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The Automotive Collision Avoidance System Program was conducted by a consortium led by Delphi-Delco Electronic Systems. Other members of the consortium were: General Motors Corporation/NAO Safety and Restraint Center, General Motors Research and Development, Hughes Research Laboratories, ERIM International, UC Davis, and STI.

16. Abstract

Since the mid-1960s there have been significant advancements in vehicle safety. Passive safety features such as seat belts, air bags, crash zones and lighting have dramatically reduced accident rates, injury severity and the number of fatalities. For example, the fatality rate per hundred million vehicle miles traveled has fallen from 5.5 to 1.7 from the mid-1960s to 1994. In spite of these impressive improvements, each year in the United States, motor vehicle crashes still account for a staggering 40,000 deaths, more than three million injuries, and over $130 billion in financial losses. Significant further gains in reducing crash costs will prove more difficult to achieve by proceeding with the current passive safety technologies alone. Consequently, there is merit to investigate other promising technologies in an attempt to reduce the severity of crashes or even complete mitigation of all collisions.

The introduction of automotive collision warning systems potentially represents the next significant leap in vehicle safety technology by attempting to actively warn drivers of an impending collision event, thereby allowing the driver adequate time to take appropriate corrective actions in order to mitigate or completely avoid the event. With this as an impetus, the Automotive Collision Avoidance System (ACAS) Program was launched.

This report documents the activities undertaken by the ACAS Consortium carried out during the period January 1, 1995 through October 31, 1997.

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Executive Summary

Tremendous progress has been made since the 1960's with regard to vehicle safety. Improvements in passive safety features such as seat belts, air bags, crash zones, and lighting have dramatically reduced the rate of crashes, injuries and fatalities. For example, the fatality rate per hundred million vehicle miles traveled has fallen from 5.5 to 1.7 in the period from the mid-1960s to 1994. However, in spite of these impressive improvements, each year in the United States, motor vehicle crashes still account for a staggering 40,000 deaths, more than three million injuries, and over $130 billion in financial losses. Significant further gains in reducing crash costs will prove more difficult to achieve by proceeding with the current passive safety technologies alone. Consequently, there is merit to investigation of other potential technologies in an attempt to reduce the severity of crashes or even complete mitigation of collisions.

The introduction of automotive Collision Warning Systems potentially represents the next significant leap in vehicle safety technology. Such systems attempt to actively warn drivers of an impending collision event, allowing the driver adequate time to take appropriate corrective actions to mitigate, or completely avoid, the event. Crash statistics and numerical analysis strongly suggest that such collision warning systems will be effective. Crash data collected by the U.S. National Highway Traffic Safety Administration (NHTSA) show that approximately 88% of rear-end collisions are caused by driver inattention and following too closely. These types of crashes could derive a beneficial influence from such systems. In fact, NHTSA countermeasure effectiveness modeling predicts that "head-way detection systems can theoretically prevent 37% to 74% of all police reported rear-end crashes." Clearly, the introduction of collision warning systems could result in the dramatic reduction of crash fatalities, injuries, and property damage.

With this as an impetus, the Automotive Collision Avoidance Systems (ACAS) Program was launched. It was originally set up to be a two-year program with activities beginning January 1995. The activities were carried out by a consortium made up of government agencies as well as, industrial and academic participants. The main objective of the Consortium is to provide a focused approach to accelerate the development of active collision avoidance systems. The nine-member consortium is comprised of recognized leaders in their respective field of expertise in the technology, manufacturing and marketing of collision avoidance products. It was believed that through the formation of this Consortium, U.S. competitiveness in the automotive electronics industry would be maintained and further enhanced. Furthermore, once systems are deployed, the expansion of employment, sales, and export of U.S. technologies will result.

The ACAS Program envisions the implementation of a comprehensive collision warning system, which is capable of detecting and warning the driver of potential hazard conditions in the forward, side, and rear regions of the vehicle. The system would use: (1) long range radar or optical sensors to detect potential hazards in front of the vehicle, (2) short range sensors to warn the driver of nearby objects when changing traffic lanes or backing up, and (3) a lane detection system to alert the driver when the vehicle deviates from the intended traffic lane. The program effort is focused on providing warnings to the driver, rather than taking active control of the vehicle.

For such a system to gain acceptance by consumers, it must be reasonably priced, possess sufficient and effective functionality, and provide highly reliable performance. In order to achieve these goals, the ACAS Program has relied heavily on the principles of system engineering as a framework to guide the highly focused design effort. The activities of the program can be grouped into three main themes. The first theme is the refinement of existing or partially developed collision warning/avoidance technologies/systems in order to achieve further cost reductions by improving the manufacturing processes. The second theme is the accelerated development of other promising but immature technologies/systems that are essential for collision warning/avoidance. The third theme is the application of human factors engineering in the design and implementation of collision warning systems. A collision warning system will be of little use to the automotive consumer, if the driver can not effectively be made aware of potentially hazardous roadway situations. The set of warning cues that is provided must not be annoying, intrusive, or confusing.

This report summarizes the major technical accomplishments during the ACAS Program (January 1995 – October 1997). The accelerated development of strategic technologies/systems that are the essential building blocks for a fully integrated comprehensive collision warning system, has mainly focused on the following three areas: (a) sensors (i.e., forward-looking radars and lasers, side detection radars, and lane tracking vision), (b) systems (i.e., path estimation, in-path target selection, and threat assessment), and (c) human factors (i.e., driver-vehicle interfaces, and understanding the effects of warning cues on drivers). The results demonstrated during this program have been broad, varied, significant, and very encouraging. Some of these achievements are discussed below.

A varied and extensive analysis of crash data has been carried out in order to focus the system requirements of an integrated collision warning system. Several demonstration vehicles, equipped with the rudimentary capabilities of a forward collision warning system, have been designed, developed, constructed, and successfully demonstrated. These vehicles demonstrated the viability of the baseline system architecture. Additionally, remarkable progress has been achieved in the individual development of strategic technologies/systems/components, in such areas as: active sensors

(i.e., radar, laser and vision), algorithm/software development (i.e., collision warning processing components), and human factors.

For instance, the linearity of FMCW (Frequency Modulated Continuous Wave) radar has been improved by an order of magnitude, while the development unit cost has been reduced by a factor of three. The production unit cost is projected to be reduced by a factor of five. A significant improvement in sensor reliability was also achieved (zero field returns versus 20% prior to the ACAS program). The collision warning processing algorithm suite has matured as evidenced by the dramatic reduction of false alarms and missed detections. Besides the conventional Path algorithm, a new approach, Scene Tracking, has been investigated and has yielded promising initial results. All MMIC (Microwave Monolithic Integrated Circuit) radar transceivers were demonstrated with good system performance via road testing, the design repeatability was demonstrated via multiple wafer runs, and the reliability of the design was verified through environmental tests. On the human factors front, a wide field of view (4.5 x 3.0 degrees) Head-Up Display (HUD) was developed with high brightness and excellent image quality. It was used for simulator studies as well as for actual vehicle installations. Several human factors studies were conducted in a simulator and in actual driving situations, to determine the best visual and auditory warnings for an effective collision warning system.

Now that the primary objective of the ACAS Program has largely been achieved, the next logical technical progression of the product development would be the upward integration of these ACAS-developed essential building blocks to form a complete seamless vehicle system which can be evaluated through a field operational test program. This test program, if carried out, will provide an ideal opportunity for the Government, industry, and Intelligent Transportation System (ITS) community to gain a more thorough understanding of the requirements, functions and societal impact of this technology. Additionally, any potentially adverse operational and safety-related issues could be identified, analyzed, and addressed while the technology is still in the early stages of product development. This program has the opportunity to make a positive impact on automotive safety through the accelerated development and early deployment of effective advanced safety technologies.

Section 1
Program Definition

1.1 Consortium Members

The objectives of the Automotive Collision Avoidance Systems Development Program are achieved by a consortium comprised of both industry and academic participants. This organization is referred to as the ACAS Consortium. The make up of this eight-member ACAS Consortium is as follows:

<u>Full Members:</u>

- Delco Electronics Corporation (DE)/Automotive Electronics Development (AED)
- Delco Electronics Corporation/Advanced Development & System Integration
- General Motors Corporation (GM)/NAO Safety & Restraint Center
- General Motors Corporation/Research & Development Center (GM-R&D)
- Hughes Research Laboratories, Incorporated (HRL)

<u>Associate Members:</u>

- Environmental Research Institute of Michigan (ERIM)
- University of California-Davis (UC-Davis)
- Systems Technology, Incorporated (STI)

The Automotive Electronics Development organization of the Delco Electronics Corporation provides the overall program management direction for the ACAS Program. Financial assistance for the program is provided by both the U.S. Government and Consortium members (GM, DE & HRL). The U.S. Government has sponsored this activity through the Defense Advanced Research Project Agency (DARPA), in accordance with the goals of the Technology Reinvestment Project (TRP). The U.S. Government actively participates in ACAS Program activities in support of the program objectives. The National Highway Traffic Safety Administration (NHTSA) administers the ACAS Program on behalf of the U.S. Government.

1.2 Overall Program Goals

The primary goal of the ACAS Program is to provide a highly focused effort to accelerate the development of active crash avoidance systems for the automotive industry. It is envisioned that the ACAS Program will assist in the

development of a comprehensive collision warning system, which is capable of detecting and warning the driver of potential hazard conditions in the forward, side, and rear regions of the vehicle. The system will incorporate the use of long range radar or optical sensors that are capable of detecting potential hazards in the front of the vehicle, short range sensors to warn the driver of nearby objects when changing traffic lanes or backing up, and a lane detection system that alerts the driver when the vehicle is changing traffic lanes. The current program effort is focused on providing warnings to the driver, rather than take active control of the vehicle.

It is imperative that the kind of implemented system that is envisaged provide utility to the general automotive consumer. For such a system to gain acceptance by the consumer, it must be reasonably priced, provide highly reliable performance, and provide functionality. In order to achieve these goals, the ACAS Program has relied heavily on the principles of system engineering as a framework to guide the highly focus design effort.

The activities of the ACAS program can largely be grouped into three main themes. They are:

- *Refinement:* Many partially developed existing technologies/systems have shown promise as an essential component for a collision warning system. Unfortunately, many of these components have not reached their full market potential as a result of economic considerations, such as: expensive manufacturing processes, lack of market pull or technology push, etc. Consequently, it is the objective of this program to undertake appropriate activities to further the refinement of promising crash avoidance capable technologies/systems in order to achieve cost reductions by improving the manufacturing processes.

- *Advanced Development:* The next goal is the accelerated development of promising immature technologies which are identified to be the essential crash avoidance components. It is imperative to leverage the advanced features of these technologies/systems in order to enhance and advance the collision warning system functionality.

- *Human Factors:* The influence of human factors considerations on the crash warning system design is deemed crucial and essential. A collision warning system will be of little use to the consumer if the driver can not effectively be made aware of hazardous roadway situations. The warning cues must not be annoying, intrusive, or confusing. It is the objective of this program to investigate the preferred method of providing warning cues to the driver. The available techniques could be visual, auditory, or proprioceptive.

1.3   Specific Program Objectives

The ACAS Program will assist in the component development of a comprehensive collision warning system. This system will be capable of detecting and warning the driver of potential hazard conditions in the forward, side, and rear regions of the vehicle. Figure 1.1 conceptually illustrates the envisioned architecture for such a system.

Information flows among the various system modules, from the sensing systems (i.e.: Forward Collision Warning (FCW), Side Collision Warning (SCW), vision, and on-board vehicle), to the Collision Warning Processing Module, and eventually the Driver-Vehicle Interface (DVI) which provides the appropriate warning cues to the driver. Each of the sensing systems receives information about the Host vehicle states (such as: yaw rate, vehicle speed, etc.) and sends appropriate parameters/information (such as: lane path, detected vehicle speed and range, etc.) relative to the Host vehicle.   The Collision Warning Processing Module will combine the information from the active sensing systems (i.e.: vision, radar, etc.) and passive sensors (i.e.: on-board sensors used to determine Host vehicle states) in order to accomplish object detection, target tracking, in-path target identification, and threat assessment.   If the identified detected target is assessed as being a potential hazard to the Host vehicle, then appropriate warning cues will be initiated and provided to the driver in the form of visual, auditory or tactile cues.
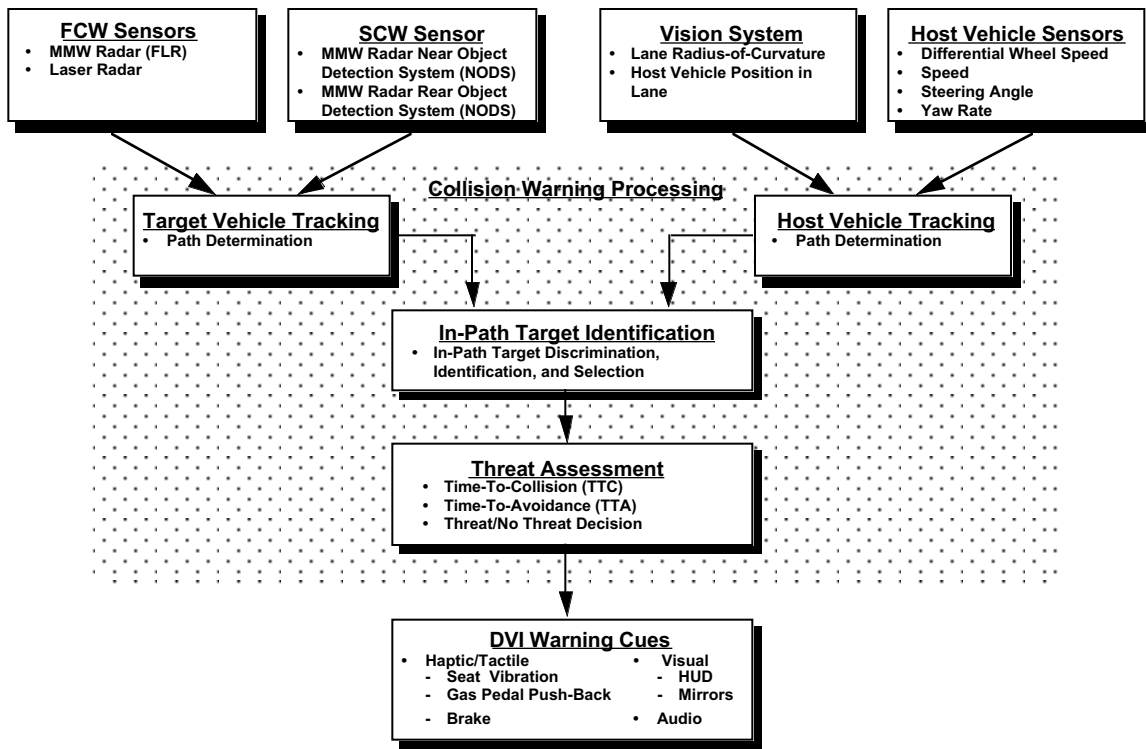
Figure 1.1: Conceptual Architecture for a Collision Warning System.

Section 2

Program Description

The ACAS Program is segmented into well defined, non-overlapping tasks. The objectives of these tasks are aligned with the collision warning system architecture, as shown in Figure 1.1. The purpose of these tasks is to support and address the overall program goals as specified in Section 1.2. Table 2.1 presents a summary of the program tasks, relationship to collision warning system architecture, and the primary Consortium member responsible for this activity. Although not shown, some of the Consortium members provide support efforts for some of the other task activities. The ACAS Program Schedule is presented in Appendix B.

Table 2.1: ACAS Program Summary.

ACAS Program Tasks		Responsible Consortium Member	Relationship To System Architecture
No.	Description		
1.1	Crash Scenario Definition	GM	FCW & SCW Sensors
1.2	Countermeasure System Functional Specifications	GM	FCW & SCW Sensors
1.3	Vehicle Level Test Protocol	GM-R&D	FCW & SCW Sensors
1.4	Validation of Vehicle Performance Testing (not completed)	GM-R&D	FCW & SCW Sensors Collision Warning Processing
2.1	Development of Near-Term Systems	GM-R&D ERIM	FCW & SCW Sensors Collision Warning Processing
2.2	Development of Cost Reduction Components for Production	DE	FCW Sensors
2.3	Studies of Long-Term Advanced Systems	DE/AED	Collision Warning Processing
2.4	Forward Laser Sensor Development	DE	FCW Sensors
3.1	Multi-beam Planar Antenna	DE	SCW Sensors
3.2	Low Cost 24 GHz Transceiver	DE	SCW Sensors
4	Lane Sensing	GM-R&D ERIM	Vision System
5	Wide Field-of-View (WFOV) Head Up Display	DE	DVI
6.1	Initial Screening of Warning Concepts	UC-Davis	DVI

		DE/AED	
6.2	Development of Simulation Sensor Models	STI DE/AED HRL	DVI
6.3	Driver-Vehicle Interface (DVI) Studies	HRL DE/AED	DVI
6.4	Closed-Course Testing	DE/AED	DVI

A summary of the tasks and their specific objectives is presented below:

Crash Scenario Definition (Task 1.1)
- To identify crash scenarios from GM's heuristic set which are relevant to the chosen countermeasures.

Countermeasure System Functional Specifications (Task 1.2)
- To define a vehicle level functional specification of the major countermeasures.

Vehicle Level Test Protocol (Task 1.3)
- To define a test methodology for each major countermeasure system.

Validation of Vehicle Performance Testing (Task 1.4)
- To support the vehicle level testing efforts of the other participants.
- Analyze the results of the vehicle level performance testing of each countermeasure system.

Development of Near-Term Systems (Task 2.1)
- To derive the requirements for the system from Task 1 and define sensor specifications.
- To contract the development of a prototype sensor to a component supplier.
- To integrate the sensor into a vehicle and confirm the concept with in-vehicle tests.

Development of Cost Reduction Components for Production (Task 2.2)
- Development of a low cost 76 GHz transceiver utilizing a single piece planar construction with MMIC chips.
- Development of high yield fabrication process and design of MMIC oscillators and components fabricated in Gallium Arsenide.
- Seek the best compromise between:

- Up-integration for reduced parts count, ease of chip placement, and reduced circuit size.
- De-integration into multiple (less complex, higher yield) chips which require more substrate space and manufacturing operations.
- The overall result must satisfy both customer performance expectations and production cost objectives.

Studies of Long-Term Advanced Systems (Task 2.3)
- Investigate more advanced forward crash warning situations.
- Develop techniques to identify and correctly respond to advanced crash warning situations.
- Utilize high performance forward sensors to facilitate the development activities.
- Provide a basis to integrate other ACAS developed sensors/system/tasks.
- Provide a basis to perform human factors studies.

Forward Laser Sensor Development (Task 2.4)
- Use available laser technology to design, develop, and demonstrate a multi-zone headway sensor for cruise control and collision warning applications.
- Produce several development units to be tested in the laboratory and in-vehicle.
- Support the requirement definition of a production intent system.

Multi-beam Planar Antenna (Task 3.1)
- Development of a 24.125 GHz antenna that has a detection pattern that "looks down the adjacent-lane".
- Antenna design must support an adjacent-lane target zone 8-10 meters long and 4.5 meters wide.
- Antenna sidelobe performance must be compatible with target discrimination requirements.
- Antenna must feature planar technology in order to be consistent with manufacturing cost and vehicle styling objectives.

Low Cost 24 GHz Transceiver (Task 3.2)
- Selection of a foundry process that supports low cost fabrication of 24 GHz MMIC devices.
- Refine and optimize the design so that performance parameters are centered around the foundry process parameters.

- Adapt system design and performance specification to foundry process capability.
- Finalize the design and fabricate multiple wafer runs to determine process variations.
- Submit final design to alternate foundries for quote.
- Build and demonstrate prototype systems using the devices developed on this program.

Lane Sensing (Task 4)

- Demonstrate a robust Lane Sensing Function (hardware and software) operating in a test vehicle, on limited access roadways, that determines the lane path and the vehicle's position in the lane.
- Build on GM's LaneLok experience to develop a more robust Lane Sensing Function.
- Demonstrate real-time operation.
- Advance the state-of-the-art in lane sensing.

Wide Field-of-View (WFOV) Head Up Display (Task 5)

- Design and develop a reconfigurable Head Up Display (HUD) with a wider field-of-view and higher brightness.
- Fabricate these HUD units for demonstration in laboratory and in-vehicles environment.
- Install HUD(s) into appropriate vehicle(s) in support of advanced systems testing (Task 2.3) and closed-course testing (Task 6.4).

Initial Screening of Warning Concepts (Task 6.1)

- Conduct human factors tests/experiments, using a simulator, on a large number of collision warning formats for both visual and auditory warnings.
    - Warnings include: synthesized and digitized speech, tones, spatially localized tonal cues, visual icons and text.
    - Propose preferred visual and auditory warning formats.
- Subject reaction times, response errors, tracking task performance and subjective workload will be collected.

Development of Simulation Sensor Models (Task 6.2)

- Develop software modules of generic, forward-looking and side zone sensors.
- Develop software modules of GM-R&D and DE sensors.
- Support the development of the HRL human-in-the-loop fixed-based driving simulator.

Driver-Vehicle Interface Studies (Task 6.3)

- Develop experimental test plan for simulation driver-vehicle interface approach.

- Design auditory and visual warnings based on input from UC-Davis study, and determine requirements for tactile warnings.

- Develop a human-in-the-loop fixed-based driving simulator to evaluate driver warning systems.

- Evaluate preferred warning interface method to warn drivers of hazardous events in a realistic human-in-the-loop driving simulator.

- Conduct human factor experiments which enable subjects to drive in a variety of realistic environments with programmed scenarios.

  - Record performance data and gather subjective data.

  - Analyze performance and subjective data.

  - Provide evaluation of preferred warning.

Closed-Course Testing (Task 6.4)

- Evaluate accuracy and reaction time of driver response for several driver-vehicle interfaces.

- Validate results of simulator studies conducted in Task 6.3 with closed-course tests/experiments in the demonstration vehicles.

- Conduct human factor experiments which enables subjects to drive demonstration vehicles with programmed scenarios.

  - Record performance data and gather subjective data.

  - Analyze performance and subjective data.

  - Provide evaluation of preferred warning.

- Conduct Engineering tests to validate sensor parameters/performance, such as: processing algorithms, resolution and temporal performance, false alarm rates, and collision warning thresholds.

Section 3
Program Accomplishments

3.1 Program Requirements and Performance Validation (Task 1)

The objective of this task was to define system requirements and test methodology for certain crash countermeasure systems. This task included identification of the relevant crash scenarios, development of vehicle level function specifications for the major countermeasure systems, and definition of test methodology for each countermeasure system. The expectation of this task was to assist in the development of the countermeasure systems by defining the crash scenarios that each countermeasure was expected to impact. A test protocol was expected so that each countermeasure system could be evaluated and its potential crash avoidance capability could be estimated. This task achieved definition of crash scenarios and a first attempt at a test protocol definition.

3.1.1 Crash Scenario Definition

Relevant crash scenarios were identified for the forward, side and rear direction of vehicle travel. The frequency of crashes, as well as estimates of annual losses due to direct cost and years of function life lost was tabulated (see Figure 3.1 below). For more information on how the tabulations were developed refer to Ted Miller's paper, _Understanding the Losses from US Motor Vehicle Crashes_ (AAAM, 1995). Currently the percentages represent estimates of the total crash avoidance opportunity and were not adjusted for a particular technology.

An important development of this study involved an analysis of crash data. By examining a number of state data bases for police reported crash data, information for over represented conditions can be developed. This was especially important when assessing potential countermeasure impact. Conditions of wet or icy road surface, alignment of the roadway, and type of road can be studied for level of involvement and whether the condition was over represented when compared to other crash types. If some condition was shown to be over represented, it was not assumed to be the cause of the crash but was included in the scenario development. If no condition was over represented, the crash has a probability model based on the distribution of all crashes.

In the forward direction, rear end crashes (same direction of travel) were the primary crash configuration. For side direction, lane changes, merge and

lane departures (all same direction of travel) were the configurations of interest. For the rear direction, backing crashes were studied. An example of a crash description as defined for this task is shown in Figure 3.2. The one page description includes a defined heuristic crash with any identified over represented condition, an estimate of the direct cost realized annually, and an estimate of years lost of functional life per year.
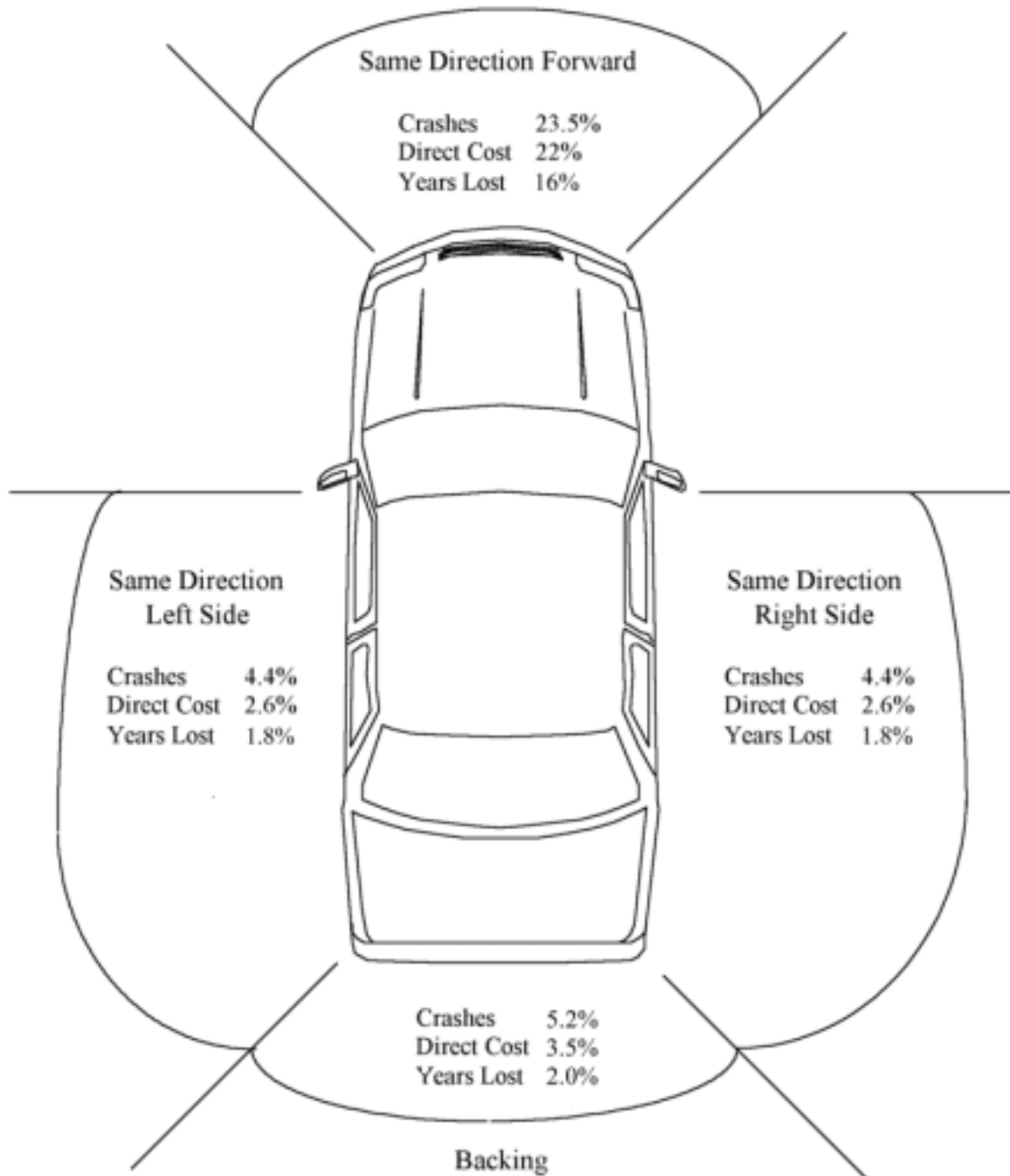
Figure 3.1: Estimate of Annual Losses due to Automotive Crashes.

Crash #62:   Inattentive, Rear

SCENARIO: A northbound vehicle, **A**, is stopped waiting at a red traffic signal in an urban area on a major artery. Another vehicle, **B**, coming from some distance behind, doesn't notice that **A** is stopped and cannot stop in time. (No other conditions have yet been identified as over-represented in this crash.)

KEY STATISTICS: In Focus Group Interviews respondents indicate driver **B** was usually looking away. Also per these same interviews, many of these go unreported.

LOSS INDEX:

Vehicle Crashed	**12.0%**
Percent Direct Cost Per Year	10.2%
Percent Functional Years Lost	4.9%

REFERENCES: From the union of the Indiana Tri-Level Causation study nine percent of all crashes involve "Driver: Inattention," and from the University of Michigan Transportation Research Institute (UMTRI) Michigan crash typology 14% are "Multiple Vehicle: Rear End," Office of Crash Avoidance Research (OCAR) found 24.2% of all crashes to be rear end crashes. Of these 70% (17% of all crashes) involved a stopped lead vehicle and therefore do not involve "coupled" vehicles. Of all the crash causes of the striking vehicle (10%), "driver inattention to the driving task" is the most common error. (Proceedings of IVHS America 1993 Annual Meeting, P.251).

Road Diagam #62:

Same Direction, Rear End

(lead stopped)
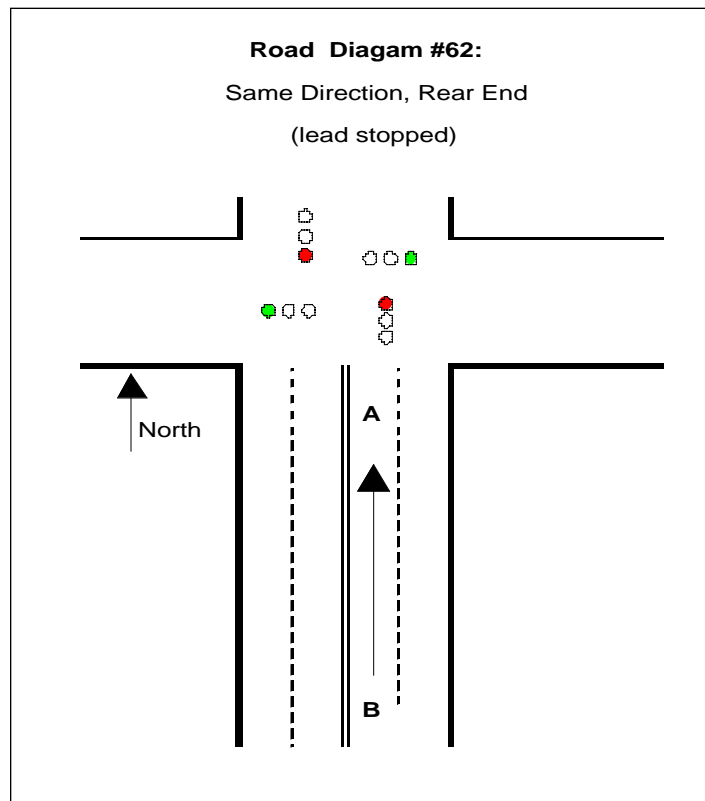
Figure 3.2: An Example of a Crash Description.

Also, a time line for a sequence of events introduced the concept of "Time to Collision" (TTC) for forward defined heuristic scenarios. Parameter values were identified for range, range rate, vehicle attitude, host velocity, host deceleration, host vehicle response time, and driver response time. Some of these values can be measured and some can be calculated based on the particular countermeasure capability. TTC was defined as the range divided by the range rate with the units of seconds. The measure of parameter improvement due to a given countermeasure was difficult to characterize. A countermeasure will eliminate or mitigate a crash when it provides an opportunity for the driver to avoid involvement in a crash by improving driver response time allowing the driver to remain in control. This can also be stated as the sum of the driver reaction time and the required stopping distance time or avoidance time (given the road conditions and capability of the vehicle) is less than the calculated TTC.

In summary, the target crashes were identified and sized and were referred to as the relevant scenarios. The relevant crash scenarios of rear-end crashes are shown in Table 3.1. In an effort to provide an alert during the relevant crashes, the system design may be vulnerable to nuisance alerts. Development scenarios require representation of a cluttered background, competing obstacles, and geometric concerns of roadway alignment to address nuisance alerts. These development scenarios, although not necessarily statistically high in crash frequency, need to be evaluated through the testing process to evaluate system performance.

3.1.2   Collision Warning System User Requirements

The purpose of this task was to establish user requirements based on quantitative evaluation of the user's ability and the environment in which the system was designed to provide the driver with an opportunity to avoid involvement in forward, side and backing crashes. This was done without reference to a specific countermeasure and no actual system design parameters were discussed. User requirements for four systems were addressed: forward collision warning, lane sensing, side near object detection/warning, and rear near object detection/warning systems.

The area of coverage for forward collision warning (Figures 3.3 and 3.4) was based on vehicle kinematics. The extent of the forward range was a function of the relative speed between the host and identified collision object. The limitations on height and width of field reduce nuisance alerts but provide lane coverage under transitions in road alignment. Increasing the width of coverage to include same and next lane (right and left sides) will allow for collision assessment based on lateral motion in the forward traffic field. Providing the driver with improved response time may reduce rear end collisions and lane departure due to unplanned avoidance maneuvers.

