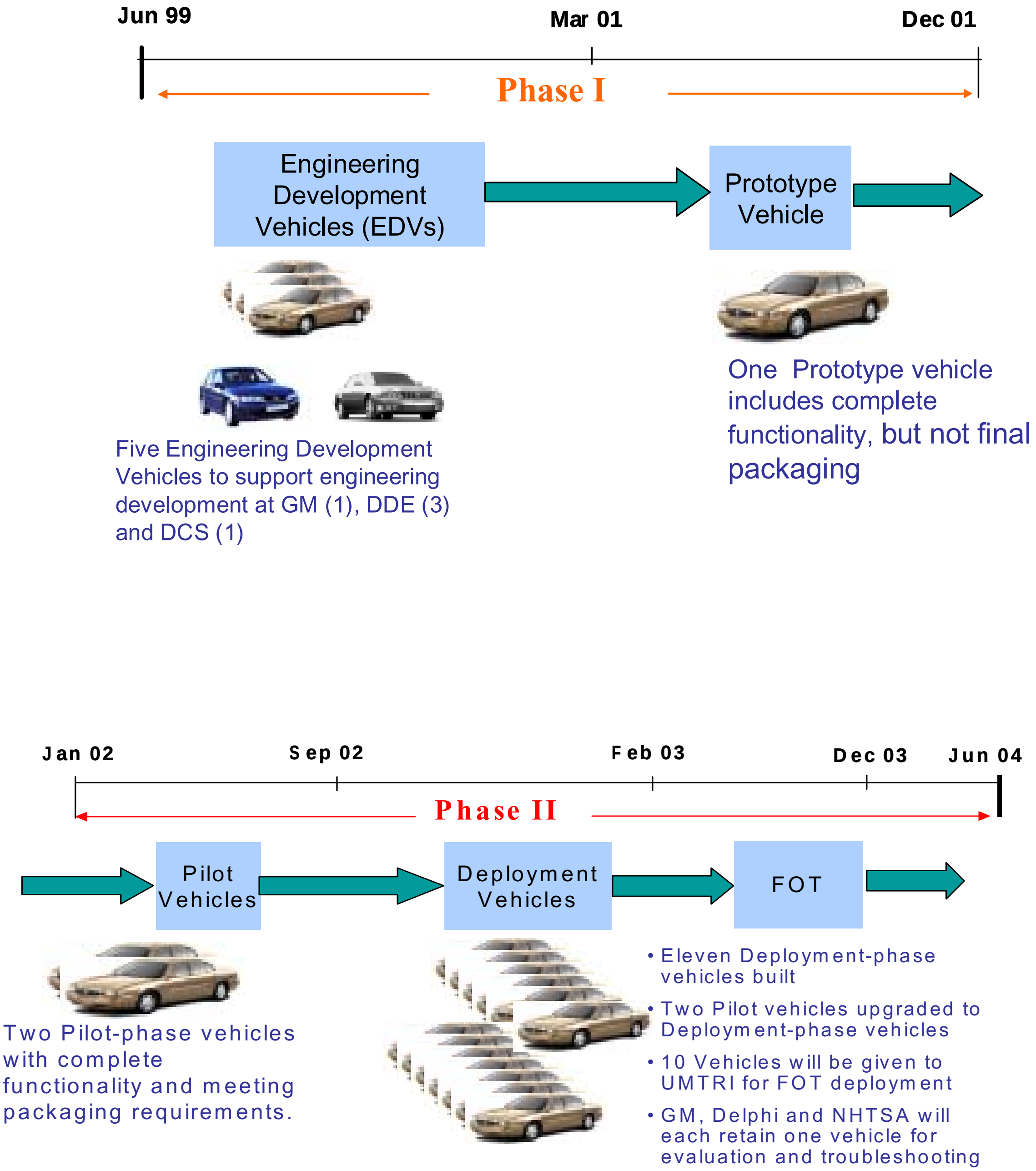
1 INTRODUCTION

The Automotive Collision Avoidance System Field Operational Test (ACAS/FOT) is a cooperative agreement between General Motors and the U.S. Department of Transportation National Highway Transportation Administration. The goal of the ACAS/FOT is to advance the science of collision warning by conducting an extensive Field Operational Test (FOT) to assess the impact of an integrated Forward Collision Warning (FCW) and Adaptive Cruise Control (ACC) system. Under the agreement, General Motors and Delphi-Electronics Systems(DDE) are working as a team to refine and integrate the required technologies necessary to conduct the FOT. The U.S. DOT, General Motors, DDE and Delphi-Chassis Systems (DCS) are each providing funds for the execution of the project).

The ACAS FCW system is designed to provide visual and audible warnings to a driver if it detects an imminent crash with the rear end of another vehicle. It also provides visual cues to help the driver maintain a safe distance when following other vehicles. The ACAS ACC system is a driving comfort and convenience feature that maintains a set speed when there is no impeding traffic, and that will reduce the speed to maintain a selected time headway when slower moving traffic impinges upon the path of the vehicle.

During the field operational test, 78 lay drivers will use vehicles equipped with the ACAS functions as their personal vehicles, unrestricted and unsupervised, for four weeks each. Extensive subjective and quantitative data will be collected to help determine driver acceptance and the impact of the system on driving safety.

Phase 1 of the ACAS/FOT program ran from June 1999 through December 2001 (see Figure 1). During the first phase of the program various subsystems were refined using five engineering development vehicles (EDV). The subsystems were then integrated into a single Prototype vehicle. The Prototype vehicle integrated all the required ACAS functionality but without the packaging necessary to look like a production vehicle.



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 will be given to UMTRI for FOT deployment
- GM, Delphi and NHTSA will each retain one vehicle for evaluation and troubleshooting

Figure 2: Program Timeline and Vehicles

Automotive Collision Avoidance System Field Operational Test Program
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This annual report covers accomplishments during calendar year 2002, the first year of Phase 2 of the program. During 2002 two Pilot vehicles were completed. These vehicles included the functionality demonstrated in the Prototype vehicle with the added feature that the packaging meets the size and appearance required for the FOT. Verification testing of the Prototype vehicles was completed in October 2002. By the end of December 2002, ten deployment vehicles had been assembled. During 2003, the last of the eleven deployment vehicles will be assembled and the two prototype vehicles will be brought to the same configuration, providing a total of thirteen vehicles. Ten of these vehicles will be provided to UMTRI for use in the FOT. GM, Delphi, and NHTSA will each receive one of the remaining vehicles for testing.

In addition to technology development and testing, during 2002 the protocols and procedures for handling the lay subjects in the FOT were developed and tested. This included trials where professionals drove the vehicles (Stage 0 and Stage 1 in Figure 3) and trials with lay subjects accompanied by a researcher (Stage 2 and Stage 2.5).

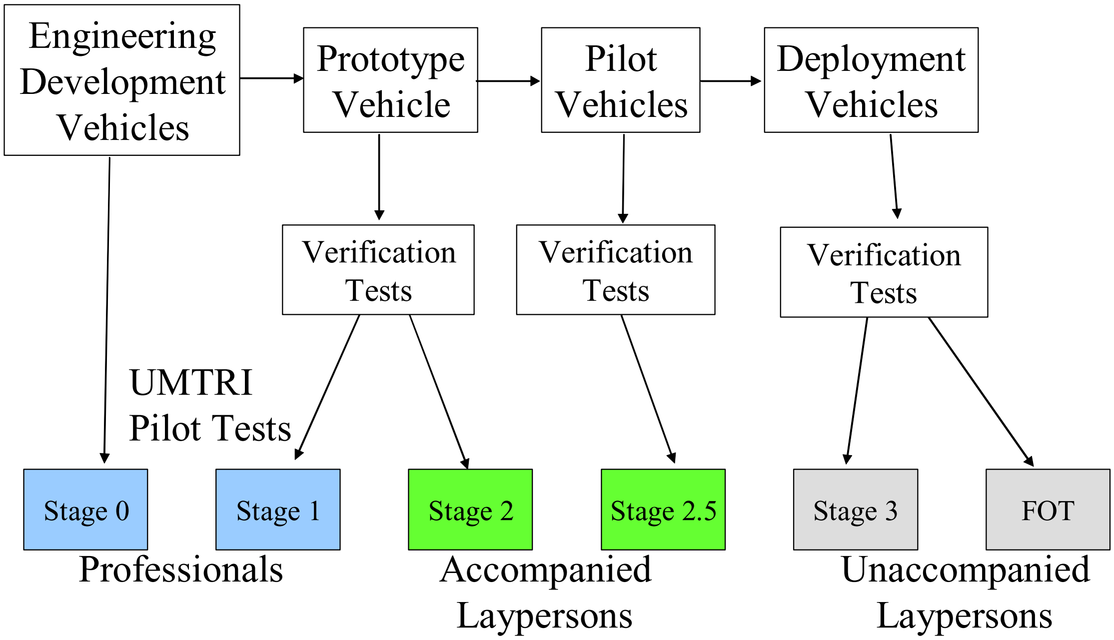

Figure 3: System Verification and Testing

A full dress rehearsal of the FOT will occur during the Stage 3 tests that will be executed in 2003. During these tests six subjects will each use the vehicles for four days. Once the Stage 3 data is analyzed, the program will proceed with execution of the FOT, which will end in December 2003. Data analysis and a final report will then be produced during 2004.

1.1 Technical Approach

During previous projects it was determined that a major limitation on the performance of ACC and FCW systems was errors in selecting which vehicles were in the path of the host vehicles, particularly when the curvature of the road was changing, such as at the transition from straight to curved or from curved to straight road segments. Therefore, much of the technical effort in the ACAS/FOT program addressed this problem. Figure 4 shows a functional breakdown of the ACAS system. At the top are four separate functions used to estimate the geometry of the road ahead of the vehicle. The conventional method is to use only a yaw rate sensor. The yaw rate, along with the vehicle speed, indicates the curvature of the road at the current location of the vehicle. However, the accuracy of this information in predicting roadway geometry breaks down when lane changes are made and at the transition between straight and curved segments of roads.

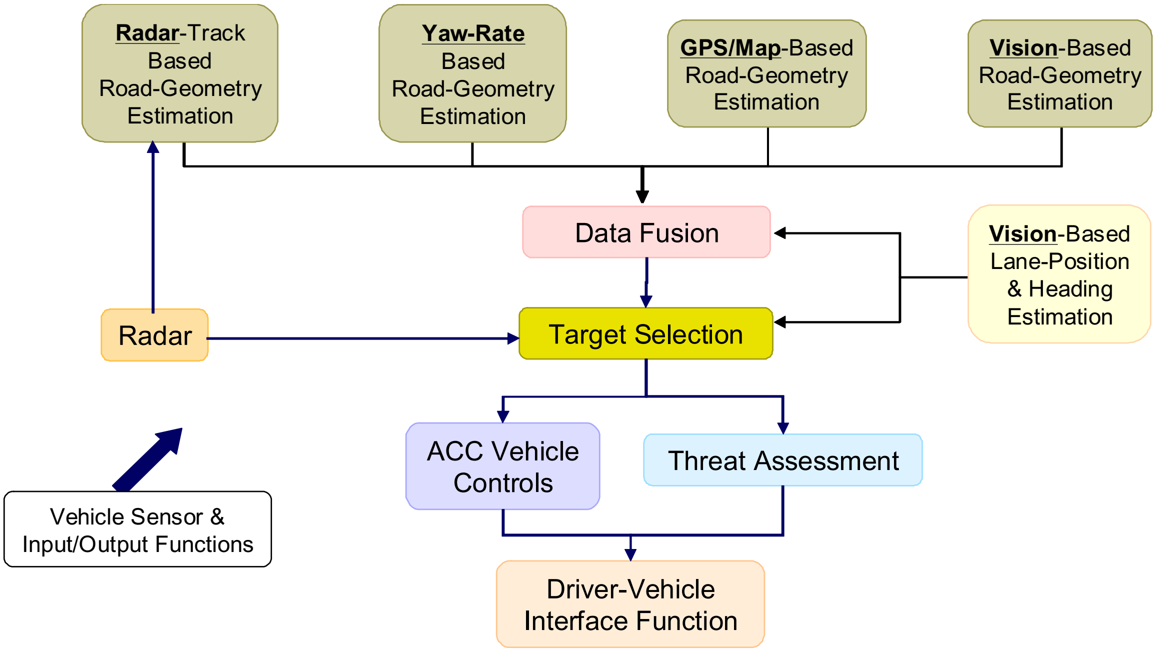

Figure 4: Functional Flow of the ACAS System

To complement the yaw-rate based road geometry estimate, the ACAS system includes other approaches that can predict changes in the curvature of the road before the vehicle reaches them. One method uses a digital map and a GPS receiver to augment the speed and yaw-rate sensors. The vehicle's position and direction of travel reported by the GPS receiver are used to determine the vehicle's position on the map. The road geometry indicated by the map is then used to predict the road geometry ahead of the vehicle.

Another approach uses video cameras placed near the rear-view mirror, looking forward through the windshield. A vision system finds the lane markings in the video images and uses them to estimate the road geometry.

The last method uses the tracks of other vehicles detected by the radar. These are analyzed to determine if there is a pattern followed by the vehicles ahead indicating the curvature of the road ahead.

Results of these road geometry estimates are combined by the Data Fusion function to produce a best estimate of the road geometry ahead of the vehicle. The road geometry estimate produced by the Data Fusion function is used by the Target Selection process to determine which objects detected by the radar are in the path of the vehicle.

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. The maximum braking authority of the ACC is 0.3g.

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1.2 Project Organization

The ACAS/FOT project is organized into six major tasks, most of which include several major subtasks. The major tasks are:

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
Task F – Program Management

The remainder of this report covers the work done under each of these major tasks in 2002.

2 SYSTEM INTEGRATION (TASK A)

The ACAS Team has been developing processes to ensure that a robust, safe vehicle is provided for the field operational test. Task A consists of the following Subtasks, which are discussed in this Section.

1. Functional Description (Task A1)
2. System Architecture/Mechanization (Task A2)
3. Interface Management (Task A3)
4. System Verification (Task A4)
5. Risk Management Plan (Task A5)

Milestones and Deliverables for Task A are summarized below. (Figure 6 at the end of Section 0 illustrates the overall schedule for Task A.

2.1 Functional Description (Task A1)

Objectives

The purpose of this Subtask was to:

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

Approach

The approach for this task is based on the work of Hatley-Pirbhai [Strategies for Real-Time System Specification, 1988, Doerst House Publishing Co.] System Requirement, Architecture and Specification models are developed using the Process Model (Data Context Diagram and Data Flow Diagram) and the Control Model (Control Context Diagram and Control Flow Diagram).

Work Accomplished and Research Findings

No recent accomplishments have resulted from this task.

Plans through June 2003

This work is complete. No changes are anticipated.

2.2 System Architecture/Mechanization (Task A2)

Objectives

Main objectives of this Subtask was 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

Approach

The total vehicle, with all its embedded systems, is considered as one super system. All ACAS functional requirements must fit and be allocated to a well-defined physical structure, interconnected by communication buses with appropriate protocols meeting safety, maintainability, and reliability requirements.

Work Accomplished and Research Findings

Figure 5 shows the physical architecture, subsystems and components of the system with connections and buses between the processors. This mechanization provides the top-level hardware required for the Pilot and Deployment Vehicles and the flow and sources of information from and for each physical box (block). This diagram has been updated from that presented for the Prototype Vehicle.

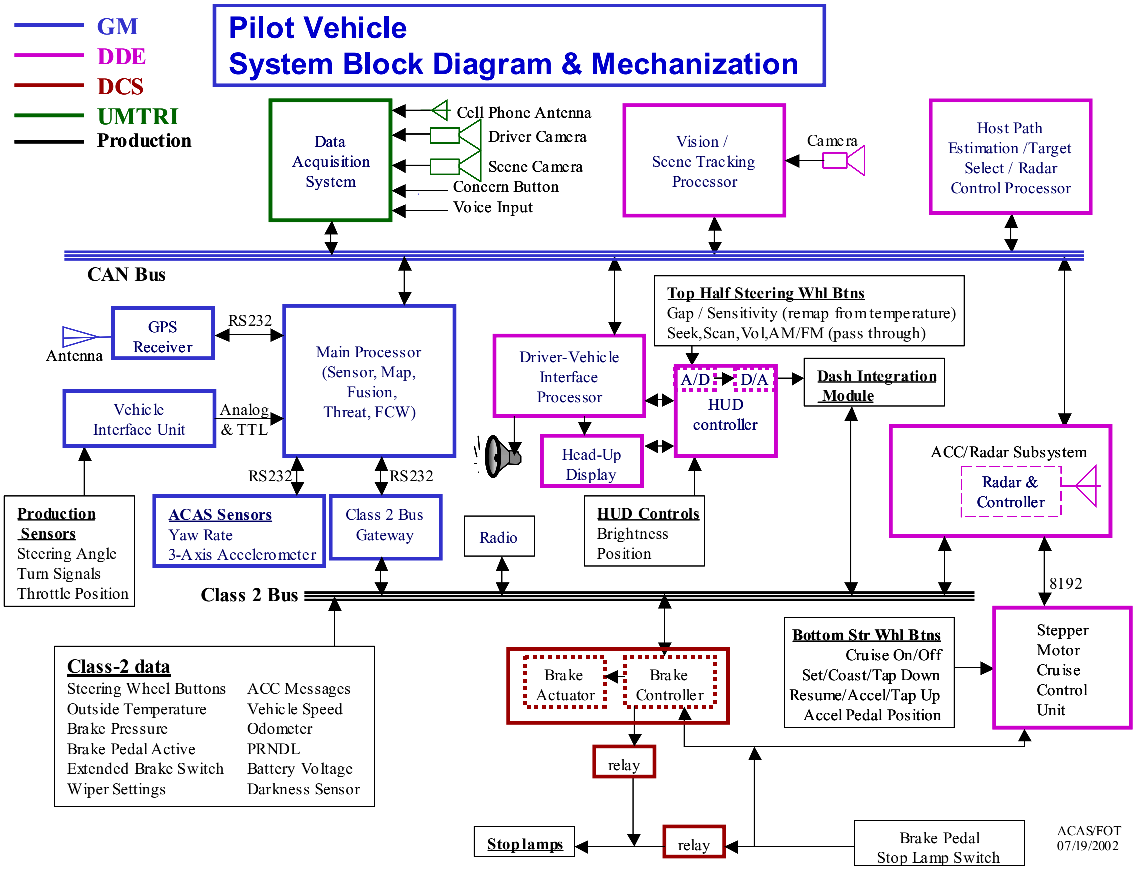


Figure 5: Pilot and Deployment Vehicle System Block Diagram & Mechanization

Plans through June 2003

This work is complete and we foresee only minor changes in the future.

2.3 Interface Management (Task A3)

Objectives

The main objective of the Interface Management Task is to ensure that subsystems or components developed independently satisfy the prescribed requirements and operate according to the specifications and in adherence with the communication protocol when connected as a system.

Approach

To ensure subsystem interface compatibility and trace ability, a systematic approach was followed. First, the interface signals between each and every hardware block in the Prototype Vehicle System Block Diagram & Mechanization diagram were labeled. For example, C1 can indicate the set of signals being communicated between the CAN bus and the Scene Tracking Processor. The individual signals between these two modules will be designated by C1_1, C1_2, etc. Then, every signal source, destination, type of harness, bit structure, and other relevant information was tabulated. This approach allows:

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

Work Accomplished

The spreadsheet of all information available on the CAN bus has been updated. The spreadsheet documents the source of the information, the CAN identifiers, byte and bit layouts, and resolution of the information. The spreadsheet also contains the original message ID of information sourced from the production Class2 communication bus and communicated on the CAN bus.

Plans through June 2003

This work is complete and we foresee only minor changes in the future.

2.4 System Verification (Task A4)

Objectives

The overall objective of the ACAS System Verification Task is to make sure the system is ready for use by lay subjects in the FOT. This requires verification that the system satisfies certain minimum performance requirements at the component, subsystem, and system level. The System Verification Task (Task A4) includes:

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

Approach

Verification occurs at several levels: component, subsystem, and system.

Component-level verification includes the operation of the ACAS-specific on-board sensors. These include sensors for vehicle kinematics, environment sensors, and driver activity sensors.

Subsystem-level verification includes testing the operation of the interfaces between the subsystems and the functionality of each subsystem. The subsystem designers are responsible for definition of the test procedures at the component and subsystem level. The subsystem designers under supervision of the systems engineers will perform execution of these tests.

System-level verification for the pilot vehicles included subjecting the vehicle to valid crash alert and nuisance alert scenarios on a test track and driving the vehicle on a prescribed route in traffic. The systems engineers defined the test procedures and executed the tests. The scenarios, shown in Table 1, were selected for system-level verification of the pilot vehicles and are a subset selected from the System Verification Plan for the Prototype Vehicle. The test number corresponds to the test number used in the System Verification Plan. Each test was passed using the criteria outlined in the System Verification Plan.

Table 1: System-level Test Scenarios

Test #	Test Name/Description	ACC Trials	FCW Trials
1	SV 60 mph to POV Stopped		5
2	SV 50 mph to POV 10 mph	5	5
5	SV 50 mph to POV Stopped on Curve	5	5
6	SV 50 mph to POV 25 mph in a Curve		5
7	SV 60 mph Cut-off by POV 40 mph	5	5
8	SV 45 mph Changes Lanes and Encounters POV Stopped		5
12	SV 50 mph on Curve to POV Braking Moderately Hard from 50 mph on Curve	5	5
15	SV 40 mph to POV Stopping from 40mph	5	5
16	SV 45 mph behind 45 mph POV Changing Lanes to Reveal Stopped POV		5
17	SV 50 mph Passing POVs 25 mph Around Curve	5	5
22	SV Daytime Public Road Test	X*	X*
23	SV Following POV on Simulated Open Road	5	
24	SV 45 mph POV 45 mph Changes Lanes in front of Accelerating SV	5	
27	SV 50 mph following POV 50 mph Changes Lanes to Reveal POV 50 mph	5	
29	SV 50 mph Throttle Override during Automatic Braking	5	
30	SV 50 mph ACC Test with Anti-lock Braking Activated	5	

* Test 22 was performed once, with FCW active throughout. During the test, the ACC function was engaged on freeways and arterial roads when traffic was light.

System-level verification for the deployment vehicles includes confirmation of the warning, set/coast, resume, automatic braking, and headway maintenance features of ACC; the timing and functionality of FCW; and the display and response of the Driver Vehicle Interface (DVI) in conjunction with ACC and FCW. In addition, each deployment vehicle is subjected to hundreds of miles of routine driving by both systems and subsystem engineers.

Work Accomplished

Pilot vehicle verification and demonstration was performed during September 2002. Summaries were prepared and delivered on the results of the pilot vehicle testing. Deployment vehicle testing is currently underway and is partially complete.

Corrections were made to the System Verification Plan to improve the test procedures and eliminate inconsistencies.

Plans Through June 2003

This task will continue to verify deployment vehicles before they are delivered for use in the FOT.

2.5 Risk Management Plan (Task A5)

Objectives

The overall objective of the Risk Management Task is to define the hazard analysis and safety risk management program to be implemented by the Team in the performance of the ACAS/FOT program.

Work Accomplished

Through December 2002 the primary focus under Subtask A5 was on:

1. Developing the Risk Management Plan
2. Implementing the Risk Management Plan

Using guidelines from Military Standard 882C and SAE J1789, the Risk Management Plan was completed and delivered to NHTSA in February 2001.

Meetings between the system and subsystems engineers have enabled plans to implement the Risk Management Plan. Currently, the process of implementing the Risk Management Plan is still underway.

Plans Through June 2003

The Safety Team's plan through June 2003 is to complete implementation of the detailed Risk Management Plan. Simultaneously, team members are reviewing the designs and testing plans for each subsystem and the systems as a whole with the responsible engineers to ensure that the Risk Management Plan is properly implemented.