Table 3.1: Scenarios for Requirements

Crash	Crash #	Requirement	Frequency	Potential *
Forward Object Stopped	56, 58, 62, 66	Maximum longitudinal range. Path accuracy to sort primary target from other stationary clutter (height and width of anticipated path). Latency in new target acquisition time.	10%	High
Forward Object Moving	56, 58, 62, 66	Target separation to identify primary target in traffic (motorcycle in lane with a large truck in the next lane). Latency in new target acquisition time and coasting of target no longer present. Maximum negative range rate for reassignment of primary target.	6%	High
Tailgating	52	Range rate threshold response	1%	Low
Cut-in	75, 80	Minimum longitudinal range	3.5%	Medium
Head On	92	Excess of maximum range rate (Maximum: host vehicle to stopped object)	2.5%	Low
Pedestrian	1	Minimum size object for detection	1%	Medium
Weather	78	System performance under low visibility conditions and / or low coefficient of friction.	2%	High

*Potential: High potential implies that the countermeasure has a 20% probability of assisting the driver. Medium implies 10% probability and Low implies 5% probability.

Lane sensing augments the function of forward collision warning with path prediction and collision assessment. There may be other benefits such as identifying lane and road departures, but no effort was made to explore this function.

The area of coverage for side detection is shown in Figures 3.5 and 3.6. The rear side zone aids the host driver in lane change maneuvers. The forward side zone function augments collision possibility involving the other driver's intended and the host's unintended lane changes for the forward area of coverage.
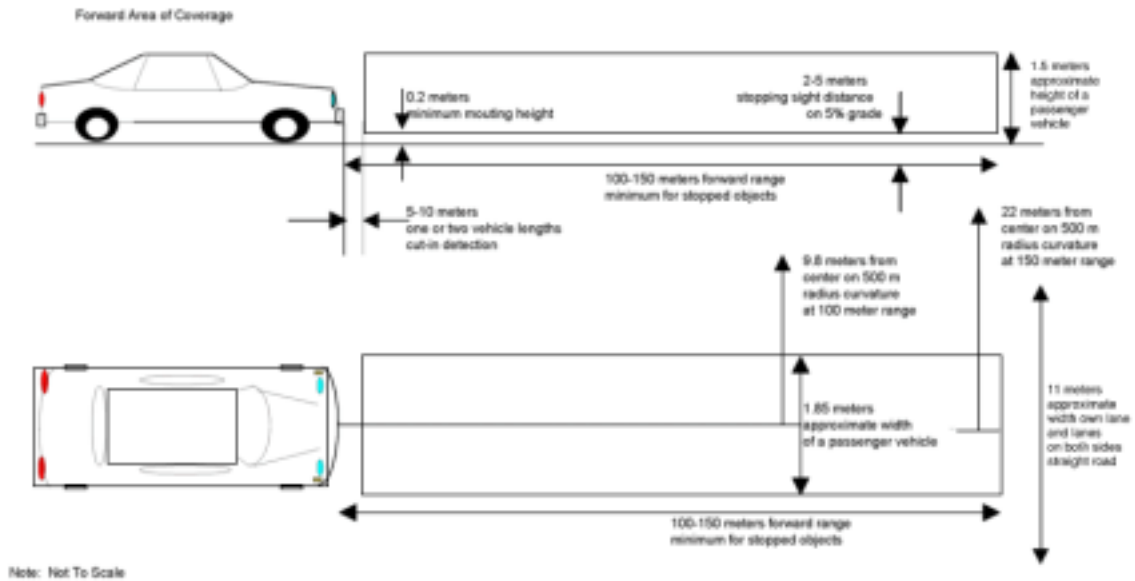
Note: Not To Scale

Figure 3.3: Forward Detection Zone
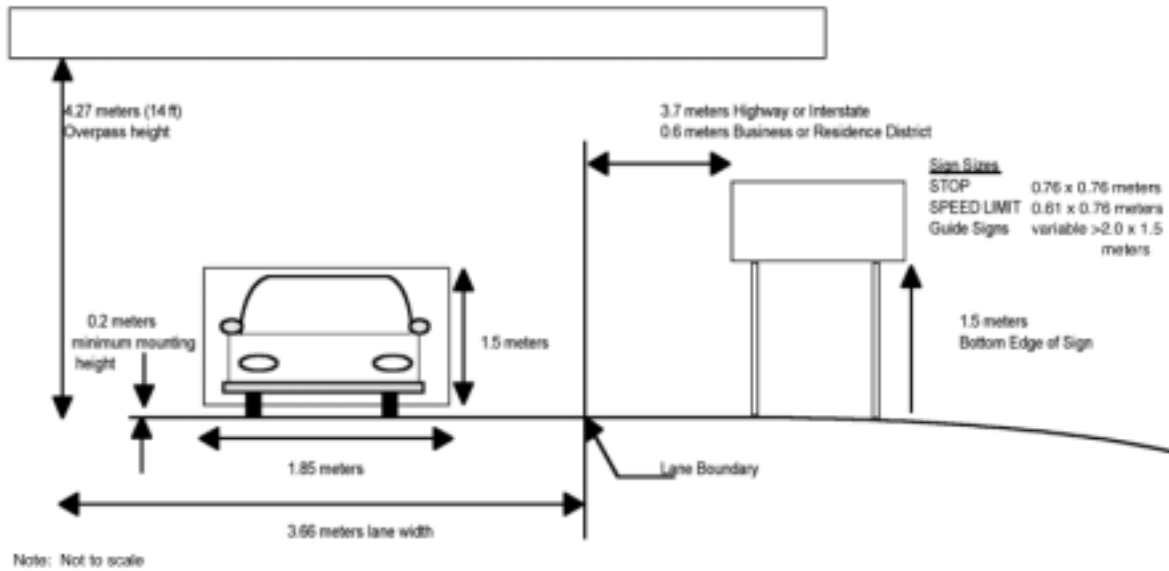
Note: Not to scale

Figure 3.4: Front View Forward Area of Coverage

Note: Not to Scale
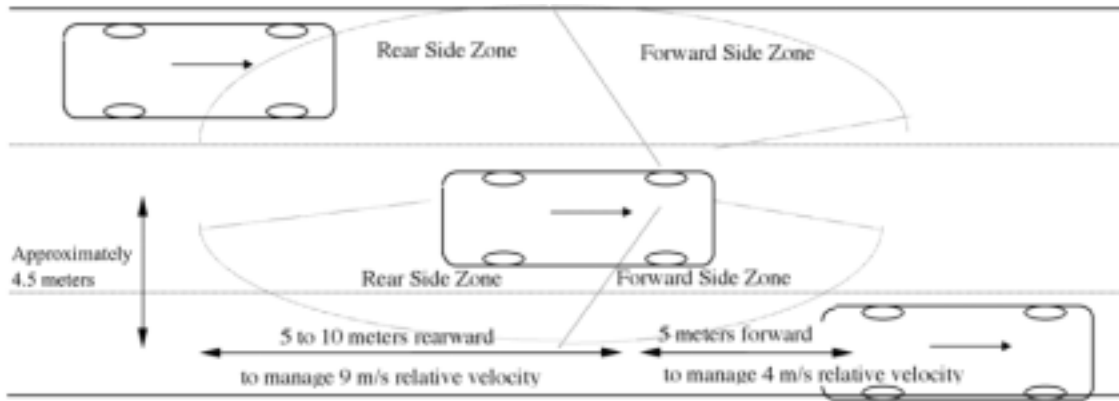
Figure 3.5: Side Near Object Detection Area of Coverage (Plan View)
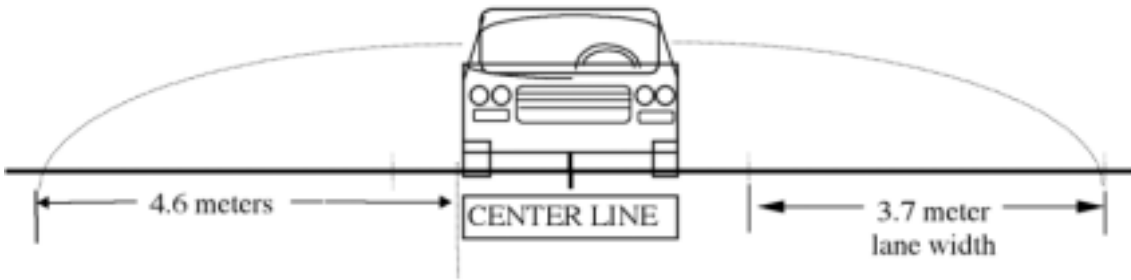
Figure 3.6: Side Near Object Detection Area of Coverage (Elevation)

The area of coverage for the rear of the vehicle (Figures 3.7 and 3.8) should assist the driver in detecting near stationary and slow moving objects. The system is only active when the transmission is shifted in reverse. The coverage zone shows a radius of 5 meters. The actual value should be representative of the turning radius of the host vehicle. An additional function of a rear detection system is as a parking aid. This requires multiple zone detection or high accuracy at close range.

The areas defined were based on both the statement of the crash scenario, vehicle kinematics, and the rational as shown in Figure 3.9. One requirement of the technology was recognition of stopped in-path objects on the roadway. Making the distinction between "in path" on the road and "threat" drove the requirements for update rate, accuracy, field of view and range.

3.1.3   Vehicle Level Test Protocol

The goal of this task was to define a test methodology at the Driver-Vehicle System level for the countermeasure system investigated. The deliverable was a summary report including a test protocol designed to assess the crash reduction potential for these countermeasures. Although the original scope of the task was only to develop this test protocol, a near term test protocol proposal was added to the driver-vehicle system test protocol. The driver-vehicle system proposal did address the statement of work but it required an investment of significant resources to develop and implement. While this test protocol has long term potential, this protocol could not be accomplished within the scope of this project.

Three concepts were stressed: (1) Testing at this level should include a high level metric that was simple to measure, (2) The tests should measure the effect a countermeasure has on the relevant crash scenarios, and (3) The near term tests can only estimate the maximum potential reduction of crashes due to a countermeasure.

The metric developed for this project was Time to Collision (TTC) and Time to Avoidance (TTA). The relative range between two vehicles divided by the range rate is TTC, and the characteristic width of the vehicles divided by the transverse velocity vector perpendicular to the range rate vector is TTA. If TTC remains less than TTA then a collision occurs. However, if TTA becomes less than TTC as a scenario proceeds, then the collision is avoided.
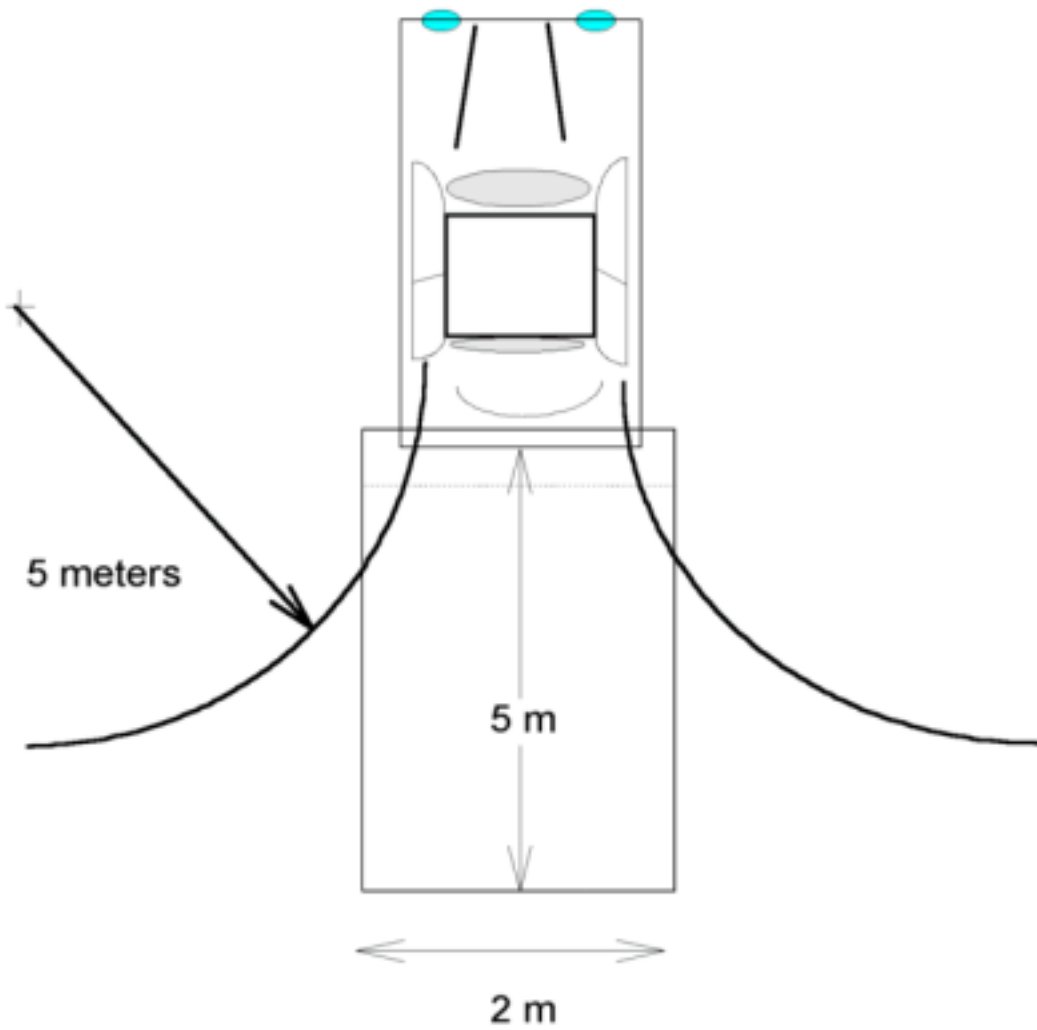
Figure 3.7: Rear Detection Zone (Top View)

5 meters

5 m

2 m

5 meters
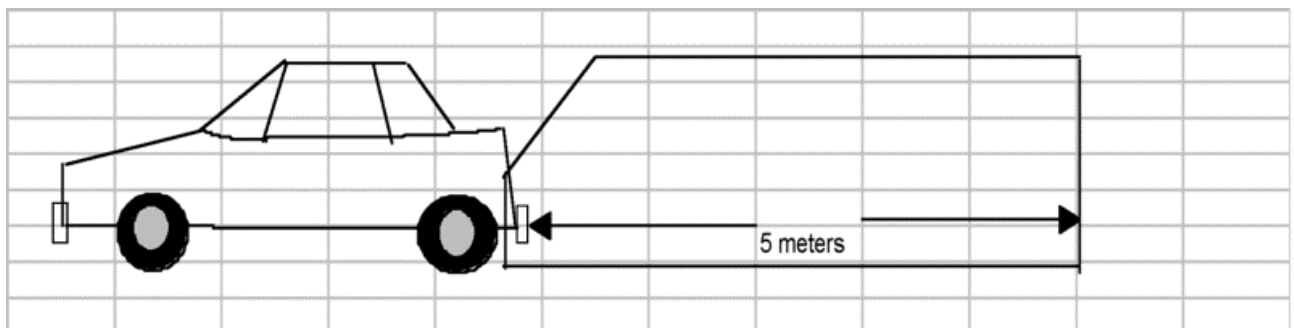
Figure 3.8: Rear Detection Zone (Side View)
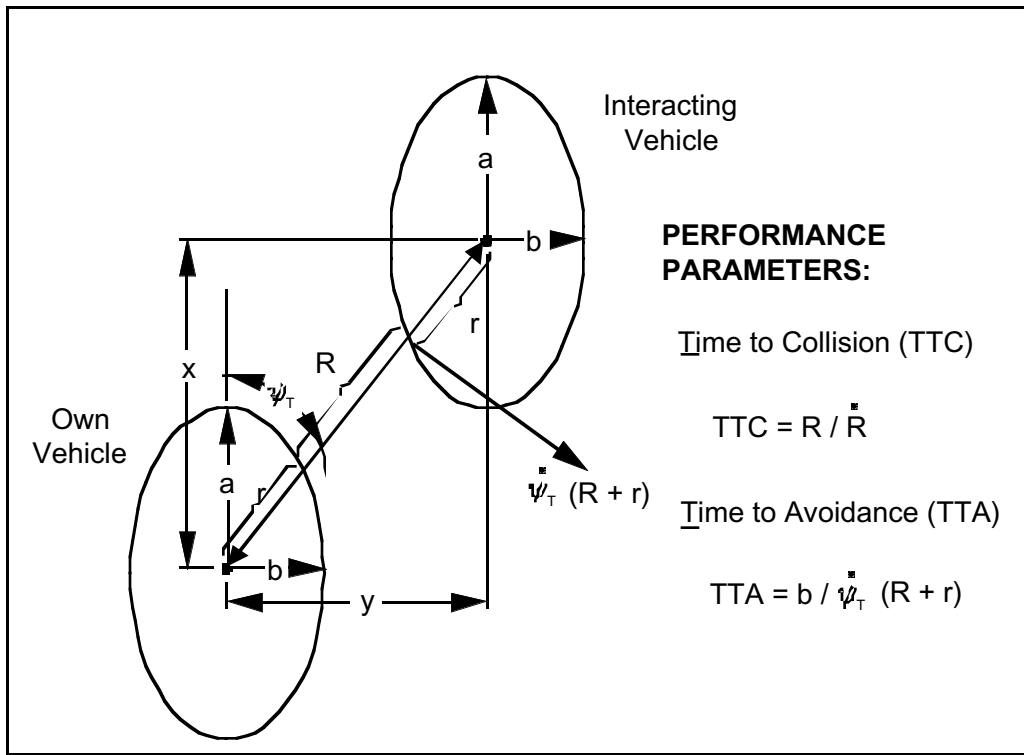
Figure 3.9: Vehicle Interaction Definition and Formulation

This metric was chosen for its ability to measure the proximity of a crash between two vehicles. It is independent of the crash scenario, the avoidance maneuver chosen by the driver, and the countermeasure used. The raw data required is a time history of the relative locations of the vehicles. It can be used in simulator and closed course tests.

The Near-Term Tests defined in this task provided a test plan for evaluation of the ACAS collision avoidance systems, with emphasis placed on the near-term testing in ACAS Task 6.4. The tests outlined in these sections would be conducted by trained drivers, who would be aware of the test scenario scripts.

The tests are designed to measure the TTC and TTA when the system provides an alert. Because the driver performance will be controlled due to this experimental design, several effects that a given countermeasure system may have on driver performance will not be assessed. These effects include those of nuisance or false alarms and early alerts. Although this phenomenon will be noted during testing, no determination of their effect on driver behavior will be made.

Due to these limitations, the results from these tests would only provide a measure to estimate the maximum countermeasure potential of crash avoidance for the scenarios tested. Because these tests will include a sub-set of the scenarios outlined

earlier in this document, the maximum potential crash avoidance would be based on only the tested scenarios.

It is not possible to test a collision avoidance system under all possible combinations of potential performance limiting factors. Instead, it is necessary to devise a reasonably sized series of tests which subjects the system to factors sufficient to infer system performance under untested conditions. The following discussion describes a possible test protocol for near-term tests.

A fractional factorial design will minimize the number of tests required for near term evaluation. This design will provide information on the effect of measured parameters. The purpose of these tests is to determine the TTA and TTC at the point when the system provides a driver with an alarm. The variables chosen will test the system's ability to provide an alarm in situations found in the driving environment. The fractional design allows for an estimate of the results of these tests regardless of whether or not they are caused by a measured parameter or an interaction of parameters.

These near term tests would consist of one experiment for each of the countermeasures being evaluated. These experiments would all include the same output variable of TTA and TTC at the point of warning. They would also include the same four control variables.

The first control variable is the test scenario. There are three scenarios for each countermeasure. The second control variable is the cooperative vehicle size. The "levels" for this variable are a medium duty truck, a medium sized sedan, and a motorcycle. The overhead view of these three potential cooperative test vehicles is shown in Figure 3.10. For the rear near object detection systems (NODS) experiment, the medium duty truck will be replaced with a child's tricycle.

Medium Duty Truck   Medium Sized Sedan   Motorcycle
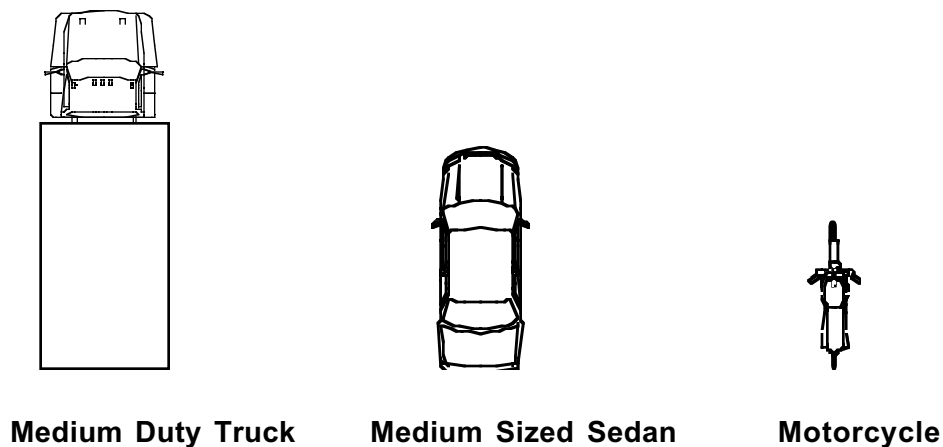
Figure 3.10: Overhead View of Potential Cooperative Test Vehicles

The third control variable is the initial relative velocity between the test vehicle and the cooperative vehicle. This variable will have three values: 25, 35, and 45 miles per hour. The velocities are listed in the descriptions of each experimental design and are dependent upon the countermeasure evaluated.

The final variable is the level of clutter. The values of clutter will be none, rural, and urban. The physical layouts of these clutter levels will be well controlled and documented in a map known as the ground reference. A clutter map will be created for each of these levels. The clutter levels are listed in the descriptions of each experimental design and are dependent upon the countermeasure evaluated.

3.1.4   Future Directions

The requirements and test protocol provide a basis for future development of test protocols to evaluate the potential crash avoidance capability of countermeasure systems. The Crash Avoidance Metric Partnership (CAMP) agreement with NHTSA should provide test procedures for forward collision warning countermeasure systems. The system requirements and crash scenarios defined in this task have provided the CAMP project an initial start in their effort to determine test protocols.

3.2   Development of Near-Term Systems (Task 2.1)

Various studies of crash scenarios have indicated that over one-quarter of the police reported crashes are rear crashes with other vehicles or objects. In addition, a large percentage of these crashes are due to an inattentive or distracted driver. If an appropriate warning could be provided to an inattentive or distracted driver, a number of these crashes may be avoided. This warning should be appropriate to the driver. That is, it should identify a true potential crash situation and should avoid nuisance alerts. Nuisance alerts could be generated too early (i.e. before the driver would consider the situation a potential crash) or due to objects which are not in the vehicle's path. Nuisance alerts may cause the driver to become insensitive to the warning and thereby miss an appropriate situation. To provide a warning of a potential rear end crash, the warning system requires a forward-looking sensor. This sensor and system should be cost-effective for the automotive market.

This task identified the requirements for a rear-end crash warning system and sensor based on the studies performed in Task 1 - Overall Program Requirements and Performance Validation. The system elements that were identified included sensor, processor, and warning device. The primary effort was devoted to identifying and evaluating a forward-looking sensor. Radar and optical sensors were researched to determine the viability of each technology for this application. The radar technology was selected because of its ability to identify objects in the forward path in rain, snow, and fog conditions. Sensor parameters required for the warning application were identified and a sensor satisfying these requirements was purchased, installed on a vehicle, and evaluated. Threat assessment algorithms, which determined the potential of a rear end crash with an object in the vehicle's forward path, were identified and were installed in the crash warning processor. Roadway evaluations of the sensor and warning algorithms were performed.

The goals and objectives of this task were:

- To derive the requirements for the rear end crash warning system and define sensor specifications

- To obtain a developmental radar sensor from a component supplier

- To integrate the sensor into a vehicle and evaluate the rear end crash warning concept with in-vehicle tests

The expectations of this task were to verify that the purchased forward-looking radar sensor met the sensor requirements which were established from crash scenarios and normal driving situations and to demonstrate threat assessment warnings due to objects identified by the radar sensor. A number of test scenarios were identified that would verify the capability and its ability to satisfy the defined requirements. Any deficiencies would be analyzed and determined whether the requirements should be adapted or the sensor design should be modified.

3.2.1   Sensor Parameter Requirements and Rationale

Based on the Forward Collision Warning (FCW) system requirements defined in Task 1, key forward-looking sensor parameters were identified as important characteristics in future collision warning systems. Initial requirement values for each parameter have been determined based on preliminary analyses and are shown in Table 3.2.

Table 3.2: FCW Sensor Parameter Requirement

Sensor Parameter	Requirement
Azimuth field of view	> 18 degrees
Elevation field of view	4 < EFOV < 8 degrees
Range of operation	5 to 200 meters
Range rate limits	-35 to 70 meters/second
Azimuth resolution	< 1.5 degrees
Range resolution	< 1 meter
Range rate accuracy	< 0.25 meter/second
Data update rate	> 10 Hertz
Sidelobe attenuation (1 way)	> 25 dB

These parameters and values were used as the basis for selecting a potential developmental radar sensor for further evaluation on vehicles and in test situations. These requirement values, however, should be considered as initial engineering estimates for forward-looking sensor requirements pending further analysis, simulation, and vehicle testing. The rationale for selecting these values is:

- Azimuth Field of View (FOV): Sensor is required to detect a stopped object in the same lane at 150 meter range while on a 500 meter radius curve. This also results in fully illuminating the adjacent lane at a range of 100 meters.

- Elevation Field of View (FOV): Sensor must be able to keep track of objects which are within range and azimuth FOV and account for road tilt (5% grade), road variation, sensor misalignment, and vehicle pitch. Further analysis and field testing are required to determine a suitable value for the elevation FOV parameter.

- Operating Range: Sensor is required to detect/track stopped objects at a range that provides time for driver reaction. Minimum range of one car length (5 meters). Maximum range of 200 meters is based on a stopped object:

  (a) at 65 mph (29 m/s) closing rate requires 150 m stopping distance (0.3 g deceleration),

  (b) with total latency of 1 to 1.5 seconds results in additional 30 to 45 meters.

- Range Rate: Needs to be large to avoid aliasing or dropping target tracks. Maximum closing rate of no more than 100 m/s (220 mph). Maximum opening rate of 50 m/s (110 mph).

- Azimuth Resolution: Needs to accurately determine if an object is in the current path even if multiple vehicles are at same range and speed. Requires accurate position/range/velocity measurement within a range of 100 meters. Requires ability to resolve objects in adjacent lanes at 100 meters.

- Range Resolution: Requires multiple resolution cells on the object without overburdening the processor. Resolution equal to one-half a motorcycle length is the criterion (< 1.0 meter)

- Range Rate Accuracy: Needs to determine an object's velocity to within 0.25 m/s to maintain a desirable track file.

- Data Update Rate: Dynamic environment dictates that the sensor data be updated in a timely fashion. If two vehicles are approaching at 130 mph (58 m/s) then the range changes by one vehicle length (~5 meters) in 90-100 ms (~10 Hz update rate).

- Maximum Sidelobes Level (1-way): Nominal vehicle signatures can vary by more than 40 dB. High sidelobes will result in small objects being masked or large objects creating ghost (false) objects. Low sidelobes will also help reduce the RF interference.

3.2.2   Prototype Radar Sensor Evaluation and Results

Base on these sensor parameter requirements, a mechanically, scanning radar sensor was selected from a number of potential forward-looking radar sensor suppliers. The field of candidates was narrowed down to mechanically scanned sensors because these sensors satisfied the azimuth resolution and the azimuth field of view requirements. With an azimuth resolution of less than 1.5°, the sensor theoretically should be able to resolve two adjacent vehicles one half of a lane width apart at a range of 100 meters. With an azimuth field of view of 18° (9° on either side of the forward line of

sight), the sensor should be able to detect a vehicle in an adjacent lane at 100 meters and detect a stopped object in the same lane at 150 meters when traversing a curved path with a 500 meter radius of curvature.

The selection of the prototype sensor supplier was based on the specified performance of the candidate sensor and the development environment available for data acquisition and algorithm development. The selected sensor met all but one parameter requirement. Its development environment provides data acquisition and algorithm evaluation support which enables GM to develop threat assessment algorithms and test the algorithms in traffic situations. The sensor and development system have multiple stationary and moving object tracking capability, access to data at various stages in the processing chain, and extensive road test experience in an intelligent cruise control application.

The sensor was initially tested and evaluated in the laboratory environment to verify basic operational characteristics. After verification of its functionality, the sensor was installed in a GMC Suburban with a collision warning controller, threat assessment algorithms, and data acquisition equipment. Controlled static and dynamic tests were performed with the radar sensor on the vehicle.

One of the goals of this task is to implement the Forward Collision Warning (FCW) system on a vehicle to obtain field data to gain real world understanding of the problem. The overall FCW system consists of an instrumented vehicle with sensors, computing elements, a data acquisition system, a driver information system, an engineering terminal, an on-vehicle development environment, a video camera, and a video recorder. The most critical element in the FCW system is the forward-looking sensor, and radar was selected as the primary sensor. This type of sensor has the ability to sense objects in a limited volume in the front of the vehicle. There are several secondary vehicle dynamics sensors to supplement this primary sensor. The sensor suite in its current form is redundant, however it enables various alternatives to be evaluated for a robust FCW system implementation.

Computing elements consist of processing sub-systems that are dedicated to the forward-looking sensor and are usually provided by the sensor supplier. They are either special purpose systems designed and built for sensor signal processing or personal computer based systems, with optional special purpose add-in boards. They are also supplemented by a special purpose FCW computer to extend and enhance the functionality of the sensor.

A data acquisition system is integrated into the Forward Collision Warning computer with a laptop personal computer for permanent data storage. This system simultaneously collects radar data, vehicle dynamics data and video for off-line analysis. A driver information system is a rudimentary device that gives feedback to the driver/experimenter on the status of current driving situation. An engineering terminal and an on-vehicle development system are implemented on a laptop personal computer. This enables the operator to control the system, observe the results, and make necessary improvements.

Two vehicles have been instrumented with radar sensors to be used as testbeds for evaluation. Early in the program a commercial off-the-shelf system (COTS) is installed in a vehicle to gain experience. Later, a carefully selected Prototype sensor

was acquired and installed in a vehicle for evaluation. The goals of the prototype system are to select a radar sensor, which exceeds the specifications of a production system sensor, to conduct in-depth analysis of the sensor, and to come up with sensor specifications for production unit. The production sensor specifications are expected to be less stringent than the prototype sensor.

A test vehicle has been instrumented to evaluate the prototype sensor as well as FCW system on test tracks and on real-world traffic. This is the testbed similar to the COTS system implemented on a Chevrolet Suburban. The block diagram of the Prototype Radar system architecture is shown in Figure 3.11.
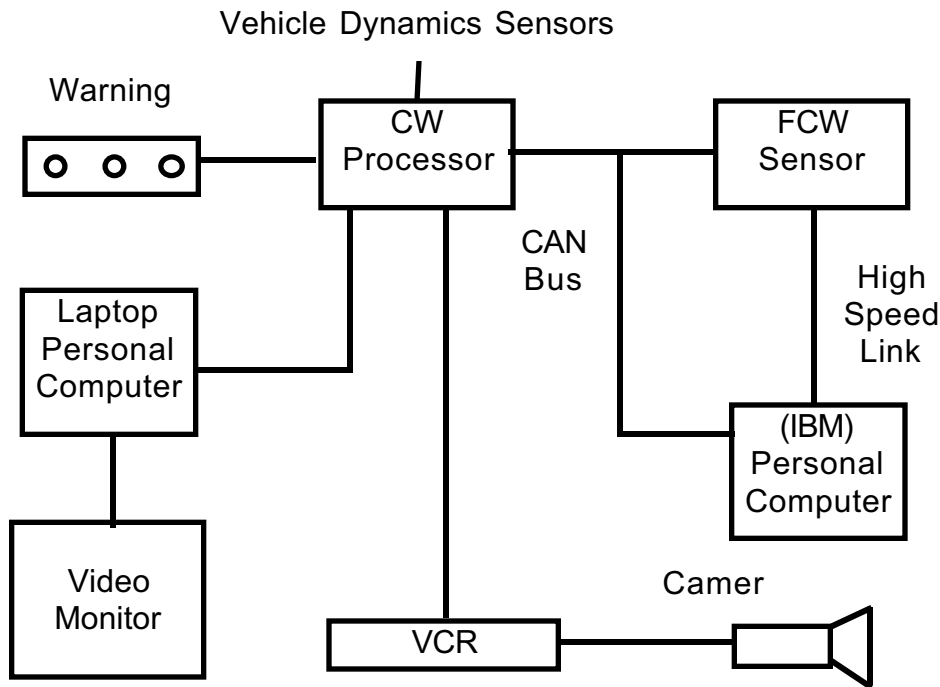
Figure 3.11: Prototype System Vehicle Architecture

The Prototype sensor has enhanced specifications compared to the COTS sensor. The most apparent characteristic of the prototype sensor, compared to the COTS sensor, is the size, mainly due to the scanning technology. Mechanical scanning is used with single antenna compared to four distinct antennas. In addition, the same antenna is used for transmit and receive compared to separate antennas in the COTS sensor. The beam scan rate is lower, 10 Hz, but with a wider field of view and a narrower beam.

Tests were conducted to evaluate the sensor parameters. No specific test has been performed to evaluate the overall FCW system. All of the tests were performed on restricted test areas or test tracks. The results reported here are for the prototype sensor only. The tests are classified in three groups; static, semi-static, and dynamic. The purpose of the static tests is to measure certain radar sensor parameters that are

hard to measure and verify when the environment is changing and the radar equipped vehicle is moving. Important radar parameters such as range accuracy and resolution, and azimuth accuracy and resolution were evaluated using the static tests. Semi-static tests are performed such that target(s) is stationary and the radar-equipped vehicle is moving. These are used for latency, range rate accuracy, and angular resolution in a real world setting. In the dynamic tests, both the target(s) and the radar equipped vehicle are moving. It is the hardest type of tests to control various parameters, especially when there are multiple target vehicles. Also, it is difficult to repeat exactly the same scenario consistently.

The tests were performed to determine the compliance of the radar with the specifications in a real world environment. The results of this testing are summarized below:

(a) Range accuracy test results were satisfactory and this parameter is within the specifications. However, range resolution results showed that this parameter was out of specifications.

(b) Field of view and accuracy tests showed that the radar meets the specifications. Again, angular resolution measurements were out of specifications. Range and field of view measurements were performed using corner reflectors initially, then with real vehicles.

(c) Range rate accuracy test proved that this parameter was within the specifications. Vehicle speed was used as a reference, which could have some error also.

(d) Range rate latency measurement is used to determine the overall latency of radar output computation. However, it also includes the communication delay associated with data acquisition. The measured value is as expected.

(e) Two stationary vehicles in adjacent lanes demonstrate the real world performance of the radar's angular resolution performance. The results indicate that these two vehicles are resolved at 40 meters that is well below the expected performance based on the specifications.

(f) When two vehicles are moving at the same speed in adjacent lanes, the radar is capable of resolving them at 70 meters when closing in and 80 meters when opening. This is much better than in the stationary case but still does not meet the specifications.

(g) In the case where these two vehicles are moving at different speeds in adjacent lanes, they are resolved at 100 meters which meets the specifications. This result indicates that the radar requires range and range rate parameters of two adjacent targets to be different to be able to resolve them.

(h) The target cut-in test verified that the radar meets the specifications for the field of view parameter under dynamic conditions.

(i) When two vehicles are moving at the same speed in two outside lanes, the radar is capable of resolving and tracking them at 170 meters. Also, when the radar vehicle approaches them and passes in between them, they are tracked up to angles of +8 and -9 degrees. These two results are well within the specifications of the radar.

In general, the radar was within the specifications during some of the tests. Those cases that the radar met the specifications were observed when the targets were moving and there was at least one parameter varying among multiple targets. In those cases where targets were stationary or all the parameters were the same, except the measured one, the radar failed to meet the specifications. In addition, the imbedded sensor processor first processes the parameters that were measured which may involve some filtering. Thus, they do not represent the raw data measured by the radar. This processing is mainly for adaptive cruise control and/or forward collision warning type of applications.

3.2.3   Simulation Approach and Results

The purpose of the Forward Collision Warning System (FCWS) simulation is to develop an engineering tool to assist in the definition of the system requirements and refinement of the functional radar sensor and to evaluate technical and functional specifications of the radar sensor. The simulation incorporates roadway geometry, traffic scenario, and radar sensor model for analysis and display. The simulation also provides a tool for analyzing different forward collision warning algorithms under normal and crash scenarios. It allows evaluation of threat assessment algorithms in repeatable simulated scenarios and performs sensitivity analyses of system and sensor parameters to substantiate specifications.

The system simulation consisting of an interactive driving model, a radar sensor model including a simplified object tracking model, an integrated threat assessment module, and the user display module. The simulation, an engineering tool, generates positional information of the host and other moving and stationary objects in the scene, host vehicle dynamics, measured radar parameters, tracked object histories, and a time to collision parameter for various traffic scenarios. The concept of the simulation is shown in Figure 3.12.

Different host vehicle driving profiles can be incorporated into a simulated scene with a given road geometry, stationary objects, and moving vehicles. The occurrence of warning alerts and potential crash situations for this driving scene can then be analyzed with various radar sensor parameters and threat assessment algorithms. The warning system can be evaluated by varying the sensor and threat assessment parameters and the driving profile. This capability expands the ability to analyze crash scenarios beyond the real world test capabilities. It also allows a theoretical estimate of the impact of potential sensor redesign concepts on the collision warning algorithms.
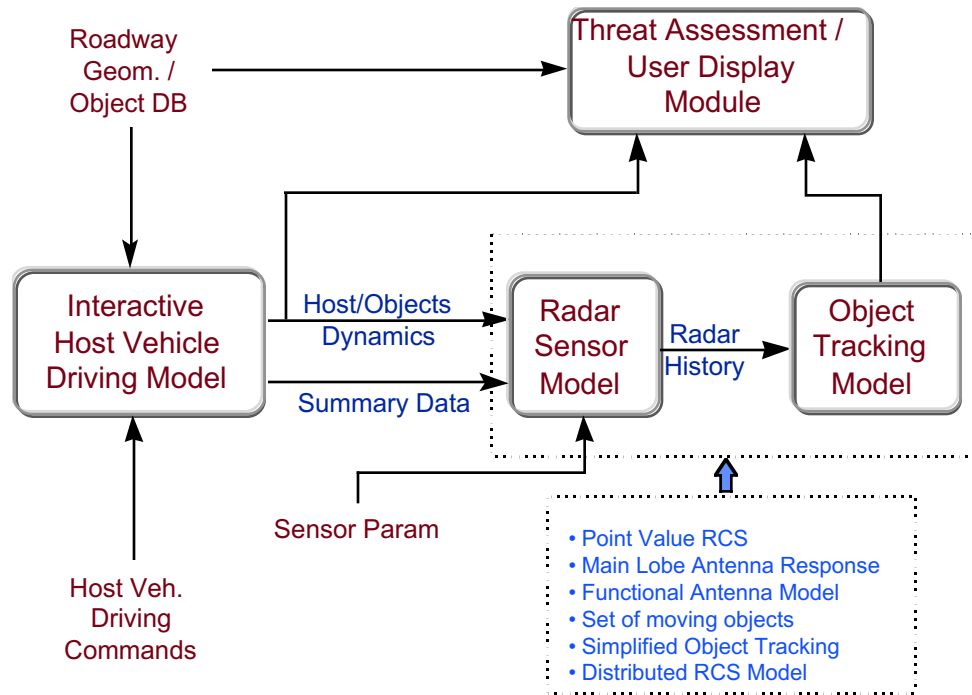
Figure 3.12: Forward Collision Warning System Simulation Concept

The threat assessment algorithms are developed in C programming language independent of the simulation effort. A set of four algorithms has been integrated. The user display module is designed to allow easy integration with any number of algorithms as they are developed. To integrate those four algorithms into the display module, they are first translated into four functions, named alg1, alg2, alg3, and alg4. When the algorithms are supplied with proper inputs, they will return flags indicating the warning status. The user display module displays the top view of the driving scene and the warning status for each of the selected threat assessment algorithms. Users can choose from the menu which algorithms, in any, to use in the simulation and they can observe the warning status as the scene progresses with time.

The simulation tool is currently being used to evaluate threat assessment algorithms. First order effects can be observed and analyzed with the current simulation and model. This is a valuable analysis tool because crash situations are infrequent in the real world environment and are difficult to obtain meaningful data. However, further enhancements for the radar sensor model are required in order to perform a parameter variation analysis on the radar sensor parameters and the threat assessment algorithm parameters.

3.2.4 Threat Assessment Analysis

The purpose of threat assessment algorithms is to warn the driver with respect to potential crashes. The collision warning sensor tracks and identifies potential targets and passes this information to the threat assessment sub-system. The appropriate parameters for threat assessment can be range, range rate, following and target vehicle velocity, longitudinal and lateral accelerations, horizontal and vertical radius of curvature

of road, target signature and quality, vehicle dynamics (such as yaw rate, heading angle, lateral position, steering angle, roll and pitch rates) and driver-vehicle interface parameters (windshield wipers, weather, road surface, brake status and powertrain status). On curved roads, multiple targets may generate false warning due to incorrect path determination, i.e., out-of-lane targets may generate false warning and in-lane-targets may be missed leading to a missed alert. The vehicle dynamics knowledge in combination with some sort of road geometry obtained by using vision-based lane sensing and GPS/map database is essential for determining the projected path of the vehicle. Ideally, very high angular resolution is required for multiple target tracking. Current systems with medium angular resolution may not be able to differentiate between 2 targets on a curved road, which could generate incorrect warning to the driver. Moreover, target's longitudinal and lateral accelerations that would predict trajectory are not available and can only be estimated roughly.

Since target acceleration is not available, current algorithms are based on fixed assumptions about target and following vehicle's decelerations for the rear-end collision scenarios. The two dominant scenarios are the inattentive driver and stopped object in the path. The collision warning algorithms are based on either computing the warning distance or computing the time to collision parameter or a combination of both approaches. Given the lead vehicle's velocity v_l, deceleration a_l, following vehicle's velocity v_f, deceleration a_f, range R (distance to lead vehicle) and the system delay time D (which includes the driver response time, brake response time and target acquisition time), the distance_based algorithms are given by:

Standard Driver Alert Equation

$$\text{distsda} = v_f^2 / 2a_f + D\, v_f - v_l^2 / 2a_l \tag{3.1}$$

Closing Rate Equation

$$\text{distcra} = (v_f - v_l)^2 / 2a_f + D\, v_f \tag{3.2}$$

If the computed values for distances (distsda or distcra) are greater than the range R, then a warning is issued to the driver.

The time-based algorithms are given by:

$$\text{Time To Collision} = R / (v_f - v_l) \tag{3.3}$$

$$\text{Time Headway} = R / v_f \tag{3.4}$$

A warning is given to the driver when the time to collision or time headway values exceeds some pre-specified threshold. The time-based warning algorithms are easy to evaluate but are incorrect for general collision warning scenarios, since no deceleration rate and system delay parameter is used. The distance-based algorithms also suffer from excessive false alarm alerts, as correct acceleration values are not being used.

The collision warning algorithms should warn the driver with minimum number of nuisance alerts and in sufficient time such that the driver can either avoid the crash or mitigate the crash. If the warning is either given too early or too often, then the driver will take that warning to be a false alarm or nuisance alert. A missed alert is defined as a warning which is either not given or is given too late for the driver to respond in proper

time. In order to perform the sensitivity analysis, various crash and non-crash scenarios for lead and following vehicles with varying dynamics are set up for using simulated data. The scenario dynamics consist of a lead vehicle decelerating at constant rate and the following vehicle decelerating after a specified delay time. For a fixed set of parameters, analytical equations predict whether the type of scenario will be a crash or non-crash. The time to crash (for a crash scenario) and other vehicle dynamics parameters are also derived. The dynamics of both vehicles such as velocities, positions, decelerations and the collision warning algorithm's response are also computed.

Results of applying several algorithms (Equations 3.1–3.4 with different parameters) on simulated data are given in Tables 3-3 through 3.5. The simulated data scenario was generated for lead and following vehicle velocities varying from 0 - 39 meters/sec and initial range varying from 5 - 150 meters. The number of scenarios for the simulated data set was 29,200. Using Monte Carlo simulation, the parameters for the lead deceleration, driver response time to lead vehicle braking and driver response time to alert warning were varied (sampled from distributions).

**Table 3.3: New Mexico Database (July Data Set, # of Samples:1,350,000,
# of Crashes: 1115, Following Vehicle Deceleration: 0.6 g)**

	Alg. 1	Alg. 2	Alg. 3	Alg. 4	Alg. 5
Hit Rate (%)	99	100	69	84	81
False Alarm Rate	17	34	0	4	1

**Table 3.4: New Mexico Database (Sept. Data Set, # of Samples: 1,616,445,
# of Crashes: 2078, Following Vehicle Deceleration: 0.6 g)**

	Alg. 1	Alg.2	Alg. 3	Alg. 4	Alg. 5
Hit Rate (%)	100	100	67	82	80
False Alarm Rate	19	40	0	4	1

**Table 3.5: Simulated Data (# of Samples: 1,314,000,
# of Crashes: 150,009, Following Vehicle Deceleration: 0.6 g)**

	Alg. 1	Alg. 2	Alg. 3	Alg. 4	Alg. 5
Hit Rate (%)	100	100	99	95	100
False Alarm Rate	15	20	7	10	13

These simulations demonstrate that for an <u>inattentive driver</u>, the false alarm rate is very high due to the fixed set of acceleration/deceleration parameters being used. Moreover, false alarm rate can be minimized at the cost of hit rate. Ideally, the hit rate

should be 100 % with the lowest possible false alarm rate. Table 3.6 shows Algorithm 1's performance on the data sets when true deceleration parameters are used. The corresponding results from Tables 3.3 - 3.5 are also shown as the first entry in each cell.

Table 3.6: Algorithm 1's Performance (Fixed / True Deceleration Parameters)

	July Data Set	Sept. Data Set	Simulated Data
Hit Rate (%)	99 / 100	100 / 100	100 /100
False Alarm Rate	17 / 2	19 / 3	15 / 8

Preliminary analysis has shown that the false alarm rate for the <u>inattentive driver</u> can be reduced to less than 8 % when true deceleration parameters are used. The recommendation for future development is to evaluate algorithm performance and sensitivity when estimated acceleration/deceleration parameters are used.

3.2.5 Future Directions

The prototype sensor specified to the vendor met most of the requirements, however some critical parameters fell short of the specifications. The azimuth resolution is the most critical one of these parameters. Poor performance of the prototype radar with respect to this parameter results in clustering of two objects into a single object under certain conditions. For example, two vehicles in adjacent lanes are reported as a single object depending on other parameters, which was demonstrated by other tests. This may compromise the performance of forward collision warning system under certain conditions. The range resolution was another parameter that did not meet the specifications. However, this may not be as critical as the azimuth resolution since there may not be a need to discriminate objects as finely as stated in the forward collision warning application. The latency measured in the system can be minimized when the application is better integrated into the sensor, at this time it is not possible to quantify the components of this delay.

The most important issue is to be able to obtain unfiltered raw information from the sensor. Vendors do have embedded preprocessing optimized for a specific application. This of course optimizes the performance of the radar for a given application, however masks some important information that might be useful in evaluation of the sensor. The issue is not technical, most vendors consider the basic data as proprietary information. Another issue that was not investigated was the elevation field of view parameter. It was observed that the sensor detected many overpasses and overhanging road signs. The solution is to investigate both hardware and software techniques to come up with a cost-effective solution. For example, introducing a low cost but crude elevation angle resolution combined with signal processing techniques may improve the performance significantly. The vendors should place additional resources on improving their sensors working jointly with their customers.

3.3 Development of Cost Reduction Components for Production (Task 2.2)

A primary factor in the deployment of a forward-looking radar (FLR) is the recurring cost of the hardware itself. The hardware configuration that exists today is typically a two piece system that has a millimeter wave radar sensor on the front of the vehicle and large complex processors and computers in the trunk of the vehicle. These systems use many commercial off-the-shelf components and cost in excess of $100,000 to implement. Marketing studies and surveys of automobile manufacturers have shown that the total cost of the system to the consumer must be less than $1,000 in order to achieve significant market penetration. Additionally, the size of the system, including both the millimeter wave sensor and the signal processor, must be reduced to less than 100 cubic inches. Therefore, significant progress must be made in the development of low cost, small size, integrated components.

The FLR sensor consists of three major elements: the antenna, the processor, and the transceiver. Of these, the transceiver is both the highest cost and the highest technical risk. The existing radar sensors typically use individual waveguide components and discrete components that require three dimensional assembly processes that are performed manually.

This task was structured to address this transceiver problem by designing a low cost planar transceiver that is manufacturable in high volume using automated assembly equipment. The task objectives are:

- Development of a low cost 76 GHz transceiver utilizing a single piece planar construction with MMIC chips.

- Development of a high yield fabrication process for 76 GHz MMIC oscillators fabricated in Gallium Arsenide.

- Seek the best compromise between:

  - Up-integration for reduced parts count, ease of chip placement, and reduced circuit size.

  - De-integration into multiple (less complex, higher yield) chips, which require more substrate space and manufacturing operations.

- The overall result must satisfy both performance expectations and production cost objectives.

3.3.1 Summary of Progress

The primary design approach featuring planar construction and a MMIC based design was defined, an initial performance specification was generated, and two potential suppliers were placed under contract. A primary factor in supplier selection was that each supplier had an existing MMIC chip set that could be used in the initial concept design. However, this resulted in separate internal block diagrams for each

supplier. The "black box" electrical performance specification was identical and the mechanical package was interchangeable. The MMIC based units received from both suppliers did not meet specification and were late in delivery. After multiple meetings, it was decided to proceed with one supplier with a design that used devices from both suppliers. Two transceivers were fabricated and tested with significantly better results than before. It was determined, however, that this design could not meet cost expectations due to the immaturity of 76 GHz MMIC technology at this time in the program.

In order to best meet the overall program objectives, the primary design approach was changed to utilize a Gunn diode transmitter with a design architecture that supports a MMIC receiver. Gunn diode based transceivers meeting the MMIC transceiver mechanical size targets were designed, fabricated, and tested. The ability to characterize multiple transceivers on the bench, in the system, and on the road was a significant benefit of the ACAS program. A total of 50 second iteration transceivers were built and tested over temperature. Analysis of this data showed that fine grain linearity and linearity stability over time and temperature were the major electrical problems. A Design for Manufacturing and Assembly (DFMA) workshop was held with representatives from H E Microwave design and manufacturing, the transceiver supplier, and Delco Electronics manufacturing and process engineering. Several design changes for thermal management and manufacturing costs were identified and incorporated in a third iteration design.

The third iteration design was completed and nine units were fabricated and tested. These units met expectations with regards to fine grain linearity, improved thermal performance, and improved manufacturability.

Throughout the program, attention was given to advancements in MMIC technology and performance, and specifications for MMIC based transmitters, receivers, and fully integrated transceivers were prepared and updated.

3.3.2. MMIC Transceiver Design

The primary design approach was defined, and an initial performance specification was generated for the Forward-Looking Radar (FLR) sensor transceiver. Two potential suppliers were placed under contract. A primary factor in supplier selection was that each supplier had an existing chip set that could be used in the initial concept design. This, however, resulted in separate internal block diagrams for each supplier.

The design shown in Figure 3.13 used an HBT device as the oscillator source. HBT performance at 38 GHz was not adequate, so a 19 GHz source was used followed by amplifier and doubler stages in order to generate the 76 GHz operating frequency. The HBT oscillator design was tried as it offers the lowest phase noise, which is a key performance parameter for the system architecture.
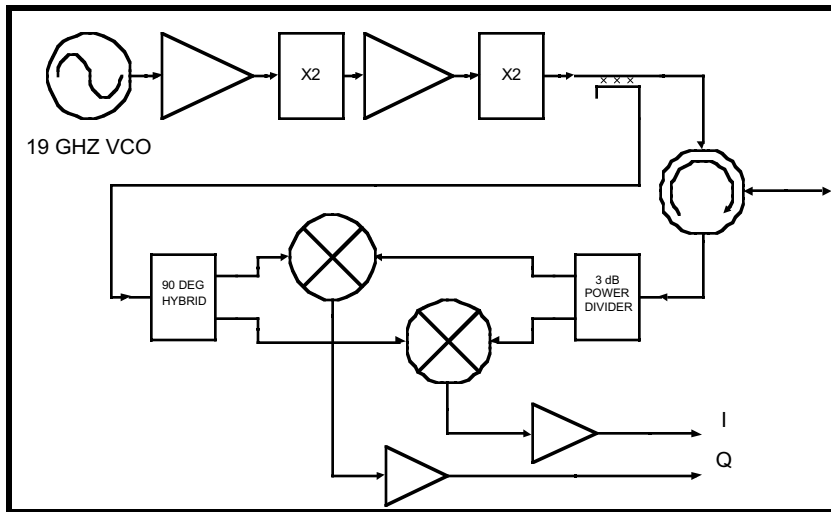
Figure 3.13: Vendor A Block Diagram

The design shown in Figure 3.14 used a Gunn diode mounted in planar configuration. Although the anticipated phase noise will be higher than an HBT oscillator, Gunn devices typically generate significantly higher power than transistor devices operating at the same frequency, thus reducing the number of amplifier stages required.
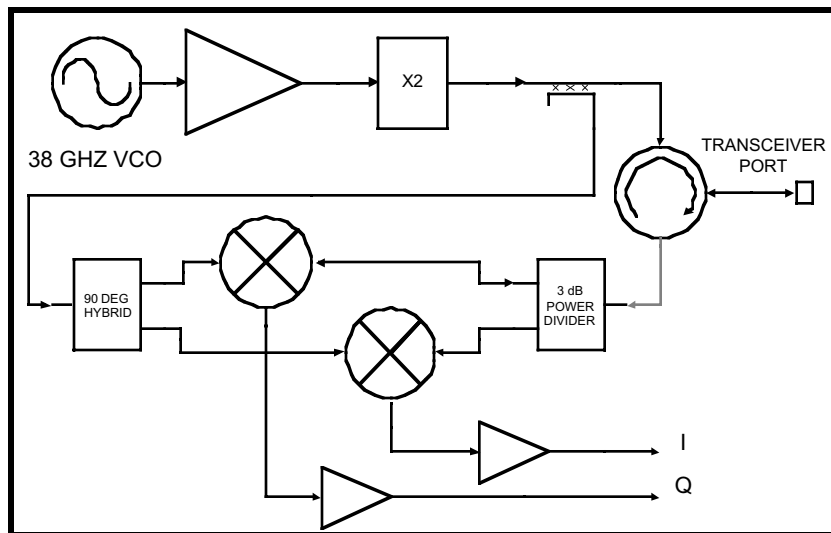
Figure 3.14: Vendor B Block Diagram

The "black box" electrical performance specification was identical for both design approaches, and the mechanical package was interchangeable. The units received from both suppliers did not meet specification and were late in delivery.

After multiple meetings it was decided to proceed with one supplier using a design incorporating the best available devices from both suppliers. Two units were

fabricated and tested with significantly better results than either of the first two designs. It was determined, however, that the design could not meet cost expectations due to the number of MMIC components required and the state of MMIC development at this time. The block diagram for this MMIC based transceiver is shown in Figure 3.15.
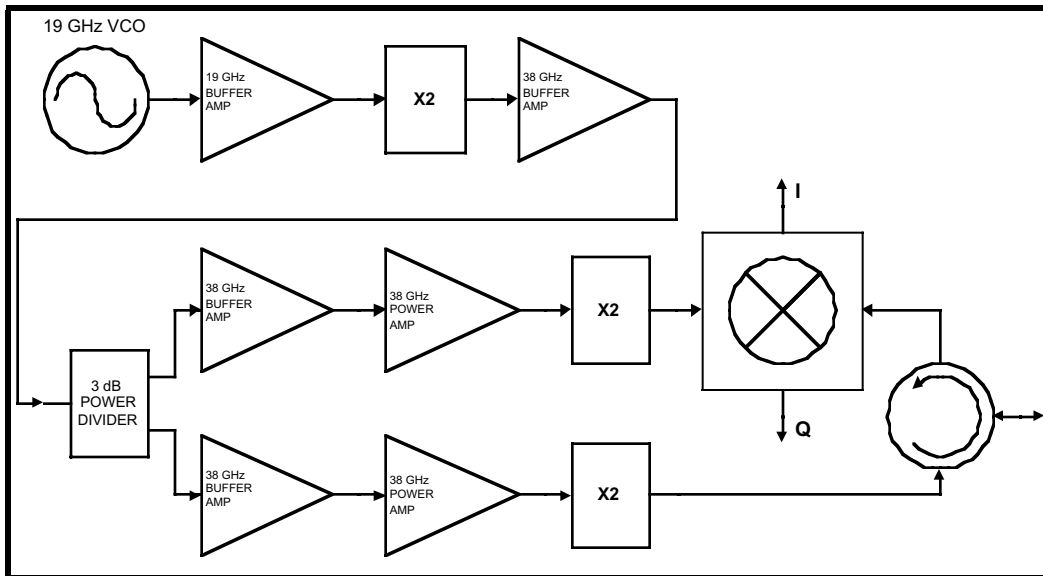
Figure 3.15: 2nd Run MMIC Transceiver Block Diagram

Transceiver results are summarized in Table 3.7. The data is presented in a format such that the recorded value is relative to the specification value. This eliminates referencing proprietary design and performance data in the table.

Table 3.7: MMIC Transceiver Performance Summary.

Parameter	1st Run Vendor A	1st Run Vendor B	2nd Run Vendor B Unit 1	2nd Run Vendor B Unit 2
Power Output	-12 dB	-1.5 dB	In Spec	-1.6 dB
Power Flatness	In Spec	In Spec	In Spec	In Spec
Phase Noise	In Spec	+10 dB	In Spec	In Spec
IF Noise	N/M	N/M	In Spec	In Spec
Receive Gain	-4 dB	In Spec	N/M	N/M
I/Q Balance	N/M	N/M	In Spec	N/M
Modulation Sensitivity	+300%	N/M	+400%	+400%
Power Dissipation	+123%	+142%	+143%	+158%

Note: "N/M" means "Not Measured"

As seen in the data summary, the transceivers based on existing MMIC designs do not meet FLR requirements, although the 2nd run transceivers were much improved and closer to specification. The circuit data and device data has been analyzed and the reasons for the poor performance are understood. The circuit design changes in the second iteration added MMIC components in order to improve the circuit function. This is not an acceptable solution as it adds cost and power dissipation to the transceiver.

The data presented is for room temperature operation. The units were not tested over temperature. It was expected that the second iteration design changes will introduce potential channel tracking problems as a function of temperature, and it was determined that the thermal rise due to excessive power dissipation could destroy the transceiver if hot temperature tests were performed.

3.3.3   Gunn Transceiver Design

A change request to use a Gunn diode VCO transceiver as baseline in order to meet cost and performance targets and schedules for introductory volumes was presented and approved at the ACAS Third Quarter Review meeting. The Gunn transceiver was designed to be compatible with a MMIC receiver, although the first units used a planar microstrip discrete diode mixer circuit. Concept Gunn diode based transceivers meeting the MMIC transceiver mechanical size and volume targets were designed, fabricated, and tested.

Gunn transceiver data is summarized in Table 3.8. The data summary shows one set of data from both the first and second MMIC transceiver iterations along with the summary from the first two Gunn transceivers. As shown, the Gunn transceivers perform quite well relative to the specification. The only area of non-conformity, modulation sensitivity on one unit, is one that can be accommodated within the overall sensor design if necessary, and is significantly better than the previous units.

Table 3.8: Concept Unit Gunn Transceiver Room Temperature Summary.

Parameter	1st Run Vendor A	2nd Run Vendor A Unit 1	Gunn Xcvr Unit 1	Gunn Xcvr Unit 2
Power Output	-12 dB	In Spec	In Spec	In Spec
Power Flatness	In Spec	In Spec	In Spec	In Spec
Phase Noise	In Spec	In Spec	In Spec	In Spec
IF Noise	N/M	In Spec	In Spec	In Spec
Receive Gain	-4 dB	OK	OK	OK
I/Q Balance	N/M	In Spec	In Spec	In Spec
Modulation Sensitivity	+300%	+400%	In Spec	150%
Power Dissipation	+123%	+143%	In Spec	In Spec

Note: "N/M" means "Not Measured"

The concept Gunn transceivers were tested over temperature and showed good performance relative to the parameters listed in Table 3.8. These transceivers were then integrated into the system, and system performance data was taken. Initial system test results indicated that all transceiver specifications were being met or were at acceptable performance levels at room temperature.

Based on these results, twenty additional Gunn transceivers were assembled and tested over the entire temperature range. Data was evaluated and system performance was predicted based on the measured data. It was determined that the stability of the frequency tuning curve was the most critical parameter, and that small perturbations could cause significant system performance changes. This is a parameter that had not been adequately specified or characterized on the MMIC and initial two Gunn transceivers.

Some Gunn transceiver units were subjected to both burn-in and temperature cycling to determine the long-term stability of the tuning curve. Long term stability is a significant design issue due to the mechanical aspects of the oscillator structure. Initial results of the burn-in test indicate that the tuning curve is prone to small but permanent changes. These changes result in range errors when processing the system radar returns. The sweep waveform applied to the Gunn VCO must compensate for these linearity changes, and the system design had planned for a one-time factory calibration and compensation curve. The data indicated that a room temperature correction was inadequate, and that the compensation needed to be adjusted over temperature in relatively small increments of temperature change. Multiple correction curve look up tables were created in software to accommodate this problem, however, this significantly increased the factory test time to levels that were totally unacceptable for production.

Additionally, it was found that although most units could be adequately compensated over temperature to pass system acceptance testing, some of the units would experience permanent sets in the tuning curve. This meant that with time and multiple temperature cycles, some units changed to an out of alignment condition that resulted in field returns at the system level for range errors. It was necessary to significantly change the transceiver test station and test procedure such that the linearity could be accurately measured at the transceiver level.

Considerable effort was expended in the area of Design for Manufacturing and Assembly (DFMA). This activity is essential to achieve the overall goals of the program. A formalized DFMA was held that included representatives from H E Microwave design, H E Microwave manufacturing, the transceiver supplier, and Delco Electronics manufacturing and process engineering. The purpose of the workshop was to address the manufacturability of the design, including in process test and screening requirements. Performance and yield issues were discussed as well as potential process flows and new process development requirements. As a result of this activity, some major action items were identified, and some major design approach changes were recommended.

These changes identified in the DFMA did not involve the primary circuit architecture or electrical function which has been developed to date, but were entirely packaging, process, and reliability improvements. Thermal stress at elevated

temperatures is a major issue due to the low efficiency inherent in Gunn oscillator designs. A rearrangement of the transceiver housing structure was suggested that greatly improves the heat spreading capability of the design. This layout change also greatly reduces the manufacturing assembly steps and is much more amenable to automation than the original design concept. The primary improvement is in the area of the IF circuit and associated voltage regulator and control circuits. No significant changes were recommended to the millimeter wave circuits previously developed. The new packaging concept also supported a reduced parts count.

A redesign to address the problems encountered to date was started. The circuit redesign was structured to address the issues of thermal dissipation, DFMA recommendations, and the small long-term linearity variations that have been identified. The redesign added an active frequency linearizer circuit as shown in Figure 3.16.
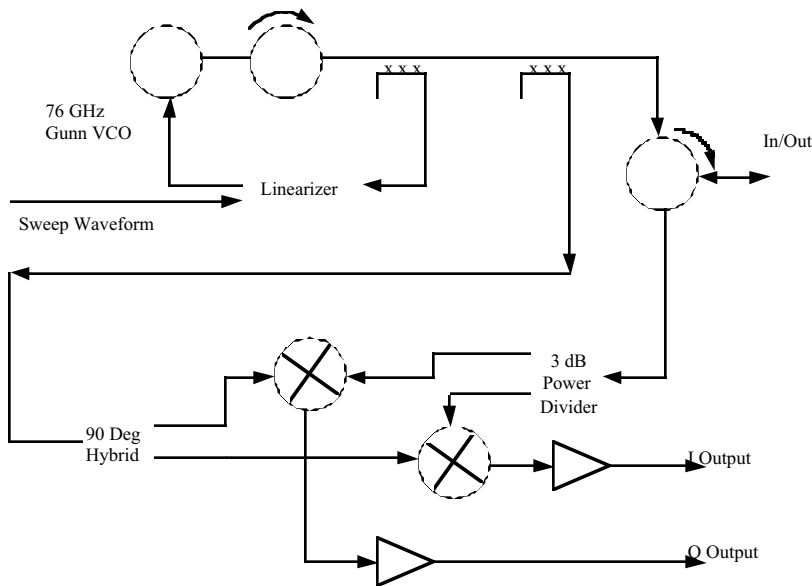
Figure 3.16: Final Transceiver with Linearizer Block Diagram

Characterization of multiple transceivers continued even as the last redesign was in progress. This characterization included extensive temperature testing, system level testing, and road testing. The intent of this effort was to fully understand the performance of the transceiver, to identify transceiver test requirements for production, to identify the most critical transceiver parameters relative to system performance, and to assure that the transceiver performance specifications were consistent with system specifications.

Thirty additional transceivers were built and tested over the entire temperature range. Data was evaluated and system performance was predicted based on the measured data. The stability of the frequency tuning as the most critical parameter was reaffirmed, and it was shown that very small perturbations could cause significant system performance changes. Results of the burn-in test indicate that the tuning curve is prone to small but permanent changes, and there has been no way to determine ahead of time which units have this problem and which do not. Additionally, there has been no effective screen identified that indicates the time period required for each

transceiver to stabilize. Some have been stable from the start and did not change with screening, and others continue to change after multiple cycles of screening. This is the primary circuit design problem that was addressed in the last redesign.