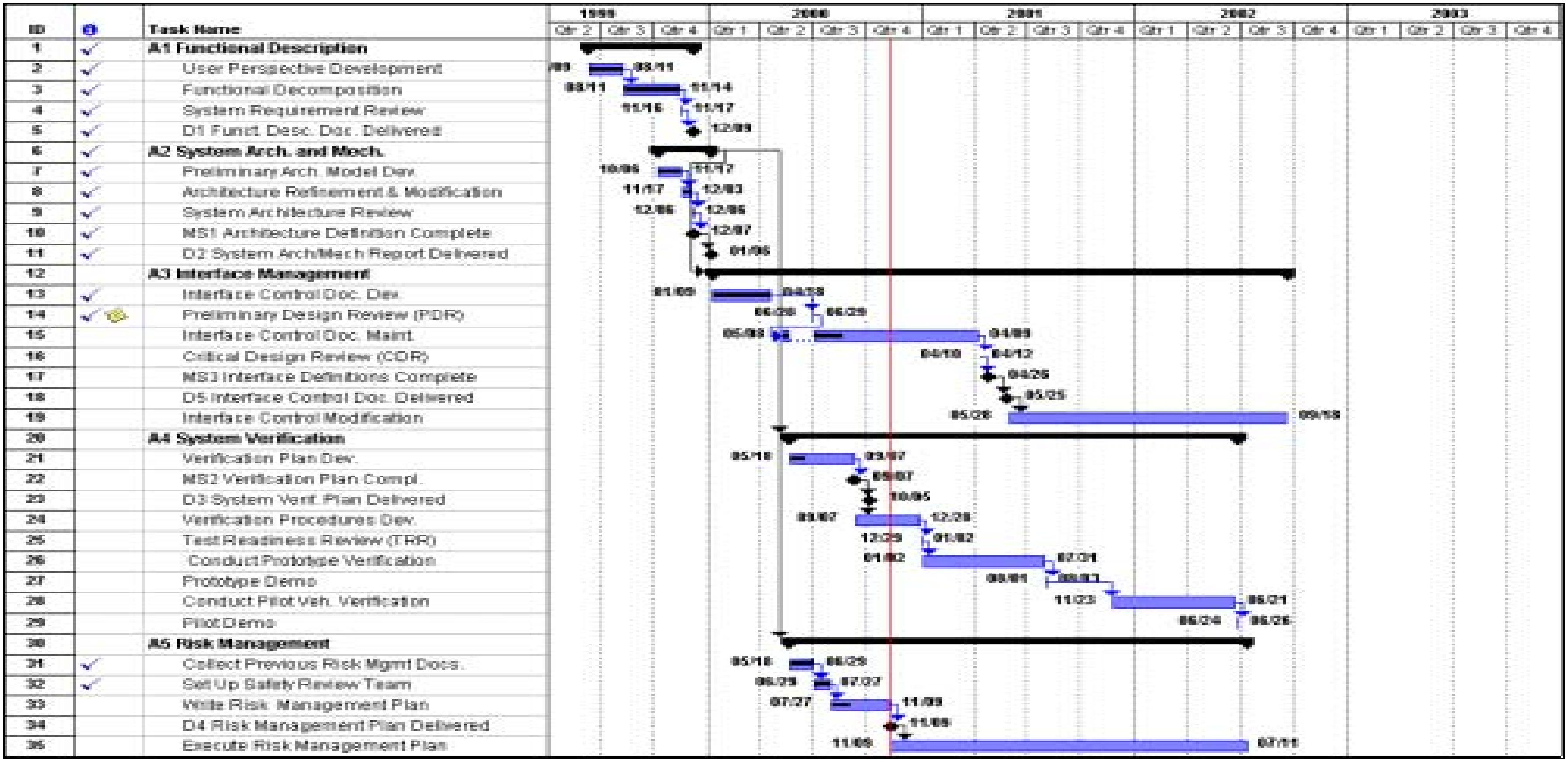


Figure 6: Task A Schedule

3 SUBSYSTEM DEVELOPMENT(TASK B)

3.1 Forward Radar (Task B1)

The Forward Looking Radar (FLR) detects and tracks objects in the forward area and outputs track data to the path and vehicle control functions to support Adaptive Cruise Control (ACC) and Forward Collision Warning (FCW). The FLR is a narrow beam, mechanically scanned, frequency modulated continuous wave (FMCW) radar operating at a frequency of 76.5 GHz (midband). The radar consists of a single transmit/receive antenna, scan motor, transceiver assembly and Radar Data Processor (RDP).

The Forward Radar Task is divided into four subtasks; Integrated Transceiver/Antenna (Task B1A), Auto Alignment Algorithm Development (Task B1B), Radome Blockage Algorithm Development (Task B1C) and Bridge Rejection Algorithm Development (Task B1D).

3.1.1 Integrated Transceiver/Antenna (Task B1A)

Objectives

The objective of the Integrated Transceiver/Antenna task was to develop a MMIC based transceiver with integrated antenna needed to meet ultimate cost and producibility requirements for an automotive forward radar. Prior technology available for a wide field of view Forward Looking Radar included mechanically scanned designs in which the transceiver and antenna were mounted on a common base plate and the entire assembly was then scanned. Environmental and life testing has shown that there are two reliability concerns with this approach. One is that the thermal path for transceiver heat dissipation is very high resulting in a large temperature rise between the transceiver case and the sensor internal ambient temperature. Another is that scanning the transceiver requires a moving flexible electrical connection for both bias and signal wires. Analysis and test have shown these factors to be the most significant contributors to sensor reliability.

The goal of this task was development of an integrated transceiver-antenna assembly to maximize performance and reliability in the FCW application with the necessary small size, low cost and producibility to introduce an FCW sensor to the marketplace. Specific antenna design goals include 1.7 deg azimuth beam width and 15 deg field of view. To meet long term cost and producibility goals, development of a MMIC transciever was deemed essential.

Short Summary of Accomplishments Prior to January 2002

As of December 2001, the MMIC based transceiver had been designed. A mechanically scanned folded reflector antenna has been developed. The antenna consists of a stationary reflector, a rotatable reflector, and a transmission grating polarizer. The scanning element (i.e., the rotatable reflector) is a small very lightweight mechanical piece. The transceiver is hard mounted to the sensor case, providing a much-improved thermal path and eliminating the moving electrical harness connection. An additional benefit is that the scanning motor torque requirements are significantly reduced, allowing for a smaller, quieter, more robust motor design that requires less drive current. This further reduces the sensor thermal dissipation, and provides more design margin for cold temperature operation on start-up and high temperature performance during vehicle operation.

The design incorporates large sections of the ACAS Program's Gunn-based transceiver in MMIC components. The sensor housing and electronics were modified to accommodate the new transceiver-antenna assembly and control electronics. The mechanically scanned, folded reflector, narrow beam antenna design was complete. Antenna performance objectives were met and the design was shown to be robust and capable of meeting environmental requirements. However, the mechanical component costs are still higher than would be required for production systems, because they are purchased as machined parts.

A high performance MMIC chipset has been designed and fabricated by Infineon technologies. The first wafers were completed in May 2000 with over-all good results. A second iteration was designed to improve the VCO temperature performance and doubler input VSWR. On-wafer measurements were encouraging. Unfortunately, all wafers were lost due to a processing error in the Au/Sn bumping operation.

Design and testing of all MMIC transceiver functional blocks was completed. The loss of the second generation wafers necessitated the use of the initial chipset in the first MMIC based transceiver. This transceiver was assembled and tested with millimeter-wave performance equivalent to Gunn based systems

A new set of wafers to replace those lost due to processing error were fabricated using Infineon's new 6 inch GaAs production line. On-wafer test results were excellent.

Work Accomplished in 2002

A MMIC transceiver using the first generation chipset has been integrated and tested (as discussed in Section 2.2). This transceiver has limited operating temperature range. In December 2001, it was reported that the second-generation (full temperature) MMIC chips were to be shipped in January 2002. That shipment did not happen due to continued problems associated with the bump, scribe, and break process that resulted in loss of the first three wafers processed. The problem was resolved in the February timeframe and shipment occurred in late April. Additionally, due to business decisions made by Delphi regarding the H E Microwave LLC, the chip to substrate process and the substrate to bulkhead mounting needed to be out-sourced. These delays put delivery of the field test radars at great risk.

Based on the unfortunate and unexpected delays associated with process development, the overall deployment schedule was in serious jeopardy if MMIC transceivers were to be implemented. If all outside supplier process development was successful and if no design turns were required on the microwave substrate, the first MMIC radar would have been available in September 2002.

In the best interest of the program, it was decided that the deployment radar would use a Gunn based radar.

The majority of the MMIC objectives were achieved. Design and testing of all MMIC transceiver functional blocks has been completed. Chip level performance of the second-generation chipset has been measured and meets all systems requirements. Operation at elevated automotive temperatures of 105 degrees C has been demonstrated. The chips have now been successfully solder bumped. The wide band phase lock loop necessary to meet system noise performance has been verified. The chips themselves are available to the general industry for use in future systems. The only aspect of the program not achieved was deployment of the MMICs in the field test hardware.

Gunn based transceivers taken from the production line at HE Microwave were delivered for the deployment sensors. These transceivers met all FOT program requirements.

3.1.2 Auto Alignment Algorithm Development (Task B1B)

Objectives

The purpose of Auto Alignment Algorithm Development was to develop a radar-based algorithm to automatically compensate for misalignment of the radar bore sight with the vehicle direction of travel. Automatic alignment is desired to reduce factory and dealer installation costs and to ensure proper system performance during vehicle operation.

For acceptable system performance, the antenna bore sight must be accurately aligned to the vehicle direction of travel. Precise mechanical alignment is time consuming and expensive to implement in an automotive manufacturing environment and could change during vehicle operation due to, for example, misalignment of the vehicle suspension. Furthermore, precise alignment may not be practical at dealerships expected to perform service replacement of radar sensors.

The objective was to develop an automatic alignment algorithm in the radar software to continuously estimate the misalignment of the radar bore sight relative to the vehicle direction of travel and to correct the radar angle data to compensate for the estimated misalignment. Based on error budget analyses and road testing, an auto alignment accuracy goal of +/- 0.25 deg was established. Furthermore, the algorithm was to be sufficiently responsive to perform initial radar alignment in about 10 to 15 minutes (e.g., after service replacement of the radar sensor) and, thereafter, to track slow changes in alignment during vehicle operation. Note, the radar design also incorporates an electronic alignment function by which the initial (or subsequent) alignment can be quickly performed given an alignment station with corner reflector placed on the vehicle centerline.

Approach

The auto alignment algorithm developed is a Delphi patented technique whereby the radar software processes detected targets of opportunity to estimate the misalignment angle. As shown in Figure 7 below, the trajectory of a target in radar x', y' coordinates is linear assuming non-zero range rate and constant lateral offset (d). Furthermore, the angle of the trajectory relative to the y' axis corresponds to the misalignment angle of the radar bore sight relative to the vehicle direction of travel.

In essence, the auto alignment algorithm performs a least squares fit to the target trajectory to solve for the misalignment angle. The implementation is limited to stopped objects since these objects cannot change their lateral offset. Host vehicle speed and yaw rate are used to compensate for lateral movement of the host vehicle. In effect, this compensation corrects for host vehicle motion on curves and during lane changes or lane wander to "linearize" the target trajectory. Otherwise, the auto alignment process would be limited to straight road sections and constant lane position for the host vehicle and would incur additional error for small deviations from these assumptions.

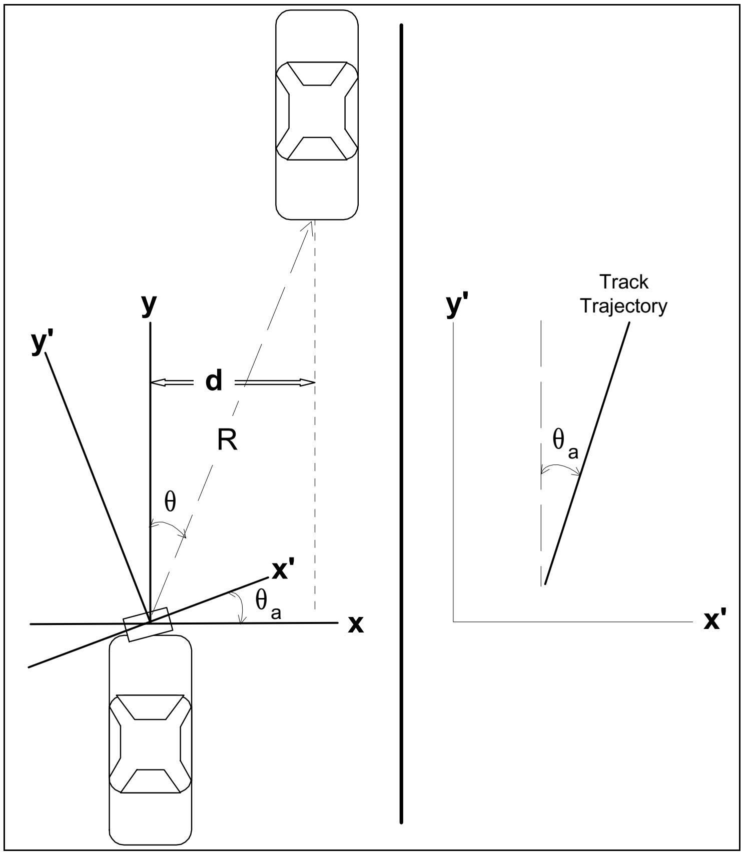


Figure 7 Auto Alignment Geometry

Short Summary of Accomplishments Prior to January 2002

The auto alignment algorithm was evaluated via extensive road testing in a variety of city, secondary road and freeway environments. To test convergence time, a series of tests were performed in which the radar sensor was intentionally misaligned by a known amount and was then operated in a variety of roadway environments. Many hours of road testing were also performed to establish the steady state performance of the algorithm. Furthermore, the algorithm has been implemented in a production ACC system for more than one year.

The time required for initial convergence of the smoothed auto alignment estimate varied as a function of the roadway environment as expected. Adequate convergence time and transition to steady state was obtained by adjusting the algorithm to simply require 100 data points (valid stopped object tracks) for initial convergence. Under favorable conditions (i.e., favorable measurement errors) more rapid convergence could be obtained if desired by reverting to the adaptive scheme.

Work Accomplished in 2002

Automatic alignment development was completed prior to 2002.

3.1.3 Radome Blockage Algorithm Development (Task B1C)

Objectives

Radar signals can be severely attenuated or blocked by build-up of a wet layer, for example slush or mud, on the radome or secondary surface. The goal of Radome Blockage Algorithm Development was to develop a radar based algorithm to automatically detect blockage conditions which severely impair system operation. With automatic blockage detection, the system controller can disable the system and instruct the driver to remove the blockage layer.

The primary objective was to develop a technique within the Forward Radar Design to automatically detect (within 20 sec) blockage conditions that completely blind the radar. A secondary objective was to detect blockage, which degrades detection sensitivity by 12 dB or more (i.e., detection range reduced by 50%). The latency goal for detection of partial blockage was 120 sec.

Approach

Four techniques were developed to detect blockage conditions. The first technique is based on processing CW radar ground clutter data. The second and third techniques are based on processing normal FMCW radar track data and the fourth technique is based on a modified radar design using a special wideband waveform and processing to directly detect the presence of a blocking layer.

The radar blockage algorithm developed integrates the first three techniques into a single composite algorithm. Blockage is declared if any of the three components detect blockage. Blockage is cleared if none of the three components detect blockage. As a whole, the integrated components detect different levels of blockage under various conditions with rapid to medium response time.

Short summary of accomplishments prior to January 2002

To develop and tune the blockage detection algorithm, test data was collected over a variety of roadway and traffic conditions including surface street, freeway and test track environments as summarized in Table 2. Data collected was analyzed to establish the distribution in ground clutter and track amplitudes needed to develop and tune these components of the algorithm.

Table 2 Data Collection and Evaluation Test Conditions for Blockage Detection

Algorithm Development	Surface street roadside clutter Surface street paved median clutter Freeway roadside clutter Freeway cement barrier median clutter Asphalt and concrete road surfaces Surface street traffic conditions Freeway traffic conditions Controlled test track targets
Performance Evaluation	Blockage conditions of opportunity (snowstorms) Controlled blockage layers Metal plate Wet paper towels in plastic bag Clear and rainy conditions (test false alarm rate)

Work Accomplished in 2002

Blockage algorithm development was nearly completed by the last interim report. Additional road testing was performed to evaluate the false alarm rate under a variety of conditions. This testing revealed that blockage could be falsely detected by the track amplitude component if following an isolated motorcycle for a period of time without any other moving objects present. This issue can be mitigated by either raising the blockage detection threshold, inhibiting update of the normalized track amplitude for scans with only a single track or screening out motorcycles based on estimated target width. The first approach will degrade the blockage detection level of the track amplitude component while the latter two approaches will increase the latency time. The approach selected was to screen out motorcycles based on a target width threshold.

The track drop component can falsely set blockage while following a vehicle over a series of crests of sharp hills. This issue can be mitigated by either increasing the number of track drops required or reducing the maximum range criteria. The approach selected was to reduce the maximum range criteria from 60 m to 50 m.

In summary, development of the blockage detection algorithm has been completed. Final acceptance testing and calibration adjustment (if needed) remains.

3.1.4 Bridge Rejection Algorithm Development (Task B1D)

Objectives

To support FCW, the Forward Looking Radar is required to detect stationary as well as moving objects. Bridges and overhead signs are stationary objects that are often detectable by the radar and must be discriminated from valid in-path objects. The objective of Bridge Rejection Algorithm Development was to develop a radar-based algorithm to classify stopped objects as either overhead (bridges) or valid in-path objects. The ultimate objective was to provide stopped object capability to 100 m range without excessive false alarms on overhead objects.

Approach

Given that overhead stopped objects will be detected along with valid in-path stopped objects, the objective was then to develop an algorithm to classify all detected stopped objects as either overhead or valid roadway stopped objects. The fundamental discriminant between overhead stopped objects and valid in-path stopped objects is of course height above the roadway. That is, bridges and other overhead objects can be correctly classified by directly or indirectly measuring target height.

Short summary of accomplishments prior to January 2002

The "bridge rejection" algorithm developed consists of a combination of geometric rejection and classification as summarized in Table 3.

Table 3: Components of Bridge Rejection and Stopped Object Classification

Algorithm Component	Rationale
Geometric Rejection (GR)	Narrow elevation beam rejects most overhead objects.
Amplitude Slope (AS)	Amplitude of roadway stopped objects increases as range decreases. Amplitude of overhead object decreases as range decreases (begins to exit the radar beam).
Short and Long Term Persistence (SLP)	Detection probability (track persistence) typically high for roadway stopped objects and often lower for overhead objects (due to radar beam and multipath effects).
Pass Through (PT)	A stopped object must be overhead if a moving object appears to "pass through" the stopped object.
Fail Safe (FS)	Elevation beam should reject all overhead objects at R<Rmin, therefore, must be a roadway object if R<Rmin.

Geometric rejection (GR) refers to the fact that many, but not all, overhead objects are rejected by the narrow elevation beam of the Forward Looking Radar. For detected stopped objects, amplitude slope (AS) is the primary classification parameter and is implemented with clear choice and non-clear choice thresholds. Amplitude slope exploits the fact that as range decreases, the amplitude of overhead objects will follow a decreasing trend as the object begins to exit the elevation beam. This trend is reliable on a long term basis but is subject to variation due to several factors, including multipath, on a short term basis. To develop the amplitude slope trend, a fading memory recursive least squares filter is used.

In the non-clear choice regions, classification is then based on short and long term persistence (SLP) thresholds. These persistence parameters evaluate the detection probability (number of detections divided by the number of scans) for the last several scans and over the long-term beginning at a specified range. Lower persistence is expected for overhead objects due to multipath and elevation beam effects while valid in-path stopped objects should have high persistence.

The pass through (PT) discriminant looks for moving tracks that appear to “pass through” the stopped object. If so, the stopped object must be overhead. Additional criteria are imposed to satisfy pass-through, for example the moving vehicle must not be decelerating at a high rate since this could indicate an evasive manuever to avoid a valid stopped object. If successful, pass through overrides AS and SLP.

The fail-safe (FS) logic states that if a stopped object is still in track within the minimum range possible for overhead objects (based on the radar elevation beam width), the stopped object must be valid. Fail-safe overrides all other classification results.

Work Accomplished in 2002

Development of the bridge rejection algorithm progressed to determine if the false detection rate could be further reduced with minimal impact on correct classification of valid in-path stopped objects. A bridge clustering component was added to the classification algorithm as well as a minimum detection range constraint. The clustering logic looked for a cluster of tracks with range and lateral spacing indicative of a bridge. The minimum detection range constraint recognized that many bridges are not detected until about 100 m range or less while most stopped objects are detected well beyond 100 m.

Performance of the modified algorithm was evaluated on a test track with a Chevy Suburban and Buick LeSabre as test targets and was also evaluated at the GM Technical Center with numerous parked vehicles of opportunity. It was concluded that the modified algorithm degraded the probability of correct classification by an unacceptable amount. For example, the probability of correct classification at 80 meters dropped below 50% and many vehicles were not “classified” as non-bridge until the “fail-safe” range of 60 m.

Further testing was performed with various calibration adjustments to improve classification of valid in-path stopped objects. Acceptable performance was not obtained until the new algorithm components were effectively disabled, essentially restoring the prior performance.

Track testing with a Buick LeSabre target showed the probability of correct classification to be near unity at 80 m. For an ensemble of stopped vehicles, performance will be similar to that indicated in Figure 5.2-5, that is, probability of correct classification of about 80% at 80 m. To confirm bridge rejection performance, drive testing was performed over the 200-mile public test route which includes about 200 bridges and additional overhead signs. Over this route, only two false warnings were obtained on overhead objects (1 bridge and 1 sign).

In conclusion, the bridge rejection algorithm provides acceptable performance for a first generation driver alert and for the FOT program.

Research Findings from 2002

Another suggested discriminant to classify bridges involves the width of detected stopped objects. That is, bridges are physically wide and vehicles are physically narrow. This approach was not pursued at this time due to several issues. For example, multiple lanes of side by side stopped vehicles present a wide target and would likely be misclassified as a bridge. Conversely, overhead signs are similar in width to vehicles and would likely be misclassified as valid roadway stopped objects. Furthermore, data analysis on bridges indicates that, at the detection threshold level, many bridges appear as a strong localized reflection source in the lateral dimension located near the center of the bridge. Radar imaging would be required to observe the lower level reflections beyond the center region and is beyond the scope of the Forward Looking Radar design at this time and in the near future.

3.2 Forward Vision Sensor (Task B2)

Objectives

The goal of the Forward Vision Sensor Task is to develop a robust, real-time, forward-looking lane tracking system to enhance the Path Estimation and Target Selection algorithms (Task C2). The system should detect and track the position of the lane boundaries providing a model of the changing road geometry as well as estimates of lane width and of the host's heading and lateral position in the lane. In the Data Fusion Module (Task C1) this information is fused with road and host state data from other sources, such as Scene Tracking and GPS Map, to provide more accurate estimates of road and host state to the Target Selection Module.

Approach

The Forward Vision Sensor consists of a forward-looking video camera mounted to the windshield behind the rear view mirror, and an image-processing unit located in the trunk of the vehicle. Images of the roadway ahead of the host are processed in order to determine the host position and orientation in the lane, and to provide an estimate of the shape of the road ahead.

The Lane Tracking Algorithm consists of three main parts. First, a low-level feature extraction process using basic image processing techniques is used to identify candidate lane markers in an image. Second, a mid-level process, consisting of outlier rejection, curve fitting, and state estimation techniques, operates on the extracted features in order to detect and track the lane boundaries. Third, a high-level process applies logic to handle special situations, such as lane changes, bifurcation/merging, and missing markers; and to determine regions of interest, produce confidence/quality metrics, and perform resets.

The perspective transform from the image coordinate frame (in which lane markers are observed) to a vehicle centered coordinate frame (in which radar targets are described) is highly non-linear with range, and significantly affected by changes in vehicle pitch. Therefore, special attention is directed at determining and monitoring the position and orientation of the camera relative to the vehicle as well as the road.

Short summary of accomplishments prior to January 2002

Over the years, a number of organizations have developed lane-tracking systems for use in lane departure warning and lane-keeping applications. At the outset of this program, the functionality of such systems was evaluated, and requirements were drafted for a lane tracking system that would meet the needs of a collision warning application. During Phase I, three groups (from the University of Michigan, the University of Pennsylvania, and the Ohio State University) were tasked to extend the range of their existing short-range lane tracking systems in order to meet these new requirements. These three University efforts allowed exploration of, and experimentation with, a variety of different feature extraction and marker/boundary detection and tracking techniques. A vision Engineering Development Vehicle (EDV) was outfitted with a special video data acquisition system that allowed the University algorithms to be designed and iterated in a hardware-in-the-loop development environment.

In order to measure the performance of the lane tracking algorithms, a significant effort was applied to developing methods of determining ground truth. Three approaches involving post-processed yaw rate, post-processed high resolution GPS, and results of a short-range lane tracking system were used to determine the amount of curve entry preview, and the quality of the road and host state information reported by the lane trackers.

The Lane-Tracking algorithms were evaluated on video sequences of typical roadway conditions, including curve entries and exits, lane changes, and distracting roadway features. Analysis of the results of these tests, summarized in the "Lane Tracking System Down-Select Summary Report," showed that, although all of the systems tracked near to mid-range lane boundaries fairly well, none of them could *reliably predict* curve entry. Further effort would be required to improve the long-range performance adequately to add value to the overall performance of the collision warning system.

While efforts continued to achieve better long-range performance, a system providing good host heading and lateral lane position was installed in the Prototype vehicle and used as a basis for continued development and algorithm iteration during Phase II.

Milestones and Deliverables January through December 2002

Vision/Scene Tracking processor hardware, camera assemblies, and necessary cables were delivered for the 13 Pilot and Deployment Vehicles. This hardware has been installed and tested in all vehicles completed thus far. Calibration of the system is being performed as each vehicle build is completed.

Work Accomplished in 2002

Lane Tracking Algorithm Improvements

The performance and robustness of the lane tracker was improved through modifications of the low-, mid-, and high-level algorithms. Improved feature extraction techniques have resulted in a wide adaptability to variations in marker width and an increased range of operation, while being more computationally efficient. Improved curve fitting, with smart constraints, provides smoother and more consistent measurements, better tracking ability, and an increased immunity to disturbances caused by exit and turn lanes.

Algorithm performance improvement was demonstrated on a library of video data collected with the Pilot vehicles and the Vision EDV. The current system provides accurate estimates of host lateral lane position and lane width, when two markers are present. It provides a good indication of host heading in the lane, and estimates of road curvature that are de-coupled from lane changes and wandering in a lane.

Camera Exposure Control

An exposure control algorithm was implemented to allow system operation over a wider range of lighting conditions. The new algorithm evaluates the gray-level distribution of pixels in a region of interest, and selects an exposure time to optimize this distribution, while maintaining a reasonable latency in adapting to illumination changes. The resulting images exhibit better exposure in the lane tracker's region of interest than had been achieved with cameras that determine the exposure based on the entire image or based on fixed regions. Due to the limitations of the CCD technology employed in the camera, the envelope of operation for the camera system still does not encompass the complete driving environment. Extreme illumination conditions, such as driving into the sun, glints from vehicles and other objects, and glare or low backscatter from wet roads create conditions where the system cannot perform. Under these circumstances, the system is designed to indicate low confidence to the Fusion subsystem.

Hardware Selection and Integration
Available hardware options were re-evaluated with a focus on improving the ability to produce and rely upon the Deployment systems. The selected system, a Matrox 4Sight-II, has an integrated frame grabber with support for camera exposure control, and is being used off-the-shelf, with only the addition of a CAN card. The Hitachi KP-F3 camera was selected for its support of external exposure control. Its progressive scan operation has resulted in crisper images, without the effects of interlacing. The new hardware and algorithms were integrated with an Embedded NT Operating System providing turnkey operation. Remote connection via Ethernet was added to support administration and diagnostic tests from a laptop.

Autocalibration
An automatic camera calibration algorithm was implemented to determine the initial camera alignment parameters and to monitor and report any subsequent alignment errors over time. This algorithm is also used to simplify the vision system installation in the Deployment Vehicles.

Merged Vision and Scene Tracking Systems
The Scene Tracking algorithm was re-hosted in the Vision processor, reducing the hardware footprint and integration complexity in the Deployment systems.

Camera Assemblies
A mount and cover assembly was designed to house both the Lane Tracker and UMTRI forward Scene Cameras. A removable shroud protects the cameras from dashboard reflections and accidental misalignment, but allows maintenance as necessary. Each camera can be adjusted independently. The entire assembly fits behind the rear-view mirror and is installed as a single unit into each vehicle.

Research Findings from 2002

During the course of this contract, the following observations were made:

- Speed and yaw rate alone result in accurate path estimates on straight and constant-curvature roads. These conditions occur the vast majority of the time with most drivers. The small, difficult remainder of driving time includes curve entries and exits, non-constant-radius curves, and vehicle maneuvers (such as lane changes). These are typically transient, very short-lived events.

- Long-range curvature estimates from lane tracking have not proven reliable enough to significantly improve path estimation and threat assessment performance for the difficult remainder. Those same scenarios are also the most difficult for lane tracking, sometimes resulting in curvature estimates with significant errors. Limited camera resolution and field of view, vertical road curvature, vehicle pitching, and high variability and poor contrast in the scene also conspire to degrade performance when it’s needed most.

- The vision system used in this program is very reliable at detecting lane changes and tracking host state during vehicle maneuvers. The system output is weighted heavily during these scenarios, noticeably reducing false alarms on roadside objects and adjacent lane vehicles. The current implementation provides reliable tracking of straight roads out to 45 meters under most conditions.

- The contribution of the vision system has been limited by its reliance on lane markers alone. The role of vision in FCW systems would be significantly enhanced by fusing, early in the process, vision and radar outputs. Working with both target and lane boundary information in the image coordinate frame should result in more accurate road model. Additionally, using the vision system to classify the radar targets would result in reliable rejection of non-threatening objects that currently trigger false alarms.

Plans for Next Six Months (through June 2003)

Installation and calibration of the Deployment vision systems will be completed in early 2003. A triage plan will be drafted detailing procedures for diagnostics and support of the Deployment systems. Data analysis of system output will be performed during the FOT as required.

3.3 Brake Control System (Task B3)

3.3.1 Brake System Verification (Task B3A)

Objectives

The key objective of this task was to replace the Original Equipment Manufacturer (OEM) brake system with Delphi's DBC 7.2 Brake System, which offers comparable functionality plus the "auto braking" feature.

Approach

DBC 7.2 production intent software executing Class II communications protocol was chosen to best meet the vehicle architecture requirements. The base software package was modified to fit the architecture of the chosen vehicle. A 2000 Buick LeSabre was used as a mule vehicle to accommodate all development and verification activities. All algorithm, calibration, and hardware changes were implemented and verified using the mule vehicle.

The development of brake controls to meet both the vehicle requirements and the ACAS/FOT program requirements are being accomplished through common best engineering practices at Delphi. The safety analysis and vehicle level verification of the brake system ensures production-level confidence in the brake system. Following system development, verification of the DBC 7.2 system was conducted per industry and federally regulated standards. The brake system is classified as a safety-critical system and thus treated accordingly.

Accomplishments prior to January 2002

The deployment of a production, road-worthy brake system with "auto braking" was dependent upon the success of the development activities conducted on the mule vehicle. Hardware modifications and brake controls development of all features were pivotal achievements for 2001. Another pivotal accomplishment for 2001 was the work done on the interface between the Radar and brake systems to offer a functional ACC system. This cooperation resulted in the completion of a fully functional ACAS prototype vehicle.

Milestones and Deliverables January thru December 2002

- January 2002 – Brake System Failure Modes Effects Analysis (FMEA) completed
- March 2002 – Winter verification completed: ABS/TCS/VSE and ACC
- May 2002 – Mild weather verification completed: ABS/TCS/VSE and ACC
- June 2002 – Program Review # 6
- December 2002 - All deployment vehicles updated with DBC 7.2 Brake System

Work Accomplished in 2002

The development work of 2001 resulted in algorithm development and software changes that required calibration and verification in 2002. Verification allowed the release of a new software package incorporating those changes. A design change to the brake lamp circuit was also implemented - this circuit is used to illuminate the brake lamps during "auto braking." A Failure Modes Effects Analysis (FMEA) was completed on the new software package. The verified software package was used to fine-tune vehicle level brake control algorithms and complete winter and mild weather vehicle level verification.

Research Findings from 2002

During "auto braking" events that cause vehicle speeds to drop below 25 mph, some level of noise and vibration was experienced. The source of the noise and vibration was identified, and improvements are underway to reduce the low-speed noise and vibration issue.

Other development activities are in process to incorporate some adaptive control techniques into the ACC algorithm to compensate for brake hardware and temperature variation.

Plans for the Next Six Months (through June 2003)

Enhancements to address the low-speed noise and vibration issue have been developed. The adaptive control scheme has also been developed. Verification of these two changes is scheduled for completion in February 2003. Other commitments include support of winter testing of the integrated ACAS system and support of the deployment fleet.

3.3.2 Vehicle Builds (Task B3B)

Objectives

Remove OEM Brake System and install Delphi DBC 7.2 Brake System in a manner such that the replacement is transparent to the end-user.

Approach

The underlying goal for the brake system replacement is to install a system that is transparent to the end user aside from the additional ACC auto braking feature. With this goal in mind, all hardware changes, wiring, etc. should resemble production line assembly.

Work Accomplished

Replacement of the brake system requires:

1. Removal of the production ABS Hydraulic Modulator Assembly
2. Installation of DBC 7.2 Hydraulic Modulator and Electronic Control Unit
3. Fabrication and installation of a harness to convert the OEM connector to a DBC 7.2 vehicle harness connector
4. Power bleed of the hydraulic unit along with a base brake bleed
5. Installation of Brake Lamp Relay circuitry

To date, the brake system of 15 vehicles have been replaced with the DBC 7.2 Brake System. The 15 vehicles updated include: Prototype Vehicle, Engineering Development Vehicle for Integration System, two Pilot Vehicles, and 11 Deployment Vehicles. All vehicles were road-tested for functionality of all brake control systems including open-loop "auto braking."

3.4 Throttle Control System (Task B4)

Objectives

To provide a throttle control system that can be controlled by the radar subsystem to maintain vehicle speed.

Approach

The approach was to take the existing stepper motor cruise control (SMCC) and modify the internal microprocessor to accept a set speed from an external source. This required defining and adding this interface between the SMCC and the ACCA radar.

The modification of the vehicle was to replace one signal from the existing SMCC harness and then replace the internal printed circuit board with the new boards.

Work Accomplished

We have provided all the controllers and spares to GM. There have been no problems reported with the throttle control subsystem.

3.5 Driver-Vehicle Interface (Task B5)

3.5.1 Warning Cue Suite Selection (Task B5A)

Task B5A (Warning Cue Suite Selection) was completed during the 2001 calendar year. Since this effort is summarized in the Warning Cue Implementation Summary Report deliverable (DOT HS 809 462), this report will focus on the activities of Task B5B (Driver-Vehicle-Interface Development).

3.5.2 Driver-Vehicle-Interface Development (Task B5B)

Objectives

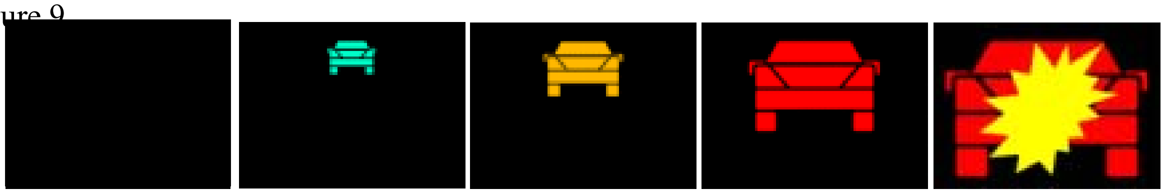
The primary objective of the Driver-Vehicle Interface Task is to develop an interface that will convey information from the ACC and FCW systems to the vehicle operator in an unambiguous fashion and allow the driver to control these systems intuitively, while maintaining an interface that is highly acceptable to the driver. For the FCW system, warning cues and presentation methodology must be selected and developed so as to direct the driver's attention immediately to the primary task of evaluating and reacting to the critical rear-end crash event, while allowing sufficient time to perform some corrective vehicle control action to either avoid the event or, at a minimum, to mitigate the crash energy. For the ACC system, sufficient information must be presented so that the driver is constantly aware of the current status of the system (e.g., cruise control set speed, selected inter-vehicle separation distance, and whether or not a preceding vehicle has been detected by the system).

Approach

Given that the design of the ACAS/FOT Driver Vehicle Interface (DVI) was selected before the 2002 calendar year, the approach to optimizing this interface in 2002 was to collect usability information from members of the ACAS/FOT program team who had extensive experience with the DVI, and use this information to reveal any unanticipated consequences of the design, and optimize the DVI based on this user feedback. During the process of verification and testing of the emerging fleet, members of the ACAS/FOT program team have spent countless hours driving ACAS vehicles.

Summary of Prior Accomplishments

Through human factors experimentation at Delphi Delco, a three-stage display sequence (referred to as the "Looming display") was selected for the FCW (see Figure 8). The sequence from left to right of Figure 8 transitions through the following threat levels: (a) no vehicle detected, (b) vehicle detected, (c) caution, (d) warning, and e) imminent threat. The imminent icon (far right) flashes at 4 Hz and is accompanied by an audio tone. Both the imminent and tone were supplied by the General Motors Safety Center. The configuration of the HUD that was selected is displayed in Figure 9.



(a) **(b)** **(c)** **(d)** **(e)**

Figure 8: Looming display

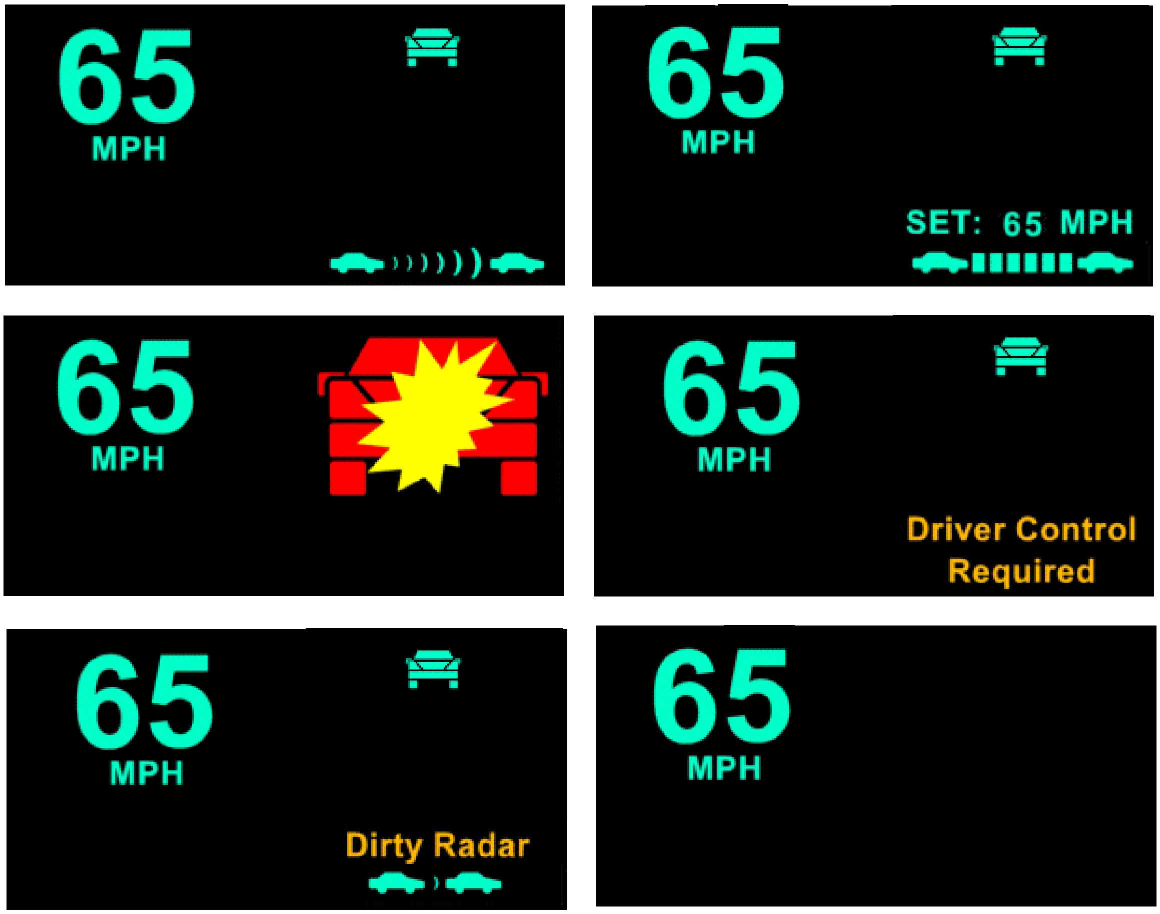


Figure 9: DVI HUD Configuration

At the top left of Figure 9, the HUD configuration for FCW is displayed. This is 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 ACC is disengaged or off. When ACC is engaged, the display would change to the top right panel. The set speed appears above 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 represents 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 3000-Hz tones, that 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 alert timing (sensitivity setting) (setting 1). Drivers could select a single-stage display by activating this setting. The lower right panel displays what drivers see when both ACC and FCW system are disengaged (e.g., when the vehicle is below 25 mph).

Messages that could appear on the message text line were:

- "Dirty Radar" (the radome is obstructed, reducing the reliability of the ACC and FCW systems, and needs to be cleaned) "
- "Heavy Rain" (the high level of rainfall is reducing the reliability of the ACC and FCW systems, so caution is required)
- "Slippery" (the current outside temperature indicates road surface coefficient of friction that the roads may be slippery and so the FCW algorithm will assume more cautious)
- "Sharp Curve" (the radar is unable to detect what is around the curve so use caution)
- "Speed too fast" (the vehicle is traveling at a speed which may mean that insufficient warning time is provided by the FCW system).

A "Malfunction" (ACC/FCW system failure) message could also appear in the unlikely event of a system malfunction, and the Driver Control Required" message (Figure 10), 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. A pair of 50-ms 3000-Hz tones accompanied some of these messages.

To accommodate the new "Gap/Warn" control button, the temperature button on the steering wheel was removed and steering wheel buttons were rearranged so 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 the specification of the DVI, refer to the Warning Cue Implementation Summary Report (DOT HS 809 462).

Most of the HUD and Driver Vehicle Interface Processor electronics design was complete by the end of the 2001 calendar year, and Delphi provided a demonstration of the functioning DVI to NHTSA in June of 2001. The block diagram for the DVI electronics is displayed in Figure 10. The haptic seat and automatic volume control functionality were removed due to the insufficient resources required for their validation. The system was designed to mute the radio when any audio from the DVI system was presented to the driver (imminent alert or system messages). A functioning DVI system was supplied to General Motors for installation into the prototype vehicle in June of 2001.

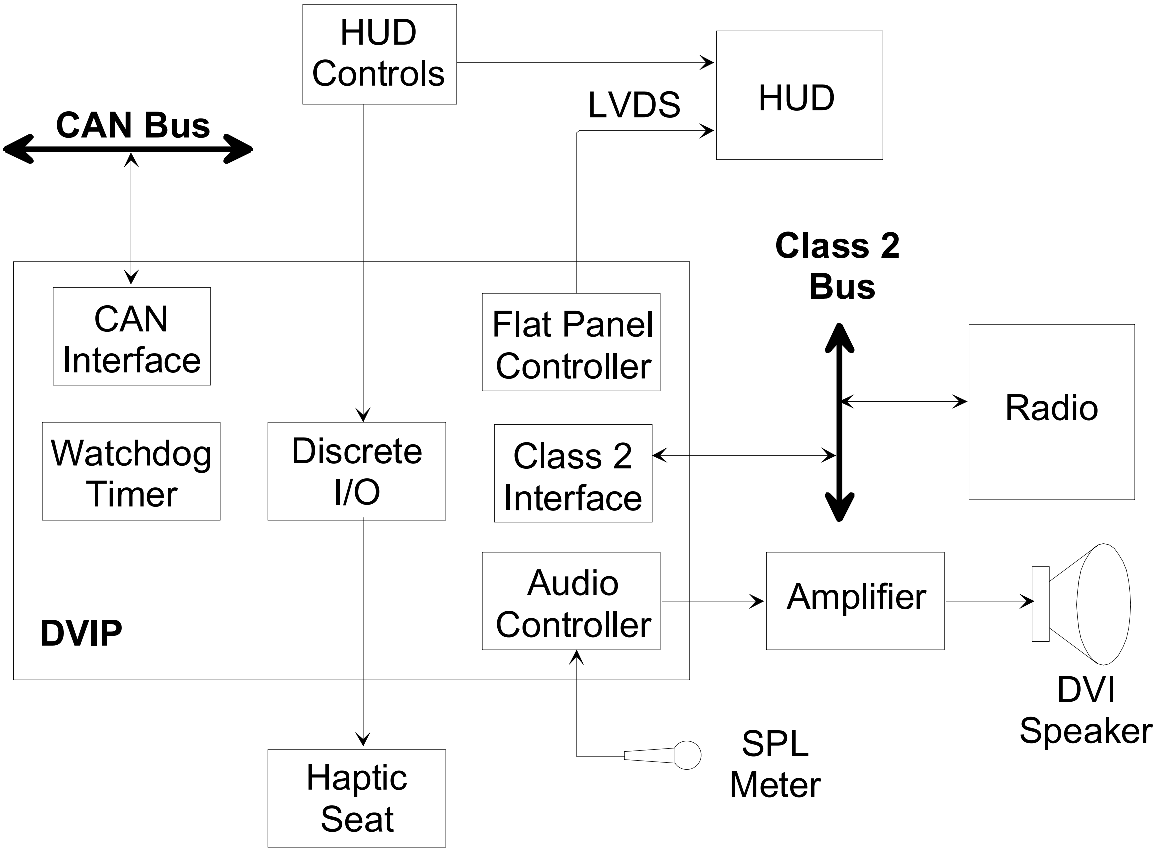


Figure 10: DVI Block Diagram

Milestones and Deliverables

Milestones

All Task B5 milestones were completed prior to the 2002 calendar year.

Deliverables

Delivery of the remaining DVI units occurred during 2002, and by December 18, all thirteen DVI systems used for installation into the ACAS/FOT fleet were designed, built, tested, and delivered to General Motors.

Work Accomplished

In the calendar year of 2002, as 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, Driver-Vehicle-Interface-Processor and Head-up Display (HUD) hardware design.

It was observed that the three-stage display (amber, red, and flashing red warnings) was overly dynamic, producing large display changes as a function of minor changes in the vehicle to vehicle kinematics conditions and could therefore potentially be annoying to drivers. It was also observed that the change from the amber to the first red icon produced a relatively salient cue to the driver that was supported by a relatively arbitrary constraint (half the distance between imminent and cautionary onsets). A decision was made to remove the red stage, reverting to a display with only two color states (amber and flashing red). To make the display smoother, so that small changes in vehicle-to-vehicle kinematic conditions corresponded to small changes in the display, the cautionary stage was expanded to include varying sized amber icons as shown in Figure 11. 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 imminent was approaching.