Transceiver performance in the system was monitored and tracked. It appears that the transceiver, when properly compensated for linearity, meets all system requirements. Primary parameters of power out, frequency stability, receive gain, and noise figure appear to be consistent with system performance requirements. The long-term concerns are fine grain linearity stability, maximum operating temperature, and recurring manufacturing cost.

Nine of the final iteration transceivers were fabricated. Significant effort was spent in testing and characterizing these units both at room temperature and over the temperature extremes. Results of the tests are summarized in Table 3.9. The table also includes a comparison of the second iteration transceiver for reference. The data in the table represents the average performance of the nine final iteration transceivers tested and the average of six earlier transceivers picked at random. Specification values considered proprietary are withheld.

Table 3.9: Final Transceiver Performance Summary

Parameter	Specification	Third Iteration (EDU)	Second Iteration (Concept)
Receive Output	313 mV	315 mV	343 mV
Video Noise	Withheld	3 dB High	2 dB High
I/Q Gain Balance	+/- 0.75 dB	0.82 dB	0.48 dB
I/Q Phase Balance	+/- 20 Degrees	9.0 Degrees	0.0 Degrees
Frequency Stability	1.6 MHz/^{o}C	0.3 MHz/^{o}C	2.21 MHz/^{o}C
Power Stability	0.016 dB/^{o}C	0.019 dB/^{o}C	0.02 dB/^{o}C
Linearity 22C	Withheld	In Specification	5x High
Linearity over Temp	Withheld	In Specification	5x High
Current	500 mA	264 mA	472 mA
Transmit Power	10 dBm	11.3 dBm	11.93 dBm
Power Flatness	2 dB	1.3 dB	1.4 dB
Phase Noise	Withheld	1.4 dB Below Limit	7 dB Below Limit

Overall, the performance of the third iteration design was good, and the primary goal of improving thermal management and linearity has been met. The linearity is excellent and is also very stable over temperature and time. This will eliminate the time consuming temperature calibration data collection necessary to generate a temperature dependent correction table that was required with the second iteration design. It will also eliminate the long term time dependent changes in linearity which in earlier designs caused slow degradation in system performance due to changes in tuning characteristics which made the temperature dependent linearity look-up tables invalid. These are very positive results of the new design.

A review of the performance table indicates that performance was degraded significantly in one area: transmit phase noise. Additionally, the Video Noise performance has degraded slightly, but the performance of both the 2nd and 3rd iteration units are out of specification for this parameter, and this parameter is a major driver in overall system sensitivity. All other parameters either meet or are within measurement error of the specification, or had no significant change from the second iteration design, and are not of concern at this time

It is believed that the increase in transmit phase noise is a result of coupling noise from the linearizer circuit onto the VCO control line. When the VCO is disconnected from the linearizer and tuned via an external power supply, the transmit phase noise is reduced by 1-5 dB (3 dB nominal). It is believed that additional filtering of the VCO control line should resolve this problem.

The increase in receive video noise is thought to be caused by two factors. First, because the system is a receive-while-transmit design, transmitter leakage during receive will cause the transmitter phase noise to be down-converted into the receive baseband. This means that any increase in transmitter phase noise will appear directly on the receive video output as an increase in the noise floor. Therefore, the transmit phase noise increase is one of the primary contributors to the increased receive video noise.

The second major contributor appears to be the T/R circulator. The amount of transmitter leakage into the receiver is a direct function of the isolation of the T/R circulator. The second iteration transceiver had a waveguide block circulator design that could be pretested and tuned to verify performance parameters were met. In the current design, the circulator has been integrated into a multiple component structure that is smaller and easier to fabricate, but eliminates the ability to verify and/or tune individual component performance. Tests on the one accessible T/R circulator port indicate that the T/R isolation may be degraded by approximately 5 dB. This then would result in a receive video noise increase of 5 dB independent of the higher transmit phase noise. The sum of the two results in a potential 8-dB nominal degradation of video noise in the system. The result will be a loss in maximum range compared to the second iteration design. The loss in range does not necessarily mean that the system does not meet minimum performance requirements, as these parameters are a part of the overall link budget which include transmit power, receive gain, antenna gain, etc. However, degradation of this magnitude consumes most if not all of the design margin, and needs to be resolved.

The third iteration transceivers were integrated into a full-up FLR system that is currently undergoing system integration and field-testing.

3.3.4   Challenges

The primary objective of this task, the development of a 76 GHz transceiver that meets system performance requirements over the extreme automotive environmental operating conditions and is cost-effective, is in itself the most significant technical challenge. There are a variety of system approaches and architectures that are theoretically feasible, and each system approach has a variety of transceiver design approaches that are also feasible. Unfortunately, there is not enough time and funding

to develop all the design approaches and investigate the design trade-offs. Consequently, the design trade-offs were instead based on certain non-verified assumptions regarding technical performance, application requirements, and manufacturability.

For this task, a system design approach was chosen prior to the inception of the ACAS Program. The transceiver architecture was the primary variable. It was decided to try an all MMIC approach based on existing design building blocks. The program was structured to allow design iterations based on facts discovered during the ACAS Program. For example, the MMIC design was fabricated and tested to determine the maturity of GaAs MMIC technology with regard to both performance and cost. A particular architecture had to be chosen early in the program to insure that the overall schedule could be met. As the design was being fabricated, cost estimates were prepared that included, MMIC device processing costs (based on estimates of achievable yields at the foundry), transceiver material costs (molded, cast, machined housings plus other non-MMIC components), transceiver manufacturing costs and yields, and transceiver test costs and yields.

As the design was iterated to meet performance goals, the cost model was updated. It was determined that all MMIC technology had not reached the maturity necessary to achieve all cost and performance goals at this time. It was also determined that transceiver architecture changes could be made that minimize the active component count such that MMIC devices may become cost-effective in the near future, but not within the time frame of the ACAS Program. Emphasis was then turned to transceiver design alternatives that could meet the primary objective of both cost and performance without the exclusive use of MMIC devices, but that were compatible with MMIC insertion in the future.

In anticipation of continued maturity of GaAs MMIC technology at millimeter wave frequencies, the transceiver design was structured to minimize the number of active components and to group circuit functions in a fashion that allows continued development of MMIC devices. New MMIC component specifications based on results obtained from the ACAS Program were prepared and are being pursed with the MMIC industry base.

3.3.5   Completeness of Task and Major Benefits

This task was completed on schedule and on budget. The task was modified to use the best compromise between design approach and deployment constraints in order to meet the critical objective of performance expectations and production cost. In order to accomplish this, the all MMIC and all planar approach was changed in favor of a wave guide Gunn oscillator, with a discrete planar receiver and frequency linearizer. Given these changes in design approach, there were significant benefits derived from the ACAS program in the areas of cost reduction, performance improvement, and reliability. These benefits would not have been achieved in the same time frame without the ACAS program.

Primary performance improvement was achieved in the area of waveform linearity and thermal management. Waveform linearity is a critical parameter for FMCW radar systems. At the start of the contract, the transceiver typically had a linearity 5 times the

specification limit. This required extensive temperature characterization and multiple look-up tables for correction over temperature. Even with these tables, intermediate temperatures often had linearity errors greater than the specification resulting in range errors during system operation. Addition of the active linearizer resulted in a transceiver with linearity up to 1/5 the specification limit at all temperatures. The need for temperature characterization and look-up tables was eliminated, and performance was significantly improved at all temperatures.

Additionally, the transceivers at the start of the program had a thermal dissipation 1.5 times the specification limit. Due to internal temperature rise, this resulted in an inability to operate at temperatures greater than 50°C baseplate. With the improvements made during the ACAS, the present power dissipation is at 50% of specification value, a factor of 3 improvement. This allows transceiver operation at baseplate temperatures of 85°C, which is consistent with automotive requirements.

Significant progress in cost reduction was also made during the ACAS contract. Development volume (<50 units) transceiver cost was reduced by a factor of 3. Additionally, estimated volume production costs were reduced by a factor of 5. The costs associated with temperature characterization for linearity were eliminated, resulting in an estimated 40% reduction in assembly and test labor costs for production quantities due to this parameter alone.

Reliability was also dramatically improved. Prior to the reduction in DC power consumption, all reliability predictions indicated that units would incur non-recoverable failures at 85°C baseplate temperatures, and concept-engineering units were never operated at the high temperature extreme. With the 3 fold improvement in power dissipation, and with additional thermal resistance path design improvements, the units are now tested and operated at the high temperatures without damage. Additionally, a field failure rate in excess of 20% was observed for linearity drift alone. Since linearity was achieved by a look-up table, any change in linearity due to either electrical or mechanical aging created errors in the correction tables. There was no mechanism available to automatically recalibrate in the field, and after drift occurred, the corrections applied often resulted in greater non-linearity than the un-compensated oscillator.

Addition of the active linearizer has eliminated field returns for linearity failures. At this time, cumulated field time for the active linearizer is approximately 25% of the total for the passive look-up table units. The absence of failures coupled with the fact that drift failures tended to occur soon after deployment is a strong indication that the problem is solved, and not just an artifact of less field time.

3.3.6   Future Directions

There are certain aspects of the current task that can use further work. The purpose of the task was development of cost-effective millimeter wave components for production. Cost targets and product performance requirements including physical size were estimated based on the facts known at the start of the program. In addition to this task, other tasks of the program were structured to measure system performance and to establish requirements for collision warning products. Independent of the ACAS program, automobile manufactures were also working to establish performance parameters, and to derive consumer acceptance criteria. As a result of these activities,

target performance and target cost were continually changing. Over the two-year program cycle, size and cost targets changed by greater than 50%.

Additionally, the state-of-the-art for MMIC devices was not as well established as anticipated at the start of the program. Cost-effective devices that met performance criteria did not exist as commercial off the shelf components, and the design cycle for MMIC devices was longer than the two-year program could tolerate. As a result, the transceiver developed during this program met the original size and cost targets and provides acceptable performance, but it does not meet the end of program changes desired by the automotive customers.

During the course of the program, significant progress has been made by some MMIC suppliers in both cost and generic designs that are compatible with FLR block diagrams. Use of these building blocks in the next generation transceiver will further improve performance, size, and cost, but are beyond the scope of the current program due to schedule and budget allocations.

3.4 Studies of Long-Term Advanced Systems (Task 2.3)

The activities of this task within the program were the studies of long-term systems. It was largely a research-and-development effort with activities concentrated on the accelerated development of promising technologies that are essential crash warning elements. The main focus has been on the systems and vehicle integration aspects of collision warning systems. Several demonstration vehicles, equipped with the rudimentary capabilities of a forward collision warning system, have been designed, developed, implemented, and successfully demonstrated. These vehicles demonstrated the viability of the baseline system architecture. Additionally, progress has been achieved in the development of a key strategic technology dealing with path estimation and target selection algorithm/software. The stated goals and objectives for this task are summarized as:

- Investigate advanced collision warning situations where a forward sensor based system might provide assistance,

- Develop techniques to identify and correctly respond to advanced crash warning situations,

- Use high performance forward sensors to facilitate the development activities,

- Provide a basis to integrate other ACAS developed sensors, systems and tasks onto Project Vehicles,

- Provide a basis for the study of the preferred human interface methods (Task 6)

3.4.1 Vehicle Integration and Testing

One of the goals of this task was to provide a viable flexible vehicular environment in which the activities of other program tasks could demonstrate, evaluate and assess

the impact of their respective technologies within the framework of a complete collision warning system.

Three FCW demonstration vehicles were developed in order to support various collision warning development and evaluation activities of the ACAS Program. These three vehicles were: (a) 1994 Toyota Lexus LS400, (b) 1994 GM Cadillac Seville, and (c) 1995 GM GMC Suburban. These vehicles were modified to provide the basic functionality of a fully integrated FCW system. These FCW-equipped demonstration vehicles were developed by using an upward integrated design philosophy which included all aspects of the comprehensive FCW design architecture, from the FCW sensor, to the human factor designed set of driver vehicle interface (DVI) cues.

These FCW vehicles were primarily used to assess the "real-world" technical issues and challenges associated with integrated collision warning systems in support of the following program tasks:

(a) Task 2.2: Demonstration and evaluation of an improved transceiver design for a forward-looking radar.

(b) Task 2.3: Development and evaluation of the collision warning algorithms suite (i.e.: target/Host vehicle path prediction, in-path target selection, etc.).

(c) Task 3.2: Demonstration and evaluation of an improved antenna design for the Side Detection Sensor.

(d) Task 5: Demonstration and evaluation of the wide field-of-view Head-Up Display (HUD).

(e) Task 6.4:. Support the human factors closed course field-testing, evaluation, and assessment of the Driver-Vehicle warning system by using the general driving population.

Each vehicle had slightly different features and functionalities. However, the design approach followed a common architectural process, which is shown in Figure 3.17. The core of the system is the Collision Avoidance Processor (CAP) which takes the inputs from the sensor suite (active and vehicle sensors), processes the sensor information using the collision warning processing suites (i.e.: path determination, in-path target selection, threat assessment), and provide the appropriate driver-vehicle warning response. A data acquisition system is used to provide diagnostic features (i.e.: datalogging, etc.)
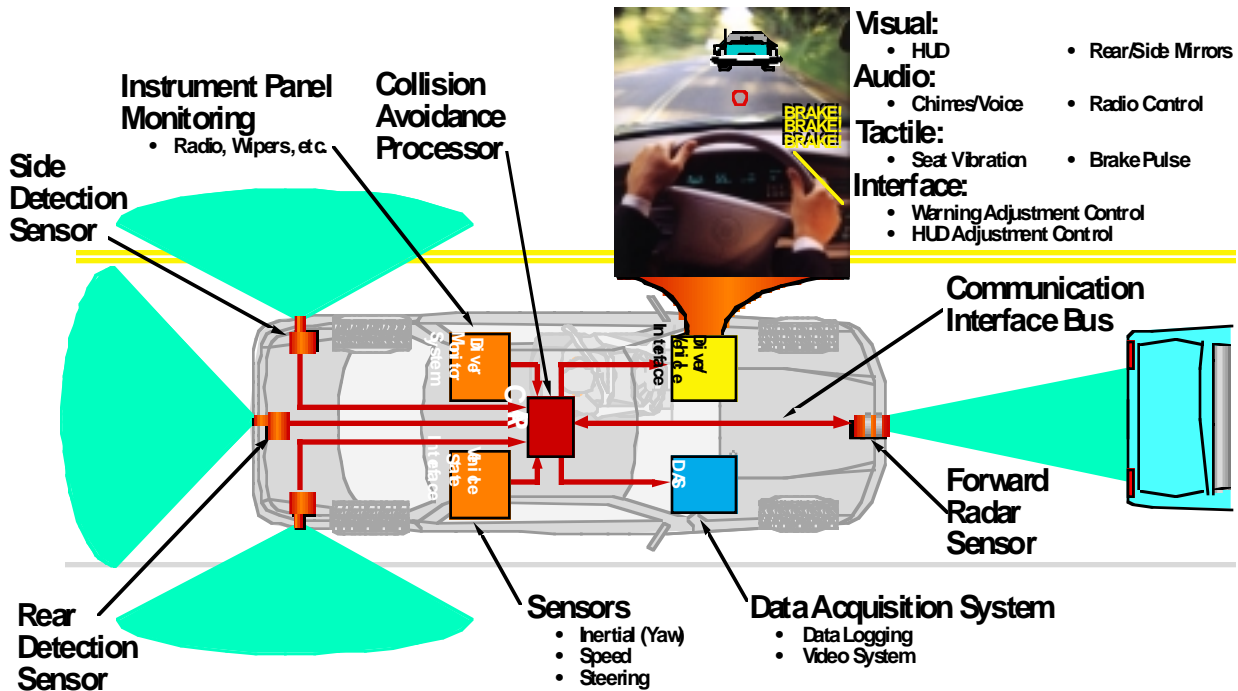
Figure 3.17: Collision Warning Vehicle Mechanization.

A functional description of each FCW demonstration vehicle is provided in detail in the *Task 2.3 Summary Report*. Each successive demonstration vehicle contained noticeably improved design features over the previous vehicle design. Lessons learned from on-road evaluations, and many of the comments provided by numerous subjects on each demonstration vehicle design, were examined and incorporated into the next demonstration vehicle design.

3.4.2 FCW Problem Definition

In order for a FCW system to provide a positive and beneficial influence towards the reduction of potential crashes, it is critical that the FCW system has the ability to correctly identify the vehicle/targets in the Host vehicle's path. The solution to this problem relies primarily on the FCW system's ability to estimate the relative inter-vehicular motion path (i.e.: range, relative speed, radius-of-curvature, etc.) between the Host vehicle and all of the appropriate targets (i.e.: roadside objects, vehicles, etc.), and on the system's ability to predict the mutual intersection of these motion paths. As one could imagine, the in-path target identification and selection problem is technically very complicated and challenging.

Figure 3.18 presents an illustration of the complexity of this problem. In this illustration, it shows a Host vehicle, equipped with a FCW system, which must correctly identify the in-lane target while navigating a random complex roadway segment in the random presence of complex driver/roadway events and rich target environment, while using realistic sensors. Some examples of the realistic driving environment characteristics that are presented to the Host vehicle are:

(a) *Complex Driver/Roadway Scenarios:* intra-lane weaving, lane changes, and varying speed of Host and/or target vehicles, etc.

(b) *Rich Target Environment*: varying number of targets, presence of stationary (e.g., parked vehicles, overhead bridge/sign, etc.) and moving in-lane/adjacent-lane roadway targets (e.g., motorcycles, passenger vehicles, trucks, etc.), presence of stationary roadside targets (i.e.: poles, signs, guard rails, vegetation, etc.), etc.

(c) *Complex Roadway Geometries*: straight roads, curved roads, curved entry/exit transitions, off/on ramps, etc.

(d) *Realistic Sensor Characteristics*: sensor misalignment, sensor drift and bias (i.e., yaw rate sensor), momentary target "drop-outs" (i.e., field-of-view limitations, glint, scintillation, etc.), etc.
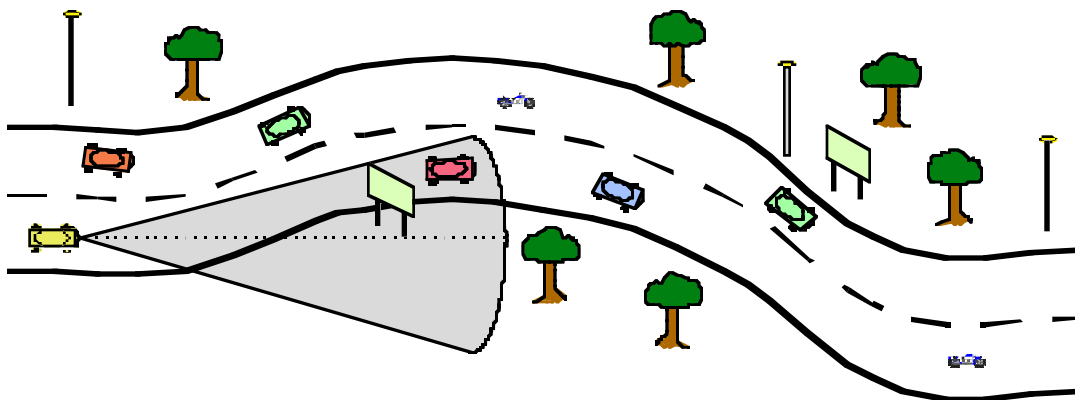
Figure 3.18: Collision Warning Path Prediction Problem.

In general, the critical scenarios which describe most inter-vehicle interactions can be grouped into three distinct categories, with the following geometric properties: (a) Straight Road Condition (i.e., Host and target vehicles are both traveling on a straight roadway); (b) Curved Road Condition (i.e., Host vehicle and target vehicles are both traveling on a curved roadway); and (c) Curved Entry/Exit Road Condition (i.e., roadway transition case in which the target vehicle is separately transitioning to another distinct curved or straight roadway). These roadway scenarios are illustrated in Figure 3.19.

STRAIGHT ROAD   CURVE ROAD   CURVE ENTRY   CURVE EXIT
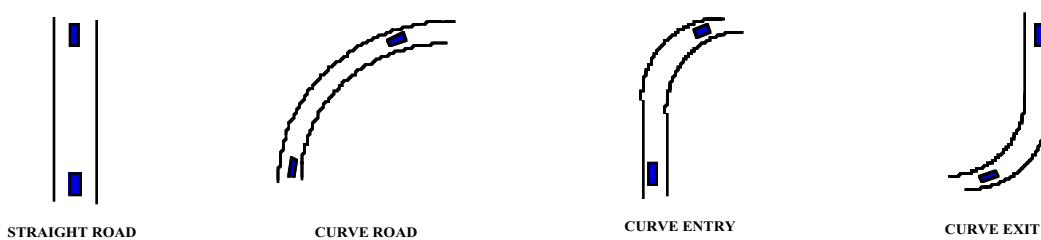
Figure 3.19: Roadway Scenarios for In-Path Target Selection Process.

Consequently, the basic FCW path algorithm issue is to develop the appropriate decision logic to: (a) determine which geometric inter-vehicular scenario the Host vehicle is executing; (b) identify the complete set of target vehicles which are in the Host vehicle's path, based upon the identified inter-vehicle geometric scenario; and (c) select the in-path target which poses the highest threat to the Host vehicle.

3.4.3   Conventional Design Approach

The "conventional" design approach is briefly summarized as: (a) predict the Host vehicle path trajectory by using the passive in-vehicle sensors, and (b) identify the appropriate detected targets that are positioned within the path of the projected Host vehicle motion. In general, the "conventional" approach heavily utilizes the yaw rate information in order to estimate the roadway curvature.

Algorithm Development Activities

The development of this FCW path algorithm suite has been a lengthy process of continual refinements and enhancements in response to noted performance deficiencies observed during the extensive road testing procedures. In particular, the following significant improvements were made to the FCW system during the ACAS Program:

(a) Yaw rate drift: Drift is a common phenomenon of sensors. In the case of a yaw rate sensor, a drift will result in an incorrect estimation of the Host vehicle path of motion, which significantly effects the correct identification of the in-path target. A new technique was developed to remove temporal yaw rate drift.

(b) Filtering: The random variability of driving behavior will result in an incorrect estimation of the Host vehicle path of motion, which significantly affects the correct identification of the in-path target. Consequently, improved filtering of the Host vehicle attributes were enhanced in order to reduce the effects of driver steering variability.

(c) Algorithms: The in-path target selection/decision processing algorithms were improved to reduce the occurrence of missed detections of in-path vehicles; reduce false alarms on adjacent lane vehicles and roadside objects; and increase the system's responsiveness to close-range cut-in targets and host lane change maneuvers.

(d) Radar sensor maturation process: The success of the FCW path algorithm suite is heavily dependent on the quality of information it receives from the active sensor (i.e., radar, laser, and vision). Consequently, it was possible for the algorithm designers to submit suggestions and provide assistance in explaining specific critical areas of performance improvements for the radar sensor (i.e.: target trackfile management, filtering of target vehicle attributes, etc.).

The algorithm development and evaluation efforts have focused on the three distinct roadway scenarios as previous depicted in Figure 3.19. In its present state, the conventional FCW path algorithm suite performance is excellent for simple scenarios, and good for complex scenarios. The performance for simple geometric scenarios (i.e.,

straight roadways with few targets, etc.) has shown a significant reduction in the number of false alarms on oncoming adjacent-lane targets and overhead bridges. Similarly, the performance for complex geometric scenarios has shown a substantial reduction in its rate of false alarms and missed detections.

Areas of further improvements which the FCW path algorithm suite still exhibits are: (a) missed detections at long range on transitions roadway scenarios and on rolling terrain (i.e.: bumps and hills); (b) false alarms on roadside object located at curved and transition roadways during both lane change and curve entry/exit maneuvers; and (c) false alarms at long range on adjacent lane cargo trucks. The root causes of these deficiencies can be attributed to the following issues:

1. *Steering Behavior Variability:* The observed random characteristics in the driving behavior still posses a significant issue. As a result of this driving behavior characteristics, it becomes difficult to rapidly assess the differences between a Host vehicle: (a) traversing a straight roadway segment, (b) initiating a lane change, or (c) initiating a "true" turning maneuver at a roadway transition (i.e.: curve entry/exit).

2. *Target Glint Affects on Heavy Duty Vehicles.* Target glint is indicative of MMW-based FLR sensors. This affect typically occurs when the aspect view of the target changes while on a curved road. For instance, on a straight roadway, the radar sensor "sees" a relatively constant radar cross section image of the target (i.e., constant aspect view of the vehicle trunk area). Consequently, the reported radar target centroid parameter attribute remains constant and stable. However, on any curved roadway, the radar sensor "sees" a dynamically changing aspect view of the target (i.e., vehicle trunk and side). When the target is a highly complex object (which is typical of most vehicles) or a large object, then the radar cross section can change dramatically between successive radar update cycle. Consequently, either the target can disappear, or the reported radar target centroid parameter attribute can become highly unstable (i.e., dramatic azimuth angle variations or shifts between successive radar update cycles). In particular, due to the glint phenomena, large adjacent-lane vehicles (i.e.: trucks, etc.) tend to provide a higher false alarm rate, in comparison to passenger-style vehicles. Moreover, the false alarms on the large vehicles tend to occur more frequently at long range, on transition roadways (i.e., curve/entry exit roadways). In general, it is possible for the centroid of a typical heavy-duty vehicle to vary by an amount greater than the real vehicle's width. This variation is due to the glint characteristics of the vehicle's numerous sharp reflective corners. Figure 3.20 illustrates centroid variations for three different types of vehicles (i.e., passenger, dump truck and rollback wrecker). The Host vehicle is passing by the adjacent-lane vehicle, while traveling on a straight roadway. The Host and adjacent-lane vehicles are traveling at 84 MPH and 65 MPH, respectively. The inter-vehicle spacing varied from 150 meters to about 20 meters. The standard deviations in the centroid position of the passenger car, dump truck and rollback wrecker were 0.42 meter, 0.52 meter and 0.76 meter, respectively. Moreover, throughout the test run, the maximum variations of the target centroids, for the passenger car, dump truck and rollback wrecker were 1.75 meter, 2.5 meter and 3.2 meter, respectively. This maximum variation roughly corresponds to the respective width of each of the vehicles.

Host Vehicle @ 84 MPH passing by Target Vehicle @65 MPH on Adjacent Lane
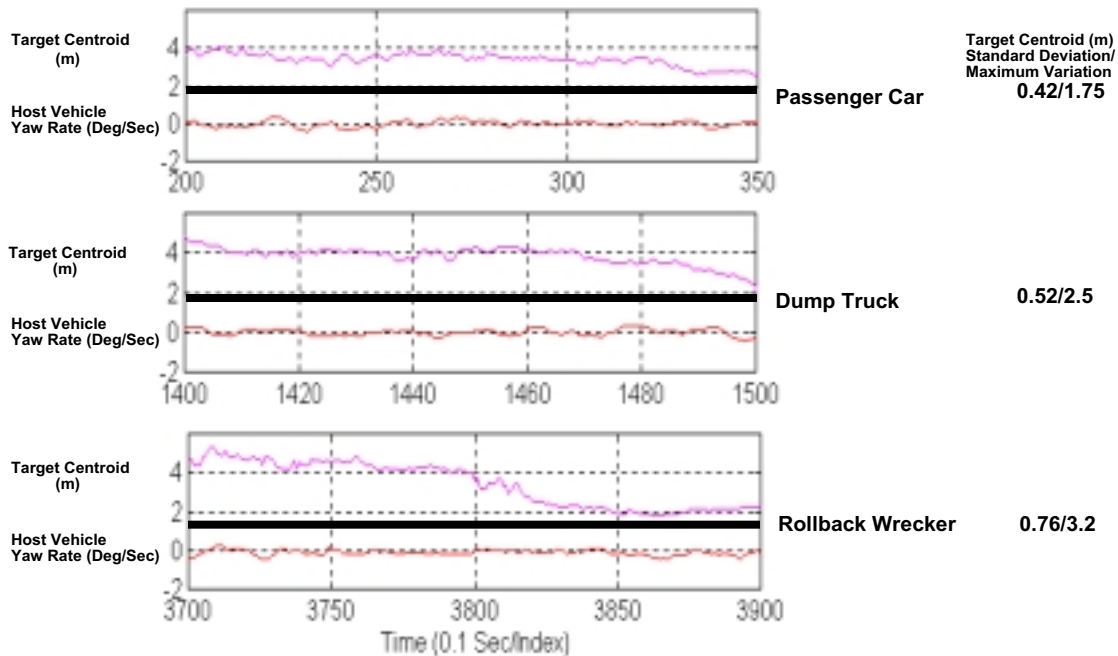
Figure 3.20: Centroid Variations for Three Types of Vehicles as a Result of Target Glint.

3. *Inadequate Filtering of Target Attributes and Host Vehicle Yaw Rate*. The filtering of the Host and target vehicle attributes is used to eliminate variability in driver steering behavior and yaw rate signal noise. However, if the filtering is too harsh, then the FCW system exhibits too much lag and respond slowly to normal dynamic vehicular maneuvers (i.e., lane changing, changing roadway curvature, and straight/curve roadway transitions, etc.). During the ACAS Program, the filtering scheme for the Host and target Vehicle's attributes were enhanced to reduce the effects of driver steering variability, and to increase the system's responsiveness to close-range cut-in targets and Host lane change maneuvers. Figure 3.21 presents a comparison of the two types of filter design implementation for the Host vehicle yaw rate parameter attribute. The "old" filter design did not provide adequate filtering characteristics; in fact it provided very little filtering action in comparison to the "new" (i.e., current implementation) filter design. However, while the new filtering scheme significantly improved the FCW system's performance for many of the critical in-vehicle scenarios, the current approach does not provide enough responsiveness to target vehicles performing very rapid lane change maneuver (i.e., cutting-in and cutting-out of the lane of the Host vehicle at a high rate of speed), and to target vehicles performing curve entry/exit maneuvers at a high rate of speed. One possible way to improve the system's responsiveness may be to filter the target attributes and Host vehicle yaw rate using some adaptive scheme. In such a suggested scheme, sets of filter coefficients could be selected based on such system attributes as the yaw rate angular acceleration, and the speed of the target and Host vehicles.
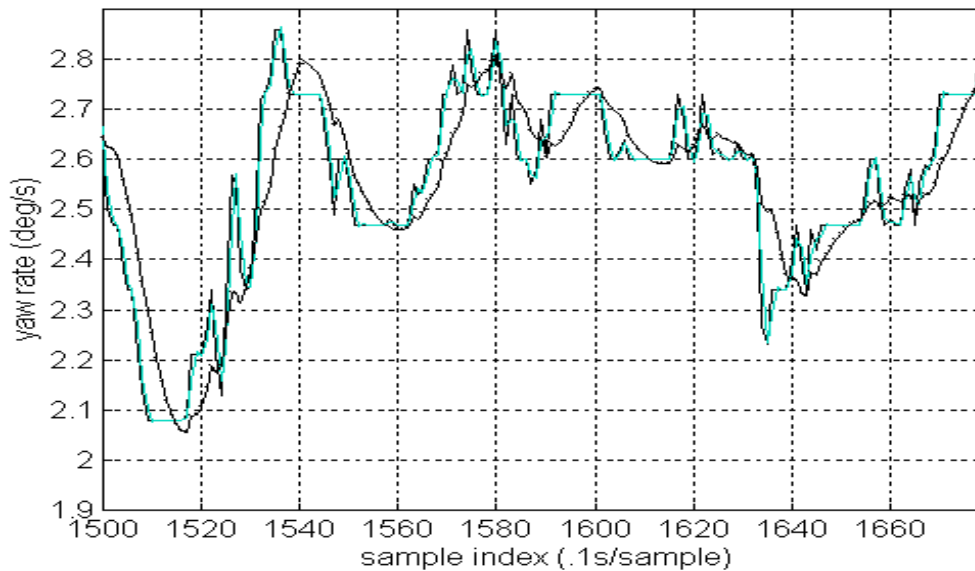
Figure 3.21: Yaw Rate Filter Design Characteristics Comparison.

4. *Collective FCW System Sensor Suite Limitations:* The conventional design approach relies on the use of a single active detection sensor (e.g., radar) and a single passive in-vehicle sensor (e.g., yaw rate, steering, and speed) in order to identify the in-path target. However, these collective set of sensors do not readily provide lateral placement in the lane or discern lane and road boundaries. In the absence of lane boundary or roadway curvature information in the area ahead of the Host vehicle, it will be very difficult to reliably anticipate/predict:

    (a) Changes in the roadway curvature (i.e.: curve entry/exit transitions),

    (b) Differentiate between target lane-change maneuvers and curve-entry/exit maneuvers.

    (c) Differentiate between Host vehicle lane-change maneuvers and curve-entry/exit maneuvers.

    (d) Determine that roadside objects (i.e.: signs, poles, parked vehicle, etc.) which are located the curve-entry/exit point do not lie along the Host vehicle path.

    (e) Identify if either the Host or target vehicles are hugging the edge of their respective lanes.