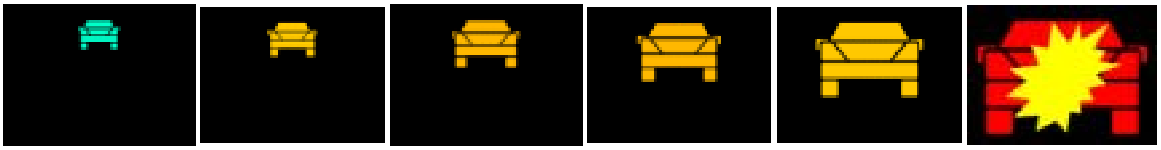


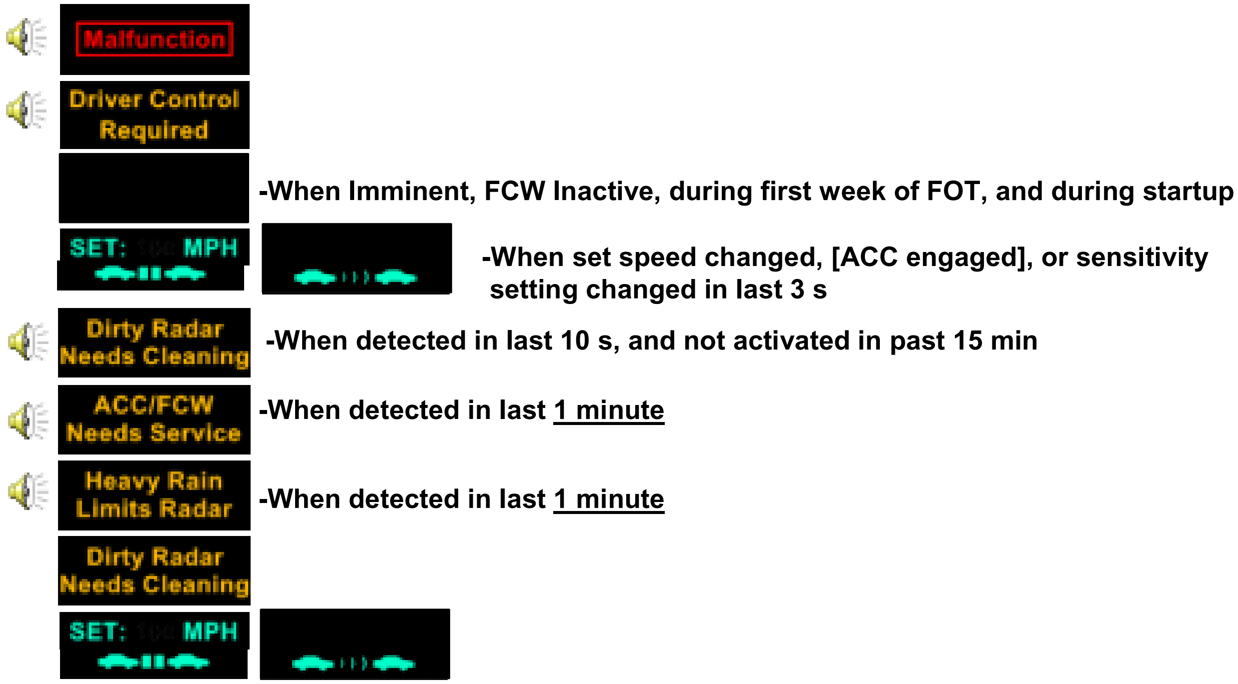
Figure 11: Looming Two-Stage Display

It was decided to adopt this display approach based upon the comments of several members of the ACAS/FOT program.

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 previous ignition cycles. Furthermore, the FCW sensitivity and ACC gap settings were separated to prevent the driver from being required to make frequent changes.

Based on observations that the DVI HUD information messages could be difficult to comprehend by the typical driving public, several modifications were introduced. The "Speed Too Fast", "Slippery", and "Sharp Curve" messages were removed because they could be misunderstood, were judged unnecessary, and had a 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). Note that the FCW algorithm still uses temperature, along with other information, to determine the imminent alert warning distance.

To try and improve the understandability of the remaining messages, these messages were changed to a two-line format. An "ACC/FCW Needs Service" message was also added to indicate when system performance would be degraded by non-critical system malfunctions. The messages were prioritized according to Figure 12.



-When Imminent, FCW Inactive, during first week of FOT, and during startup

-When set speed changed, [ACC engaged], or sensitivity setting changed in last 3 s

-When detected in last 10 s, and not activated in past 15 min

-When detected in last 1 minute

-When detected in last 1 minute

Figure 12: Message Priorities (Highest Priority At Top)

After it was observed that the daytime/nighttime HUD transition occurred at an inappropriate level of ambient brightness (transitioning to nighttime during overcast conditions), the daytime/nighttime HUD transition point was optimized to eliminate this problem. To improve the uniformity and brightness of the HUD image, a new light ray alignment package was designed. In order to improve reliability, other changes and additions were made to the DVI software and hardware that were not noticeable to the driver, including:

- Expanding the status message sent via the CAN bus to report HUD graphics content and software revision number
- Re-routing the “Radio Mute” command from the Class2 bus to the CAN bus (removing the second SAINT converter) so that the Main Processor now relays the mute message to the radio
- Upgrading the software utility to automate loading of new software
- Designing a restore software utility that automates full recovery from a backup disk
- Delivering a training/demo keypad for demonstrating or exercising the HUD graphics

- Designing printed circuit boards to replace hand-wired perf boards and developing a dual-timer watchdog circuit to guarantee boot, respond quickly to reset conditions, and assure safe shutdown
- Consolidating installable components into fewer packages by installing the audio amplifier inside the PC104 enclosure and encapsulating the steering-wheel control button re-map circuit in the HUD control box
- Reducing the installable cable count
- Designing a mounting bracket to stabilize the HUD under vibration conditions
- Designing a more robust HUD glare trap and associated glare trap retainer

Research Findings

No new research was performed in 2002 under this task.

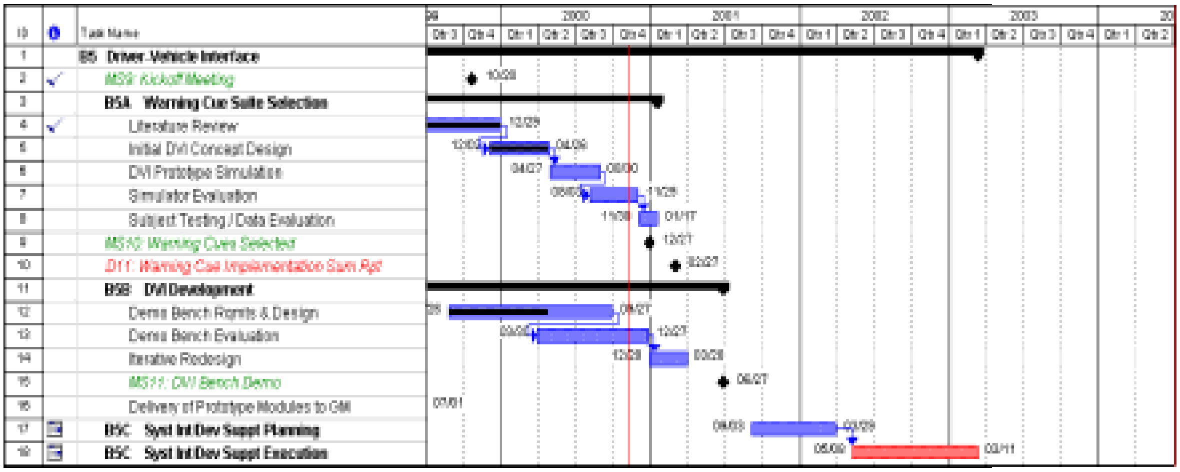


Figure 13: Task B5 Gantt Chart

Plans through June 2003

Some DVI systems that have already been installed in the fleet vehicles will be retrofitted to incorporate the changes described earlier. Subject to the availability of the vehicles requiring DVI retrofits, it is expected that retrofitting will be complete by the end of January 2003. During this time, two spare DVI units will also be delivered to General Motors, thereby concluding Task B5.

4 SUBSYSTEM PROCESSING DEVELOPMENT (TASK C)

4.1 Data Fusion (Task C1)

4.1.1 Requirements Definition and Architecture Development (Task C1A)

Objectives

The objective of Task C1A was to develop requirements (performance and interface) and the architecture for the data fusion subsystem.

Approach

The approach was to gather information on each sensor subsystem (the sensor output, performance specifications, confidence measures), and gather information on the requirements for the subsystems that use the output of the data fusion subsystem to develop performance and interface requirements. This information was used to determine the fusion algorithms and set requirements on the data fusion architecture.

Summary of Accomplishments prior to 2002

HRL developed performance and interface requirements for the data fusion subsystem. The performance and interface requirements have been incorporated into the Data Fusion requirements.

Milestones and Deliverables prior to 2002

MS12: Architecture and Performance Requirements Definition - A meeting was held at HRL on 9/16/99 in which HRL presented performance and architecture requirements of the data fusion subsystem. In addition, HRL presented a preliminary architecture for the data fusion subsystem.

Research Findings

The main research finding of this task is that the data fusion subsystem must be robust and able to detect and handle situations when there is missing or invalid data.

Plans through June 2003

This task has been completed.

4.1.2 Initial Algorithm Development (Task C1B)

Objectives

The objective of this task is to develop fusion 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 environmental state.

Approach

The data fusion subsystem can be divided into four main functional sub-units:

1. Host lane geometry estimation: The data fusion subsystem provides 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 is the best approach. 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 done using Kalman filters as it provides a natural framework of fusing incomplete and inaccurate information from multiple sources. It provides more accuracy and improved robustness to stochastic errors (e.g., sensor noise) because it acts as a low-pass filter. A fundamental issue in fusing different forms of information about forward lane geometry in a Kalman filter framework is the choice of a good road model. HRL investigated several different road models testing conducted with simulated and real data.

2. Hose state estimation: The data fusion subsystem provides a “fused” host state estimate by fusing information from vision and scene-tracking subsystems. Host state primarily consists of host vehicle offset and orientation in its lane. HRL used a Kalman filter approach for host state estimation for the same reasons as discussed above. In addition, since host vehicle sideslip angle needs to be estimated in the process model, this parameter was also included in the state-space representation of the Kalman filter.

3. Driver distraction estimation: The approach to estimating driver distraction is based on determining if and what type of secondary task the driver is performing. HRL then uses a fuzzy rule-based system to estimate the driver distraction depending on the type of task and when the task was initiated.

4. Environmental state estimation: When used to interpret environment state, the data fusion subsystem detects and reports conditions indicative of slippery road surfaces. Data on conditions is used to modify the expected braking intensity the driver will achieve when responding to an alert. In turn, the expected intensity has an impact on the timing of the alerts. HRL's approach is to develop a fuzzy rule-based system to indicate road conditions and an associated confidence measure as a function of windshield wiper activity and outside temperature.

Summary of Accomplishments Prior to 2002

HRL developed, implemented, and evaluated, using simulated data, initial versions of algorithms for host lane geometry, host state, driver distraction and environment state estimation. HRL developed a "higher" order road model and tested it along with several different commonly used road models and compared errors in estimating road geometry in both a recursive (Kalman) and a non-recursive (least-squares) framework. Results showed that this higher order model is superior to a conventional "single clothoid" road model as it has smaller road geometry estimation errors, especially during sharp transitions in road curvature. HRL also developed an adaptive Kalman filter approach for road geometry and host state estimation, which is superior to a conventional Kalman filter. The adaptive Kalman filter performs better during sharp transitions in road geometry compared to a conventional Kalman filter.

HRL developed fuzzy-rule based algorithms to estimate driver distraction and environment state. 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 (radio) or vehicle climate (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.

The environment state estimation algorithm detects and reports conditions indicative of slippery road surfaces. HRL defined road conditions 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 upon the windshield wiper activity and outside temperature measurements.

Milestones and Deliverables prior to 2002

MS13: The Preliminary Data Fusion Algorithm Demonstration was completed with a presentation to NHTSA, GM and Delphi in December of 2000. This milestone demonstrated non-real-time performance of all four parts of the data fusion subsystem: host lane geometry estimation, host-state estimation, driver distraction level estimation, and environment state estimation.

Although not part of the official list of program deliverables, a preliminary version of the data fusion software was delivered to GM for insertion into the Engineering Development Vehicle (GM EDV) in September of 2000. Also, a model of the data fusion subsystem was provided to University of California Partnership for Advanced Transit and Highways (PATH) for use in the PATH simulator.

D12: The Data Fusion Algorithm Simulation Summary Report was delivered to GM in December of 2001. This report describes data fusion algorithms developed in Task C1B and the performance of those algorithms on simulated data.

Research Findings

1. The "new" road model is superior to a conventional single-clothoid road model as it produces smaller road geometry estimation errors, especially during sharp transitions in road curvature. Better road geometry estimation should translate into lower errors in identifying in-path targets versus out-of-path targets.

2. The adaptive Kalman filter performs better during sharp transitions in road geometry compared to a conventional Kalman filter. This allows the system to respond rapidly to changing road curvature and could provide increased accuracy in determining host vehicle path and reducing errors in detecting in-path versus out-of-path targets.

Plans through June 2003

This task has been completed.

4.1.3 Real-time algorithm development (Task C1C)

Objective

The objective of this task was to develop real-time versions of the algorithms developed in Task C1B for integration into the pilot and deployment vehicles.

Approach

To develop real-time versions of the algorithms developed in Task C1B, our approach was to port the algorithms onto the real-time hardware platform specified by GM for the data fusion subsystem. After porting the algorithms, real-time algorithm performance was evaluated to determine if there were portions of the fusion algorithm that needed to be tuned or modified to meet real-time processing requirements.

Summary of Accomplishments prior to 2002

The original fusion architecture for host lane geometry estimation was based on the idea of fusing the subsystem estimates based on their 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. HRL developed and tested several different fusion methods on real driving data. The confidence-based fusion (COF) algorithm (the original approach) uses the subsystem confidence measurements for fusion. The disadvantage of this approach is that since confidences are not always correct/reliable, fusing subsystems based on confidence "as is" can make matters even worse. The consensus-based fusion (CNF) algorithm uses agreement between subsystems to detect "incorrect subsystems(s)" 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, fused 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.

HRL also developed a variety of tools to develop ground truth and for data playback, visualization, and subsystem performance analysis. These tools were used to evaluate performance of the fusion and sensor subsystems and further modify/tune their performance.

Due to sensor limitations that preclude information fusion, environmental state estimation is no longer a data fusion requirement. The threat assessment algorithm makes an estimate of the environment state using a few sensor inputs (temperature and windshield wiper activity).

To summarize, the real-time data fusion software has been completed and successfully ported into the prototype vehicle. All interfaces (inputs and outputs) have been thoroughly tested and validated. The software has been fully integrated within the overall ACC/FCW system and is fully functional. Real data has been collected from the prototype vehicle and analyzed using ground-truth tools developed at HRL. It has been verified that data fusion is providing all the expected output estimates and operating at the expected 10 Hz rate.

Milestones and Deliverables Prior to 2002

MS14: Data Fusion Algorithm Demonstration, which was a demonstration of the real-time data fusion algorithm, was completed in May 2001 with a demonstration to GM and Delphi at HRL.

Research Findings

The main research finding for this task is that the confidence outputs from the various sensor 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. Based on the analysis of limited driving data under different scenarios, it appears that the confidence-based fusion approach can be further improved by identifying/developing special rules and heuristics that can be applied under special conditions. Some examples of such rules are those based on speed, detection of 90-degree turns and specific road types.

Plans through June 2003.

This task has been completed.

4.1.4 System Integration and Development Support and Execution (Tasks C1D and C1E)

Objective

The objective of these tasks is to support integration of the data fusion algorithms into the Prototype, Pilot, and Deployment Vehicles and to modify/tune the data fusion algorithms as needed.

Approach

HRL's approach in this task is to provide support to GM for the integration of the data fusion algorithms into the Prototype, Pilot, and Deployment Vehicles. To tune or modify the data fusion algorithms, HRL's approach is to use the ground truthing and data analysis tools developed in Task C1C to determine under what conditions the sensor and fusion subsystems do not perform well and develop heuristic rules that can be used to tune the fusion subsystem.

Milestones and Deliverables prior to 2002

D29: Data Fusion Algorithm In-Vehicle Summary Report was delivered to GM on December 20, 2002. This report provides a description of the data fusion algorithms that are implemented in the Prototype, Pilot, and test vehicles and provides a summary of the performance of these algorithms on collected vehicle data.

Work Accomplished in 2002

Several improvements to the data fusion algorithm were accomplished in 2002.

Host State

The vehicle host state consists of *heading* (in lane), *lane offset*, *lane width*, and a *lane change indicator*. 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 provide lane change indicators. 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 the lane change, vision's lane change indicator and confidence is used because an analysis of collected vehicle data discovered that the vision subsystem lane change indicator is more reliable.

Road Model

Simulations and initial analysis on some collected vehicle data indicated that the higher-order road model was superior to the conventional “single clothoid” road model. However, after collection of more real-vehicle data and extensive analysis, it was discovered that the conventional single clothoid model out-performed the higher-order road model. At near ranges (60 m or less) both road models perform equally well.

However, at far ranges the performance of the higher order road model is determined solely by the statistics of the far range road estimates, which have large variance, whereas the performance of the single clothoid model at far ranges is due to both far range and near range estimates. As a result, the single clothoid model has lower variance in the far range estimates and is, therefore, the better road model choice.

Fusion Algorithm for Host Lane Geometry Estimation
In evaluating the performance of the Kalman filter-based fusion algorithm for host lane geometry estimation, it was found 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, it was ineffective for host lane geometry estimation. The reasons for this 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.

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 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 as the road transitions. The Kalman filter-based approach did not improve host lane geometry estimates at road transitions and so a new algorithm was needed.

After extensive processing of vehicle data using data fusion, the host lane estimation approach was changed to a simple, zero delay, estimator that we refer 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:

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

(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:

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

As mentioned above, the weights (w_i) are adjusted based on a set of heuristic rules. Heuristic weighting rules were found to improve the performance of the host lane geometry estimation algorithm by reducing both the average and maximum error. The heuristic rules also improve overall robustness of the fused host lane geometry estimate. The rules that we developed adjust the weight (or confidence) of a sensor subsystem depending on the situation. For example, the yaw rate sensor produces more accurate measurements at higher speed. Therefore, one of the rules is that when the speed of the host vehicle is greater than 50 MPH, then we increase the weight given to the yaw rate sensor by 40%.

Rules were developed that adjust the weight given to each of the sensor subsystems (yaw rate, scene tracker, map, and vision) 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 attempts were tried to automatically determine 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.

Host Lane Geometry Estimation Results

Table 4 and Table 5 show typical results of host lane geometry estimation. Table 4 represents a typical freeway-driving segment. Table 5 contains a mix of driving on freeways, primary, secondary, and unpaved roads. The rows of the tables are the sensor subsystems that are inputs to the data fusion host lane estimation algorithm, and the output of the data fusion algorithm. These tables compare 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 the look-ahead distance[1]. (Look-ahead distance equals the product of the look-ahead time, T_{look} = 2.5 sec, and the vehicle speed, i.e. Look-ahead distance equals 72.6 m at 65 MPH.)

The first information row of the table indicates the percentage of time that the ground truth is available (marked as valid), the look-ahead time, and the driving time. The "%avail" is the percent of time that ground truth is marked as valid *and* the subsystem

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[1] 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.

has a new measurement estimate. The columns "%err > *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 m error corresponds to approximately a half lane width. A 4 m error at the look-ahead distance means that the system might miss-identify targets in the adjacent lane or road shoulder as threats. Ideally, %err > 2 m would be zero, but the current sensor subsystems cannot yet achieve this performance. The single measure, %err > 2 m, best characterizes 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 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, %err > 2 m will be small.)

Note that GPS/MAP, Vision, and especially Scene Tracker subsystems, can all potentially have low availability, %avail. For example, Scene Tracker is available 20% of the time in the L1031_02H data set in Table 5. In this data set there are frequently no other vehicles for the scene tracker to track.

Table 4: Road Geometry Results, Freeway

L1004_05H	Ground Truth available 89.6%, T_{look} = 2.5 sec, 687.7 sec (freeway)					
Sensor	Mean(err)	Std(err)	%avail	%err > 1m	%err > 2m	%err > 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 5: Road Geometry Results, Mixed Roads

L1031_02H	Ground Truth available 85.9%, T_{look} = 2.5 sec, 2831.7 sec (Mixed, freeway, primary, secondary, unpaved)					
Sensor	Mean(err)	Std(err)	%avail	%err > 1m	%err > 2m	%err > 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 almost all cases the fused estimates have lower mean and variance than any of the individual subsystems; additionally fusion improves the %err > 2 m metric. Note that in these examples, the new, instantaneous fusion algorithm performs better that the Kalman filter-based approach in every performance category and specifically reduces the %err > 2 m metric by more than a factor of 3.

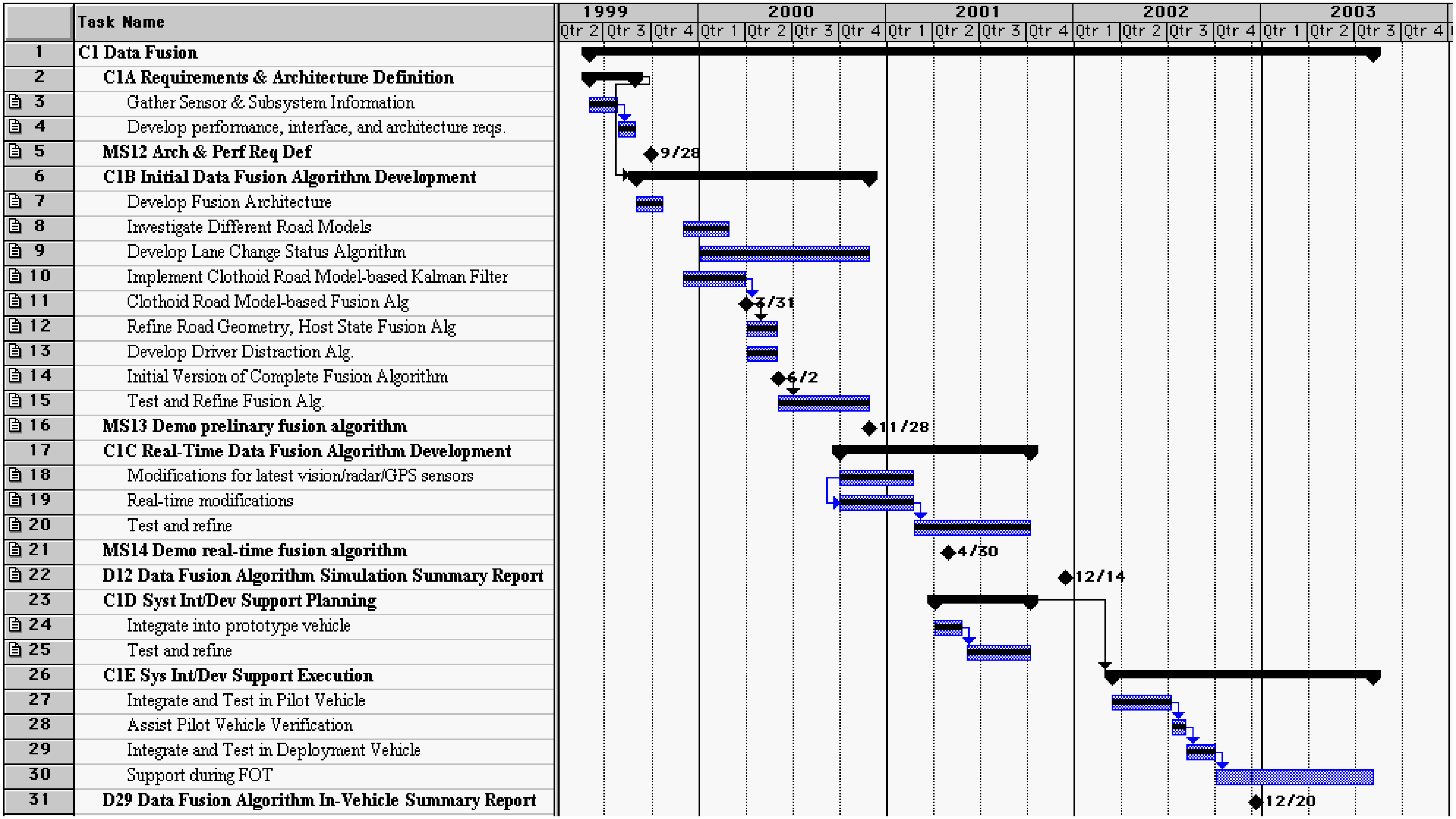
Research Findings

1. The conventional single-clothoid road model produces smaller road geometry estimation errors than the higher-order road model when tested with real vehicle data. We found that with real vehicle data, 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 former model.