    Consequently, in face of these challenges, it will be difficult for the currently implemented conventional FCW path algorithm design approach to correctly select in-path targets (or reject adjacent-lane target) during roadway transition scenarios, or reject adjacent-lane line-hugging vehicles as in-path targets.

    At this time, it is believed overall system performance can be further enhanced by augmenting the current conventional FCW path algorithm design approach by

incorporating a model-based scene tracking estimation technique (see discussion in the next sub-section), and/or incorporating a hybrid sensor architecture (i.e.: multiple active detection sensors), as suggested by the CW system architecture presented in Figure 1.1. For example, a vision system, which has the ability to provide an estimate of the road curvature and boundaries ahead of the Host, could assist in enhancing the system performance.

5. *Limitations in the Current Collision Warning System Configuration/Architecture.* With the use of a radar sensor and yaw rate sensor, it is not possible to estimate the lateral lane position of the Host vehicle within its lane. Consequently, the in-path target selection decision logic might incorrectly select an adjacent-lane target when the adjacent-lane target and Host vehicle are both "hugging" their respective lane edge. Another issue is related to momentarily missed detections of target vehicles and obstacles on roadway with unusual geometry (i.e.: bumps, up-hills and downhill). At this time, it is believed this limitation can only be overcome with the inclusion of a vision system. The inclusion of a vision system into the system architecture should assist in confirming radar-based data.

6. *Radar Sensor Limitations*. The forward-looking radar sensor has both software and hardware (i.e.: limited field-of-view) limitations which restricts the performance of the current implemented FCW path algorithm design approach.

3.4.4 Conventional Algorithm Improvements

Presently, the performance of the conventional FCW path algorithm design approach is overall very good. It provides excellent performance in the presence of simple roadway/driver scenarios, and good performance for complex roadway/driver scenarios. This is a significant improvement when compared to the level of performance at the program inception. The performance for simple geometric scenarios (i.e., straight roadways with few targets, etc.) has shown a significant reduction in the number of false alarms on oncoming adjacent-lane targets and overhead bridges. Similarly, the performance for complex geometric scenarios has shown a substantial reduction in its rate of false alarms and missed detections. In addition, the duration of over 95% of the missed detections, and over 90% false alarms, has been reduced to less than 0.5 seconds.

In this sub-section, several figures are presented as a means to provide a qualitative comparison of performance improvements of the FCW path algorithm suite. The comparisons will correspond to three distinct time periods during the ACAS Program: (1) "new" algorithms at the completion of the program (December 1997), (2) "old" baseline algorithms developed at the fifth quarter (February 1996), and (3) "intermediate" algorithms developed at the seventh quarter (October 1996). These figures depict actual real-time FCW path algorithm performance in a "real-world" driving environment for a variety of roadway events. They will demonstrate the following performance improvements: (i) reduction in the duration and frequency of false alarms (i.e.: out-of-lane targets incorrectly identified as in-path targets) due to adjacent-lane vehicles or roadside objects, and a reduction in the frequency of missed detections (i.e.: in-lane targets not identified as in-path targets) due to driver lane hunting/wandering; (ii) significant reduction in the number of false alarms triggered by opposing traffic on a two-

way surface streets; (iii) development of a new and effective bridge discrimination capability (i.e.: ability to differentiate between vehicular objects and overhead freeway bridges and stopped surface objects; (iv) reduction of the average response time for target vehicle cut-in and Host vehicle lane change maneuver; and (v) reduction in the duration of 90% of the FCW systems false alarms and missed detections to an average duration of between 0.1 and 0.2 seconds.

Simple Geometric Scenarios

Figure 3.22 shows the progression in the system performance on a simple geometric roadway scenario, in which two moving vehicles (i.e.: Host vehicle and target vehicle) are traveling on a straight roadway segment. The target and Host vehicle are both traveling in the same lane with a constant velocity of approximately 50-MPH. The separation between the vehicles is about 55 meters. Multiple isolated sign poles are also located along the Host/Target vehicle's lane edge (i.e., roadside).
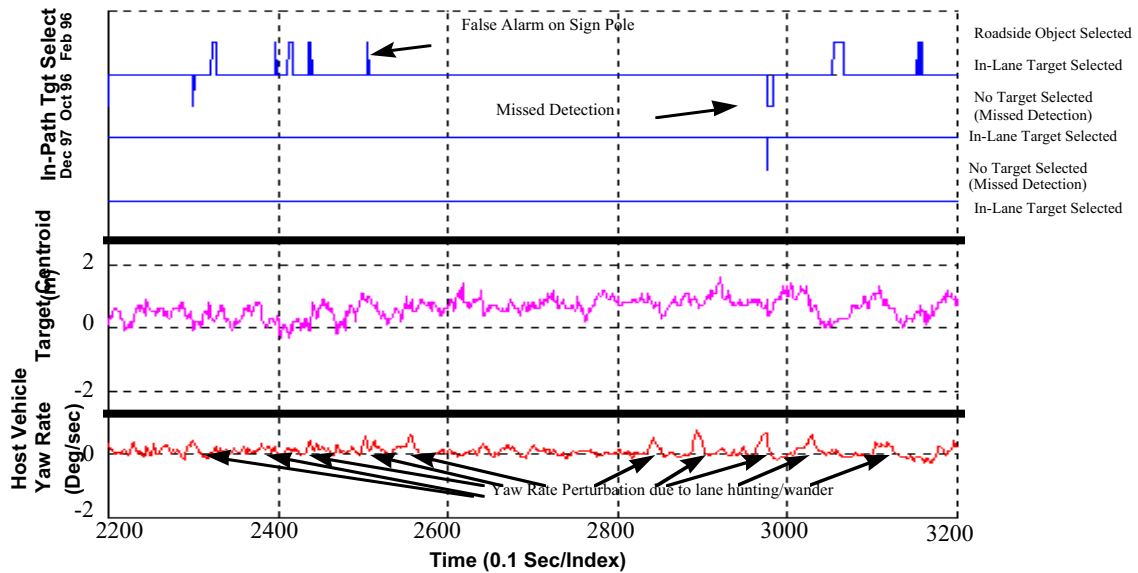
Figure 3.22: Performance Comparison (Lane Hunting/Wander Scenario).

During the course of the test drive, the Host vehicle driver simulated various lane-hunting maneuvers, which resulted in yaw rate fluctuations of approximately 0.5 deg/sec. This figure shows that the "old" (Feb 1996) FCW path algorithm suite incorrectly selected many of the sign poles as in-path targets (i.e.: false alarms), and also failed to identify the primary in-path target vehicle on several occasions (i.e.: missed detections). As a comparison, the in-path target selection performance was significantly improved with the use of the "new" (Dec 1997) FCW path algorithm suite. The improved algorithm suite eliminated all the false alarms and all the missed detections that were observed using the "old" baseline algorithm suite.

Figure 3.23 compares the system performance for a simple geometric roadway scenario, in which two moving vehicles (i.e.: Host vehicle and target vehicle) are traveling

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in the same lane on a straight surface roadway with two-way traffic. There were also several on-coming vehicles approaching in the opposite direction. All of the moving vehicles are traveling between 40 MPH and 50 MPH. The separation between the Host and the lead vehicle varies from 30 to 120 meters. This figure shows that the "old" baseline FCW path algorithm suite exhibited many false alarms by selecting the oncoming adjacent-lane vehicles. On the other hand, the "intermediate" FCW path algorithm suite exhibited only a single false alarm on the oncoming adjacent-lane vehicle, while the "new" improved FCW path algorithm suite eliminated all occurrences of the false alarms experienced by the "old" baseline approach.
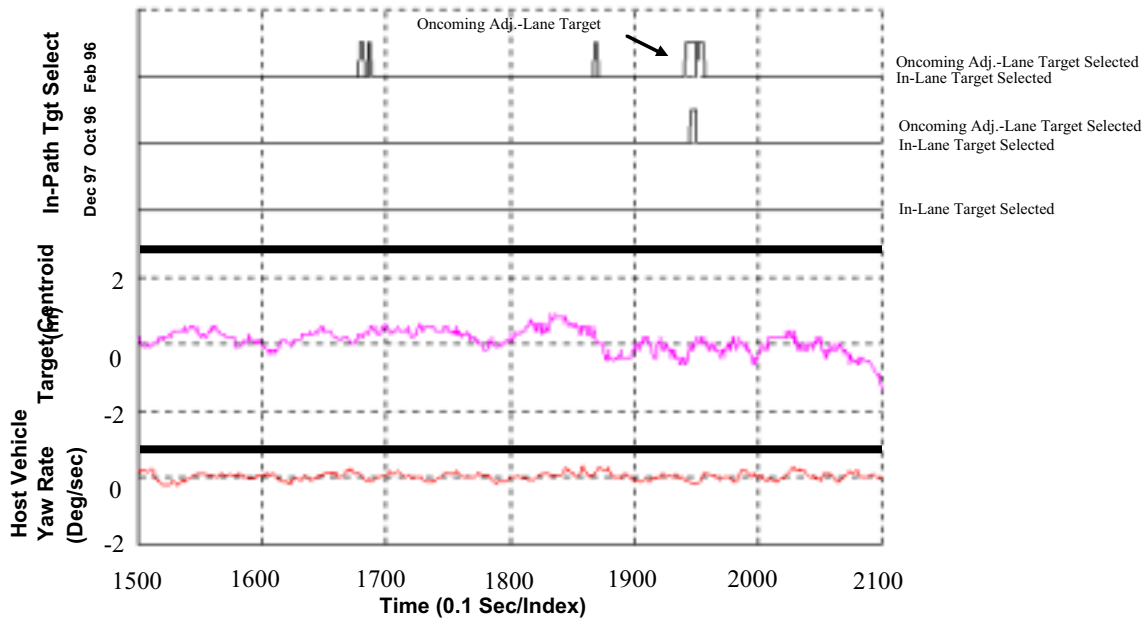
Figure 3.23: Performance Comparison (Oncoming Adjacent-Lane Vehicles Scenario).

Figure 3.24 compares the system performance for a simple geometric roadway scenario, in which the Host vehicle is traveling on a straight section of a freeway with an overhead bridge. The Host vehicle is approaching an overhead bridge at 65 MPH. The bottom of the overhead bridge is located approximately 4.5 meter above the roadway surface. The radar sensor detects the overhead bridge as a stopped object at a range from 125 meters to 75 meters (i.e.: with in the elevation field-of-view of the radar sensor). This figure shows that both the "old" baseline and "intermediate" FCW path algorithm suite incorrectly selected the overhead bridge as an in-path surface target for a duration of about 1.3 second and 0.6 second, respectively. However, the "new" improved path algorithms successfully recognized the overhead bridge as a non-vehicular object, and rejected it as an in-path target.

Figure 3.24: Performance Comparison (Overhead Bridge Scenario).

Complex Geometric Scenarios

Figure 3.25 compares the system performance for a complex geometric roadway scenario, in which three moving vehicles (i.e.: Host vehicle and two target vehicles) are traveling on a curved roadway with a counter-clockwise curvature of 2000 meters. One of the target vehicles is in the same lane as with the Host vehicle, while the other target vehicle is in the right adjacent-lane. The Host vehicle is traveling at a constant speed of 60 MPH, while the two target vehicles are traveling next to each other at a constant speed of 55 MPH (i.e.: closing speed of 5 MPH). The inter-vehicle separation distance, between the Host vehicle and both target vehicles, is varies from between 100 to 60 meters.
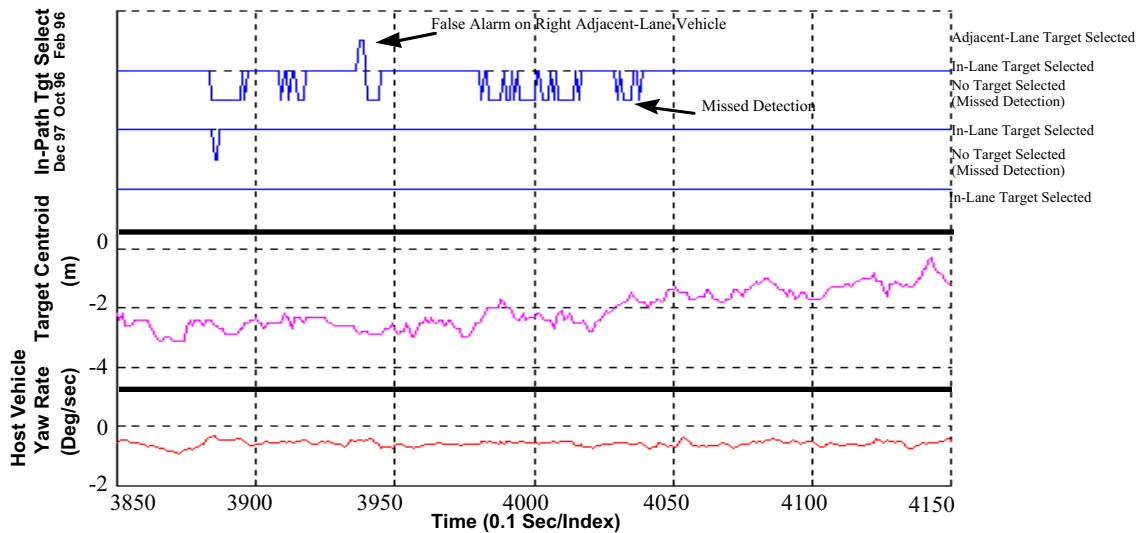
Figure 3.25: Performance Comparison (In-Lane & Adjacent-Lane Vehicles Scenario).

This figure demonstrates the "old" FCW path algorithm suite frequently failed to detect the in-lane target vehicle as the primary in-path vehicle. Moreover, on one occasion, the right adjacent-lane target vehicle was incorrectly identified as the primary in-path target. In comparison, the "intermediate" FCW path algorithm suite did not experience any false alarms due to the presence of the right adjacent-lane target vehicle. Moreover, the number of missed detections was reduced dramatically. The in-path target selection performance was significantly improved with the use of the "new" refined FCW path algorithm suite. The improved algorithms eliminated all of the false alarms and missed detections for this scenario. As a result, the correct in-path vehicle was selected throughout the entire test run.

Figure 3.26 compares the system performance for a complex geometric roadway scenario, in which two moving vehicles (i.e.: Host vehicle and target vehicle) are traveling on a multiple-lane curved roadway with a straight road transition. The curved roadway has a radius of curvature of 1800 meters. Initially, both vehicles are traveling at about 65 MPH. The target vehicle is traveling on the left adjacent lane relative to the Host vehicle, and is approximately 40 meters ahead of the Host vehicle. The target vehicle accelerates to 70 MPH, and then cuts into the Host vehicle lane. This figure shows that the responsiveness of the FCW system to this cut-in maneuver varied significantly between the various versions of the FCW path algorithm suite. The figure demonstrates that the "old" FCW path algorithm suite exhibited a delay of 0.4 seconds and 1.2 seconds in response to this target vehicle cut-in maneuver, as compared to the "intermediate" and "new" algorithm suite. This quick response is very significant because 60% of the rear-end crashes could potentially be avoided if the driver has an extra 0.5 seconds in reacting to the situation.
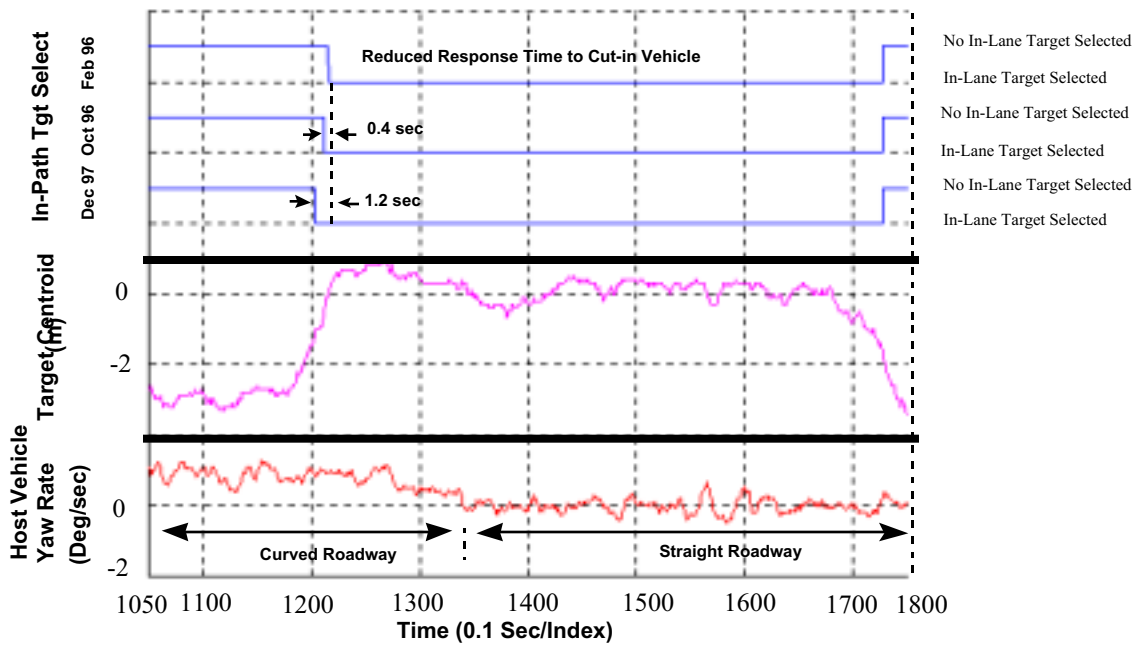
Figure 3.26: Performance Comparison (Target Vehicle Cut-in Scenario).

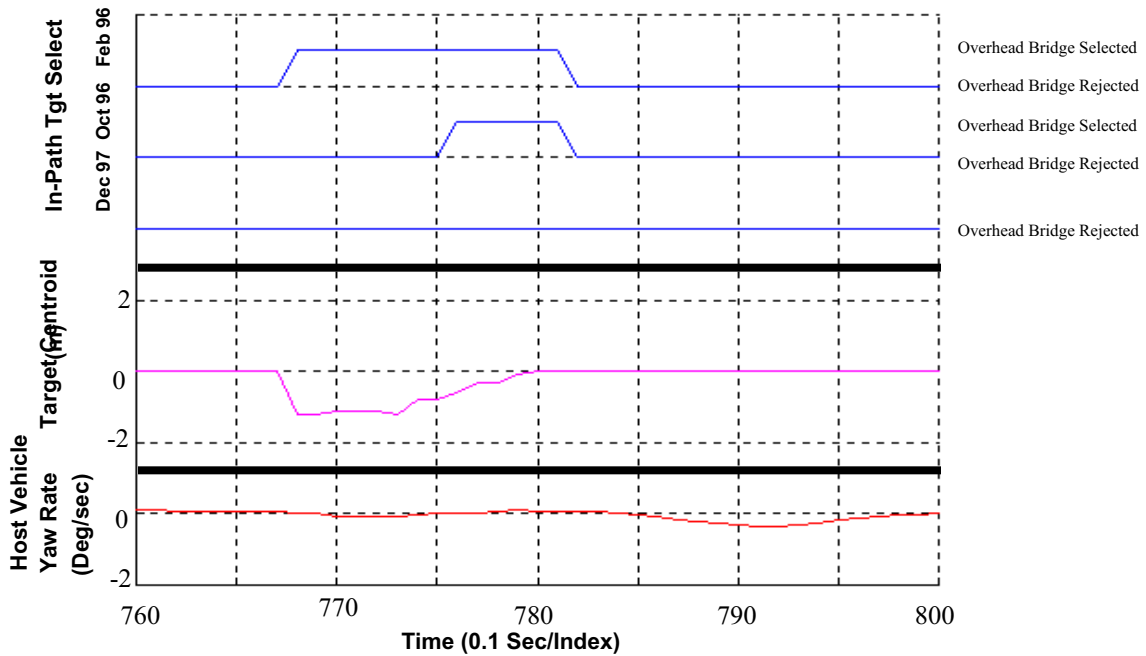Figure 3.27 compares the system performance for a complex geometric roadway scenario, in which two moving vehicles (i.e.: Host Vehicle and in-lane vehicle) are traveling on an S-curved roadway with a straight road transition. The first part of the S-curve has a radius of curvature of 1500 meters, while the second part of the S-curve has a radius of curvature of 1100 meters. Both the Host and target vehicles are traveling at 45 MPH, with the inter-vehicle separation distance of 50 to 70 meters. This figure demonstrates the "old" FCW path algorithm suite frequently false alarmed on the poles along the second part of the S-curve (i.e.: incorrectly identified the poles as in-path targets). Moreover, it also failed to identify the in-lane target vehicle as an in-path target on several occasions. On the contrary, the "intermediate" algorithm suite did not experience any false alarms due to the presence of the sign poles at the S-curve transition. Moreover, the number of missed detections was reduced to one with duration of only 0.2 seconds. The in-path target selection performance was significantly improved with the use of the "new" refined " FCW path algorithm suite. The improved algorithms eliminated all false alarms and missed detections. As a result, the in-lane vehicle was correctly selected throughout the entire test run.
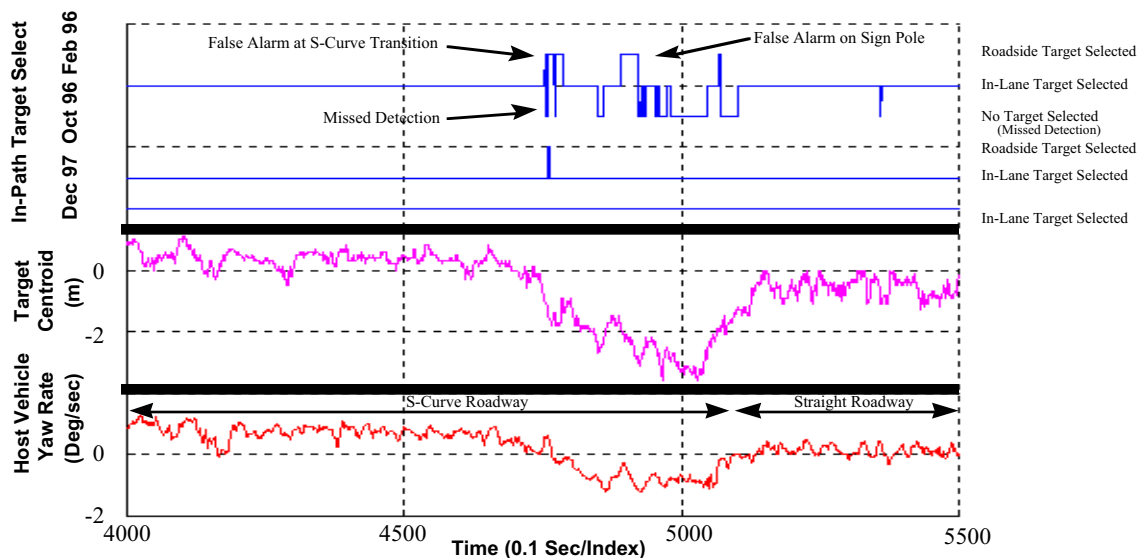
Figure 3.27: Performance Comparison (In-Lane Vehicle on S-Curve Scenario).

Observations & Comments

Significant progress has been achieved in developing the "conventional" path determination/estimation algorithm suite in addressing the collision warning target selection function. Areas of future activities and investigations are: (a) improving the FCW path algorithm suite performance in response to complex geometric scenario events, and (b) validating the consistency and robustness of the FCW path algorithm suite in response to various different performing yaw rate sensors and Host vehicle platforms.

3.4.5 Model-Based Scene Tracking Design Approach

As discussed in the previous section, the currently implemented conventional FCW path algorithm suite design approach does not provide the capability to reliably anticipate/predict changes in roadway curvatures ahead of the Host vehicle (i.e.: roadway transition scenarios), due to its inability to readily discern lane and road boundaries. Consequently, it is difficult to correctly select the actual in-path target (or reject adjacent-lane target) during roadway transition scenarios. Figure 3.28 illustrates a typical scenario in which the current conventional FCW path algorithm suite implementation might have difficulty in identifying the correct in-path target. In this scenario, the Host vehicle is operating on a straight roadway segment, while the in-path target has entered onto a sharp curved roadway segment. In general, the current conventional algorithm implementation heavily utilizes the yaw rate in order to estimate the instantaneous roadway curvature at the Host vehicle. As such, while the Host vehicle is on the straight roadway segment, the current algorithm implementation would accurately estimate the roadway curvature to be a straight roadway, but would not provide any indication of a dynamically changing roadway curvature ahead of the Host vehicle. In general, the current algorithm implementation does not fully utilize the active detection sensor (i.e.: radar, laser, vision, etc.) generated data (i.e., range, range rate,

angle, etc.) to assist in estimating the roadway curvature. Consequently, for this scenario, the current conventional FCW path algorithm suite might incorrectly select the roadside light pole or sign as the in-path target, rather than the proper actual vehicle.
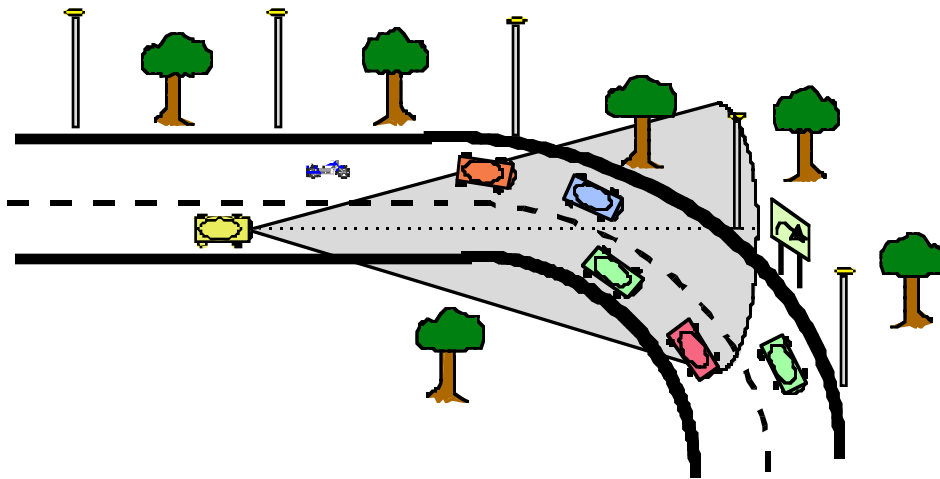
Figure 3.28: Typical Roadway Scenario.

In order to address this issue in the near term, another FCW path algorithm design approach was investigated to fully utilize all the information from the active sensor. This has led to the development of a vehicle/roadway model-based estimation technique, which provides a dynamic estimation/prediction of the road curvature ahead of the Host vehicle by tracking the position and trajectory of all of the detected objects within the active sensor field-of-view. By using all of the relevant data collected by the forward-looking active sensor (i.e., radar or laser), and other in-vehicle passive sensors (e.g., speed, yaw rate, etc.), it is possible to dynamically reconstruct the scene ahead of the Host vehicle in order to significantly improve the in-path target selection process. This scene tracking technique makes much greater use of the available scene information and sensor data than does the conventional FCW path algorithm suite.

In the future, this issue could also be addressed by the integration of a vision sensor which provides an improved estimate of the roadway curvature and boundaries ahead of the Host vehicle. In addition to the potential for improved performance, the model-based scene tracking approach provides a natural setting for the fusion of data from multiple forward- looking sensors (i.e.: radar and vision together).

Simulation Environment

The model-based scene-tracking design approach was initially developed in a simulation environment, rather than as a direct real-time vehicle implementation. This simulation environment provides an ideal setting from which controlled, repeatable evaluation of system performance, and sensitivity to alternative configurations, scenarios and error sources can be performed without having to deal with real-time vehicle implementation considerations. Moreover, this simulation can be used to investigate

the use of different combinations of on-board sensor data (e.g., yaw rate, steering angle, wheel speeds, lateral acceleration, forward-looking sensor data, etc.) in order to understand their influence on possible FCW path performance improvements.

The Simulation Environment consists of several modules which provide the following capabilities: (a) generate an arbitrarily prescribed roadway, generate trajectories for an arbitrary number of targets; (b) steer the Host vehicle with realistic driving dynamics along an arbitrarily prescribed trajectory; (c) model the collection and corruption of sensor data (including the forward-looking radar); and (d) pass the sensed data to a path algorithm under study, and perform data logging. The simulation is implemented using the software package *Matlab*™, operating on a PC platform.

The simulation assumes that the Host and multiple target vehicles are traveling down a multi-lane road of a prescribed shape. The simulation allows the user to independently specify the desired road scenario, on-board sensor configuration, and kinematic behavior of the vehicles. Moreover, the simulation includes both a forward-looking radar model, and models of other in-vehicle sensors (speed, yaw rate, steer angle, etc.). The radar model simulates a variety of realistic major radar parameters, such as: number of detected targets, detection range, field-of-view, resolution and quantization of the radar's target features (range, range rate, azimuth angle), and various other error sources. Furthermore, the characteristics of the radar model is representative of the Delco Electronics/HEM radar sensor that has been used in the ACAS Program.

Model-Based Scene Tracking Algorithm Architecture

The structure of the model-based scene-tracking algorithm is shown in Figure 3.29. It analyzes the features of the Host vehicle (i.e., speed, yaw rate, steering angle) and "n" detected targets (i.e., range, range rate, and azimuth angle). The algorithm has four main components:

(a) *Host Vehicle State Filter*: A model-based filter which combines information from several in-vehicle sensors which are used to estimate critical Host vehicle states (i.e.: longitudinal and lateral velocity, sideslip angle, etc.).

(b) *Target Tracking Filters*: A bank of model-based filters which estimate critical states for each target (i.e.: heading angle, yaw rate, and longitudinal distance to the Host vehicle, etc.) by utilizing spatial and kinematic target information generated from the radar sensor (i.e., range, range rate and angle) and relevant Host vehicle state information generated by the Host Vehicle State Filter.

(c) *Road Curvature/Path Angle Estimator*: A unified filter which generates estimates of parameters describing the curvature of the upcoming road segment and of the Host vehicle path angle (i.e.: angular orientation with respect to the local lane center tangent).

(d) *Lane Position Estimator*: A filter which utilizes road curvature, target position, and Host path angle information to provide an estimate of the lane position of each target (i.e., Host vehicle lane, left adjacent lane, right adjacent lane, etc.).
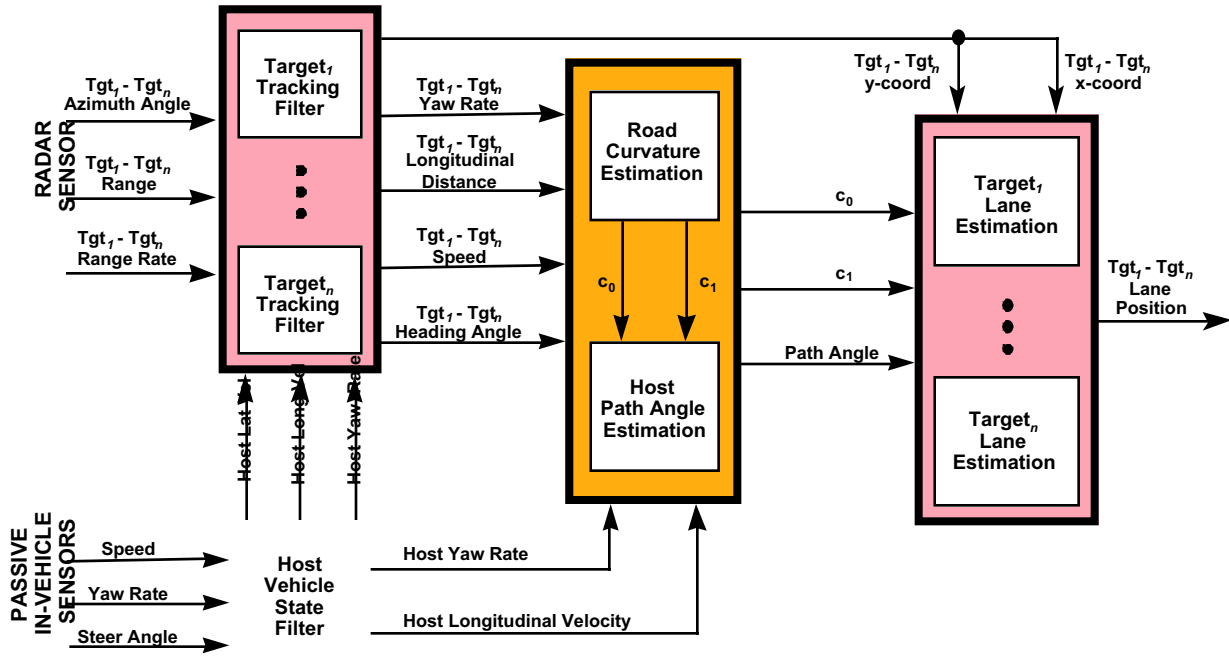
Figure 3.29: Model-Based Scene Tracking Algorithm Architecture.