2. The Kalman filter-based approach for producing a fused estimate of host lane geometry does not work well. In road sections that have constant curvature, the Kalman filter approach does reduce the variance in the estimates, but the added value is not significant because the sensor measurements are already pretty good. Where the sensor subsystems fail (and a fused estimate is most valuable) are at road transitions (e.g. straight-to-curve, curve-to-straight). Unfortunately the Kalman filter-based approach cannot predict the occurrence of road transitions, and as a result the Kalman filter does not produce a good fused estimate of road transitions. The instantaneous data fusion algorithm works much better on road transitions than the Kalman filter-based fusion approach, and hence, is the algorithm of choice.

Plans through June 2003

The data fusion team will provide appropriate support as required to address any FCW system anomalies experienced during the FOT phase.



	Task Name
1	**C1 Data Fusion**
2	**C1A Requirements & Architecture Definition**
3	Gather Sensor & Subsystem Information
4	Develop performance, interface, and architecture reqs.
5	**MS12 Arch & Perf Req Def**
6	**C1B Initial Data Fusion Algorithm Development**
7	Develop Fusion Architecture
8	Investigate Different Road Models
9	Develop Lane Change Status Algorithm
10	Implement Clothoid Road Model-based Kalman Filter
11	Clothoid Road Model-based Fusion Alg
12	Refine Road Geometry, Host State Fusion Alg
13	Develop Driver Distraction Alg.
14	Initial Version of Complete Fusion Algorithm
15	Test and Refine Fusion Alg.
16	**MS13 Demo prelinary fusion algorithm**
17	**C1C Real-Time Data Fusion Algorithm Development**
18	Modifications for latest vision/radar/GPS sensors
19	Real-time modifications
20	Test and refine
21	**MS14 Demo real-time fusion algorithm**
22	**D12 Data Fusion Algorithm Simulation Summary Report**
23	**C1D Syst Int/Dev Support Planning**
24	Integrate into prototype vehicle
25	Test and refine
26	**C1E Sys Int/Dev Support Execution**
27	Integrate and Test in Pilot Vehicle
28	Assist Pilot Vehicle Verification
29	Integrate and Test in Deployment Vehicle
30	Support during FOT
31	**D29 Data Fusion Algorithm In-Vehicle Summary Report**

Figure 14: Task C1 Schedule

4.2 Tracking and Identification (Task C2)

The objectives of the Tracking and Identification task are to refine the Path Estimation and Target Identification algorithms, to incorporate Vision and Global Positioning System (GPS) derived information, to integrate these components into the FOT vehicle system, and to support Field Operational Test (FOT) deployment.

Significant progress was made during the first three years of the Automotive Collision Avoidance System (ACAS) FOT program under Task C2. Delphi is responsible for the Conventional Target Path Estimation (Task C2A) and radar-based Scene Tracking activities (Task C2B) associated with the Tracking and Identification Task. General Motors is responsible for the Enhanced GPS approach (Task C2C). This section provides a summary of the major activities that were initiated and the achievements that were accomplished under these tasks.

4.2.1 Conventional Approach Development (Task C2A)

The performance of Delphi's conventional yaw rate-based path estimation and target selection algorithms has shown a steady and continuous improvement during the ACAS/FOT program. During the first two years of the program, the number of false target selections (incorrectly selected non-in path targets, such as adjacent lane or roadside objects) and missed detections (non-selected valid in-path targets) were substantially reduced. During the third year of the ACAS/FOT program, the responsiveness of the target selection process to close range maneuvering targets and host lane changes was further improved.

The refined path estimation and target selection algorithms were then tested and validated in the Delphi ACAS/FOT lab bench environment, and later integrated and validated on the ACAS/FOT Prototype and Pilot test vehicles.

Objective

The objective of Conventional 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 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.

Approach

The Delphi target selection algorithms identify the closest in-path stationary and moveable targets in the forward path of the host vehicle. In order to accomplish this, the target selection algorithms must differentiate between in-lane and adjacent lane targets. In addition, they must handle: (a) host and target vehicle lane changes, (b) close range target cut-ins, (c) driver variability due to host vehicle lane hunting and in-lane weaving, and (d) dynamic changes in forward road curvature (i.e., curve entry and curve exit transitions).

The Delphi target selection and path estimation algorithms use two primary approaches to estimate the forward path of the host vehicle. The baseline target selection approach uses yaw rate and host vehicle speed to estimate the road curvature ahead of the host. The state based target selection approach uses a parametric representation of the host and road state to estimate the road geometry ahead of the host.

The ACAS/FOT radar sensor provides target position information relative to the host frame of reference. In order to identify the primary targets that are in the path of the host vehicle, the Delphi path estimation algorithms use the estimated forward road curvature and host state to translate the radar target position information into a frame of reference that is relative to the host path and the road. This reference frame uses the *host's predicted lane center* to describe the path of the host vehicle, on both straight and curved roads.

The determination of when a target vehicle is in the path of the host vehicle can be visualized as a *target selection zone*. The Delphi target selection algorithms define this zone b: (a) the left and right edges of the host vehicle's lane, (b) the host's *predicted lane center* at some future time, (c) the target's current longitudinal position and kinematics, (d) the length of time that the target has previously been in the zone, and (e) the target's proximity to the edge of the radar sensor's field of view.

Accomplishments prior to January 2002

During the first two years of the ACAS/FOT program, significant progress was made in enhancement and refinement of the path estimation and target selection algorithms, and in the integration, validation, and testing of the Target Selection subsystem within the ACC/FCW Prototype vehicle.

During the first year of the ACAS/FOT program, the baseline Path Estimation algorithms used host speed and yaw rate to estimate the road geometry ahead of the host vehicle. The low cost analog yaw rate sensor in the Delphi radar unit was replaced with a highly accurate and robust KVH digital yaw rate sensor. Enhancements were made to the baseline path estimation and target selection algorithms to improve performance during curve transitions and host lane changes. Stationary Object false alarms were reduced by (1) refining target selection heuristics and persistency requirements, (2) optimizing target lane position estimation during severe right and left-hand turns, and (3) and 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 utilized FOT steering sensor data together with a bore sight-based path estimation approach to estimate the host's predicted path at low vehicle speeds.

During the second year of the ACAS/FOT program, path estimation and target selection algorithms were modified to incorporate fusion-derived parametric estimates of the host and road state. The fused road and host state information was used to provide an improved estimate of the roadway shape/geometry in the region ahead of the Host vehicle, and an improved estimate of the host vehicle's lateral position and heading within its own lane. The fused road and host state information was provided by the Data Fusion subsystem (Task C1), and was derived from the following four complementary approaches:

- vision-based road prediction and host state estimation (Task B2)
- GPS-based road prediction (Task C2C)
- radar-based scene tracking (Task C2B)
- yaw rate-based road and host state estimation (Task C2A)

The target selection algorithms were tuned to switch between the conventional yaw rate-based approach and the state-based fusion approach based on the data fusion confidence measures and on the continuity of the fused road and host state information. 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.

Milestones and Deliverables January through December 2002

Date Completed	Milestone
Jan 2002	The Path Prediction and Estimation Summary Report
Aug-Sept. 2002	Successfully Completed the Pilot Validation Tests
June-Oct. 2002	Provided 13 ACAS Deployment Vehicle Target Selection Processors (RCAPs)

Work Accomplished in 2002

During the third year of the ACAS/FOT program, the responsiveness of the target selection process to close range cut-in / cutout targets was improved.

In addition, Host vehicle state information was incorporated into the path selection process to improve the system's responsiveness to host lane changes. The improved path estimation and target selection algorithms were then tested and validated in the Delphi ACAS/FOT lab bench environment, and later integrated and validated on the ACAS/FOT Prototype and Pilot test vehicles.

Algorithm Improvements
The close range moving target cut-in/cut-out response 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 funnels were tuned to minimize false alarms on adjacent lane targets, while maximizing the identification of long-range in-lane targets.

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. The current target selection process only uses the vision-based host state information during, and for a short time after, each detected host lane change. The vision-based host state information is not used at other times. This is because the host state estimates have been found to be inaccurate and unreliable on roadways with divergent lane markers, Botts' dots(reflective ceramic tiles used instead of lane markers) lane markers, or visible vertical curvature.

Subsystem Interface Changes
The Target Selection subsystem's CAN interfaces were modified to: (a) provide target selection software version information, (b) provide more detailed internal algorithm information, (c) setup the ACCA radar instrumentation to output additional internal ACCA radar and controller performance data, and (d) reduce the latency of the in-path target CAN messages sent to the ACCA controller.

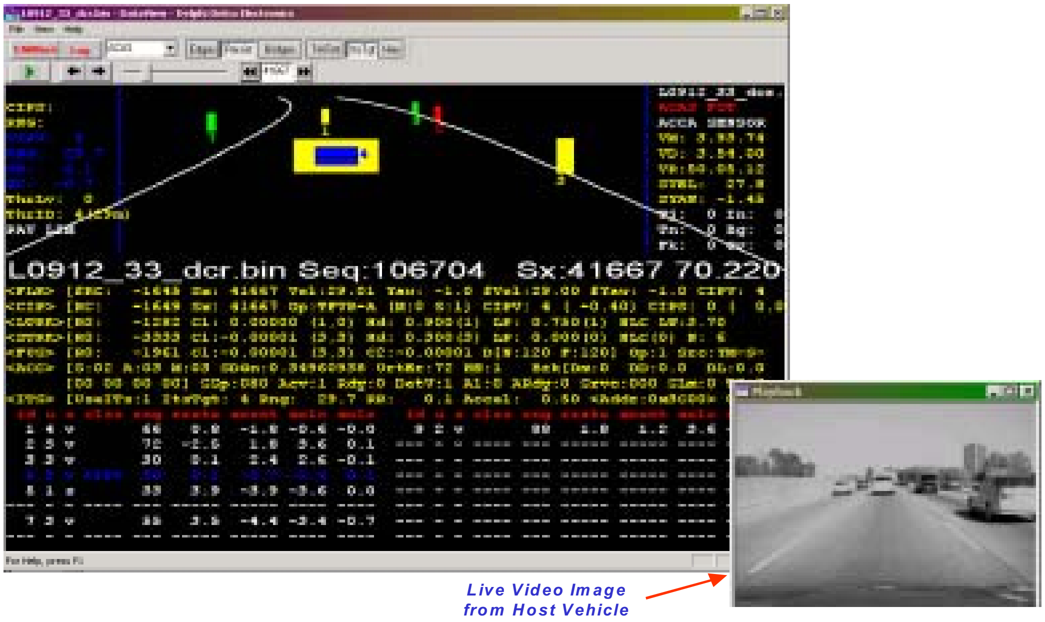
Data Collection and Analysis Tool Upgrades
During the first phase of the ACAS/FOT program, Delphi developed a suite of data collection and playback tools that used a PC-type laptop to (a) interface to the CAN bus, (b) display a graphical representation of the CAN bus derived road and scene targets, and (c) log the CAN messages to disk. In addition, an 8mm camera, mixer, and video recorder were used to mix and record time-stamped video with the graphical representation of the road.

Delphi's data collection tools were designed to:

1. Observe near real-time and real-time system behavior while performing system integration on laboratory bench hardware
2. Evaluate real-time system performance while performing on-road vehicle testing
3. Perform in-depth ACC/FCW system data analysis and quantify system performance
4. Iterate, refine, and validate key algorithm improvements with collected road test data, both in simulation and on the lab bench

During the past year, Delphi's real-time PC laptop-based data collection and playback tools were upgraded. The mixer and video recorder were eliminated, and a PCMCI frame grabber was added to digitize live video of the road. The current data collection tools compress and time stamp the digitized video data. The compressed video data is then written out to disk in an AVI file format. The live CAN bus data and the time stamp of the last video frame are then written out to disk in a binary file format. The video and CAN bus data can be later replayed synchronously. The replay provides a continuous view of the captured video that is matched to a graphical representation of roadway scene, and to a textual representation of key subsystem information.

Figure 15 depicts several display windows from the upgraded Delphi data collection and replay tools. The small display window depicts a live video scene of the road. The upper portion of the large display window depicts a real-time graphical representation of the detected radar scene targets. The targets are drawn as rectangles and their exterior color is based on their speed relative to the host vehicle. For example, green rectangles denote targets "moving away" from the host vehicle, and red rectangles denote targets that the host vehicle is "closing on." Similarly, magenta rectangles denote "oncoming" targets (targets traveling in the opposite direction). Yellow rectangles denote targets that are "matched in speed" to the host, and white rectangles depict "stationary" targets. The relative size of the rectangular-shaped "targets" is based on the target range and in-path target status. A large rectangle with a solid rectangular center denotes the closest in-path moveable (CIPV) target selected by the target selection process.
The middle and upper left portions of the large display window contain text that describes the Target Selection, Lane Tracking, Scene Tracking, Data Fusion, and Radar subsystems. Moreover, the lower portion of the large display screen lists the radar track file data, with the track file features of the CIPV target highlighted in blue.



```
L0912_33_dcr.bin Seq:106704  Sx:41667 70.220
```

Live Video Image from Host Vehicle

Figure 15: Display from Upgraded Delphi Data Collection Tools

Integration and Test Activities
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 Delphi's real-time system bench, and on both the Prototype and Pilot test vehicles. Extensive open road and track tests were performed by GM,

Delphi, and UMTRI on freeways, city streets, and rural areas to collect a robust suite of test data. Individual subsystem performance and overall ACC and FCW system performance was evaluated. Key areas of improvement and problematic scenarios were identified, corrected, and flowed down to the lower level subsystems. Subsystem algorithms and interfaces were subsequently improved, and the collected data was re-run on the real-time bench to verify the improvements.

Figure 16 summarizes Delphi's validation and refinement process and the suite of tools that were used. The data recorded by the various data collection utilities was used to build up a scenario database. The database was then played back, in real-time, through the system bench hardware. The playback capability provided a mechanism to refine and iterate the various subsystems, and verify key algorithm improvements.

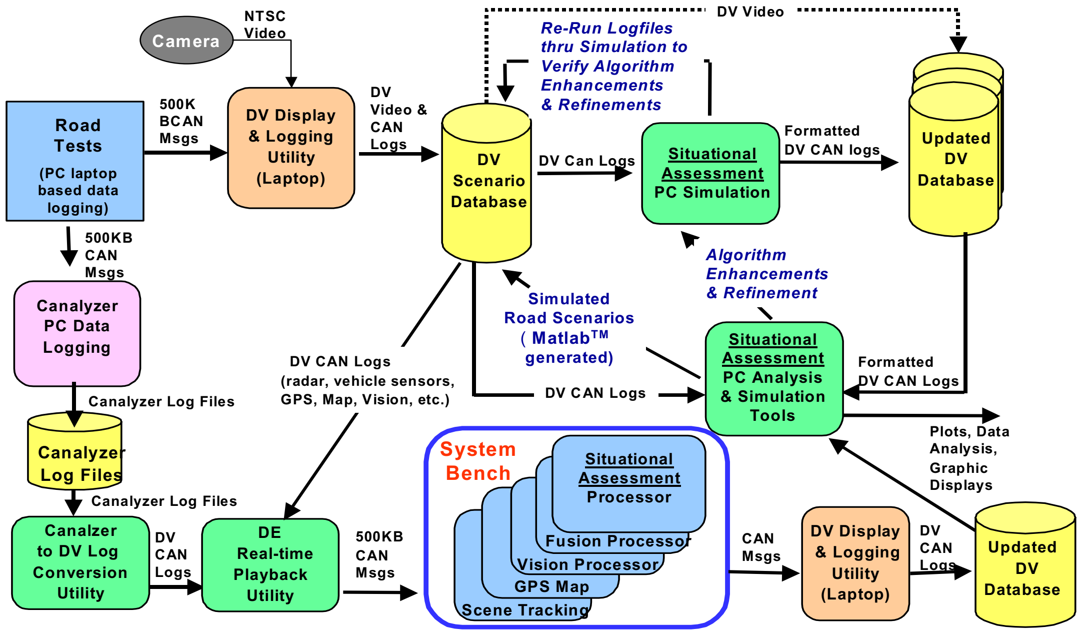


Figure 16: Subsystem Test, Validation, and Refinement Process

The data collection and validation process was performed in real-time either on a vehicle or on lab bench hardware. Delphi's custom utilities and tools were used to dynamically record performance results and interfaces for various key ACC/FCW subsystems, and to graphically depict the target environment and road geometry in front of the ACC/FCW vehicle. Delphi's laptop based Data View (DV) and CAN bus recording utility was used to record, collect, time stamp, and display all of the system's CAN bus messages and events, in real-time. A commercial Canalyzer™ CAN bus utility, by Vector CANtech, was also used to generate test vectors and to gather CAN bus timing measurements.

Custom Matlab™ tools were used to decode and analyze the collected CAN bus data, and to categorize the data by subsystem (Radar, Threat Assessment, Fusion, Vision, Scene tracking, GPS/Map, Target Selection, ACC, Brakes, Sensor Processor, etc.). Performance statistics were then accumulated, and the road and host state information was extracted, correlated, and compared with computed ground truth data.

UMTRI Validation Tests

In May 2002, UMTRI performed the Stage 2 tests, consisting of a series of open road tests with accompanied subjects in one of the Pilot vehicles. The performance of various ACAS/FOT subsystems was analyzed against this collected road test data. After the analysis, Target Selection, Threat Assessment, GPS-Map, and Data Fusion subsystems were tuned and refined. A subset of the collected road test data was then re-run through the Delphi lab bench system. Some of the target selection and threat assessment performance improvements that were observed after post-processing of the collected field test data will now be briefly discussed. A more detailed discussion of the of the UMTRI validation tests is provided in Section 6 of this report.

In general, over all roads, there were 2.9 alerts from stationary objects per 100 miles driven. A total of 41 alerts were detected over all of the test runs. The majority of alerts from stationary objects were found to occur at (or near) curve entries. Moreover, no false alarms from stationary objects were found to occur on freeways. In addition, two specific light posts were found to trigger over 50% of the false alerts from stationary objects.

Discussion of FCW Performance on Subset of the Original and Re-logged UMTRI Data

Under the Target Selection task, a 6-hour subset of the UMTRI road test data was selected, analyzed, and re-run on the system bench to verify subsystem improvements. Three UMTRI F test runs with a high incidence of stopped in-path stationary object (CIPS) events were selected. In addition, one test run with a medium incidence of CIPS events was selected. The selected subset of the UMTRI test data was then re-ran and re-logged on the system bench. During the re-logging process, upgraded versions of the ACAS GPS/Map, Data Fusion, Target Selection, and Threat Assessment subsystems were used. Note that CIPS event is when a stationary object is incorrectly identified as the closest in-path object by the target selection software.

Table 6 summarizes the performance of the Target Selection and Threat Assessment subsystems on both the original and re-logged subsets of the UMTRI test data. The table shows that for both the original and re-logged data sets, the number of CIPS events detected was much larger than the number of imminent CIPS alerts from stationary objects that were observed.

Most of the false CIPS detections did not trigger audible alerts for the following reasons: (a) the host speed was below the FCW operating range, (b) the host was braking, or (c) the CIPS event did not persist for a significant amount of time.

Table 6 also shows that after re-logging the test data, the performance of both the Target Selection and Threat Assessment subsystems improved. The table shows that there was

42% reduction in the number of CIPS events, and a 36 % reduction in the number of imminent alerts from stationary objects.

The reduction in the number of CIPS events can be attributed 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 heuristics. Similarly, the reduction in the number of the CIPS alerts can be attributed to (a) improvements made to the road geometry estimation and target selection processes, and (b) to refinements made to the threat assessment algorithms.

Table 6: FCW Performance on the Original and Re-logged UMRTI Data Subsets

	Original UMTRI Data Subset	Re-logged UMTRI Data Subset
Number of CIPS Events	53	31
Number of CIPS Imminent Alerts	11	7

Table 7 breaks the observed imminent CIPS alerts into the three road categories: (a) curve entries, (b) straight roads, and (c) intersections. The table shows that most of the CIPS alerts occurred during curve entries. The table also shows that after the re-logging of the original data sets, the CIPS alerts that occurred on straight roads or in intersections were completely eliminated. This reduction in the number of CIPS alerts in intersections and on straight roads can be attributed to improvements made to the GPS/Map and Threat Assessment subsystems.

Table 7: FCW Performance vs. Road Type on the Original and Re-logged UMTRI Data Subsets

Number of Imminent CIPS Alerts	Original UMTRI Data Subset	Re-logged UMTRI Data Subset
Curve Entries	8	7
Straight Roads	2	0
Intersections	1	0

Table 8 provides a breakdown of the number of CIPS events and imminent alerts on each of the selected UMTRI test runs. The table also provides a list of CIPS alert event ID numbers for each CIPS alert.

Table 8 Detailed FCW Performance Breakdown on the Original and Re-logged UMTRI Data Subsets

			Original UMTRI Test Data			6/10/02: Rerun Test Data		
Driver	**Circuit (58 mile route)**	**Duration (min)**	**#CIPS Events**	**#CIPS Imminent Alerts**	**CIPS Alert Event ID**	**#CIPS Events**	**#CIPS Imminent Alerts**	**CIPS Alert Event ID**
201	FCW	73	9	2	*#1, #13*	8	1	#1
204	FCW	75	13	3	#1, #2, #12	6	2	#1, #4
206	FCW	70	17	3	#1, #5, #10	9	2	#1, #2
213	FCW	76	14	3	#1, #2, #6	8	2	#4, #6
TOTALS	**FCW**	**224**	**53**	**11**		**31**	**7**	

Table 9 provides a detailed description of each CIPS alert event Id number. For example, Figure 9 indicates that alert event Id #2 corresponded to a light-post that was situated near a curve entrance, on the rightmost side of the host lane.

Table 9 Identification of Objects That Caused Imminent Alerts from the Original and Re-logged UMTRI Data Subsets

CIPS Alert Event ID	# Occur Originally	# Occur Rerun	Object Type	CIPS Alert Event Description	Road Geometry
1	4	3	light-post	Directly ahead in curve entrance, just past intersection with a large driveway. First light-post before guardrail.	In Curve entry
2	2	1	light-post	Nearly ahead in curve entrance	Curve entry
4	0	2	sign	Sign directly ahead of exiting lane.	Curve entry
5	1	0	sign	Large sign (3x5m) approx 3m from lane, mounted on ground, past curve entrance	Curve entry
6	1	1	sign	Diamond-shaped caution sign	Curve entry
10	1	0	sign	Small road sign near curb	Straight
12	1	0	vehicle	Large truck parked in middle turn lane, narrow lanes	Straight
13	1	0	sign	Sign at closest corner of intersection where vehicles turn right	Intersection

Plans for Next Six Months (through June 2003)

During the six months of the ACAS/FOT program, the following efforts will be undertaken to improve to support Target Selection Task C2A:

1. Enhance the fault tolerance of the Target Selection subsystem

2. Maintain the Delphi System bench to re-run collected field test data and validate software changes

3. Support the Deployment vehicle validation tests and field tests.

Schedule and Progress for Task C2A

The deliverables and milestones for Task C2A activities are presented Figure 17 below. Each milestone and deliverable have been successfully completed.

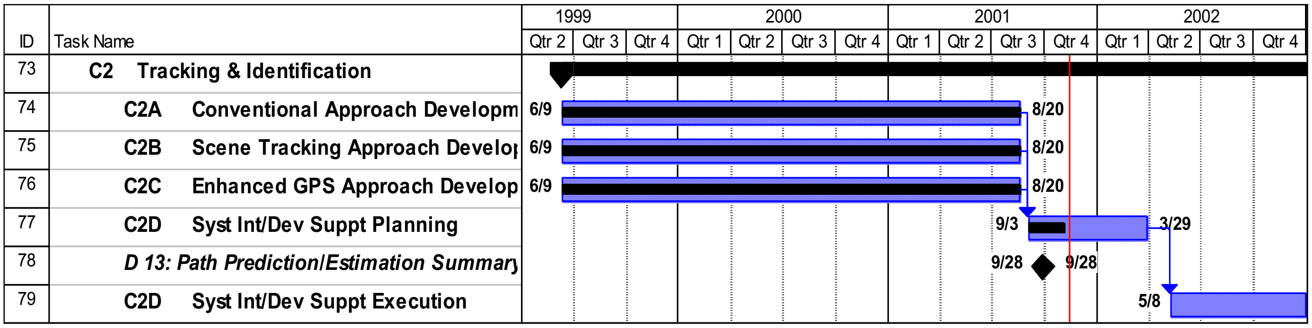


Figure 17 : Task C2A Schedule

4.2.2 Scene Tracking Approach Development (Task C2B)

Objectives

This task concerns the development of the Scene Tracking subsystem. The Scene Tracking subsystem provides estimates to the Data Fusion processor describing the geometry of the upcoming road segment and the heading angle of the host vehicle in its lane. An estimate of the confidence in the accuracy of these estimates 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.