The Host's path angle is the angle between the Host's longitudinal axis and the tangent to the local lane center, as depicted in Figure 3.30.. It provides a measure of the extent to which the Host vehicle isn't pointing parallel to the nearby road. In the vehicle/roadway model, the path angle indicates the direction in which the estimated nearby road segment should be projected, relative to the Host (i.e., not necessarily straight-ahead), for the target Lane Position Estimation process.
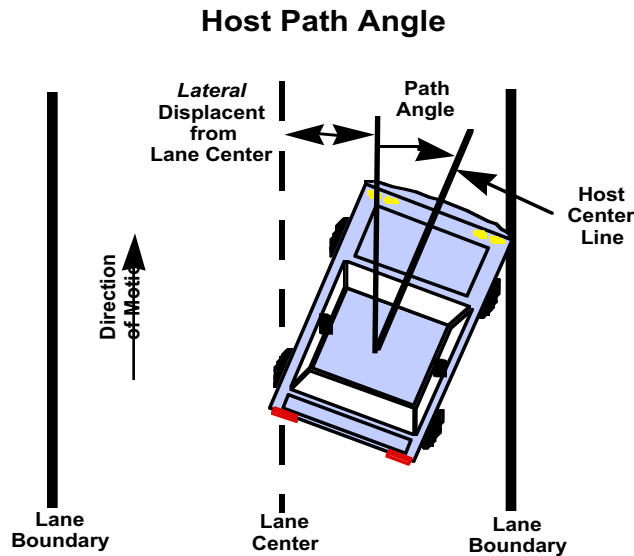
Host Path Angle

Figure 3.30: Path Angle Definition.

Algorithm Performance

The scene tracking algorithm was fine-tuned to maximize its performance with regard to anticipated non-idealities of "real-world" driving/roadway such as: (a) weaving of Host and target vehicles in their respective lanes; (b) lane changes by Host and target vehicles; (c) variable number of targets; (d) varying speeds of Host and targets; (e) complex roadway scenarios (i.e.: straight, curve, transition to curve); and (f) sensor characteristics (i.e., sensor misalignment; target dropouts, or momentary loss of target data due to limited field-of-view, glint and scintillation).

A "real-world" driving/roadway event which can robustly be handled by the scene-tracking algorithm is the in-lane weaving of both the Host and target vehicles. Figure 3.31 presents a scene tracking algorithm comparison for a complex geometric roadway scenario, in which four moving vehicles (Host Vehicle and 3 target vehicles) are traveling on a roadway which transitions from a straight to a curved road, with a constant 800 meter radius-of-curvature. In this event, all the vehicles are traveling at 20 m/s. A target vehicle is present in the left adjacent, right adjacent and same lane of the Host vehicle. The target orientations are: (a) left adjacent lane vehicle (Target 3) is located 70 meter ahead of the Host vehicle; (b) same lane vehicle (Target 2) is located 90 meter ahead of the Host vehicle; and (c) right adjacent lane vehicle (Target 1) is located 50 meter ahead of the Host vehicle. This figures compares the lane position estimation errors for each target, for the following two driving cases: (i) Neither Host nor targets are weaving; and (ii) Both Host and all targets are weaving (i.e.: weaving characteristics: sinusoidal, harmonically unrelated periods, and 1m peak-to-peak amplitude). As it can be seen, the scene tracking system provides very acceptable lane position estimation performance in the presence of weaving. As would be expected, the worst performance was for the most distant target (target 2 at 90m). In fact, for the near-range targets (targets 1 & 3), very little performance differences are observed between the "weaving" and "non-weaving" scenarios.
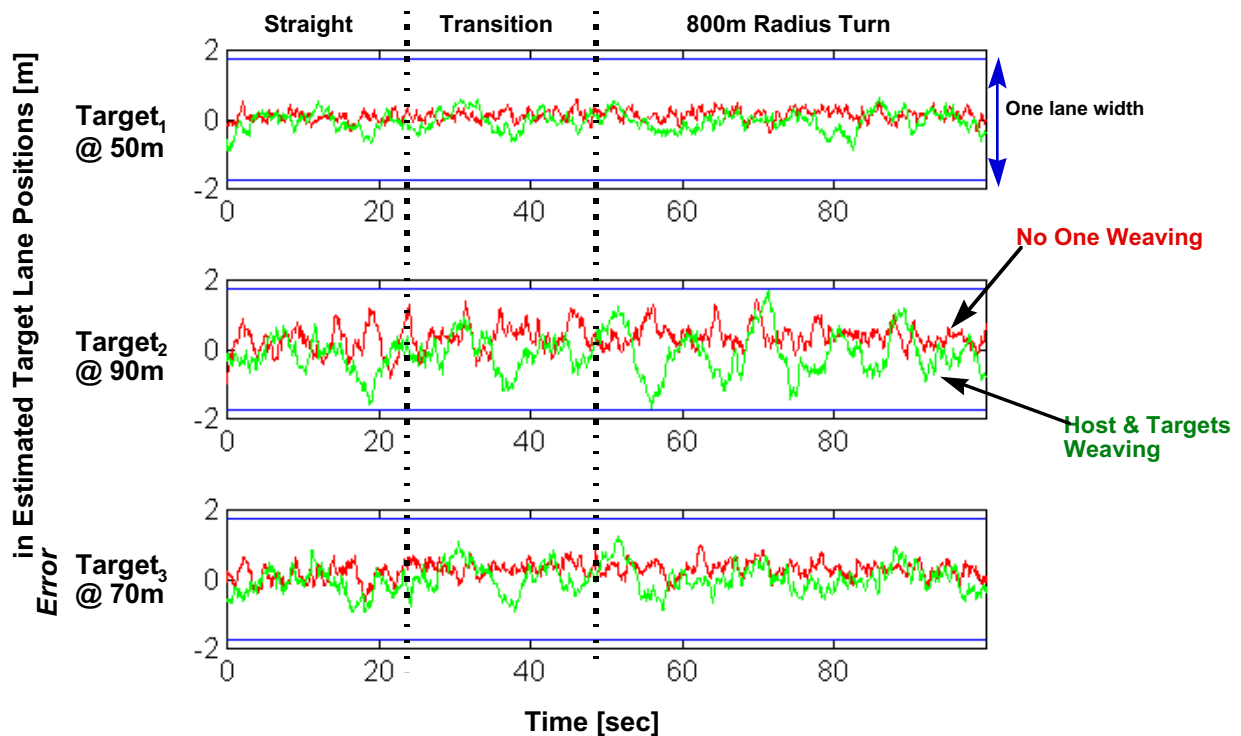
Figure 3.31: Weaving Scenario (Curve Transition vs. No Transition).

One interesting and intuitively reasonable finding of the scene tracking development effort is that a performance tradeoff is required between: (a) detecting lane changes, (b) maintaining proper target lane classification in curve entry & exit scenarios, and (c) maximizing insensitivity to in-lane weaving of targets. This is particularly true when only one target is visible in the scene, since there are no other targets available to corroborate information related to the shape of the upcoming road segment.

One aspect of this tradeoff can be seen in Figure 3.32. This figure depicts two plot windows which shows a comparison between the estimated and actual target lane positions for a two different single target roadway scenarios. The characteristics of the target/roadway events are: (a) Single target traveling on straight roadway segment and changes lanes [See Top Plot]; and (b) Single target traveling on a straight roadway segment which abruptly changes in a 800 meter radius-of-curvature turn and remains in the same lane (i.e. no lane changes) [See Bottom Plot]. In the lower plot window, it can be seen that the target's lane position is accurately tracked as it enters the sudden turn. This indicates that the scene-tracking algorithm is rapidly changing its estimate of the road shape, while allowing the target to remain centered in the lane. In upper plot window, it shows that as a consequence of this rapid road shape adaptation, it takes a few seconds to realize that the target changed lanes on the straight road.
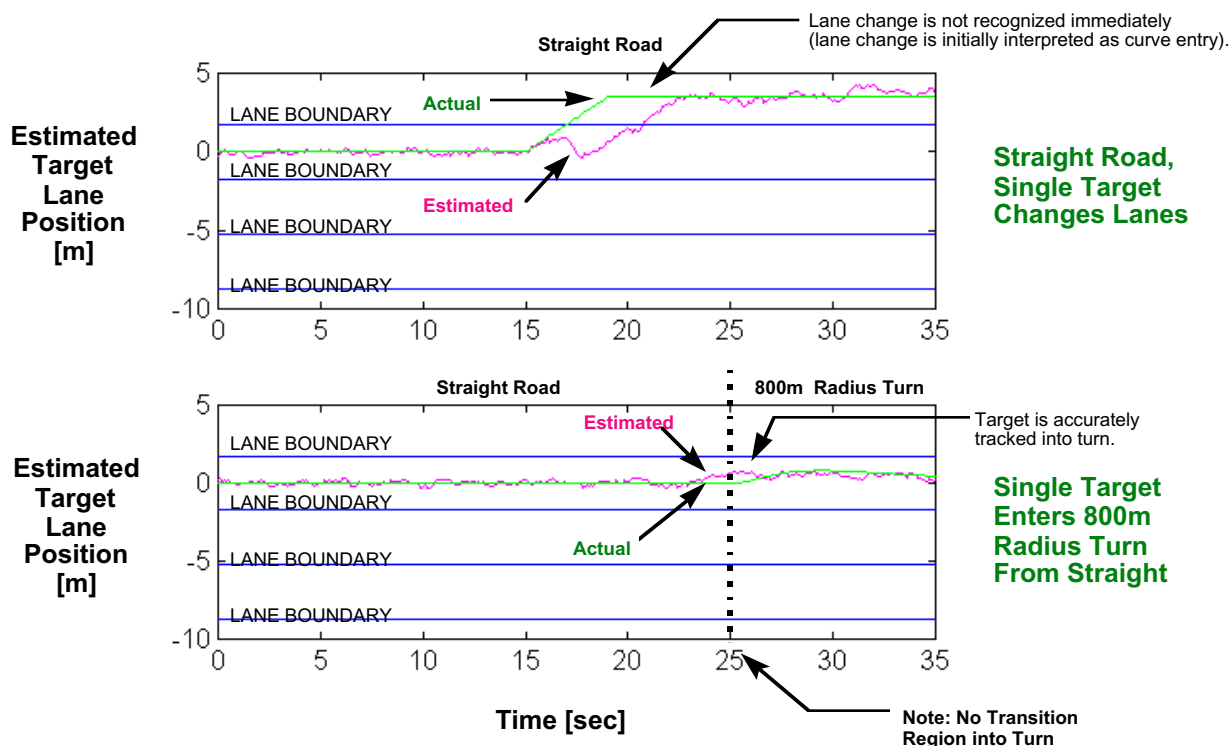
Figure 3.32: Comparison of Lane Change vs. Turn Entry Maneuver.

Figure 3.33 clearly illustrates what is happening in the lane change scenario described in Figure 3.32. Five overhead view snapshots are shown covering the interval of time (i.e.: time from 40 to 44 seconds) which completely encompasses the lane change. Each overhead snapshot shows the front end of the Host vehicle at the bottom of the picture, and the target near the center. The estimated target position, as calculated by the Target Tracking Filter, is shown as a small circle inside the box representing the target. The Host's estimate of the upcoming road shape is shown as a dashed line. Prior to any lateral motion of the target (i.e.: t = 39 sec), the Host's estimate of the road shape is straight and directly through the center of the target. In the subsequent two snapshots (i.e.: t = 41 and 43 sec), the target is seen to be changing lanes, and the Host's estimate of the road is bent to follow the target into the next lane. At t = 45, the target is now going straight again, and the Host's road shape is again bent to account for that. There is now a nonzero path angle estimate evident (i.e.: the estimated road doesn't come straight out of the front of the Host). After seeing the target go straight for several seconds (i.e.: t = 49 sec), the algorithm now realizes that the road is actually straight and that the target has changed lanes.

As might be expected, a lane change by one target can be more easily recognized if there are more than one target in view. This is due to the greater amount of road curvature information that is available from two or more targets.
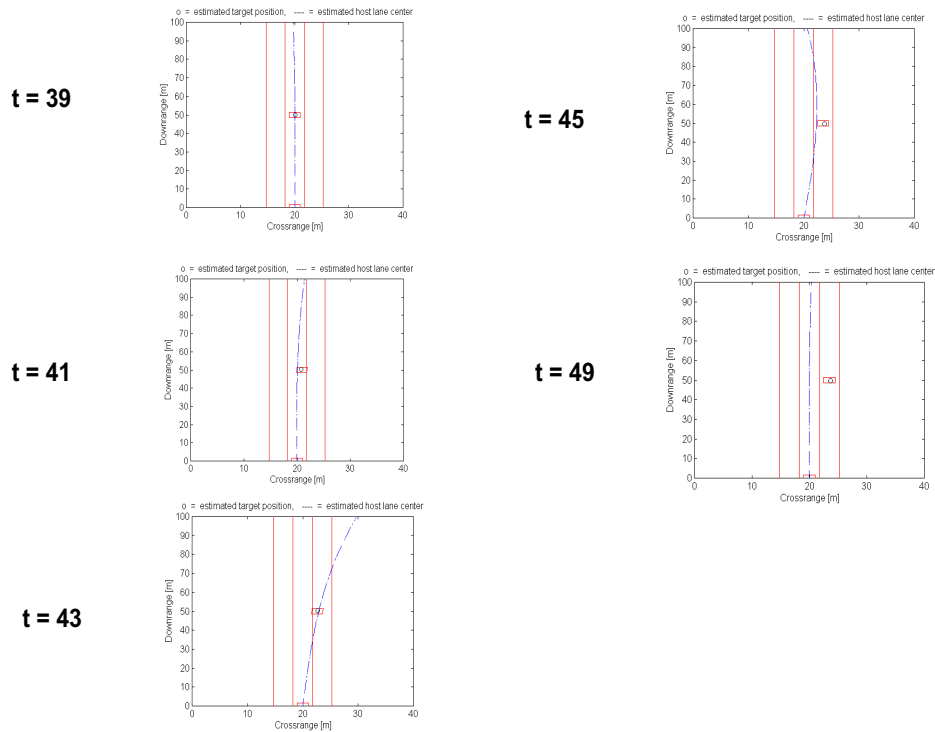
Figure 3.33: Evolution of Upcoming Road Segment Estimate.

Figure 3.34 reveals another interesting problem which merits further attention, which involves the target lane change event, for a simple geometric roadway scenario, in which three moving vehicles (i.e.: Host Vehicle and 2 target vehicles) are traveling on a straight roadway segment. In this event, all the vehicles are traveling at 20 m/s. The upper plot window depicts a two-target straight road scenario in which the near target makes a lane change. Similarly, the lower window depicts a two-target straight road scenario in which the distant target makes a lane change. The lower plot window shows that when the distant target makes a lane change, the lane change is recognized with less delay than in the single target case, and the target which does not change lanes is tracked very well. On the other hand, in the upper plot window, the near target lane change causes the upcoming road estimate to be projected into the adjacent lane, which makes it briefly appear that the distant target is making a lane change in the other direction. This apparent range-dependent influence on road curvature estimation requires further study.
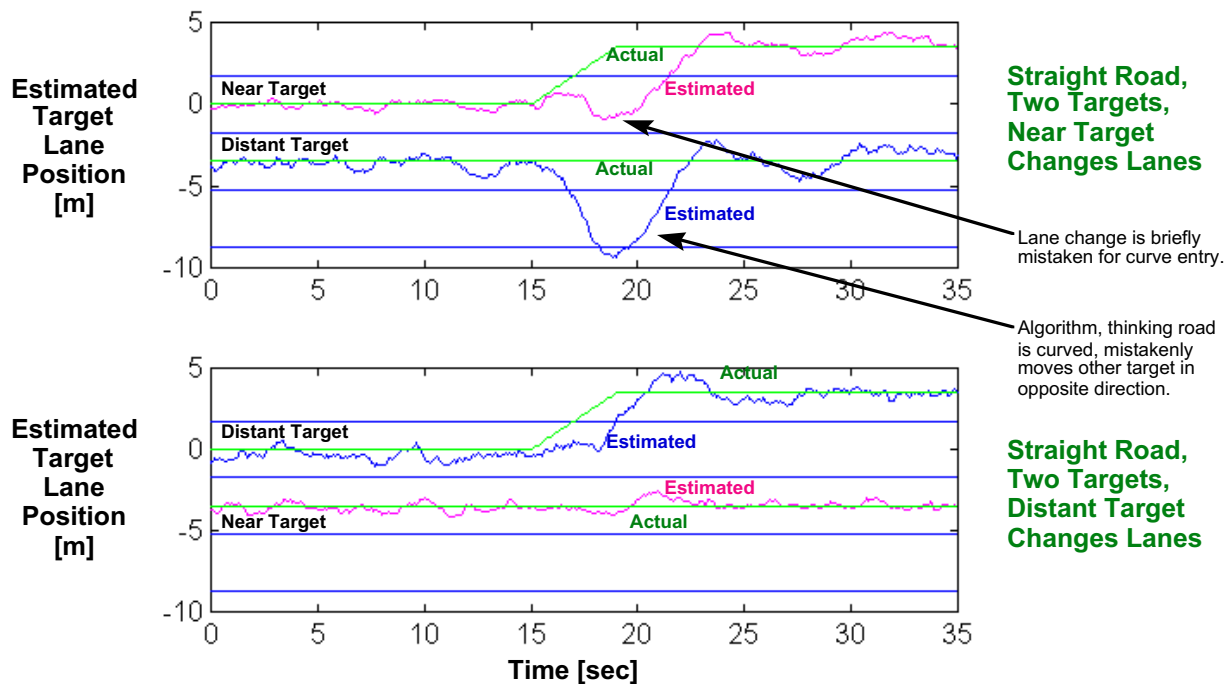
Figure 3.34: Straight Road Scenario: Distant vs. Near Target Lane Change.

Comparison between Scene Tracking and Conventional Yaw Rate Based Path Estimation

As discussed previously, one of the benefits of using a simulation environment is that controlled performance comparisons of different algorithms can be conducted. In general, the scene tracking approach has better tracking capability in the presence of targets performing sudden curve entry maneuvers, and can better deal with steering maneuvers made by the Host (weaving and lane changes). However, the scene tracker also has more difficulty in handling the scenario of only weaving targets.

Figure 3.35 illustrates the errors in estimating the target lane positions, as a comparison between the "scene tracker" and the "conventional" path algorithms. This scenario involves a single target and the Host vehicle, where the roadway is straight and then abruptly changes into a 500m constant radius-of-curvature turn. The target is 90 meters ahead of Host vehicle and is located in the same lane. In this figure, the conventional algorithm, sensing that the road is straight (since the Host vehicle is still traversing the straight road segment), initially believes that the target has changed lanes (since the target has entered the curve). Only after the Host vehicle has also entered the curve, and is well into the turn, then the "conventional" algorithm will again correctly classifies the target as in-lane. On the other hand, the scene-tracking algorithm is only minimally bothered by the abrupt transition in the roadway.
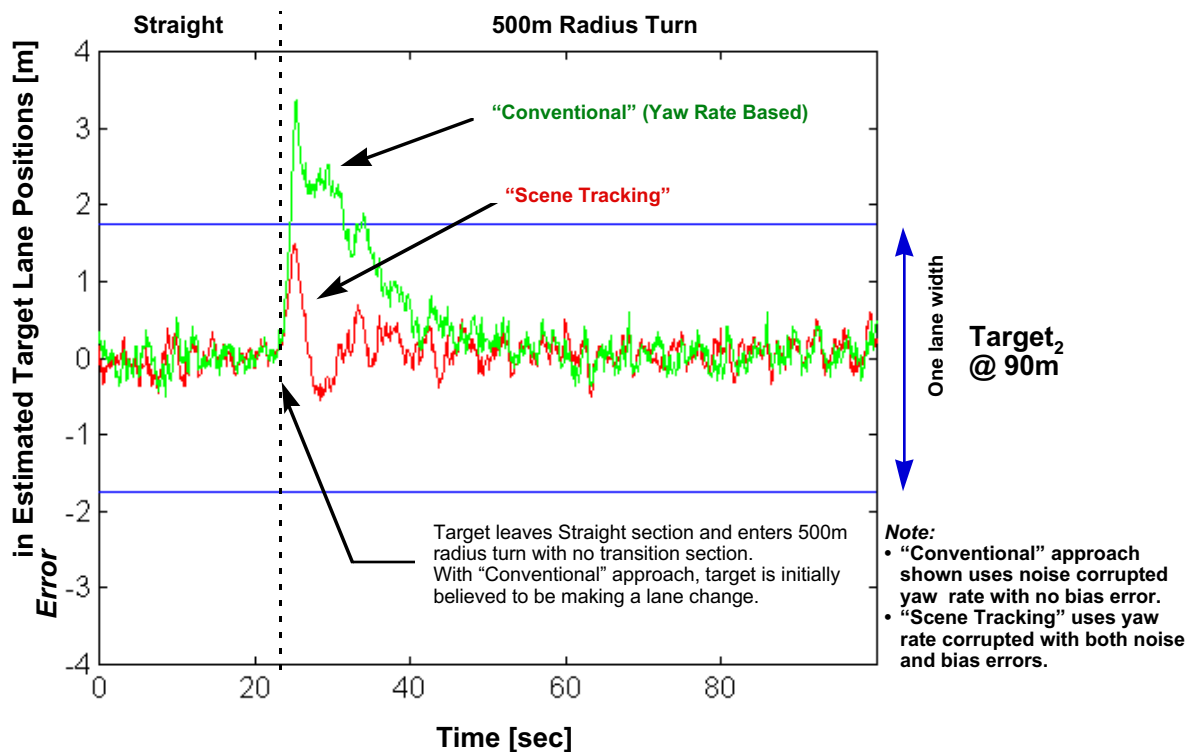
Figure 3.35: Comparison Approaches (Host Remaining In-Lane without Weaving).

Observations & Comments

The model-based scene tracking approach offers the potential for improved path estimation performance in a number of areas in which the conventional approach has deficiencies. Moreover, it also provides a basis for the fusion of data from a variety of sensors. However, several topics related to scene tracking require further study. For example, an approach to integrate and utilize both scene tracking and conventional path estimation techniques to provide added robustness and redundancy to the system needs to be developed. A tradeoff analysis between recognition of target curve entry, timely detection of lane changes, and immunity to weaving of targets needs to be carried out. The relative influence of targets at different ranges upon road curvature and path angle estimates needs to be investigated. The extension of the scene tracker to handle variable speeds of Host and target vehicles, the steady state implementation of all the filters, and the investigation of the potential for using the scene tracker attributes to estimate yaw rate sensor bias and forward-looking sensor misalignment should also be tackled.

3.5 Forward Laser Sensor Development (Task 2.4)

The Forward-looking Laser Sensor (FLLS) was developed to explore the benefits of laser technology as an alternative to millimeter wave radar for automotive headway sensors. It was felt that a laser based approach might be less costly and could potentially offer performance advantages. Headway sensors are a key element for future

collision avoidance and intelligent cruise control systems. The specific task objectives were:

- Use available laser technology to design, develop, and demonstrate a multi-zone headway sensor for cruise control and/or collision avoidance applications.

- Produce several development units to be tested in the laboratory and in-vehicle.

- Support the requirements definition of a production intent system.

The system described here (Engineering Development Unit Version 1 or EDU1) is for development only. As such, it provides many development features to support the definition of a production intent system. A vendor with experience in low-cost pulsed laser rangefinders carried out most of the sensor development.

3.5.1   Summary of Progress

A raster scanned laser rangefinder was designed, built, and tested in the laboratory and on a vehicle. The range to 375 points in a unique interlaced raster (as illustrated in Figure 3.36) are determined every 150 ms. The wide (20°X8°) field of view allows multiple targets in 3 lanes to be identified and tracked in both azimuth and elevation within the sensor's 100 meter range. The ability to overcome some of the problems found in existing laser rangefinder systems for collision avoidance was demonstrated.
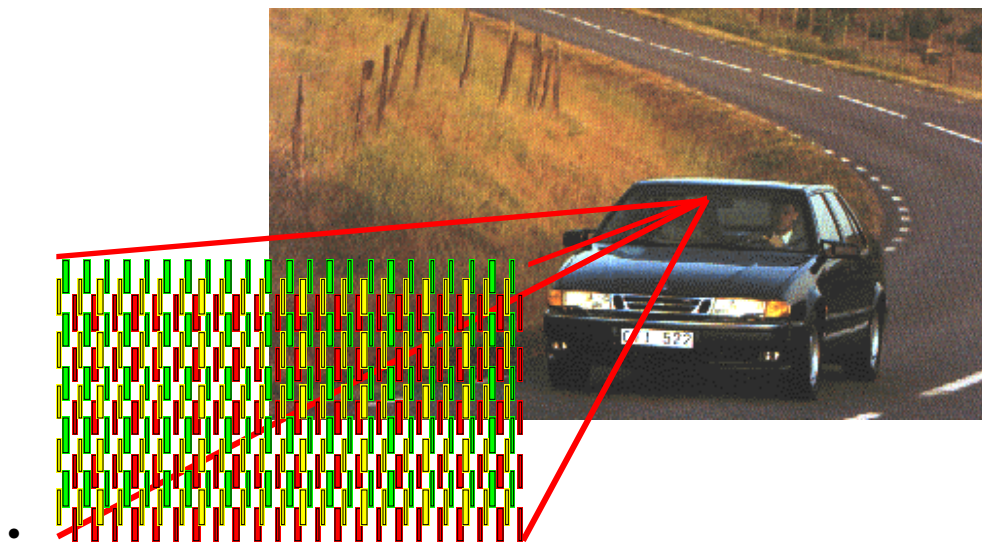
Figure 3.36: Raster Scanned Laser Sensor

Raster scanned laser rangefinders may ultimately provide the high performance and low cost necessary for automotive collision avoidance applications. The engineering development sensor reported here is a first step toward designing a production sensor. The sensor uses pulsed time-of-flight laser rangefinder technology to show the feasibility of this approach. In addition, the development sensor includes data capture features to evaluate various levels of scanning so that the most cost-

effective approach can be selected. Several diagnostic capabilities are included to support development. A video camera records real time traffic events with a sensor data overlay and a PCMCIA memory card interface is available for high-speed sensor data capture.

3.5.2   Laser Sensor Development and Evaluation

The basic requirements for a forward-looking laser sensor are as follows:

1.   The system must simplify the driving process.

- Operation of the system must not require any special training or skills to understand and operate.

- The system must be fully automatic and not require the driver to perform any new task such as mode changing for weather, road type, or day/night.

- The human interface must be simple, natural and intuitive based on previous driving experience.

- Control inputs from the driver must override any control signals from the system.

2.   The system must react correctly to <u>all</u> targets found on public and private roads that could pose a threat to the safe operation of the vehicle.

- This includes all types of towed objects such as the 100' wood pole towed by a truck, very low trailers, and towed corrugated pipe.

- The merge threats posed by vehicles entering the freeway must be handled correctly (i.e., when a tracked target moves to an inside lane, the Host vehicle should not accelerate toward a merge threat even if the cruise is set at a higher speed).

- The system must react and warn of objects such as vehicles that are stopped in the vehicle path. The same system must also ignore stopped objects that are not a threat such as overhead bridges.

3.   The system must enhance the safety of driver and passengers.

- The system must not have a reaction time less than that of a skilled driver in the same situation.

- The system must not react to a false target in a manner that poses a threat.

Using these requirements as guidelines, a scanning laser rangefinder based on time-of-flight rangefinder technology was selected. A narrow (20 Ns) pulse of light from a semiconductor laser is timed as it travels from the transmitter to the target and returns. This is a relatively mature technology with thousands of military and commercial systems in service. The basic criteria for the design selection were: (1) the ability to detect non-cooperative automotive targets at 100 meters, and (2) .the system be eye safe.

The FLLS system uses the time-of-flight rangefinding technique. The distance to the target is obtained by measuring the time interval between the transmitted and

received light pulses. To measure this time interval a high-speed counter is started by a trigger pulse when the laser diode is fired. A signal generated by the receiver when a light pulse is received is used as an enable signal to latch the current value of the counter into a location in a FIFO (first in first out) memory device. After the field of view has been scanned, the contents of the FIFO are then analyzed to determine the ranges of returns based on the counter values loaded into the FIFO. These counter values are a record of the total time of flight and thus the range to the targets. This analysis is done with assembly language subroutines highly optimized to take full advantage of the more powerful special features of the TI C31 processor. This raw range data is then transmitted to the target tracking PC for further analysis as a sequence of 25 range values each corresponding to a different azimuth angle in the single line sweep.

During vehicle testing phase, a software was developed and used to create and track targets. The system has demonstrated the ability to create targets from pixels and track multiple targets in 3 lanes of traffic. Depending on the traffic, the system has been observed to track up to 4 and 5 targets simultaneously. These traffic scenarios were captured on videotape using a vehicle system depicted in Figure 3.37.
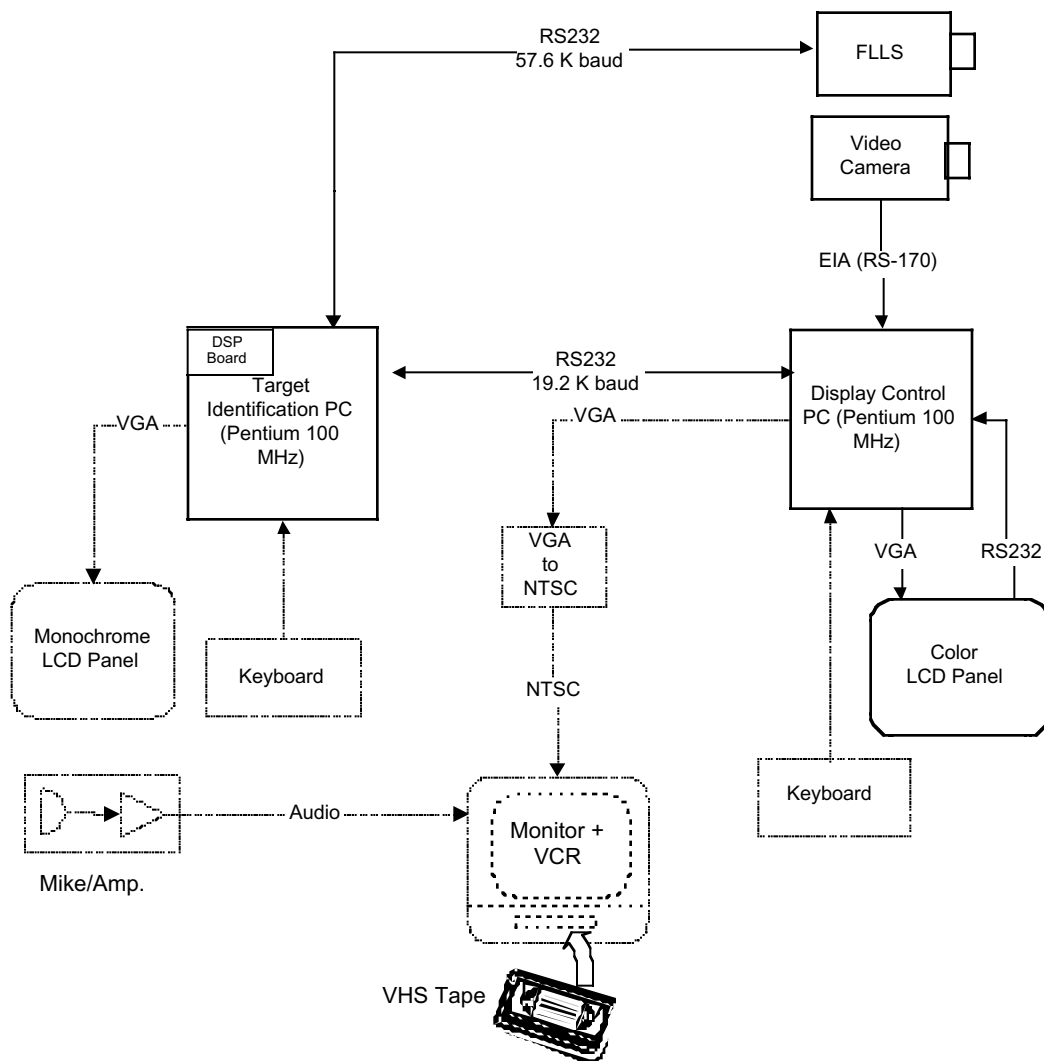
Figure 3.37: FLLS Vehicle System Mechanization

3.6   Multi-beam Planar Antenna (Task 3.1)

A major factor in the deployment of an automotive side detection system (SDS) is vehicle styling. Vehicle stylists require the surface area of any sensor to be as small as possible, such that the sensor is ideally not visible on the outside of the vehicle.

The performance parameters defined at the start of the ACAS program required a zone of coverage extending from the side mirror to 10 meters behind the vehicle that is exactly one lane width wide. The system was also expected to have target discrimination capability such that objects stationary with respect to the ground (parked cars, guard rails, bushes, etc.) and objects traveling in the opposite direction were not reported as hazards.

Preliminary work completed prior to the ACAS program indicated that a three-beam antenna system was required. Initial design efforts showed that for a standard planar patch array, the feed structure was 70% of the surface area, and limited the side lobe performance at high squint angles. The antenna board was also one of the highest cost components in the sensor design.

This task was structured to address the surface area and feed radiation problems with a low-cost small-area antenna design. Specific goals and objectives are:

- Development of a 24.125 GHz antenna that has a detection pattern that "looks down the adjacent lane".