Figure 18 depicts the concept involved in estimating road shape and host in-lane heading angle based on observed trajectories of preceding vehicles.

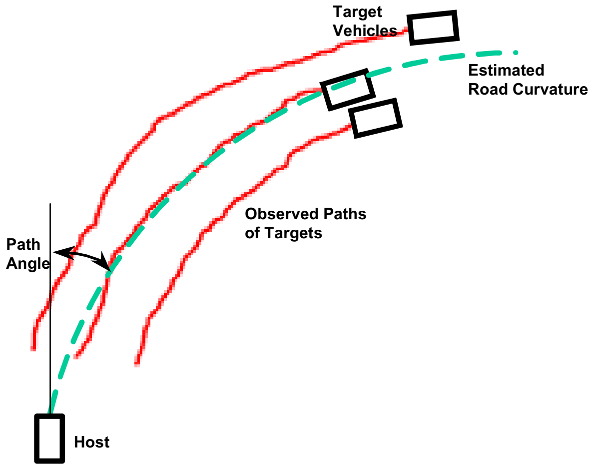
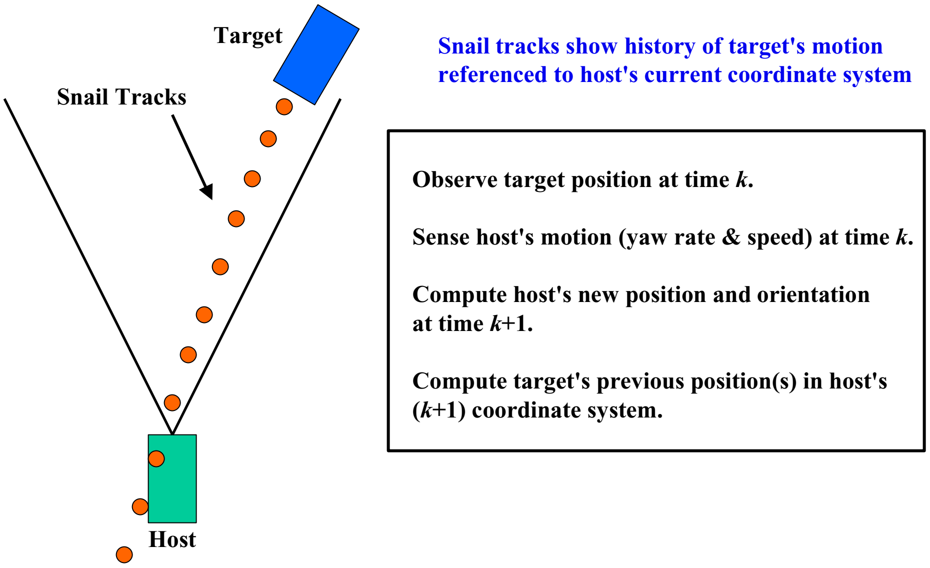


Figure 18: Intuitive Introduction to Concept

Approach

The current version of the Scene Tracking algorithm uses recent range and azimuth angle measurements for all moving targets in the field-of-view of the radar, along with host vehicle speed and yaw rate measurements, to produce at each time instant an overhead-view image of the recent trajectories of all preceding vehicles. This image shows, in the host vehicle's current coordinate system, all of the locations on the road where a moving vehicle was sensed by the radar. Through the use of the track ID assigned to each vehicle by the radar, the collection of returns from each vehicle can be identified as a representation of the trajectory of that vehicle. In analogy to a snail which leaves a dotted trail on a sidewalk showing where it has recently been, the group of returns for a particular vehicle is called a 'snail trail', and each dot in a snail trail is called a 'snail track'. The Scene Tracking algorithm analyzes this image of snail trails and calculates the required estimates. The host's speed and yaw rate are required to allow a particular radar return (snail track) to properly propagate through successive images in response to the host's motion.

Figure 19 depicts the snail tracks left by a preceding vehicle, each snail track being a point on the road where the vehicle was previously seen.



Snail tracks show history of target's motion referenced to host's current coordinate system

Observe target position at time *k*.

Sense host's motion (yaw rate & speed) at time *k*.

Compute host's new position and orientation at time *k*+1.

Compute target's previous position(s) in host's (*k*+1) coordinate system.

Figure 19: Example of Snail Tracks

The confidence estimate is based on the number of snail trails, which are available in the image, and the extent to which they appear to be in agreement regarding the shape of the upcoming road segment.

Note that, because of the movement of the host vehicle and the history of radar returns that allow the snail trails to be calculated, the image may have snail trails, which are outside of the current field-of-view of the radar. In fact, portions of the snail trails, which are behind (or to the side of) the host's current position, are still utilized in the processing.

Figure 20 shows some example snail trails and flow vectors generated.
The analysis of the image of snail trails, which is available at a particular instant of time can be described in the following general manner. Three road geometry parameters are sought: the two clothoid parameters c0 and c1, and the host's in-lane heading angle. Values of these three parameters are calculated which provide the best fit to the set of snail trails. One of these snail trails may first be determined to be an outlier and be discarded (e.g., target lane change or target taking off ramp).

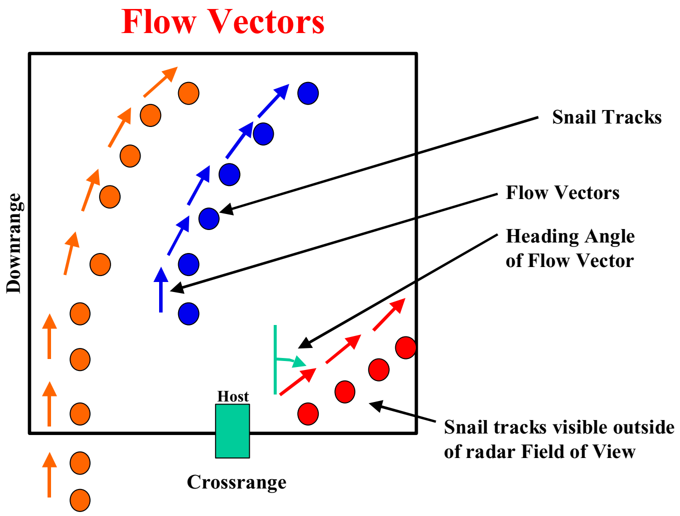
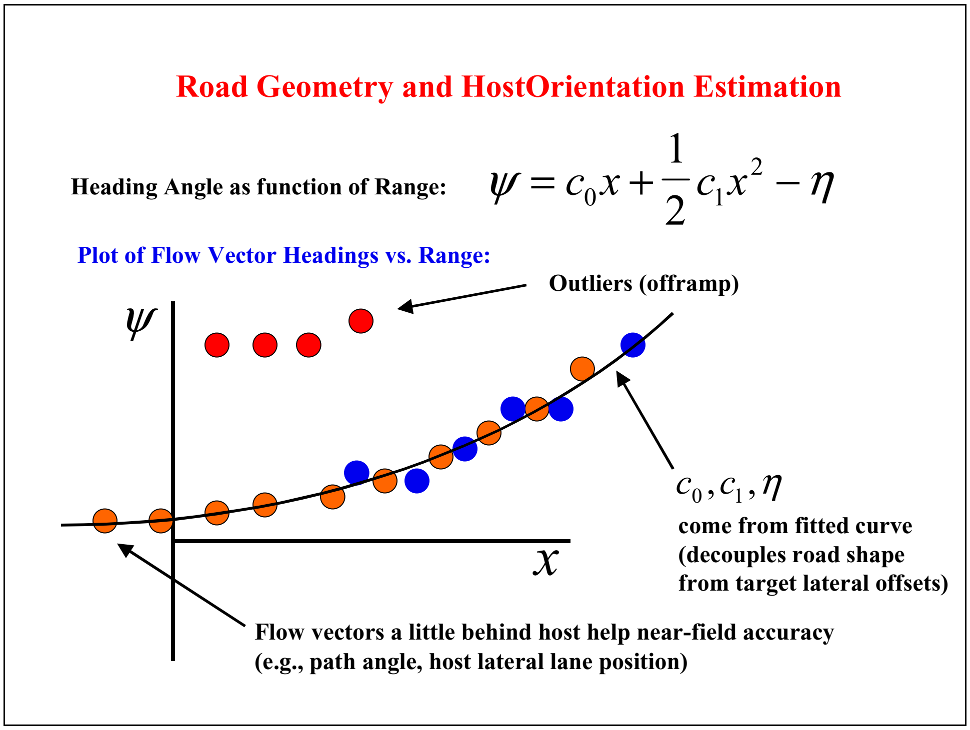


Figure 20 : Example Snail Trails and Flow Vectors

The three desired parameters are obtained by fitting a curve to the heading angle versus downrange distance information. The host's in-lane heading angle is related to the angle that the fitted curve indicates at zero meters downrange. The two road geometry parameters adjust the shape of the curve with distance.

Figure 21 shows the flow vector headings plotted versus downrange distance, along with the best-fit curve based on the three parameters to be estimated. The flow vector headings related to an 'outlier' snail trail are completely ignored in the curve fitting process.



Road Geometry and HostOrientation Estimation

Heading Angle as function of Range: $\psi = c_0 x + \frac{1}{2} c_1 x^2 - \eta$

Plot of Flow Vector Headings vs. Range:

Figure 21: Curve Fitting in Heading vs. Range Plane

Accomplishments prior to January 2002

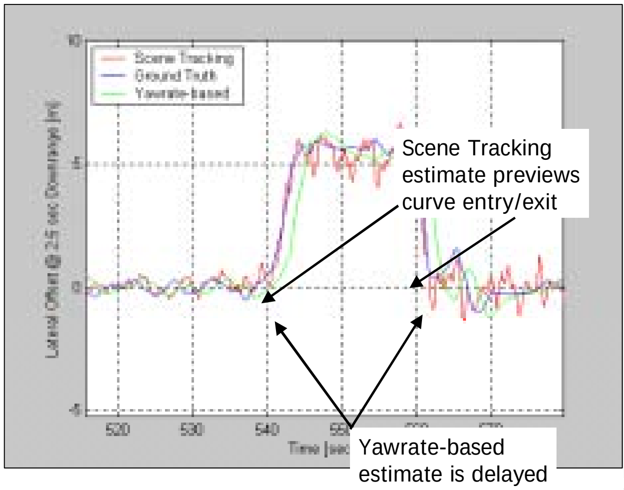
The bulk of the Scene Tracking algorithm development was accomplished prior to January 2002. The snail track / flow vectors approach was one of several approaches which were investigated. This approach was selected due to its superior performance relative to the other approaches.

Work Accomplished in 2002

In the year 2002, the three main accomplishments in the Scene Tracker development were: (1) the processing lag was reduced, resulting in improved curve transition preview without significant increase in noise on the road geometry estimates; (2) the confidence estimate was 'tuned' for improved performance; and (3) the Scene Tracking source code was combined with that of the Forward Vision subsystem, allowing the two algorithms to run in the same hardware box.

The result of the above-described snail trail image processing is a set of 'raw' estimates of the clothoid parameters c0 and c1, and of the host's in-lane heading angle. Prior to the year 2002, these raw estimates were passed through low-pass filters to remove noise prior to being sent to the Data Fusion processor. The amount of curve transition preview obtained using this scheme was found to be disappointingly inadequate. The time constants of these filters were subsequently adjusted to values which rendered them largely ineffective. This provided nearly 500 msec of extra preview of curve transitions. The amount of noise on the estimates did not increase substantially as a result of this adjustment. Intuitively, this makes sense due to the strong similarity between images formed at nearby instants of time.

Figure 22 shows the Scene Tracker's estimate of lateral lane position at a downrange distance 2.5 seconds in front of the host vehicle. This estimate faithfully tracks the estimated ground truth, indicating at least 2.5 seconds of preview under these conditions. An alternative estimate based solely on the host's yaw rate and speed (and therefore having no preview) is also shown and is seen to 'lag' the other two curves.



Scene Tracking estimate previews curve entry/exit

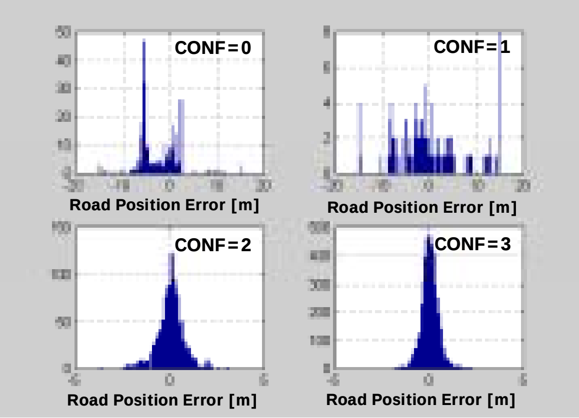
Yawrate-based estimate is delayed

L1004_05
SNTRK3

Figure 22: Depiction of Scene Tracker Preview in Curve Transition

The Scene Tracking confidence measure indicates to the Data Fusion processor how much weight to give to the Scene Tracking estimates when combining them with estimates from other subsystems. For example, if there haven't been any visible preceding vehicles for some time, and consequently there are no snail trails in the image processed by the Scene Tracker, then the Scene Tracker will signal a very low confidence level.

During the year 2002 this confidence measure was refined to be highly satisfactory. Figure 23 shows that the low confidence levels (0 or 1) correspond to rather large errors in the Scene Tracker's road geometry estimates, that level 2 corresponds to fairly good accuracy, and that level 3 indicates the best accuracy.



L1004_05
SNTRK3

Figure 23: Confidence Levels Correlate Well to Estimation Accuracy

The third main Scene Tracking accomplishment of 2002 was the porting of the code into the Forward Vision hardware box. The algorithms for both of these subsystems run concurrently on the same processor with no evident conflicts or problems.

<u>Plans for Next Six Months (through June 2003)</u>

During the next six months of the ACAS/FOT program, the following efforts will be undertaken:

(1) Enhance the fault tolerance of the Scene Tracking subsystem
(2) Support the Deployment validation field tests.

4.2.3 GPS/Map Based Road Geometry Estimation (Task C2C)

Objective

The objective of this 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 assisting in classifying detected targets as obstacles/non-obstacles using dead reckoning, differential GPS and a digitized roadway map database. In particular, the goal was to examine the suitability of the road maps as a preview sensor to develop a robust path prediction method during lane changes and curve transitions, and 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 these curve positions) potentially useful in enhancing the performance of other subsystems.

Approach

Path prediction is achieved by continuously estimating the location of the vehicle on the road, searching a stored road database for road segments in the vicinity of the vehicle's location, matching the vehicle location to a point on a road in the stored roadway map, tracking the path traversed by the vehicle and extracting the upcoming road geometry from the map. The objectives of this task are met using several sensors such as DGPS, dead reckoning and a digitized road map. The overall functional block diagram of this subsystem is shown in Figure 24.

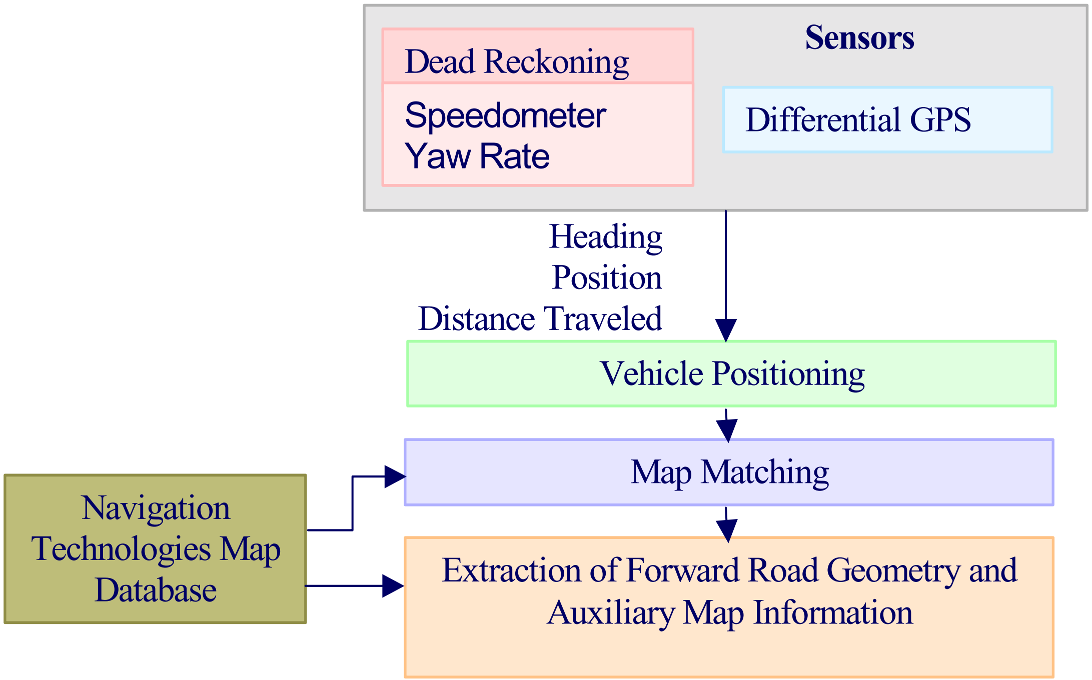


Figure 24: Overall Block Diagram of the GPS/Map Subsystem

DGPS is used to compute the heading and distance traversed by the vehicle. The accuracy in determining the heading and distance is further enhanced by computing the heading angle and distance relative to the previous position of the host vehicle. Despite the benefits that DGPS based systems offer, they are hindered by outages in GPS signals that occur in the presence of tunnels and tall buildings (referred to as 'urban canyons'), among other things. In order to overcome this shortcoming the developed approach is augmented with dead reckoning sensors, where vehicle speed is used for distance measurement and yaw rate is used for relative heading measurement.

The combination of dead reckoning and DGPS with the map database was explored to obtain a map-based path prediction system. DGPS in conjunction with the map database can provide fairly accurate path prediction except in situations of GPS signal outages. At such times, the dead reckoning is expected to carry forward the task of path prediction.

Summary of accomplishments prior to January 2002

The development of this subsystem was completed prior to January 2002 and is briefly summarized in this section. This subsystem receives inputs, at the rate of 10 Hz, in the form of absolute vehicle position (latitude and longitude information) from a GPS receiver, heading information from GPS (absolute heading) and a yaw rate sensor (relative heading), and information regarding the distance traveled by the host vehicle from the vehicle speed. It also uses a commercially available digital road-map database provided by Navigation Technologies.

Algorithms were designed, developed and implemented to output the following information at the rate of 10 Hz:

1. Forward road geometry 120m ahead of the host vehicle spaced 10 meters apart (along the vehicle path) in terms of 12 offsets to the current direction of the host vehicle

2. Road shape classification of the upcoming 120 m forward geometry, in terms of continuing straight or curved road that could be a gentle, sharp or S-shaped curve, or a curve transition from straight or to straight from a curved road (gentle curve/sharp curve/S-shaped curve)

3. Confidence estimates in terms of possible error in conjunction with every offset in the forward geometry specification. These estimates were derived from heuristics and statistical analysis of recorded trip data

4. Additional map-derived information related to upcoming forward geometry such as Presence of and distances to forks, ramps, intersections, T-junctions and tunnels; and Presence of curves, and distances to start and end of curve from current host vehicle position with its curvature estimation

5. Information related to road class (freeway, ramp, arterial, local) along with its surface type (paved/unpaved)

It was determined that the data rate as obtained from the map database 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.

This subsystem was housed in a PC104-based computer and communicated with other subsystems via a CAN bus interface. The timing, message content and format of its input and output have been verified for all the subsystem interfaces.

Extensive development and testing of this subsystem was performed using the GM Engineering Development Vehicle, the Prototype test vehicle, and on a bench setup that is essentially a real-time vehicle simulation (using GM R&D developed diagnostic tools). This subsystem was exercised using a rich suite of scenarios captured on open roads in the Detroit and Southern California areas. This scenario suite comprised a variety of road types (freeways, non-limited access roads, rural roads, congested city streets, intersections, paved and unpaved roads), number of lanes, road geometries (straight, curved, S-shaped and curve transitions), time of day conditions, traffic densities, different weather conditions and GPS outages caused by satellite obscurations due to bridges, tunnels and urban canyons.

The performance of the predicted forward geometry was evaluated against a GM R&D developed ground truth method. This method uses the vehicle speed and yaw rate to determine the actual path traversed by the vehicle. The performance in terms of accuracy of predicting forward road geometry and associated geometry attributes was found to be satisfactory.

Milestones and Deliverables January through December 2002

- May 2002 - Refinement of confidence measures
- June 2002 - Validation of the subsystem
- July 2002 - Improved reliability and robustness of the subsystem
- July 2002 - GPS/Map subsystem software complete

Work Accomplished in 2002

The development of this subsystem in terms of providing smoother road geometry transitions, confidence estimates, road geometry classification, and auxiliary map-derived information was complete prior to January 2002, and was found to perform satisfactorily with sufficient accuracy and latency. The focus of the effort during 2002 has been to improve the confidence estimates that were previously determined to be conservative, improve the robustness and reliability of the system, and reduce its overall size.
During the current year the map-matching function was enhanced to obtain better longitudinal positioning of the vehicle by performing matching onto the Spline representation of the road as opposed to the link representation (piece wise linear road representation), as done previously.

Prior to 2002, road classification was used to develop heuristics-based curve-fitting approaches to better handle curve transitions in the upcoming road geometry and provide smoother transitions to compensate for errors in the map database. In 2002, using heuristics, further enhancements were made to detect and handle severe map errors, thereby improving the accuracy of forward road geometry predictions. In addition, several internal results of the subsystem were output on the CAN bus, including road classification and curve transitions, to enable the development of better data fusion algorithms.

Although, the performance in terms of accuracy of predicting forward road geometry and associated geometry attributes was found to be satisfactory, the development of appropriate confidence measures required further refinement. Prior to the current year, a very conservative approach to expressing confidence was adopted. It was observed from the analysis of the results that, in many instances, proper predictions by the GPS/Map system were being ignored by the data fusion subsystem due to low values of confidence associated with them. Unfortunately, this fact was true for the cases related to curve transitions and S-curves, where the data fusion module depended on the output of this subsystem for meaningful path prediction. During 2002, further refinement of this method was undertaken to produce better confidence estimates and to capture these lost cases.

With regard to reducing the system size, the goal was to house all the GM developed subsystem algorithms in a single PC104-based system. Although the GPS/Map subsystem resided in its own processor (prior to 2002) it was designed in a modular fashion (it is internally self-sufficient), and could be housed in its own processor or it can reside in a processor that runs other subsystems. During 2002, along with the other GM developed algorithms, this subsystem was ported onto a single processor, thereby helping to reduce the number of GM-supplied processors from 3 to 1.

During 2002, effort was made to ensure the speed, reliability and robustness of the implementation, because this subsystem now resides within the processor that performs other FCW-critical system functions, namely the processing of sensor data, data fusion and threat assessment. In addition, system reliability was improved by installing the map database on the hard disk instead of the flash media (as previously done). The earlier lack of reliability was due to the incompatibility between the flash media and other components.