- Antenna design must support an adjacent lane target zone 8-10 meters long and 4.5 meters wide.

- Antenna side-lobe performance must be compatible with target discrimination requirements.

- Antenna must feature planar technology in order to be consistent with manufacturing cost and vehicle styling requirements.

3.6.1 Antenna Design Approach

The performance specifications were completed, and the key electrical parameters are summarized in Table 3.10. Each zone requires a separate transmit and receive antenna, and each transmit / receive pair must meet the same performance specification. The surface area was specified as 2.25 x 5.5 inches for the six-antenna array. The combined requirement for high squint angle and low side lobes is the primary technical challenge for this task.

Table 3.10: Planar Antenna Key Performance Requirements

Parameter	Zone A	Zone B	Zone C
Gain	7 dB	7 dB	9 dB
Azimuth Beam Width	26 Degrees	26 Degrees	24 Degrees
Azimuth Side Lobes	-12 dB	-12 dB	-22 dB
Squint Angle	+30 Degrees	-30 Degrees	-64 Degrees

Based on these specifications, a design approach was selected. Theoretical analysis on boresight performance was completed and a concept for construction of the feed circuitry, housing, and radome was determined. The antenna was fabricated on a multi-layered printed substrate material in a planar configuration. This approach is consistent with the vehicle styling objective. Test structures for evaluation of single antenna elements and feed transitions were designed, and work on developing test software to test and characterize these elements was initiated. The original vendor selected to fabricate the test structures backed out after one attempt. A replacement supplier was found and an initial set of test structures were fabricated and tested.

Work continued on developing the planar antenna simulations using a Finite Difference Time Domain (FDTD) analysis program while the first iteration boards were

in fabrication. Additional simulations showed that via holes would be required to suppress unwanted stripline modes and a variety of via distributions were simulated and theoretically evaluated.

The first set of boards were received and tested. There were a number of problems discovered with the first set of boards that complicated obtaining accurate and reliable modeling data. First, the boards were slightly over etched in the area of the ground pads for the co-planar waveguide probes, resulting in a ground repeatability problem. Also, there was a problem with the microstrip to stripline transition design that caused a high VSWR. As such, it was not possible to accurately calibrate the measurement system in order to properly de-embed the radiating element impedance data. Finally, the initial circuit design was made before the FDTD analysis program was available, and the test circuits did not have adequate suppression of undesired parallel plate modes. Existence of these modes, as predicted by simulations during the fabrication cycle, prevented adequate calibration of the measurement system.

The microstrip to stripline transition was modified to correct the impedance match and parallel plate mode problems. Design of a partial array test circuit to model mutual aperture coupling coefficients was also completed. These circuit designs were submitted for fabrication.

During the second iteration fabrication cycle work continued on developing the planar antenna simulations. Multiple new simulation programs were reviewed in order to find a simulation program more compatible with the overall analysis problem than program originally selected. A simulation program, named *Eminence™*, was selected and purchased. Circuit simulation was started with the new program.

The second iteration mutual coupling boards were received in December 1995. These boards were severely over-etched and adequate tests could not be performed. The ground pad spacing was wider than the coplanar probe contacts, resulting in no connection on one or both ground pads. The supplier was notified and replacement boards were ordered. These boards arrived one week after the quarter ended, and were of good quality. The boards were tested, and data showed good correlation with simulation, and good repeatability.

The second iteration transition test circuits were received in January 1996. The quality of the boards was good, and the boards were assembled and tested. Simulation of the circuit, on *Eminence™*, showed a large unexpected shunt inductance that caused a large mismatch in the transition. Test data correlated very well with the simulation, and a new transition was designed to compensate for the mismatch.

The array architecture was modeled and analyzed. It was found that the addition of vias around the radiating slots, required to suppress parallel plate modes at the radiators, created a very high inductance at the slot. Analysis on the simulation program showed that, although the slot could be matched at a single frequency, the high Q associated with the large inductance made the match very narrow band. The bandwidth was determined to be far too narrow to meet design performance parameters over frequency and over nominal manufacturing tolerances. Additionally, it has been determined that multiple simulation and layout programs must be used in order to fully analyze the entire structure. This discovery forced a change in the physical architecture of the array. Multiple configurations were evaluated before an acceptable solution was

found. A new array design approach was completed, and the layout for the array was started.

During the sixth quarter, work continued on designing the new array using a radiating patch structure instead of the originally proposed radiating slots. The patches are slot coupled and provide a broader band match to the feed structure. Simulation showed that the design would provide a broader band match, and would also provide more manufacturable tolerances on etched dimensions.

In order to meet the design parameters, the $\pm$ 30-degree antennas require 2 vertical patches and 6 horizontal patches. The -64 degree antennas require 2 vertical patches and 8 horizontal patches. In order to minimize the number of variables, reduce the sources of error, and extract data to verify design models, the antennas were first designed with only 1 vertical patch (1D). The 1D prototype arrays were designed, layouts were completed, and the board was fabricated.

Figure 3.38 shows a sample patch array configuration. The layout is for a 2D-test array that is a 2 vertical patch and 4 horizontal patch configuration. The feed structure is shown as viewed from the bottom side of the multi-layer board, with the topside patches shown as if the board material were transparent.
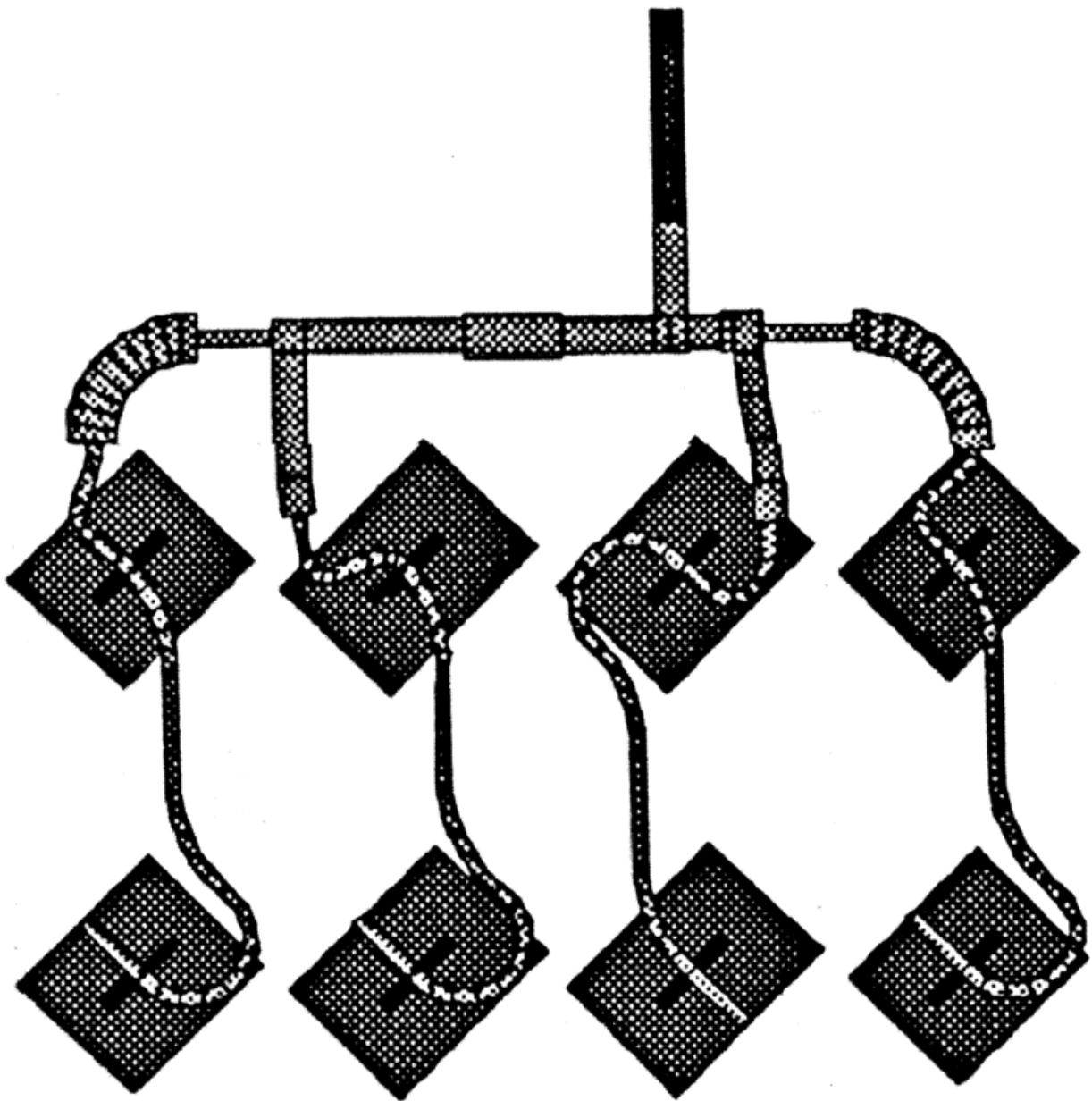
Figure 3.38: 2D 64 Degree Array Layout

Tests on the first 1D-array boards fabricated resulted in good performance on the 30-degree squint design. The 50-degree squint performance was moderate, and the 64-degree design was poor.

The assembly was X-rayed and it was determined that some mis-alignment between layers had occurred during the fabrication process. An initial review of the simulation model indicated that this will degrade side lobe levels, however the degradation should not be as severe as the measured data. The supplier was contacted and agreed to fabricate a replacement array of this design. The second 1D array was fabricated to correct for the layer to layer misalignment that was discovered on the first unit. There were no design changes made.

The replacement array was received and tested. Test results for the 30-degree squint angle are summarized in Table 3.11. The design for -30 degrees is the mirror image of the +30 degrees, and the test results are similar.

Table 3.11: 30 Degree Squint Data Summary

Parameter	Specification	ACAS Design	Baseline
Gain	7 dB min	8.6 dB	8.5 dB
Azimuth Beam Width	26 +/- 4 Degrees	23 Degrees	24 Degrees
Azimuth Side Lobes	-12 dB max	-14 dB	-11.5 dB
Squint Angle	+30 +/- 4 Degrees	+30 Degrees	+28 Degrees

This data indicates that the buried feed structure antenna gives improved performance relative to both the design target and the existing baseline antenna structure for the 30-degree squint angle. The buried feed structure reduces the required sensor height by approximately 40%, and significantly reduces the sensitivity of system side lobes to the location and spacing of the absorbing material in the radome, thereby opening production tolerances which will both lower cost and increase yields.

Two high squint angle designs were made, one having a target of 50 degrees and the other a target of 64 degrees. Both designs were fabricated in order to help verify the design models, which become much more critical when trying to obtain performance at the high squint angles.

The 50-degree squint data, Table 3.12, shows good performance with regard to gain, beamwidth, and squint angle. Side lobes were significantly higher than specification, and were higher than the 30-degree antenna. The 64-degree squint data, Table 3.13, is similar to the 50-degree data except that the beam width is slightly higher than specification and the gain is slightly lower than specification. The Baseline design did not have a high squint angle antenna due to the poor pattern resulting from top layer feed structure radiation.

Table 3.12: -50 Degree Squint Data Summary

Parameter	Design Targets	ACAS Design	Baseline
Gain	9 dB min	9.3 dB	NA
Azimuth Beam Width	24 +/- 4 Degrees	25 Degrees	NA
Azimuth Side Lobes	-22 dB max	-12 dB	NA
Squint Angle	-50 +/- 4 Degrees	-52 Degrees	NA

Table 3.13: -64 Degree Squint Data Summary

Parameter	Design Targets	ACAS Design	Baseline
Gain	9 dB min	6.6 dB	NA
Azimuth Beam Width	24 +/- 4 Degrees	32 Degrees	NA
Azimuth Side Lobes	-22 dB max	-14 dB	NA
Squint Angle	-64 +/- 4 Degrees	-63 Degrees	NA

A comparison of measured data to design simulations was made for all of the designs. In all cases, the gain, beam width, and squint angle were as predicted, and the side lobe levels were 10-15 dB higher than the mathematical model. The array patterns were improved, side lobes lowered, and VSWR improved on the replacement array. This 2nd array was also X-rayed and although the fabrication alignment was improved, the measured errors exceeded both design tolerances and quoted vendor process tolerances. The design was based on 2 mils maximum alignment error, and errors up to 5 mils were measured on the 2nd fabrication run.

Tests were run with absorber in the radome and with the radome removed to see the effects on side lobe performance. In both cases, the side lobes did not change significantly. At the close of the program, the side lobe issue had not been resolved.

3.6.2   Challenges

The primary task of designing a planar antenna with an electrical boresight squint angle of 64 degrees poses a significant design challenge. The primary problem with this design is maintaining the low side-lobe levels required for the application, and meeting the aperture size requirements dictated by vehicle styling issues. Based on a review of technical journals and discussions with suppliers, this design requirement exceeded all known previous art. Additionally, there was effort placed in trying to select a microwave board supplier that was capable of the high volume delivery requirements expected for automotive requirements.

Vendor Selection

One of the early problems encountered was the selection of the antenna board supplier. The first supplier, after initially indicating the capability to do the task, made one unsuccessful attempt and refused to bid any follow on business. The supplier underestimated the difficulty of the small sizes and tolerances and was not willing to work on his process for the small quantities being ordered at this time. Future production was too far in the future to interest him once he attempted the fabrication. Alternate suppliers needed to be identified, which required two months of calendar time, and resulted in a corresponding two-month delay in schedule.

<u>Simulation Approach</u>

Another early problem was in selecting an appropriate simulation software package. There are multiple microwave analysis programs available with differing degrees of capability. Although multiple programs were evaluated, a final determination of program capability can not be made without attempting to simulate a representative structure.

The original antenna architecture that was pursued was an array of radiating slots etched in a ground plane, and fed by stripline transmission circuitry. The simulation package required for this type of structure must support a multi-layer design, including plated through holes, radiating apertures, and stripline source excitation. The initial analysis package available was a "Method of Moments" package which did not support apertures in ground planes. A non-commercial simulation package under development that used Finite Difference Time Domain (FDTD) analysis and could handle arbitrary 3D structures, including radiating apertures, was available. Time was spent developing this tool for the 24 GHz antenna application, but it was discovered that the program was deficient in a number of ways. First, moderately sized problems (even single radiating elements) took many hours to simulate, and the results of any given simulation were questionable. For some problems, the results matched measured data well, for others there was a discrepancy. Second, the implementation of plated through holes appeared inadequate, and the accuracy of the effects of through-holes was doubtful. Third, the software lacked a user-friendly interface. Obtaining the S parameters from a simulation required significant external spreadsheet calculations, which further added to the overall cycle time and complexity. Commercial FDTD programs are available, but the high costs of these packages made making an immediate purchase without careful evaluation of the adequacy of these programs relative to this particular application less attractive than the decision to use the available non-commercial FDTD program.

Because of the problems encountered with the simulation programs available to us, and using the knowledge gained attempting to simulate the required antenna structure, an investigation into alternate existing commercial programs was conducted. After completing the investigation, a commercial program that utilizes a Finite Element Method (FEM) that can simulate arbitrary 3D structures, that can analyze radiating slots, and that can simulate stripline input excitation, was purchased. Additionally, the program had been on the market for a number of years and appeared to be a mature user-friendly program. The major drawback to the package was that it required a very large memory even for moderate sized structures, and again required a considerable length of time to execute a simulation. The program did give very good correlation between simulated and measured results for individual stripline fed radiating elements.

The array was simulated using the new FEM software. This iteration showed that the input impedance of the radiating slot was highly inductive due to the presence of plated through holes. These vias must be located very near the radiating slot in order to suppress the excitation of unwanted stripline modes. It was found that it was possible to tune out the inductive effect with a capacitive stub, but the resulting element impedance had a very narrow theoretical bandwidth and would not be adequate for an array design due to manufacturing tolerances.

When designing the final array, three different simulation programs were required. The radiating patches were simulated in one program that was optimized for microstrip design. A second simulation program was used for the stripline junctions in the feed structure. The resulting S-parameter matrices were imported into a third simulation package that was optimized for strip line design.

In summary, it is important to define the proposed architecture well enough prior to selection of a simulation program to ensure that the program is capable of accurately analyzing the proposed structure and that the time and equipment required for the analysis is allotted. When evaluating a new simulation program, simple representative elements of the design should be fabricated and test data available such that these test structures can be analyzed by the software under evaluation and the simulation results can be compared to measured data. Doing this gives the evaluator a method for quantitative evaluation of the simulation program's accuracy, speed, user interface, and host equipment compatibility in a timely fashion before the purchase of the program.

<u>Fabrication Processes</u>

Finally, the current suppliers experienced similar problems as the first supplier with their initial fabrication runs, resulting in circuits that were not suitable for accurate testing. These suppliers have been willing to work the processing issue, and have now delivered parts that are closer to required tolerances. It did, however, require two fabrication cycles to understand the process. In the future, delays can be avoided by having the supplier fabricate a representative sample board during the actual circuit design phase. This will give the supplier adequate time to work process development in parallel with the detailed circuit design such that the fabrication process will be correct when the first circuit iteration is ready for fabrication. It should be noted that the most significant fabrication problems encountered were with structures required to design and test the antenna elements. These structures are required only during the design phase and are not a part of the final design. The final design tolerances are compatible with quoted standard fabrication processes.

3.6.3   Completeness of Task and Future Directions

The overall progress on this task did not meet the goals and objectives planned. Time delays associated with simulation software, vendor selection, and fabrication process problems prevented completion of the final 2D full array. Additionally, interest in SDS systems at the automotive platforms waned, and the interest that remained was directed at lower performance, lower cost systems that did not have target discrimination. The system architecture required to meet system performance specifications established at the start of the ACAS program was more sophisticated and more expensive than needed to meet evolving specifications. The combination of schedule delays and business decisions based on customer desires resulted in a decision to terminate efforts on this task prior to completion of a full 2D array. The task was stopped with $300,000 left in the original budget.

During the course of this task, we have identified certain items that need development in order to better achieve low cost commercial systems. Improved

simulation software packages are required. Additionally, a process to quickly determine the optimum simulation programs for the particular design task needs to be developed. Fabrication processes for thin multi-layer microwave printed circuit boards need to be improved before high volume cost objectives can be met. There are "specialty houses" that can fabricate boards to the accuracy required in small quantity at "development level" prices, but the ability to achieve the required accuracy and repeatability at high volume, cost-effective facilities has not yet been demonstrated. A solution to this fabrication issue will be required for future side, rear, and forward systems.

A materials and fabrication process development program for multi-layer microwave and millimeter wave circuit boards should be considered in the future.

3.7   Low Cost 24 GHz Transceiver (Task 3.2)

A primary factor in the deployment of a Side Detection System (SDS) is the effort required to define final performance specifications and design a system that meets production cost targets. This task was structured to establish the requirements for a side detection system, to design a cost-effective sensor using MMIC based technology, and to verify the design by both on road and product assurance testing. The intent was to design a MMIC that was compatible with both the SDS and with a Rear Detection System (RDS) such that the same device could be used in both applications. The market strategy was to introduce the system for the commercial trucking industry and then extend the product to consumer automotive applications.

The task objectives are:

- Selection of a foundry process that supports low cost fabrication of 24 GHz MMIC devices.

- Refine and optimize the design so that performance parameters are centered around the foundry process parameters.

- Adapt system design and performance specification to foundry process capability.

- Finalize the design and fabricate multiple wafer runs to determine process variations.

- Submit final design to alternate foundries for quote.

- Build and demonstrate prototype systems using devices developed on this program.

3.7.1   MMIC Design Approach and Accomplishments

The design approach for the low cost transceiver was established and a vendor selected. The supplier was changing the standard process to a 4" diameter wafer line and to include scratch protection. This was a significant change from the initial development work on the 3" line. A first iteration was run to determine model changes associated with the new process. Tests indicated that changes were required on the MMIC circuit design. The first quarter milestone, design approach, and the second

quarter milestone, first run of MMIC wafers, were completed ahead of schedule. The mask set was iterated to accommodate the new circuit and device models based on the new 4" process. Devices from 5 wafer runs were received during the first year. The first wafer run was prior to the inception of the ACAS Program contract and served as the baseline reference (3" design on 4" process). The plan included running wafers at different times to improve the design models, to determine the key processing parameters relative to RF performance, and to determine the variability of the process.

Characterization testing of the first four MMIC runs and characterization of MMICs in the final assembly over temperature was completed. All wafer runs completed during the first year were made from a "pizza" mask with four versions of Transmitter and four versions of Receiver chips.

A summary of MMIC performance for the four 4" wafer design runs fabricated from the developmental mask is shown in Table 3.14. As seen from the table, MMIC performance appears to be a function of gate length, and shorter gate length is not necessarily better in terms of overall performance. Even though the gain and maximum operating frequency (Ft) may be higher, the impedance characteristics of the devices change enough such that the interstage matching is inadequate and chip performance degrades. Additionally, we have not made enough wafer runs to determine chip performance for gate lengths longer than nominal. Minor design changes occurred between wafer runs, therefore care must be taken in reviewing the data and drawing conclusions regarding performance variations as a function of repeated wafer runs. Lot-to-lot variability will be correlated after the design is frozen.

Table 3.14: SDS MMIC Performance Summary.

Parameter	1st Iteration (March)	2nd Iteration (June)	3rd Iteration (July)	4th Iteration (October)
Gate Length	-25%	Nominal	-25%	Nominal
Power Out	-2 dB	In Spec	-2 dB	In Spec
LO Power	In Spec	In Spec	In Spec	In Spec
Center Frequency	+20%	In Spec	+10%	-10%
Conversion Gain	-5 dB	In Spec	-5 dB	In Spec
Tx Isolation	6 dB Low	6 dB Low	6 dB Low	2 dB Low
Rx Isolation	10 dB Low	5 dB Low	5 dB Low	2 dB Low
DC Offset	+100%	+50%	+10%	+50%

The specifications for Tx and Rx isolations are the original engineering estimates of performance for the devices. These estimates were based on breaking down the overall system requirement into specifications for all components and leakage mechanisms in the system, including package leakage, antenna cross coupling, and MMIC leakage. Further investigation showed that the isolation is a strong function of the test fixture. It has been shown that the devices are within measurement accuracy of meeting the isolation specification when measured in a special fixture. It has also been

shown that wafer level tests for isolation are invalid at this time. Integrated system tests, and further refinement of system performance parameters indicate that the overall system Tx to Rx isolation performance is being met with the devices as currently designed. These system level tests also indicate that the system isolation is being set by the integrated antenna assembly and not by the MMIC. At this time, it is expected that the individual chip specification can be changed, and no further redesign to improve isolation is planned.

A fifth wafer run of devices designed to vary gate length as a designed experiment parameter was made. Test data on the gate length experiment, as presented in table 3.15, shows predicted variability with regard to transmitter characteristics. The extremely low power on wafer #3 does not appear to be related to gate length and is discounted in the transmitter data analysis.

Table 3.15: MMIC Data From Gate Length Experiment

Parameter	Gate Experiment #1	Gate Experiment #3	Gate Experiment #4	Gate Experiment #7
Gate Length	-.06	-.03	-.02	+.02
Power Out	In Spec	-15 dB	In Spec	In Spec
LO Power	In Spec	-15 dB	In Spec	In Spec
Center Frequency	2% High	In Spec	In Spec	In Spec
Conversion Gain	TBD	TBD	TBD	TBD
Tx Isolation	2 dB Low	2 dB Low	In Spec	2 dB Low
Rx Isolation	N/M	N/M	N/M	N/M
DC Offset	See Note	See Note	See Note	See Note

Note: The DC offset has been identified as a design problem that is highly susceptible to a "non-standard" process step. This process step was necessitated by the conversion to the new process and 4" line during Summer 1995. The transformer design on the mixer input is not compatible with the new foundry process, and a special step must be performed. This step is not well controlled (because it is non-standard), and appears to be a primary cause for both the magnitude and variability of the DC offset. The signal processor circuit card has been redesigned to accommodate the DC offset variability, but the receiver MMIC will require one more design iteration in order to eliminate the need for the "non-standard" step. This step has the potential to adversely affect the receiver gain, as well as, the DC offset.

All wafer runs during the first year were fabricated from the developmental "pizza" masks that contained multiple versions of the MMIC chips. Based on a review of all of the performance data, a final chip set was selected, and the mask was redone to include only this one chip set and associated process control monitor (PCM) sites.

Four wafers were fabricated from the production mask, and all appear to be acceptable based on DC PCM monitors. All four wafers have been RF tested at the wafer level for transmitter power and frequency, and appear to meet specification. The first wafer was delivered and had an overall yield of 70%, including yield losses due to DC, RF, and visual criteria. The remaining wafers are at the foundry awaiting RF testing

of the receiver chip. Receiver chip wafer level RF test development is a part of the next quarter's planned activity. Efforts in the seventh quarter included developing an RF test for the receive MMICs. Three wafers were tested at the foundry for receive gain on one of the three receive channels, and one of these wafers was delivered for correlation tests in the system.

A total of 100 SDS prototype sensors were fabricated using the devices from the first production intent wafer. Although the fabrication cost for this volume of prototype SDS units are not a part of the ACAS program, the collection and analysis of MMIC performance data associated with these devices is necessary to determine the overall viability of the MMIC design. Transceiver performance data was measured over temperature at the microwave assembly. Twenty-nine performance parameters were measured at four temperatures, and the data from the eight deemed most critical was tabulated and analyzed statistically. As an example, the average transceiver loop gain, which is a function of transmitter power and receiver gain, has a 3 dB margin with regard to the specification limit, and has a standard deviation of 1 dB. All performance trends, including rates of change vs. temperature, tracked values that had been determined during the MMIC development and were consistent with the overall system design.

Twenty production units were assembled using MMICs from the final production mask for a designed experiment to determine the correlation between foundry data and system performance. MMICs were binned according to transmitter power and receive gain. Units were assembled to have different combinations of transmit power and receive gain, including combinations that should result in a lower than required system loop gain. The results of this experiment were very encouraging, in that it was shown that receive gain has a strong correlation with system loop gain, and that transmit power is a secondary effect. This result is not unexpected in that the transmitter is in gain compression, and less likely to vary over temperature, and the transmitter bin range was 1 dB. The receiver is operating in the linear region and the receiver bin range was 2 dB. Additionally, the receive gain is also a function of transmitter chip LO drive power, so the in-system receive gain is a function of both the chip level gain correlation and the difference between actual transmitter chip LO and a fixed MMIC test LO. It was determined from this test that the total number of receive bins could be reduced to 2, and that the need to bin transmitters may be eliminated in the future. It was also shown that RF screening at the MMIC level is viable for chips operating at this frequency.

3.7.2   SDS Sensor Fabrication and Test

Fabrication of SDS sensors using the MMICs fabricated as a part of the ACAS program was started. Sixty of these sensors were allocated for system qualification testing. Most of these qualification tests verify the integrity of the overall design and are not particularly stressful or directed toward the MMIC itself. Of particular interest to the ACAS program is the 1,000 hour powered temperature cycle life test. This tests the integrity of the MMIC and associated bonds and epoxy joints. The test has been split into two separate phases, an initial group of 10 and a second group of 15. This was done because a preliminary test on an early design iteration revealed a potential problem with a via design, and it was desirable to determine if the design change made to solve the problem was effective. The 10 units completed the 1,000-hour continuous powered temperature cycle with no failures associated with the MMIC design or fabrication. The

second group completed testing in the sixth quarter. Final tests indicate one SDS unit had failed. The unit was submitted to failure analysis, and testing showed that the transmitter MMIC had failed. More extensive tests to determine the actual cause of failure were performed, but the root cause for the single transmitter failure could not be found. An additional 10 units were subjected to the powered temperature test and passed with no failures or measurable degradation. The qualification tests are 100% complete.

The units required for the last ACAS milestone associated with this task, vehicle demonstration, were completed and delivered for installation.

3.7.3   Challenges

Foundry Selection

An initial problem encountered was selection of the initial foundry. Operating frequency is dictated by Federal Communication Commission regulations regarding allowed operating frequency bands and associated power levels, and bands allowed as of January 1995 were 5.8, 10.525, and 24.125 GHz. The 5.8 and 10.125 GHz bands were not acceptable for the application due to antenna size restrictions imposed by the vehicle styling requirements. MMIC fabrication processes for gate formation are either photolithography or E-beam, and the general consensus is that E-beam is more expensive. Process tolerances are such that the less expensive photolithography process limits gate length to greater than 0.3 microns, and many foundries limit the process to greater than 0.5 microns. A gate length of 0.5 microns limits operating frequencies to less than 20 GHz. Therefore, the primary design had to be in a foundry that had a photolithography process that provided adequate gain at 24 GHz. This limited the number of foundries that were viable candidates. The initial foundry selected has performed well throughout the program, and the foundry process has been shown to be viable at 24 GHz in terms of performance, cost, and yield.

Design Compatibility

The only major problem relative to this task is the uncertainty of the final vehicle system application requirements. At the start of the ACAS Program, certain assumptions were made for both RDS and SDS system performance requirements. Specifically zones of coverage and target range reporting criteria are important parameters in selecting a system architecture. During the ACAS Program, the SDS specifications have not changed significantly, however, the RDS requirements have been very volatile. So volatile, that it is not certain that the original architecture chosen for the rear system is compatible with the new performance specifications as defined by the individual vehicle manufacturers. It is also not certain that the performance specification has yet stabilized. The MMIC design has been made to be compatible with both RDS and SDS requirements as initially defined, thus meeting the original ACAS Program objective of design compatibility between RDS and SDS. The specific task objectives were modified to concentrate on the SDS application and sensor development, even though the MMIC is compatible with the original RDS requirements and design architecture.

3.7.4 Completeness of Task and Major Benefits

This task was completed on schedule, but exceeded the original budget by 11%. The task overrun was projected early in the ACAS program, and was covered by reallocating funds from task 3.1. The task met all of the program goals and objectives as modified in the third quarter, which eliminated the demonstration of the MMICs in a rear detection system (RDS). The MMIC design met the intent of the original program objectives in that it was compatible with the RDS architecture and performance that was specified at the start of the program. (Reference Section 3.7.3)

The ACAS program enabled completion of a MMIC transceiver design that demonstrated good performance, high yields, and high reliability. The program provided the opportunity for multiple wafer runs in a short time frame that provided an adequate data base for design centering, wafer probe test correlation to system performance, and establishment of MMIC wafer probe acceptance test requirements. The MMICs were demonstrated in a side detection sensor that provided state of the art performance in road tests. Sensors using these devices passed stringent automotive product assurance tests. Sensors were also installed on a number of commercial trucks and accumulated hundreds of thousands of miles over all weather and road conditions.

3.7.5 Future Directions

There are challenges remaining with regard to successful implementation of side detection systems in automotive applications that were identified during the ACAS program, but are beyond the scope of the this task.

The number of foundries capable of meeting performance requirements using a cost-effective process is very limited at this frequency band. Although the foundry selected performed very well, the MMIC fabrication process is unique to that foundry, and the design would need to be modified for use in any alternate foundry. MMIC specifications were prepared and submitted to alternate foundries, but development costs for a second source were prohibitive. During the course of the ACAS program, significant progress has been made in process capability such that additional foundries are capable of meeting performance requirements. Adequate design building blocks must be developed at these foundries in order to minimize the non-recurring engineering development costs.

Automotive performance requirements for both side and rear detection systems must be defined and stabilized. Performance, styling issues, and cost targets changed significantly from the start of contract. This minimized the effectiveness of the program relative to immediate application of the technology and hardware developed. The ability to demonstrate MMIC feasibility, and to characterize the MMIC design and process was invaluable to the future of these types of sensors. As the application specifications mature and stabilize, the knowledge gained from this program can be effectively applied, and will reduce the development schedule and cost for these systems.

3.8 Lane Sensing (Task 4)

Lane sensing is an essential component of a Forward Collision Warning System (FCWS). To assess threats correctly, the FCWS must know both the lane path and the host vehicle's position in the lane. This is especially important to prevent false alarms that would annoy and possibly confuse the driver. The primary objective of this task was to develop and demonstrate a robust, real-time lane-sensing system that determines the lane path and vehicle position in the lane on limited access highways. A secondary objective was to advance the state of the art in lane sensing technology.

Soon after the program began there were two major shifts in the project's underlying assumptions. These were motivated by the discoveries of: (a) There was no existing set of roadway image data to use for algorithm development and testing, and (b) There was no existing software that could be transferred from GM to ERIM to serve as a starting point for our efforts. To meet these challenges, ERIM added tasks to develop a data-collection system and to survey the technical literature in the field to create an algorithm resource. These tasks produced the following accomplishments.

To develop the Lane Sensing Module (LSM), ERIM created a suite of hardware and software that enabled the LSM research team to collect high-fidelity image data, perform controlled experiments, and quantitatively evaluate the results. A thorough literature search was also conducted, creating a searchable database of previous research and development, and compiled an extensive library of image-data sequences along with a modular library of software algorithm components. These tools enabled us to make substantial progress in advancing lane-sensing technology and give us the capability to continue that progress, through sound scientific investigation and the engineering of reliable solutions. No other organization in the world has equivalent capabilities.