Prior to 2002, the Trimble AG132 with a dome-shaped antenna was used as the DGPS receiver because it met the overall ACAS FOT system specifications, in particular, it is able to operate at the rate of 10 Hz and to accept satellite-based differential corrections which offers the FOT participants the flexibility to travel outside their local areas. However, the major disadvantage of the use of the dome-shaped antenna (shown in Figure 25) was its bulky size (6.1 inches in diameter and 5.5 inches in height) and weight (1.2 lbs). Although, the AG132 performed satisfactorily and sufficed during the development phase, the dome-shaped antenna mounted on the trunk lid of the vehicle is very conspicuous and was found to be esthetically unsatisfactory for deployment during the FOT.

Figure 25: Domed GPS Antenna

For the FOT, a smaller (2 x 1 x 0.25 inches) and lighter (8 ounces) antenna (the AT1665-0) has been chosen for use with the AG132 receiver. This antenna has been flush-mounted on the front-center of the FOT vehicle rooftop (shown in Figure 26). Apart from the size, the other difference between the two antennas is the type of differential corrections they can receive. The AT1665-0 can receive only those corrections that are satellite-based, for example, from the Omnistar satellites and Wide Area Augmented Service (WAAS). On the other hand, the dome antenna could use both the satellite-based (including Omnistar and WAAS) and differential corrections transmitted by the NDGPS beacons (US Coast Guard system). As related to the ACAS FOT, the USCG beacons are not being used for two reasons (1) we are unsure of the timing and availability of the full nationwide DGPS coverage and (2) the quality of the corrections degrade as the vehicle moves away from the base station. Although the AT1665-0 does not receive differential corrections transmitted by the USCG, it does meet our requirements as it can receive Omnistar corrections (when available) and can seamlessly switch to WAAS when the Omnistar provided satellite-based corrections are not available, thereby providing continuous differential corrections of uniform accuracy throughout the continental US.

Figure 26: AT 1665-0 Antenna

Extensive verification tests of the overall FCW System which included the GPS/Map subsystem were conducted on open roads because of the variety of road types and conditions that are encountered that make the tests more realistic and applicable to real driving as compared to any predefined course. This subsystem was tested under a wide variety of road types (freeways, non-limited access roads, rural roads, congested city streets, intersections, paved and unpaved roads) road geometries (straight, curved, S-shaped and curve transitions), times of day, traffic densities, and weather conditions. This type of testing was especially important for this subsystem because its performance is mainly dependent on maps and GPS signal reception, and open test road test sites are the only way to get map data (of varying quality – superior, adequate, poor and non-existent) and GPS measurements over a variety of locations (normal, and challenging-namely urban canyons, and under bridges, tunnels and leafy trees).

The performance evaluation of this subsystem in terms of accuracy of predicting forward road geometry and associated geometry attributes, and accuracy of estimating confidence was found to be satisfactory and useful to the downstream subsystems such as data fusion and target selection.

Plans for the next 6 months (through June 2003)

All Task C2-C milestones have been reached, and no new tasks have been scheduled.

4.3 Threat Assessment Algorithm Development (Task C3 & C5)

Objective

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

Background

The Threat Assessment Algorithm uses data supplied by the Target Selection function, radar, and vehicle sensors to produce an alert to the driver warning that an imminent collision will 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. This was thought to be possible only with the use of additional sensors and algorithms beyond what was previously in use. The additional sensors and algorithms are vision, scene tracking, GPS/data map and data fusion. These additional technologies make it possible to better discern the road geometry and thus better identify the closest in-path object when operating near transitions to or from curved road segments.

The usefulness of the driver alert warning depends on the robustness of the Threat Assessment algorithm. The algorithm must determine 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 vehicle and object, and the driver's brake reaction time. The time of collision 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 non-deterministic 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.

Summary Of Accomplishments Prior To January 2002

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 requirement of development of the FCW algorithm was to make it compatible with ACC operation.

The results of the computer simulation studies to develop the Threat Assessment algorithm are reported in the Threat Assessment Simulation Summary Report of July 2001. The Threat Assessment algorithm was implemented in GM's Engineering Development Vehicle and then in the Prototype Vehicle. Enhancements were made at each stage to reduce the number of nuisance alerts. The Threat Assessment algorithm was tested during the verification tests of the Prototype vehicle described in Deliverable Number 27 – ACAS/FOT Phase I Interim Report.

Work Accomplished During 2002

The design and implementation of threat assessment algorithm was completed by the fourth quarter of 2001. During 2002 the main emphasis was on further testing, validating and fine-tuning the algorithm. As a result of this testing a number of issues with the algorithm were identified and worked on. False alarms under certain conditions were observed and although the frequencies of these incidents were already 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.

Turning Lead Vehicle

One of the scenarios is the host vehicle approaching the closest in path vehicle (CIPV) where CIPV is starting to turn to leave the predicted path of the host vehicle. An alert driver normally perceives this situation, thus even if the host vehicle is closing in on the lead vehicle the driver does not take an evasive action (braking or steering). The reason is that the host vehicle driver estimates the lead vehicle will be out of the predicted path before the host vehicle reaches that point. However, under certain range, range rate and speed conditions the threat assessment algorithm generates a warning to the driver. The algorithm has been modified to detect that situation and not issue a warning to the driver.

Three-Second Filter

The threat assessment algorithm is a two-stage algorithm. The first stage is a 'cautionary warning' where only a visual warning is issued to the driver. In this stage, a car icon is displayed on the head-up display (HUD), and this icon gets larger in size as the condition approaches the 'imminent warning' stage. Also, part of the first stage warning is a tailgating warning, where the car icon on the HUD behaves similarly, that is, gets larger as tailgating approaches imminent warning stage. Especially under tailgating condition, it has been observed that the car icon was changing its size very frequently, in effect becoming a distraction to the driver. To eliminate this situation, a 3-second filter has been 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, 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 while the tailgating warning is in effect.

Alert Delay on Brake Release

The aural and visual collision warning to the driver is suppressed as soon as the driver actuates the brakes, indicating that the driver is 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 warning will come on again. This is unsatisfactory and is a nuisance to the driver since the driver is already aware of the situation. To overcome this problem, a delay has been introduced from brake release to a new warning. The threat condition has to persist beyond the delay period before the warning is activated again.

Low Speed Low Range Rate Alerts

The threat assessment algorithm factors in many different situations for generating the driver warning. It has been observed that at low vehicle speeds, 20 mph to 35 mph, and low closing rates, 10 mph or lower, the warning was perceived to be activated too early. The algorithm was modified to correct this condition.

4.4 ACC Function (Task C4)

Objectives

The objectives of task C4 are to:

1. Provide an ACC (ACC) for the 2000 and 2002 Buick LeSabres
2. Determine the interface requirements to the other vehicle subsystems
3. Provide support to other development and deployment groups

Approach

The approach is to utilize the ACC subsystem that is part of a future production program. The ACC subsystem is a complete control system that uses integral radar to detect objects in front of the vehicle, and provides throttle and brake control to maintain a driver-selected distance to the car ahead. The radar also detects objects for the FCW system in the vehicle. Since the ACC is being used unalerted, the design work focused on the interfaces between the ACC system and the rest of the vehicle.

Work Accomplished through 2001

As described in the First Annual Report, and in the Interim Report, the work accomplished in this task has consisted of determining the interfaces to be used between the ACC module and the rest of the vehicle, implementing those interfaces, tuning the ACC for the Buick LeSabre, and testing and evaluating the entire system.

A simple simulator was developed that allows A/B comparisons of potential algorithms and alternative parameter values. The simulator also allows the tracking of the flow through the code to determine what causes anomalous behavior.

Preliminary tuning of the algorithm began in 2000, and has continued through 2002. As the prototype and development vehicles were built, the opportunities to drive and evaluate the ACC subsystem increased, and the tuning activity intensified, to the point where work on this subsystem became continuous.

Work Accomplished during 2002

The effort over the last year has been devoted to three areas: (1) improving processes, (2) improving performance, and (3) removing anomalies. For the purposes of this discussion, anomalies are defined as events that occur in some “incorrect” manner. Performance improvements are changes that are made to events that already occur “correctly”, but not satisfactorily. For example, if a braking event occurs for no apparent reason, which is an anomaly. If it occurs one second before optimal time, that is considered a performance issue.

Process Improvements:

1. A program that automatically looks up and loads the correct calibration values into the radar units was developed and, is now being used. This replaces the former laborious manual lookup and byte-by-byte loading procedure. It also provides a central facility for collecting and holding all the relevant radar data.

2. Further improvements to the data gathering software were made. These improvements allow ACC internal variables to be stored for later analysis.

Performance improvements:

1. ACC Startup Problem: sometimes, when the car was started, ACC would not engage. It was necessary to power down the car and restart it to get ACC to engage. The cause of the problem was an improperly initialized Class 2 chip. The fix was to reconfigure the Class 2 chip whenever the "bus shorted" fault is detected.

2. Approach Roughness: When approaching a Lead Vehicle, there is a tendency to apply brakes suddenly in order to arrive at the required headway distance. This tendency has been reduced. The consequence of this reduction is that a small amount of overshoot (being, temporarily, slightly closer to the lead vehicle than desired) is now allowed.

3. Lead Vehicle Deceleration Roughness: Upon light decelerations of the lead vehicle, the host vehicle sometimes responds with forceful braking. This issue is still being addressed. A tradeoff exists between smoothness in this situation and reducing the frequency of brake applications when following (see #2 under "Anomalies"). In order to make the responses smoother (less severe), the braking must begin earlier, when less information is available to make a determination of the lead driver's intentions. This may increase the frequency of ACC brake applications.

4. Downhill Cyclic Braking: When following a vehicle on a down slope, the host vehicle may apply brakes several times. This phenomenon has been reduced, but it probably will not be eliminated on very long downhill section of road. The brake system has been modified to allow braking (but not require it), even when zero decelerations are requested, as is the case when the vehicle is on a downhill slope. The key to this function is determining when the vehicle is indeed on a downhill slope. This issue is still being worked.

5. Turning Vehicles: When following a lead vehicle that slows and changes lanes to make a turn, the host vehicle sometimes continues braking, as though the lead vehicle were still in front of it, even when the driver can clearly see that the lead vehicle has left the lane. This tendency has been reduced by dropping the target (lead vehicle) sooner if it is at the edge of the radar field of view. The downside of this change is that target reacquisition must occur if it changes direction and moves back in front of the host vehicle.

6. Lane Change to Slow Vehicle: When changing into a lane in which there is slowly-moving lead vehicle, the ACC system takes a seemingly long time to react to the new situation.

This is a very difficult situation for the radar and ACC systems. The prediction of the vehicle path, necessary for proper target identification, is quite unreliable during and shortly after the lane change because of the filter time constant on the yaw rate signal. Further complicating the situation is the radar field of view, which may not be wide enough to acquire the vehicle in the new lane until the lane change maneuver is nearly completed. Also, the lead vehicle in the old lane may have occluded the new lead vehicle in the new lane, so there may be no opportunity to acquire the new lead vehicle before the lane change maneuver starts.

These facts delay the selection of the new target in the new lane. But since the Lane Change to Slow Vehicle scenario probably comes about with the driver in full control of the host vehicle and aware of the new lead vehicle, the risks are substantially diminished, and resources have been applied to problems of a higher priority.

Anomaly Removal:

1. Spurious Driver Intervention Required: When following in normal situations, ACC sometimes disengages and the “Driver Control Required” message appears, for no apparent reason. This anomaly is rare and was hard to reproduce. It appears to be related to the effort to improve performance by reducing latency in some of the message traffic between processors. It is an extremely complex problem, and has so far resisted significant attempts at resolution. Work is continuing on this problem.

2. Too-Frequent Braking: When following a lead vehicle, a braking event occasionally occurs for no apparent reason. This anomaly results from being overly sensitive to the decelerations of the lead vehicle, and from trying too hard to keep the host vehicle at the required headway distance. The proper balance between maintaining headway accuracy on the one hand, versus driver comfort on the other will be achieved through continued tuning of the parameters available.

Plans for Next Six Months

The plans for the next 6 months are to continue with improvements to the ACC subsystem until final system freeze and support the deployment of the vehicles in the field test.

5 FLEET VEHICLE BUILD (TASK D)

Objectives

The objective of the Fleet Vehicle Build task during Phase II of the program is to build, test and validate two Pilot Vehicles and Deployment Vehicles. Subsequently, the Pilot Vehicles will be upgraded, functionally and cosmetically to Deployment Vehicle status providing a total of thirteen Deployment-level vehicles. Ten of these vehicles will be used by UMTRI for the FOT, and one each will go to NHTSA, GM and Delphi.

Approach

Since the functionality of the system was validated rigorously during the Prototype Vehicle phase of the program, the main thrust of the current task was to productionize the system. The vehicles will be handed over to lay subjects for four weeks each and will be driven unaccompanied under naturalistic driving conditions. This requires that ACAS packaging is transparent to the customer so that the customer perceives the vehicle as a regular production car similar to one he/she might purchase rather than a special test vehicle. Otherwise, the behavior of the subject may be biased in how he/she drives or handles the vehicle. Another important issue is the space that the ACAS equipment occupies in the vehicle. The design of the vehicle modifications needs to be such that there is no intrusion in the cabin area, especially around the driver. The next issue is the cargo area, where the subject should have reasonable cargo area to accomplish daily tasks. Finally, the exterior of the vehicle should not be modified drastically so that it would attract attention of others as well as the subject.

First, the 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 to be limited by performance or the hardware of the computers. In the Pilot Vehicle all these functions were integrated into a single computer. This was feasible for the following reasons. First, all the functions were already developed and verified. The performance and hardware requirements were known at this time. Thus, some of the functions communicated via software calls rather than over the CAN bus. Second, computer technology progressed during this time such that new systems were available that met the requirements of all the individual components. The computers that perform all these functions are in the trunk of the vehicle. The functions that GM is responsible for that were implemented in a single computer are as follows:

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

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

Delphi Delco Systems integrated the functions that they are responsible for into two hardware systems. First, the following two functions were integrated into a single computer located in the trunk

- Vision processing
- Radar Scene Tracking.

A second computer was used to implement the following functions and is located in the trunk:

- Radar Control processing
- Host Path Estimation processing
- Target Selection processing

The DVI processing resides in a single computer packaged with an audio amplifier and HUD controller. This computer is located in the trunk.

The final major unit located in the trunk is the Data Acquisition System designed and implemented by UMTRI. This is the only unit that needs to be accessed during the FOT. When each subject is finished using the vehicle the data will be offloaded by manually connecting the Data Acquisition Unit to a land-based computer network.

All the systems installed in the trunk of the vehicle are mounted on a metal chassis, enclosed in a metal box that is placed in the front end of the trunk (under the back shelf of the passenger compartment). The enclosure is secured to the floor, occupies minimal amount of trunk space, is locked to be tamperproof, and is on rollers for easy access and maintenance. There is an additional locked access door in the front to be able to connect the Data Acquisition System to a land-based computer network.

The picture of the sub-systems in the trunk is shown in Figure 27.

Figure 27: The Picture of Sub-Systems in the Trunk

The interior of the vehicle is more important from the subjects' point of view. There are only a few modifications compared to the production version of the vehicle. First, there are a few Driver-Vehicle Interface modifications. The temperature control button was changed to a "Gap" setting button. Thus, the driver/occupant has to adjust the temperature through the front panel of the HVAC system. The "Gap" setting adjusts the timing of the FCW warnings or the headway in ACC, depending on the system mode The driver output is achieved through two separate means. The common one is the HUD. The HUD is custom made but fits in place of the production HUD. Thus there is no perceived difference from the packaging point of view, but the HUD can achieve higher brightness and has higher resolution. The HUD intensity and position adjustment controls in the vehicle are the same as in the production vehicle.

There are two forward-looking cameras mounted on a bracket behind the rear-view mirror (from the driver's point of view). A shroud that eliminates tampering as well as reflections from the windshield covers the complete mechanism. Another camera is mounted on the A-pillar on the driver side, and is aimed at the face of the driver. This has a built-in housing to eliminate tampering.

A picture of the HUD is shown in Figure 28. A picture of the steering wheel controls is shown in **Error! Reference source not found.**. A picture of the forward-looking cameras is shown in Figure 29. A picture of the driver face camera is shown in Figure 30.

Figure 28: Head-Up Display

Figure 29: The Picture of Steering Wheel Controls

Figure 29: Forward-Looking Cameras

Figure 30: Driver Face Camera

The exterior of the vehicle is modified. The most visible modification on a pillar is the GPS antenna mounted on the roof, centrally located, above the windshield. This antenna is much smaller in footprint than the original antenna provided by the GPS manufacturer and an aftermarket antenna manufacturer supplies it. The gray color of the antenna is not matched to the body color of the vehicle. The second modification is in the grill of the vehicle. The radar is mounted behind the grill and must be able to transmit/receive through the grill, thus a small window is carved out of the grill. A special material that is transparent to radar waves covers this window. The original Buick emblem is moved to the side, but is still on the grill. A cellular telephone antenna is attached to the rear window, in addition to a similar antenna used by OnStar on the production vehicle.

A picture of the radar is shown in Figure 31. A picture of the GPS antenna is shown in Figure 32.

Figure 31: Radar with Front Grill Removed

Figure 32: GPS Antenna on Roof of Vehicle

There are some modifications under the hood. A heavy-duty alternator is installed instead of the original production alternator to provide the additional power needed by the overall ACC/FCW system. Also, a new brake actuator and controller are installed under the hood. This is to provide the electronic braking function needed by the ACC system. This replaces the production brake actuator and is transparent to the driver.

Overall, a complex system is added to the production vehicle, however, these modifications are not intrusive or intimidating to the driver and/or to the occupants. The reduced size of the trunk is the most notable impact of this additional system.

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 may 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 General

Motors Engineering Development Vehicle (GM EDV) was to develop, design, implement, and investigate a number of technologies that would potentially be available on the deployment vehicles of the ACAS/FOT Program. 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 the Assistware System
- Human factors

Delphi Delco worked on a number of development vehicles. Two vehicles were dedicated to the ACC (ACC) function to optimize this function for the Deployment Vehicles. ACC was improved and tuned for use in the Buick LaSabre, the vehicle selected for the FOT. Another function that was developed by Delphi Delco 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. Delphi Delco designed the Driver Vehicle Interface on a dedicated Engineering Development Vehicle. This work entailed designing a completely new Head-Up Display (HUD) system to be used on the Deployment Vehicles. Delphi Chassis Systems developed an electronically controlled brake system that is required for the ACC function.

This included a new controller development as well as new brake actuator.
The GM EDV is a 2000 model year Buick LeSabre that has been significantly modified to accommodate all the instrumentation required to investigate the intended technologies. Our 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 finally determining the best approach for this task. Important factors in this determination were:

a. Simplicity and ease of implementation
b. Compatibility with our partners' architectures
c. Ease of debugging the system
d. 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, the first step taken in this task was to implement the pertinent vehicle architecture in the laboratory. The configuration that was intended for the vehicle was implemented on a bench with the identical computers, communications scheme, and was add-on sensors. However, integrating the vehicle sensors on the bench system is not possible in a laboratory environment.

The goal and purpose of building the Prototype vehicle was to integrate all the technologies developed, evaluated, and down selected by the partners in the program into a single vehicle. The Prototype vehicle is a precursor to the Pilot vehicles. The Pilot vehicles have the same functionality as the Prototype, however, the hardware partitioning of functions, hardware form factors, and the packaging and layout in the Pilot vehicles are different. Functionality of the Prototype, with improved packaging, carried over to the Pilot vehicles and finally to the Deployment vehicles. However, the Prototype vehicle has the full functionality as required to support the ACAS/FOT.

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 was not a straightforward task, and 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. Delphi Chassis Systems in Brighton, MI, installed the brake system. Delphi Delco Systems in Malibu, CA installed the throttle control and ACC system. Delphi Delco Systems in Kokomo, IN installed the Driver Vehicle Interface. GM R&D Center built the vehicle infrastructure and installed the remainder of the systems in the vehicle as well as performed 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 has 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, this vehicle will contain a full-featured data acquisition system, which will be installed after the validation tests. The data acquisition system that was on the GM EDV was used throughout the development and validation of the Prototype vehicle.

The software system is 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
- Driver-Vehicle Interface with the Head-Up Display
- ACC
- Throttle control for ACC
- Brake control for ACC

The architecture of the Prototype vehicle integrates the functions of the GM EDV with the partners' EDV. The major differences compared to the GM EDV are the additions of the ACC System (which involves throttle and brake control) and the DVI (mainly due to the use of HUD). The Path prediction function has been 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 is unlike the GM EDV because each partner delivered one or more of the functions already implemented in various engineering development vehicles.

Work Accomplished in 2002

The architecture of Pilot and Deployment Vehicles were defined during this phase of the program. This architecture (shown in Figure 33) was implemented and installed into the vehicles as described in 'Approach' Section of Fleet Vehicle Build (Task D). It is a streamlined version of the Prototype Vehicle design. In addition, a number of vehicle modifications were made to assist the installation.

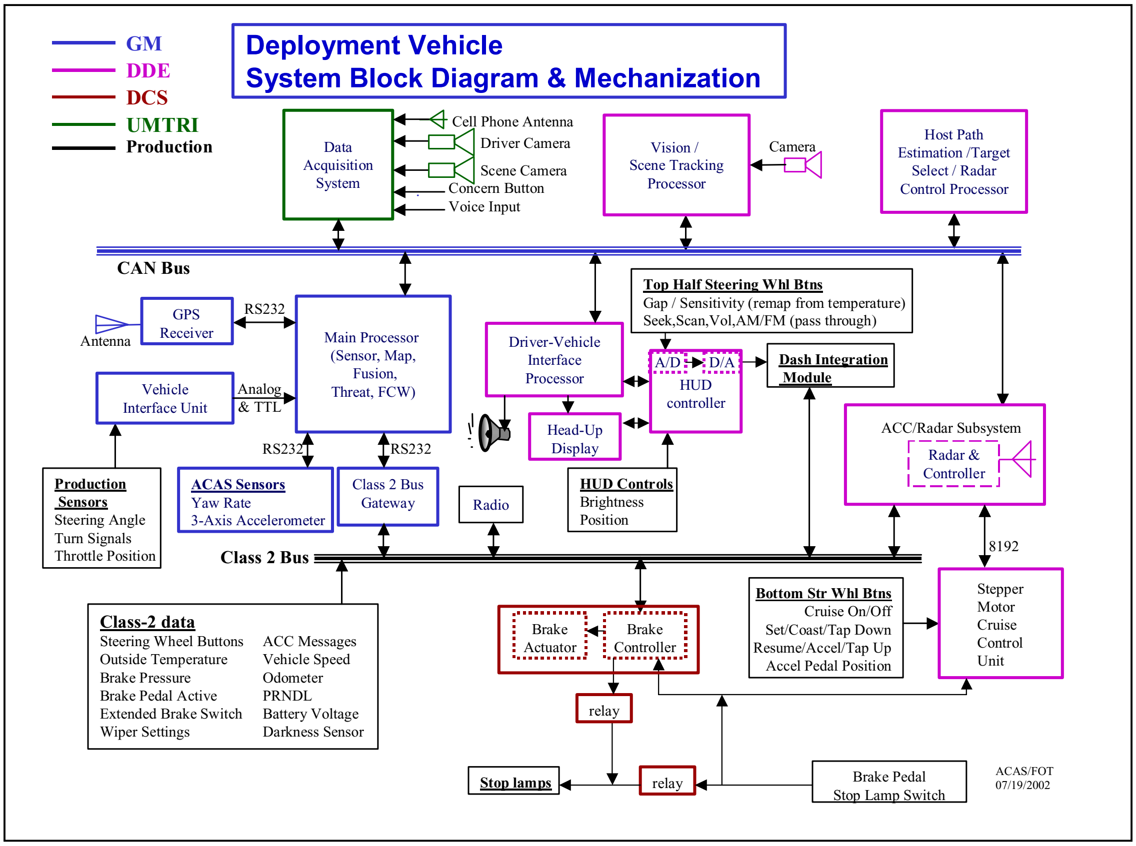


Figure 33: Architecture of Pilot and Deployment Vehicles

There are two major data communication busses 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 is accessed. This eliminated the need to duplicate a number of sensors as well as providing access to data related to the state of the vehicle. In addition, data communications between the brake controller and throttle controller is 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. All elements of the system exchange information through this bus. The central sub-system is the Main Processor. All the vehicle sensor information is accessed and handled by this processor. 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. The GPS receiver communicates its information over a serial bus to the Main Processor. The processor contains the map of the continental USA, which is matched to the coordinates provided by the GPS system for road curvature determination. The Data Fusion algorithm runs on this processor based on the information provided by other subsystems. Finally, Threat Assessment and FCW algorithms are executed in this processor.

The Vision and Scene Tracking Processor is interfaced to a forward-looking camera. Vision algorithms determine the lane marker position and curvature ahead on the roadway, and the heading of the vehicle within the lane. This processor also receives the radar data to execute the Scene Tracking algorithm, which is one of the input components of the Data Fusion.

The Host Path Estimation, Target Selection and Radar Control Processor perform multiple 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 Driver-Vehicle Interface 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 aural feedback to the driver.

ACC/Radar sub-system is communicating both through the Class 2 bus and the CAN bus. There is a controller embedded in the radar that controls the throttle and the brakes based on the algorithm running within the sub-system.

The final sub-system 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 sub-system is also interfaced to two cameras (for recording road view and driver face) and a cellular telephone (for communicating with the base station) and a microphone with concern button (for recording voice input from the driver).

Research Findings From 2002

The Deployment vehicles are currently being tested and validated. Early results demonstrate that the Deployment vehicles are functioning in compliance with the technical specifications. The most important issue is the reliability of the vehicles. The subject should experience predictable behavior from the ACAS system whenever they drive with the system enabled. These issues are being investigated and addressed.

Plans for Next Six Months (through June 2003)

The plan calls for a total of thirteen vehicles to be built, two Pilot and eleven Deployment Vehicles. During 2002 ten vehicles were completely built and three vehicles were partially completed. These three vehicles will be finished by the end of January 2003.

The next step is to observe the vehicles during the Field Operational Test to identify any common problems or failures. The task will be to fix these common problems by design modifications so that they are completely eliminated. There could be isolated problems with any of the vehicles during this period. These kinds of problems will be investigated and proper actions will be taken to resolve the issues.

6 FIELD OPERATIONAL TEST (TASK E)

Objectives

The primary objective of UMTRI's effort has been to measure and analyze ACAS system performance by means of pilot testing in order to assist GM in the system refinement process, and prepare for the launch of the FOT. This activity involved sub-objectives as follows:

1) To conduct Stage-2 Pilot testing, using the ACAS Prototype vehicle
2) To conduct follow-up analysis by which to define performance problems observed in the field and to suggest/explore system revisions as appropriate
3) To finalize design on the Data Acquisition System (DAS)
4) To build DAS packages for equipping the FOT fleet
5) To conduct an ad-hoc Pilot testing activity that became dubbed "Stage 2.5"using virtually FOT-ready vehicles having several new system improvements,
6) To perform Stage 3 Pilot testing, as the dress rehearsal of the FOT

Approach and Accomplishments Prior to 2002

Since the FCW function within ACAS had not been the subject of a field test before, it was intended that both "hands-on experience" and sample data be obtained through testing in the normal driving environment, prior to the formal FOT. It was felt, at the time of proposing the ACAS project, that so many complex issues would eventually determine the success or failure of the combined ACAS functions that only a substantive preliminary test experience could establish the level of confidence and reveal the needed refinements that would be required for an FOT. Figure 34 shows the sequential process of approach toward the FOT is diagrammed.

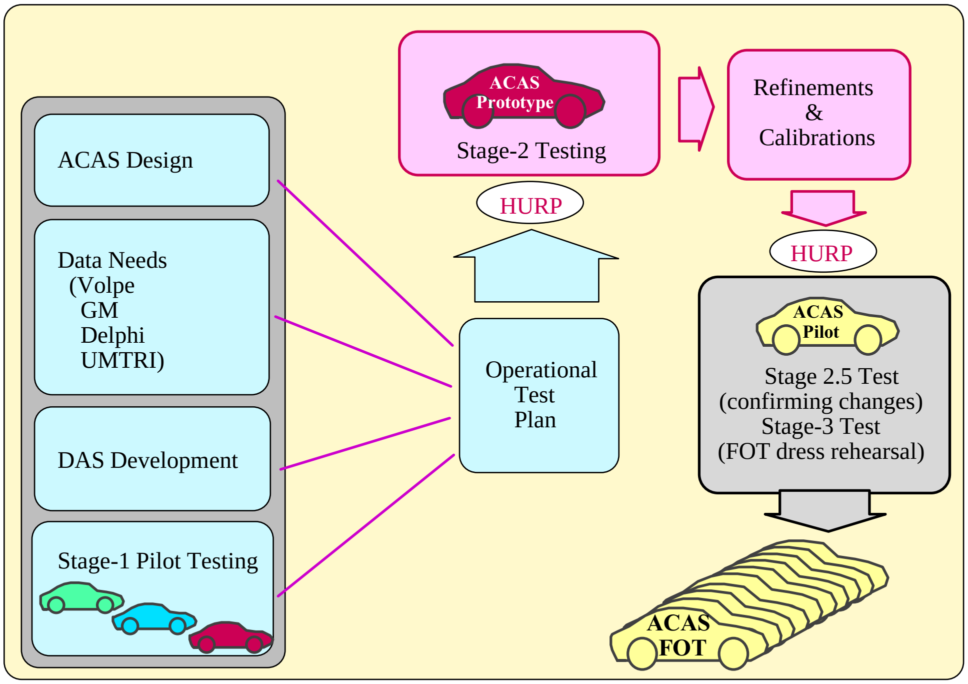


Figure 34: FOT Preparation Process

The left side of Figure 34 shows that several activities and considerations contributed to the Operational Test Plan that was submitted first in the summer of 2001 and then in an updated form in May of 2002. Included in UMTRI's early activities was a series of Stage 1 pilot tests using an ACC-equipped Opel, an FCW-equipped Opel, and finally the GM EDV for ACAS. In the last year, this work has been succeeded by layperson testing using two integrated versions of the ACAS vehicle. In Stage 2 pilot testing, laypersons drove the ACAS Prototype vehicle over a defined route. The results of this test highlighted the need for refining aspects of ACAS performance, given subjective observations by the drivers, as well as, results from the quantitative data.

A major set of system changes ensued, requiring a repeat of portions of the Stage 2 test set before handing the vehicles on for unaccompanied use by another group of laypersons in Stage 3. The purpose of the repeat testing—in what was termed Stage 2.5—was to confirm that changes to the ACAS design (almost all in the domain of software) had been accomplished successfully. This was confirmed and the present approach (in December 2002) is to proceed into the Stage 3, "FOT dress-rehearsal" test as a final step before launching the formal FOT early in 2003.

Beyond the test-based evaluations of ACAS prototypes, UMTRI's prior work on the project also entailed the development of the DAS package that is tailored to match the ACAS platform. This package, in turn, is supported by a data management and archiving system by which test data are stored and analyzed. This system has been operated successfully in support of all stages of pilot testing to date.

Milestones/Deliverables January through December 2002

Milestone 34: FOT Pilot Testing with Accompanied Laypersons

- April 2002 – completed (finishing Stage 2 Testing)
- November 2002 - completed (finishing Stage 2.5 Testing)
  (Note that the Stage 2.5 Pilot Test was added to the project plan during 2002 and had no milestone of its own.)

Milestone 35: Completion of FOT Data Acquisition Package

- August 2002 - completed first FOT DAS
  (DAS changes occurred through the rest of the year, in light of ACAS system refinements and in-field experience with DAS components and software. Components were on hand for all 13 DAS packages by mid-December and 7 packages had been completed. Five packages had been put into service supporting ACAS development and Pilot Testing.)

Milestone 36: Completion of FOT Second HURP Approval Process

- May 2002 - completed HURP approval process for Stage 3
- September 2002 - completed HURP approval process for Stage 2.5

Deliverable 32: Submission of FOT Second HURP Request (unaccompanied…)

- April 2002 - submitted application
- September 2002 - submitted revision (for Stage 2.5 approval)

Accomplished in 2002

The work in this task spanned the following accomplishments in 2002:

- Final design of the DAS and completion of half of the assembled packages
- Preparations, HURP-approval, and conduct of Stage 2 and Stage 2.5 tests of the ACAS vehicle with accompanied subjects
- Extensive analysis of test data so as to support GM/Delphi in the refinement of ACAS system performance in light of realities observed from quasi-naturalistic driving
- Refinement of the Operational Test Plan
- Adaptation of DAS design, subject orientation materials, and FOT planning and scheduling to accommodate changes in ACAS design and performance

Since extensive presentation of the DAS design and the Operational Test Plan have been provided in previous progress reports, it seems appropriate here to focus on the most significant work to date in Task E: the Stage 2 and 2.5 Pilot Tests. A brief sketch of the test protocols is given here, followed by a summary of the principle findings.

Stage 2 Pilot Test Protocol

The Stage 2 Pilot Testing was conducted using lay subjects in March and April of 2002, employing the following approach:

- Twelve lay drivers as test subjects, - four drivers in each of three age groups (20, 40 and 60)
- Six men and six women - two of each respectively in their 20's, 40's, and 60's
- Driving over three successive circuits of a 58-mile route (comprising 42 miles on freeway segments and 16 miles on surface streets), as follows:
    - ♦ 1st lap: ACAS disabled (like in the first week of the formal FOT)
    - ♦ 2nd lap: ACAS enabled, but without using ACC
    - ♦ 3rd lap: ACAS enabled, ACC use encouraged on freeway segments
- Accompanied by a researcher in the back seat
- All testing conducted in daylight, under mid-day (moderate) traffic conditions, on dry roads
- Questionnaires administered to obtain subjective ratings
- Quantitative data obtained to show system performance
- Data analysis used to support the ACAS refinement process

The test amounted to 2045 miles of exposure over which a full set of measured data was obtained.

Stage 2.5 Pilot Test Protocol

The Stage 2.5 Pilot Testing was conducted in October and November 2002. As a follow-up to Stage 2, several changes had been made to the ACAS threat assessment algorithm, sensitivity settings, and the HUD-displayed warning. Before the ACAS vehicles could be given to unaccompanied subjects in Stage 3 protocol, it was decided that a modest "rerun" of Stage 2 was necessary to ensure that the modified algorithms were effective and that the system was benign for layperson usage. The test activity involved the following elements:

- Five men and one woman lay drivers as test subjects; all participants of Stage 2 testing.
- Two drivers each in age groups of 20, 40, and 60
- Driving over two circuits of the same 58-mile route as used in Stage 2, as follows:
    - ♦ 1st lap: ACAS enabled, daytime, ACC use encouraged on freeways
    - ♦ 2nd lap: ACAS enabled, nighttime, ACC use encouraged on freeways
- Accompanied by a researcher in the back seat

- All testing under off-peak (moderate) traffic conditions, on dry roads
- Questionnaires administered to obtain subjective ratings
- Quantitative data obtained to show system performance
- Data analysis to determine readiness for unaccompanied driving in Stage 3.

The Stage-2.5 driving amounted to 700 miles of exposure over which a full set of measured data was obtained.

Research Findings from 2002

In this section, the prominent findings from Stage 2 and 2.5 testing are reviewed.

Stage 2 Pilot Test Results – Imminent Alerts

Test data showed a relatively high rate of imminent alert production during all driving in which the ACAS function was enabled. A total of 92 imminent alerts were experienced by the group of twelve drivers, corresponding to an overall rate of 6.6 imminent alerts per 100 miles of driving. A detailed breakdown showed that alerts occurred almost exclusively on surface streets and when driving manually, with ACC disengaged. The alerts were split about evenly between moveable targets and stationary targets. The general view of the project team was that the overall rate of imminent alert occurrence was at least twice too high for a successful FOT.

Stage 2 Analysis of Imminent Alerts – Stationary Targets

In order to help refine the ACAS algorithms to reduce the rate of imminent alerts, further analysis classified the alert events by attributes that could be addressed in the threat-assessment and warning code. By scrutinizing the video record at each alert event, a total of 42 specific *stationary* devices were identified as the cause of an imminent alert, together with the nominal maneuvering condition under which an alert was triggered. Later study of these details led to certain algorithm changes that helped to reduce the very high rate of alerts that occurred at curve-entry points.

Stage 2 Analysis of Imminent Alerts –Moveable Targets

A somewhat larger set of imminent alerts were derived from *moveable*-target interactions. Scrutiny of the video tape from these episodes led to classification of so-called “in-lane” and “lane-transition” incidents. In-lane alert incidents are those in which the target has remained within the host vehicle’s lane throughout the sequence that produced the alert. These include conflicts due to lead vehicle braking, host vehicle approaching, host vehicle accelerating, and host vehicle tailgating a preceding vehicle. In general, these scenarios were seen as difficult to address in threat assessment algorithm in a manner, which did not impact the desired timing and value of the alert.

The Lane-Transition incidents are those in which either the target or the host vehicle has transitioned from their initial lane in the process of triggering the alert. Five specific scenarios were identified from the data, including conflicts due to cut-in, host vehicle moving into turning lane, host vehicle moving to pass, lead vehicle moving into adjacent lane, and lead turning onto an orthogonal road/driveway. The data showed that the “lead turning" scenario is the dominant type of movement producing an imminent alert. In all of these incident scenarios except that of the lead vehicle-cut-in, the host driver is basically electing to drive into a developing conflict zone. Each of these scenarios offers some opportunity for modifying the threat assessment algorithm.

Stage 2 Analysis of Imminent Alerts – Immediately Following Brake-Release

One of the major opportunities for reducing nuisance alerts was noted in the high incidence of imminent alerts that occur immediately upon release of the brake. For example, 22 of the 92 imminent alerts in Stage 2 occurred within 1.2 seconds following brake release. This result suggested that the host driver is often in the process of braking to manage a developing conflict at the time an imminent alert is issued. Assuming the driver is attentive to the forward scene while braking, suppressing the alert for a brief interval following brake release is believed to be a practical strategy due to the persistence of a sort of "halo effect" of the attentiveness that naturally accompanies braking. Thus, the analysis of test data supported a change in the threat assessment algorithm to suppress imminent alerts when they occur within 1.5 seconds following any brake-release event.

Stage 2 Analysis of Cautionary Alerts

A surprisingly large incidence of cautionary alert was also observed during Stage 2 testing. Recognizing that cautionary alerts often involved a choppy sequence of displays that include short gaps due to braking or brief fluctuations in the threat level, it was convenient to summarize the experience by counting all cautionary alert episodes that were continuous except for gaps lasting less than four seconds. The test data contain a total of 747 episodes of cautionary alert, using this metric for discounting short gaps, over the course of "ACAS-enabled" driving in Stage 2. The general view of the research team was that this frequency of cautionary alert was much too high.

Considering a change in the cautionary alerting rules, it was noted that the cautionary alert experience derives primarily from the subjects' selection of FCW sensitivity level, on the 1 through 6 scale of adjustment. Since the highest setting, (6), was the default value that each subject encountered upon beginning each drive, much of the overall driving exposure occurred without any adjustment toward settings below the highest setting. However, the rate of cautionary display at setting 6 was about 140 times higher, for example, than accrued at a sensitivity setting of 2. Thus, it was determined that a lower default value should be selected and that, further, the so-called "tailgating" feature of the related algorithm be constrained to further manage the rate of cautionary alert production.

Stage 2 Results – ACC

With regard to ACC activity, a total of 425 driving miles and 6.2 hours of exposure were accrued, with approximately half of the ACC drive time spent with a target vehicle less than 3 seconds ahead. Due to the moderate traffic conditions, there were only 33 auto-braking events, such that most of the headway-management corrections of the controller involved modulation of only the throttle. The ACC driving data yield a histogram of headway time that looks very similar to that seen in the data from the ICC-FOT conducted for NHTSA in 1997. As in the ICC-FOT, preferred time headway margins increased with age.

Stage 2 Results – Subjective Questionnaires
Each participant in the Stage 2 tests filled out subjective questionnaires. The results indicate that ACAS was judged to be as safe to operate as was the system reported in the ICC-FOT although the safety-enhancing value of ACAS as an automotive feature, per se, was less clear. On the general matter of driver acceptance, results tended to indicate that the FCW. The alert display was also seen as somewhat distracting, although with wide variance of opinion. Moreover, the subjective results confirm that while the FCW functions of the system are considered benign, they did not offer compelling value that would justify their purchase on a new vehicle. These results served to prompt a reconsideration of the warning criteria and presentation display, in order to enhance the acceptability of the system.

Subjective comments related to the ACC feature of ACAS were broadly positive, showing the same high levels of enthusiasm for this function as seen in UMTRI's ICC-FOT results from 1997. These results suggested that ACC can be operated safely. Participants perceived a high value in this ACC system, as indicated by their interests in buying it on their next vehicle.

Stage 2 Pilot Test Conclusions

Stage 2 testing supported the following conclusions regarding the respective FCW and ACC functions of the ACAS package:

Regarding FCW…
- The system reliability was in need of improvement for FOT usage, primarily to ensure that the automatic boot-up process is faultless
- The rate of imminent alert on freeways was very low
- The rate of imminent alert on surface streets was higher than desired
- Cautionary alert rates and times were high, especially at the default sensitivity level
- Several opportunities for reducing the rate of imminent alert were identified
- Subjective ratings for FCW safety and ease of use were high
- Subjective ratings on FCW utility and value to the customer were moderate, suggesting that improvements in alert algorithms are warranted
- Given the several identified opportunities for final refinement in these algorithms, it is anticipated that an FOT suitable version of the FCW function is within reach

Regarding ACC…

- The system reliability was fine
- ACC decelerations were moderate and yielded no imminent alerts
- ACC's headway control was rather soft (and may warrant some further tuning)
- The observant headway-keeping performance approximated that of the system used in the ICC-FOT
- Subjective ratings for safety, usability and acceptance were uniformly high
- Subjective ratings, generally, tended to exceed those from the ICC-FOT
- The ACC system was seen as suitable for FOT usage

Stage 2.5 Tests –Hi-Level Results

Results from Stage 2.5 testing showed that major improvements in ACAS performance were achieved through the refinements made during the summer of 2002. The imminent alert rate was seen to fall from about 6 alerts per 100 miles over the test route to less than 3 per 100 miles. We also observed a drastic reduction in the rate of cautionary alerts, using a default value of 4 for the FCW sensitivity setting.

Subjective ratings measured from the six participants in Stage 2.5 showed comparable or modestly improved opinions relative to the Stage 2 results. Moreover, the Stage 2.5 testing confirmed that several algorithmic changes succeeded in reaching the level of performance considered acceptable for the FOT.

Task Gantt Chart

A high-level schedule of major activities leading up to the FOT is shown in Figure 35. This schedule accords with the recently amended plan for the overall project. The figure shows that Stage 2.5 tests occurred between mid-October and November 3rd, and that the Stage 3 dress rehearsal testing was slated to run from the third week of November to mid-December. At the writing of this report in mid-December, it appears that only two of the six subjects scheduled for Phase 3 will be run prior to the end of the year, suggesting that Phase 3 will not be concluded until the middle of January 2003.

With two to four Pilot vehicles currently on hand at UMTRI, delivery of the remainder of the FOT fleet is to be completed by mid-January. Delphi and GM equip vehicles with all components except the UMTRI DAS, and a checkout procedure confirms the desired ACAS functions and performance. Once received at UMTRI, the DAS is installed in each car and several check tests occur by which the ACAS and DAS functions are confirmed.

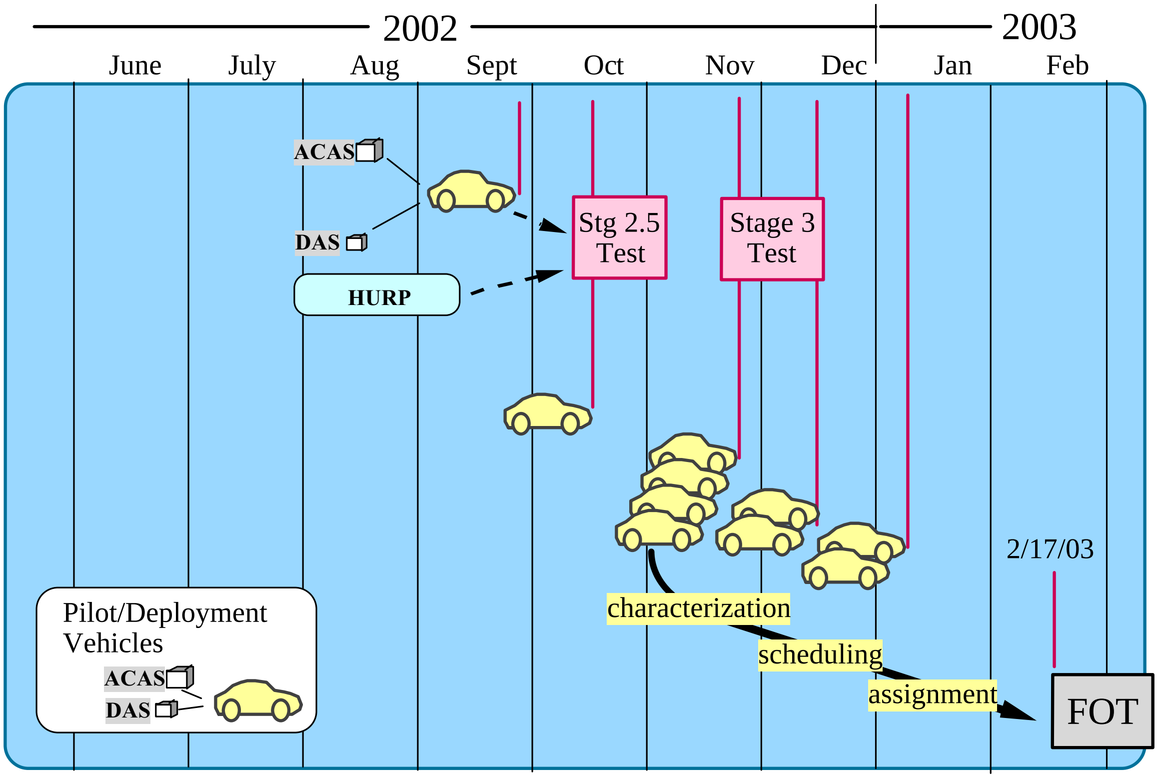


Figure 35: Activities during run-up tothe FOT

The process of run-up to the FOT also includes many forms of preparation, characterization, and the recruitment/scheduling of subjects. The FOT is currently scheduled to be launched in March of 2003.

Plans for Next Six Months (through June 2003)

The launch of the FOT is clearly the dominant event in the next six months. The expectation is for the completion of Stage 3 testing by mid-January and the initiation of the first FOT subjects in March.

Per the Operational Test Plan, two FOT vehicles will be dispatched each week, on 4-week assignments to individual subjects until the fleet is fully deployed. In the normal weekly cadence of the field test, two vehicles will return to UMTRI on Monday or Tuesday and will go out again to two new subjects on Thursday or Friday. The intervening turnaround time is for recovering data, cleaning and prepping the vehicle, and running check tests to confirm proper operation before the next dispatch.

The monitoring and management of field operations, analysis of test data, and transmission of datasets to Volpe are the primary efforts that continue throughout the field test period. Assuming a March start, the field test would conclude on or about December 2003.

7 ACRONYMS

ACAS	Automotive Collision Avoidance System
ACC	Adaptive Cruise Control
CIPS	Closest In-Path Stationary target
CIPV	Closest In-Path Moving target
DAS	Data Acquisition Subsystem
DCS	Delphi Chassis Systems
DDE	Delphi Delco Electronics
DGPS	Differential Global Positioning System
DVI	Driver Vehicle Interface
FCW	Forward Collision Warning
FOT	Field Operational Test program
GM	General Motors
GPS	Global Positioning System
HUD	Head-Up Display
HURP	Human-Use Review Panel (NHTSA)
NHTSA	National Highway Traffic Safety Administration
PCM	Powertrain Control Module
RCAP	Radar Collision Avoidance Processor
SI	Symbol for the international system of units
SV	Subject Vehicle
TCS	Traction Control System
VSE	Vehicle Stability Enhancement

DOT HS 809 600
May 2003

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