Because of the delay in the acquisition of a radar subsystem, the integration of the LSM with the other equipment were not able to be carried out in a timely fashion. Therefore, the primary result of the lane-sensing task was a demonstration of the LSM as a stand-alone system.

3.8.1   Preliminary System Design

At the outset of the task, a functional requirements specification for a lane-sensing module was prepared. This report defined preliminary requirements for the lane sensing function of the FCWS. Then, a preliminary system design for the LSM was created, with specifications for algorithm development and the real-time demonstration of the system.

A searchable database, Figure 3.39, was constructed using Lotus Notes GroupWare so the team could take advantage of previous research. A literature search and review was conducted and the results were scanned into the database using an optical character scanner. The database now contains reports on most of the important work that has been done in this field, along with reviewers' notes and comments.
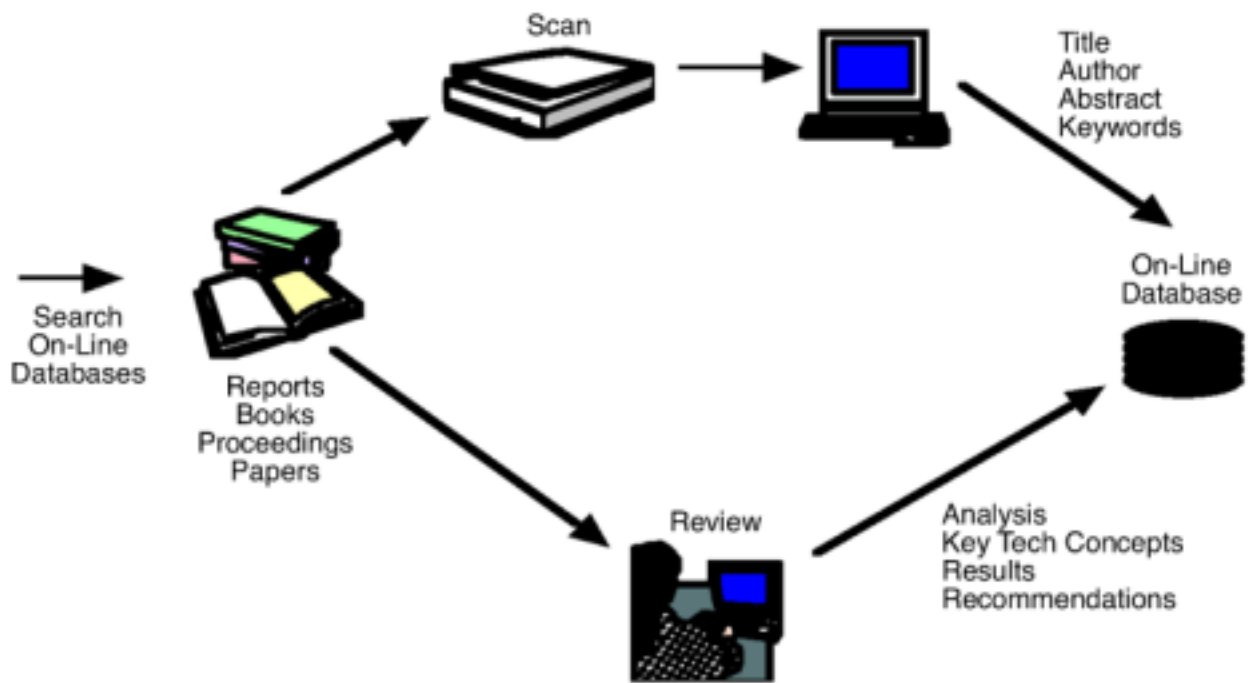
Figure 3.39: Lane Sensing Requirement Database Process

ERIM also worked with GMR to review crash statistics as they relate to lane sensing. The relative frequency and severity of some types of crashes indicate a real safety need for improving lane sensing at night, especially in rural areas.

An analysis of the image sensor's functional requirements was key, since image quality is the limiting factor in system performance. Spectral, geometric, and sensitivity requirements were prepared. A spectral analysis of road materials, lane-marker paint, windshield glass, typical sources of illumination, and sensor response characteristics was prepared. This analysis was used to select the equipment for collecting training data for the algorithms and for choosing the sensor/filter combination for the demonstration system.

As was pointed out earlier, it was necessary to construct a video data acquisition system (VDAS). To begin this effort we had to define the requirements, including the camera, the storage subsystem, and the control unit. Literature from equipment vendors was gathered and analyzed, and a set of criteria was developed to rank the available products. Requirements were also defined for vehicle instrumentation to obtain motion and attitude information (roll, pitch, speed, etc.), and existing products were evaluated. The VDAS was used to collect a library of real-world roadway data, to both develop and test the lane-sensing algorithms. Later, the VDAS became the foundation of the demonstration system.

3.8.2 Algorithm Development

The software modules that implement the algorithm use techniques from ERIM and GM's existing technology, along with other researchers' approaches. Specific

techniques were selected for each module based on expected performance and ease of implementation. The basic steps in the final algorithm, and the baseline techniques associated with them, are summarized in Figure 3.40.
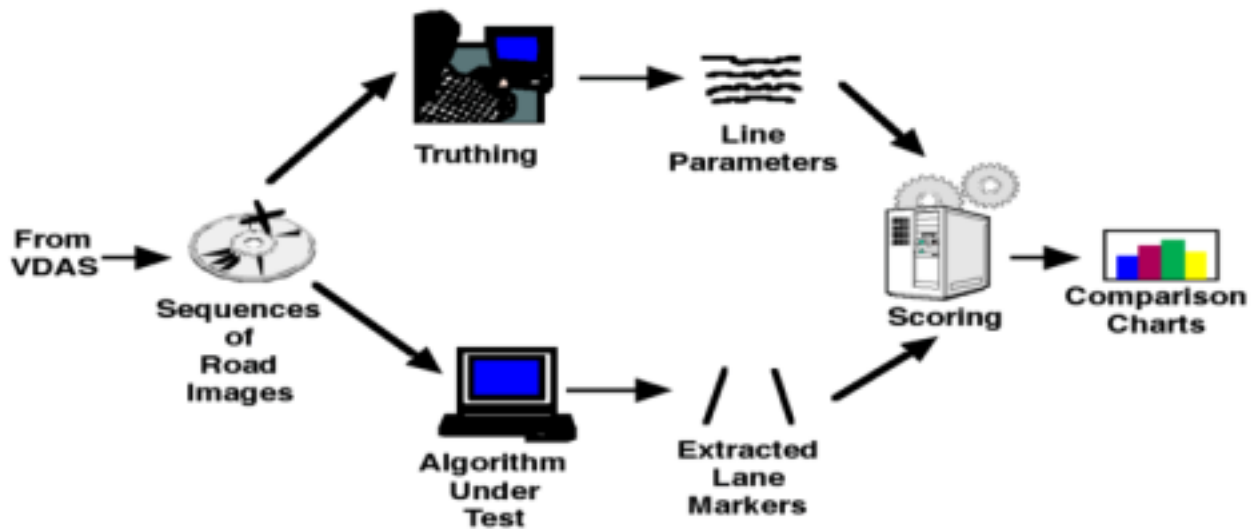
Figure 3.40: Video Truthing Software

In addition, an interactive software package was assembled for Truthing the video data. The software enables an operator to locate the lane markers in sequences of recorded images. These locations were recorded and used later to score the performance of the algorithm. The software that automatically scored the algorithm was also developed by ERIM International, making it possible to perform large-scale, automatic testing of alternative algorithms and parameter sensitivity.

Training data for developing the lane sensing algorithms was collected first with existing ERIM International equipment and later with the VDAS.

3.8.3   System Demonstration

The ACAS Consortium successfully demonstrated lane-sensing algorithms for the Department of Transportation sponsors on March 24, 1997. This demonstration was presented in ERIM's instrumented Vehicle Systems Test Bed van while driving on US 23. The remarkable aspect of this demonstration was that it was performed at night, Figure 3.41 using only the vehicle's headlights for illumination. This has never been done before. During the demonstration, vehicle state information (speed, roll, and pitch) was passed from sensors on the vehicle. The computer displayed an image of the road with the sensed lane markers highlighted, as shown in Figure 3.41.
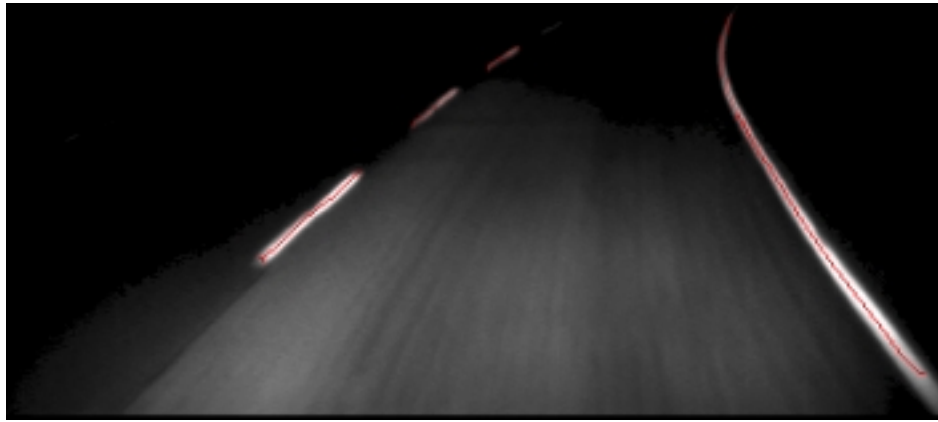
Figure 3.41: Night Time Lane Sensing

3.9 Wide Field-of-View Head Up Display (Task 5)

This task was to create a large field-of-view (FOV), high-performance head-up display (HUD) to be used in the study of HMI related issues for the ACAS project. Main features of the HUD were to be high brightness and uniformity of the virtual image, high FOV, and reconfigurability of the image source. The HUD would use largely existing individual technologies, but in combination would yield a system with performance levels not yet demonstrated in previous concept HUD development projects. Specific goals and objectives are:

(a)　To design and develop a reconfigurable HUD with wider FOV and higher brightness

(b)　To build some of these HUD units for demonstration in the lab and in vehicles

(c)　To install HUD(s) into appropriate vehicle(s) in support of advanced systems testing and closed-course testing

(d)　To achieve the following performance parameters:

- FOV　　　　　　　　　　2.0° vertical by 4.0° horizontal
- image distance　　　　　4000mm
- lookdown angle　　　　　6.0°
- image brightness var.　　　2:1

The intended use of this HUD was to be part of driver interface studies, therefore it was important to create a very high-quality HUD virtual image. This would then reduce the influence of HUD image viewability on driver performance data to be gathered during close-course testing. Thus, an essential part of this project was the development of display source and backlight. The future trend of HUD image content strongly suggests reconfigurability, and this project would demonstrate an image source having color, high resolution, high contrast, high brightness and good brightness uniformity.

3.9.1 Preliminary Designs and Benchtop Demonstration

The first design iteration of the HUD used the Cadillac Seville as the target installation vehicle. As in all automotive HUD development exercises, some compromises had to be made with regard to the original specification. For example, the display source had to be changed. The originally specified Sony display was not available in sufficient quantity and with appropriate drive electronics, so instead a Seiko-Epson display was used for the initial design. The main difference in using this source was a loss of vertical display resolution, which went from 5.3 pixels per milliradian to 2.2 pix/mrad. (Horizontal resolution remained adequately high.)

The horizontal field-of-view (HFOV) of the virtual image had to be reduced to 4.5° from 5.0°. The original spec actually called for only 4.0° HFOV, but an internal goal was set at 5.0° based on a very preliminary assessment of package size and other estimated optical parameters. Similarly, the projection distance (PD) of the virtual image was reduced from 4000 to 2500mm. Both the PD and HFOV were reduced to enable better overall optical system performance, particularly *vertical disparity*. This is the angular difference strictly in the vertical direction between two eyes trying to resolve a single point on the virtual image, and it is considered a key measure of overall image quality.

Vertical disparity (VD) tends to be increasingly worse as one looks away from the center of the virtual image, meaning that it is worst at the edges of the image. Reducing the FOV helps to alleviate the maximum VD values seen in the earliest 5.0°-wide designs. Similarly, reducing the required projection distance in turn reduces the system magnification and VD, resulting in better overall optical performance.

Lastly, the lookdown angle was reduced from 6° to 3°. This was purely a packaging issue as there is no way to physically position a HUD in this particular vehicle such that the nominal driver has a 6° lookdown angle. In fact the upper edge of the dash top pad is designed to stay below a 5° lookdown angle, implying that 6° down will be looking where there is no appreciable windshield area to be used as a combiner, and some or all of the HUD image will be below this lower limit. 3° down was chosen as a maximum value that could allow drivers of various heights (99th percentile) to see all of the HUD image from the specified eye motion box. Either the 3° lookdown was to be accepted against the 6° specified requirement or a new vehicle would need to be chosen.

The benchtop demonstration originally called for using the installation-intent unit (the Cadillac Seville design). It was determined, however, that this would require a premature design freeze on the Cadillac design in order that an in-vehicle version and a benchtop version could be fabricated in parallel. Instead, a "borrowed" HUD from a different, unrelated program was utilized for the benchtop demo. This allowed full design optimization and completion for the preliminary Cadillac design while the bench demo was built as a now dissimilar parallel project.

The main objective of this benchtop demonstration was to show the installation-intent LCD and representative backlight, not necessarily to show the whole HUD system and its other optical performance parameters. The HUD used was not originally designed for a 1.3"-diagonal LCD, so there was some degradation in distortion and vertical disparity. However, the unit showed installation-intent performance from the display and the single halogen bulb backlight in terms of color, brightness, contrast,

image size and resolution. This demo hardware was later used to evaluate various potential backlighting solutions for the final system installation.

Because the lookdown angle was so "shallow" in the Cadillac Seville design (3° rather than 6°), an alternative vehicle was sought. It was thought that a sport utility vehicle would provide a more ideal HUD seating and viewing arrangement from a human factors perspective. It appeared at the time that a Chevy S-10 Blazer would be available for the project, thus a new design for this vehicle was developed (the vehicle would become unavailable at a later time).

The resulting design achieved a 5° lookdown angle, much closer to the specified 6°. The image projection distance was raised to 4100mm, much more in line with the 4000mm requirement. Also, overall optical performance, including VD and distortion, were improved thanks to a spherical fold mirror introduced into the design.

Mechanically, a larger HUD package did result from the increased projection distance, but the Blazer had more dash volume available so it was of little impact. However, alignment of internal optics was more critical with the powered fold mirror. A flat fold mirror is much more forgiving in regard to alignment as it serves the same function at any range of positions and angles, while a curved mirror is intended to function at a very specific location and angle in the optical path.

Although the Blazer was the better of the two vehicle-specific designs, the vehicle to be used became unavailable and the Cadillac design was eventually built. However, the Blazer hardware did get used in the intermediate operational demonstration.

3.9.2   Operational Demonstration

Between the benchtop demonstration and the full vehicle installation, an operational demonstration was put forth to have a first turn at this type of HUD in a vehicle. This would allow for any intermediate lessons learned to be incorporated into the final design. The demo was done in the Blazer while the vehicle was still available. The HUD system showed installation-intent performance in image qualities such as FOV, image location, resolution and brightness. Showing this image and the HUD opto-mechanical unit itself was the primary focus of the demonstration.

A number of other things were *not* as intended for the final vehicle presentation, such as:

- the graphics shown were very preliminary (final versions were still in development)

- locations unknown for light sources and support electronics

- there was no dash board in the vehicle

- backlighting was done via two HIDs and one halogen bulb, with fiber bundles delivering light to the LCD (thought to be the final backlight scheme at the time; later replaced with single bulb coupled to a light tunnel).

The main requirement relative to backlighting was that uniformity must be such that no greater than a 2:1 variation in brightness across the area of the LCD is present. 2500 ft-L was established as a goal for brightness given initial known quantities such as bulb/HID brightness, LCD transmissivity and HUD optical efficiency. The first system

trial was thought to be best of all possible approaches, that being a combination of 2 HIDs (high-intensity discharge lighting) and one halogen bulb delivering light via a glass fiber bundle. The intent was to use the HIDs during daytime and the halogen bulb at night. It was understood that there are challenges to using HIDs in automotive applications over more conventional lighting techniques, but it was thought that the highest brightness would be achieved this way.

The challenges that became apparent were cost, packaging size, and dimming difficulties. Dimming cannot take place as it does with other lighting techniques by simply lowering voltage or varying signal pulse width; the source light must be only fully on or off. This led to the use of a polarizer that could be rotated to modulate the amount of light reaching the LCD. This approach worked adequately except for its sensitivity to heat (discolored and/or melted polarizers) and its non-linearity of dimming relative to the linear rotation of the polarizer.

Following the operational demonstration in which this approach was used, a single halogen bulb-only approach was revisited. Originally, the single bulb was not considered because of its resultant nonuniformity at the LCD (nearly 10:1). However, a "light tunnel" was developed that not only captured and recycled stray light, but also redirected the distribution of light such that significant uniformity gains were realized. When combined with a diffuser, the final system uniformity was 1.5:1, while achieving brightness levels very close to that of the HID system. With significantly less risk involved using the single bulb approach, this was the final backlight system used.

3.9.3   Final Design Iteration and Performance

This step was essentially a refinement of the preliminary design created for the Cadillac Seville. With the Blazer vehicle unavailable, the Cadillac was indeed the final target vehicle. Recall that the virtual image projection distance (PD) was limited to 2500mm in the preliminary design since optical performance was degraded at higher values of PD. This preliminary design used an eye motion box size of 175mm in the horizontal direction, while the spec only called for 140mm. 175mm is used in most typical automotive HUD applications, including high-volume production programs. Reducing it to 140mm enabled an increase in the PD to 3600mm while maintaining good overall optical performance. This result was much closer to the original goal of 4000mm PD.

With the final design built and installed in the Cadillac Seville, the following performance parameters were measured (Table 3.16):

Table 3.16: HUD Performance Parameters in Cadillac Seville.

Parameter	Target	Actual
VFOV	3.0°	3.0°
HFOV	4.5°	4.7°
Projection Dictance	3600 mm	3500 mm
Ghosting	Zero	Zero
Vertical Disparity	< 1 mrad average	Negligible (not measured)
Brightness	> 2500 Ft-L	2900 ft-L
Uniformity	< 2 : 1	1.5 : 1

The increase in PD to 3600mm caused a increase in package size that was difficult to accommodate in the dash volume available, but proper integration for presentation was achieved. It was originally thought that the HID and fiber bundle approach to backlighting was superior to other methods. It was seen, however, that a single halogen bulb with an appropriate light tunnel interface to prevent light loss and increase uniformity could have very similar performance while involving significantly less risk, cost, and packaging constraints.

A significant challenge was the shallow lookdown angle present in the Cadillac design. With the only solution being an alternate vehicle, the Blazer was chosen and an even better overall design resulted, including a lookdown that increased from 3° to 5°, although not fully the recommended 6°. This solution was not fully utilized, though, as the Blazer couldn't be used for the final vehicle installation.

3.9.4   Future Directions

Nighttime brightness of the HUD was not measured in the demonstration vehicle, and it is possible that the backlight dynamic dimming range does not extend low enough for extremely dark conditions. This was not addressed during the program since the focus of the effort was on daytime and because of a lack of development time.

The lookdown angle was reduced significantly in this vehicle installation due to packaging constraints. This is largely a function of the particular vehicle with its particular windshield rake angle, available dash depth and volume, and location of other systems such as HVAC, steering column, etc. Two vehicles total (Cadillac Seville and S-10 Blazer) were adequately evaluated for suitability to this HUD application. The Blazer was more favorable in terms of lookdown angle, but was not available for the final build. Perhaps a number of other specific vehicles as well as generic vehicle types (passenger car, light truck, class-8 truck, etc.) should be assessed for HUD applicability. This list could then be referenced at the beginning of similar HUD demonstration projects at the vehicle selection stage, and the risk of surprise vehicle insuitability would be reduced.

3.10   Initial Screening of Warning Concepts (Task 6.1)

The focus of this task was to conduct human factor testing on a large number of collision warning formats. This work was being conducted to try and determine the factors that make up the best combination of components in a warning system and to reduce the number of warning systems that will eventually be tested in the HRL Driving Simulator (HDS) which is a real time, interactive driving simulator.

The primary objective of the task was to conduct all necessary human factors studies to determine the best visual and auditory warnings for use in the HDS. Once the tests were completed and the data analyzed, the best combinations of warnings would be determined, and a final set would be chosen and integrated into the HDS for use during Task 6.3 (Driver-Vehicle Interface Studies).

This task was carried out by personnel from DE/AED and the University of California at Davis (UC-Davis). The initial warnings tested include both visual (icons and text) and auditory warnings (synthesized and digitized speech, tones, and spatial cues). At the conclusion of Task 6.1, the following goals were attained:

- Conduct human factors tests of various warning components

- Determine the best visual and auditory warnings for use in the HDS

- Integrate the final set of warning combinations into the HDS

- Document the studies that were conducted and their results

3.10.1   Human Factors Tests

A collision warning system will be of little use to the consumer, if the driver can not effectively be made aware of potentially dangerous roadway situations. Consequently, an important feature of the collision warning system will be the proper method to warn the driver of potential crash events. This task has been a cooperative effort between UC-Davis and DE/AED. UC-Davis screened the initial set of collision avoidance warning concepts and conducted the rapid prototyping study of these warning interfaces. DE/AED provided feedback to the UC-Davis research group, and aided in the review of the results gathered from UC-Davis.

A final set of auditory and visual warning alerts were defined for testing using the following categorization scheme:

(a)   set of visual alerts using pure icon-based symbology (8 alerts designated A1-A8);

(b)   set of visual alerts using visual text only (B1-B9);

(c)   auditory alerts identical to the "B" set but using digitized speech, some with male voice and others with female (C1-C9);

(d)   set of earcons and tones (D1-D8);

(e)   set of purely visual alerts combining icons and text (E1-E8);

(f)   set of alerts containing combinations of icon, text and auditory cues (including voice, tones and earcons) designated alerts (F1-F8).

A videotape was prepared documenting all 50 alerts used in the experiment.   In addition to the categorization based upon modality (i.e. A through F), each of the 50 alerts was assigned a type (i.e. number 1-6) which indicated the content of the information in the alert (i.e. whether the alert gave a general warning, gave an indication of the direction of the impending collision, gave an indication of what to do, and combinations of the above).

Seven dependent measures were developed, all 7 point likert-type scales capturing the following alert attributes:

(a)   get attention

(b)   convey urgency

(c)   be annoying

(d)   be understandable

(e)   be effective at indicating where the collision is

(f)   be effective about what to do

(g)   overall utility.

Subjects rated all alerts on all dimensions yielding a sample of 350 observations per subject.   In addition, a focus group type of discussion was conducted to capture additional qualitative information about each alert in the category. Finally, a subset of the subjects were asked to provide importance rankings for the first 6 attributes of the alerts (i.e. how important were each of the attributes in their ratings of the utility of the alerts). Independent variables included age in three categories (less than 35, 35 - 55, greater than 55) and gender. Number of years driving, number of crashes in the last two years and annual mileage driven was also collected.

The most significant challenge to this task was the recruitment of subjects that provide an even distribution of age. In particular, it was very difficult to recruit subjects over the age of 55. The initial recruitment activities yielded only 2 subjects older than 55. These recruitment activities included posting fliers around the UC-Davis campus and distributing announcements directly to university departments.   Finally, a more aggressive effort was undertaken to recruit elderly subjects. Distributing an electronic mail message throughout the UC-Davis computer system, and networking within UC-Davis yielded an additional 11 subjects that were tested. While this complicated data coding, it was believed to be important enough to the goals of the study to make the extra effort to obtain older driver data.

The presentation of the alerts to the subjects was randomized to control for order effects. A script was prepared for the session moderator to use in conducting the experiments. Subjects were simply told that we were interested in their opinions and feelings about the alerts, that there were no right or wrong answers and that the alerts should be thought of as appearing in the instrument panel or transmitted through their radio. Consent forms were signed and the subjects provided their responses in a Response Booklet that facilitated data coding and subject response.

All sessions were conducted in the same room, with the identical configuration of the display screen and the subjects. In the front of the room were large display boards (approximately 3 x 4 feet) that displayed the seven full rating scales with anchor points. In addition, each subject was provided with a 1 page summary of the scales to use for ready reference. It took approximately 2 hours to complete the rating and focus group discussion for all of the alerts.

A total of 74 subjects were recruited and data was collected over four sessions during September 1995. The number of subjects in each session varied from a low of 5 to a high of 17, but was typically about 10.

A set of statistical measures were derived from the raw data including: age and gender distribution; means, standard deviations, minimum and maximum values for each alert and scale (50 alerts by 7 scales); means, standard deviations, minimum and maximum values for each alert category (i.e. A - F) and for each alert type (i.e. 1 - 6) separated by age and gender; bi-variate correlation among the seven ratings scales individually and by alert type and category; mean, importance rankings by gender (age was not possible due to only 30 observations of these measures); and focus group comments pertaining to each of the set of means and standard deviations. The SAS statistical software package was used to analyze the responses from the 74 subjects.

Analyses of variance was used to determine how the first six scales predicted the rating of overall utility of the alert. Such a model has coefficients that may be interpreted as the relative importance of each factor (predictor variables) in the rating of overall utility (dependent variable). This model largely substantiated the direct rankings of factor importance provided by a subset of our users. That is, getting attention is by far the most important factor in relative importance, and understandability as an alert is next in urgency. The last three factors are nearly equal in where to look for a problem. A series of additional models were requested and estimated from the data including the prediction of overall utility, and attention and urgency as a function of the six alert types. This is used to quantitatively test for differences in mean ratings between alert types.

UC-Davis completed all analyses and submitted a Task Final Report in February 1996. The report included a description of all experimental procedures and protocols, experimental controls, subject recruitment and interfaces tested. A series of analyses were reported which consisted of a comparison of means of the ratings of all the alerts tested. The report included recommendations concerning devices to be tested in the HDS as well as more generic characteristics of desirable devices.

3.10.2   Warning Review and Selections

In an attempt to determine the visual and auditory warnings that would be used in the Task 6.3 simulation studies, DE/AED evaluated the results gathered from the UC-Davis study. The UC-Davis study presented the top 10 warnings found to have the greatest 'overall utility' for young and old subjects. From these results, commonalties across the young and old subjects were found. From the set of warnings presented to the subjects, old and young subjects highly rated auditory voices that stated "Caution", "Caution-Front" and "Crash-Left Side". One auditory tone that was rated high was the 'clock alarm' tone. The text presentation of "Caution-Front" was also highly rated. The icons that were rated high for both groups were the car icon with the word "Caution"

printed above it, and the car icon with a sweeping triangular area. Warnings currently designed for the DE/AED demonstration vehicles were also gathered, and a set of warnings was generated for further study.

Two types of potential visual warning icons were examined, cautionary and emergency. Figure 3.42 illustrates the various types of cautionary-level warnings that could be used to signify a potential front-end collision is possible. These warnings would appear in amber. Warnings A and D are currently being used in the DE/AED "Gold Car", and warnings B and C were gathered from the UC-Davis study results. Figure 3.43 illustrates the various types of emergency-level warnings that could be used to signify that a front end collision is imminent if no action is taken. These warnings would appear in red. Warnings A and E are currently being used in the DE/AED "Gold Car", and warnings B, C and D were gathered from the UC-Davis results. We added investigation of warning B, since it is very similar to the "Gold Car" icon.

CAUTION

A   B   C   D
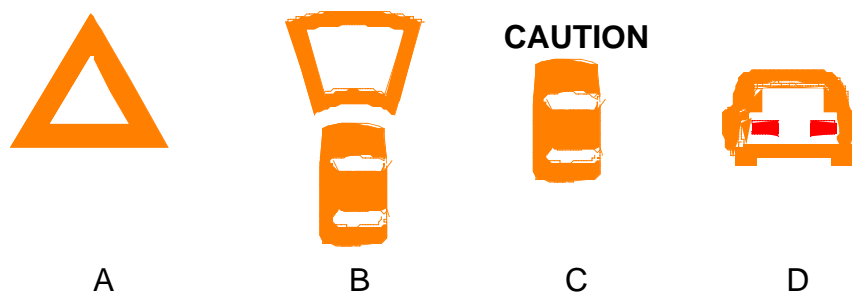
Figure 3.42: Cautionary Situation Warning Icon Set

STOP   **BRAKE**

A   B   C   D   E
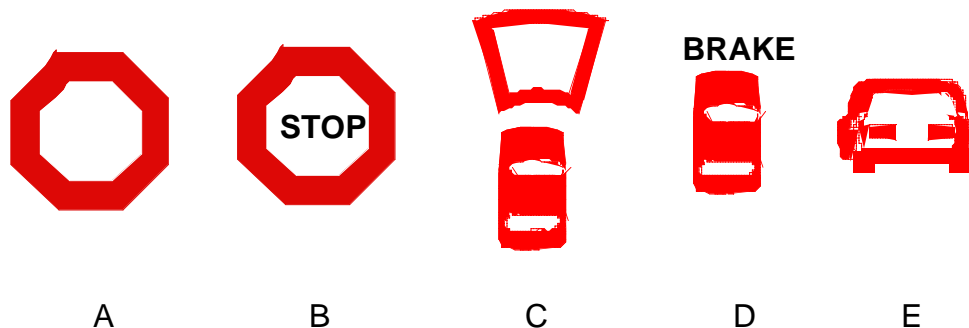
Figure 3.43: Emergency Situation Warning Icon Set

In addition to the visual warning icons, two types of potential auditory warnings were also included for future examination, tone and voice. From the UC-Davis study, the top auditory warning tone and an additional tone used in the DE/AED demonstration vehicles will be further studied. Voice auditory warnings from the UC-Davis study and the DE/AED demonstration vehicles were also selected for further study. These included:

(a) "Brake, Brake, Brake" (DE/AED)

(b) "Caution, Caution, Caution" (UC-Davis)

(c) "Caution-Front, Caution-Front, Caution-Front" (UC-Davis)

(d) "Crash-Front, Crash-Front, Crash-Front" (UC-Davis)

Using the results obtained from the UC-Davis study, DE/AED conducted further studies to finalize the warnings that will be used during the Task 6.3 simulator studies. To accomplish this, the study determined which visual warning(s) were understandable. In "real-world" applications, the visual warning will need to be quickly identified and understood. For instance, the visual warning may be paired with auditory tones, and/or proprioceptic warnings or it may be presented alone. In such cases, auditory tones and proprioceptic warnings will not provide a clear indication of the warning situation. Therefore, the visual warning will need to provide enough information to cue the driver to the potential hazard. To gather this information, the icons were presented to a group of subjects, and they were asked to rank order the warnings based on how 'immediate they understand the warning' if it was presented on a HUD. From these results, the most understandable warnings were determined.

Subsequent to this study, further rapid prototyping work will be conducted in the simulator. The most understandable visual icons were incorporated into the simulator along with the auditory warnings. Subjects were asked to drive the simulator for a short period of time, during which combinations of the visual and auditory warnings were presented. Subjects were then asked to provide subjective feedback on the visual and auditory warnings that they experienced through a set of questions similar to those posed during the UC-Davis study. Questions on the warnings overall utility, attention-getting ability, urgency, annoyance, communication of type of collision, and what action should be taken, were all gathered.

From results gathered during the DE/AED experiment, a final set of visual and auditory warnings was chosen for use in the simulator. The visual icon that was chosen was icon C in Figure 3.42, while the auditory tone was simply a tone with no voice message used. Both of these warnings were then successfully integrated into the HDS architecture for use during the Task 6.3 studies.

3.10.3 Task Accomplishments and Future Directions

During the performance of the work required to complete Task 6.1 all of the objectives that were desired were met. However, a possible deficiency may have occurred because the warning icons may not be the most recognizable during time critical situations. This is due to the subjects being tested under none critical situations where they were able to think more clearly about the icons they were viewing. Even with this problem, the following major accomplishments and program objectives were realized:

- Completed multiple human factors tests of various warning components

- Determined the best visual icon and auditory warnings for use in the HDS

- Integrated the final visual icon and auditory tone into the HDS

- Produced and delivered the final report entitled "The Rapid Prototyping of Collision Warning Alerts" documenting the results of the study.

One of the drawbacks of the study conducted during Task 6.1 was that the subjects that were initially tested were not facing critical decisions that were time limited. Therefore, they were allowed to take their time when reviewing the information that was presented to them. In a real driving situation where a warning is being presented to the driver, the driver does not have the luxury to think about what the warning means, instead, they must be able to recognize it and respond as quickly as possible. Therefore, additional work needs to be conducted to see if subjects can "blindly" recognize the warnings that they are given. In addition, work needs to be performed in order to determine the warning cues that are best at conveying the necessary information to the driver when the driver has had no training and knows nothing about the system.

3.11   Development of Simulation Sensor Models (Task 6.2)

The focus of this task was to provide vital information for the development of driver-vehicle interfaces which will evoke appropriate and timely responses from the drivers in order to avoid collisions. The approach was to develop software models of generic forward-looking and side looking sensors that were designed to be used in a real time, interactive driving simulator.

The primary objective of the task was to develop software modules that accurately modeled radar sensors developed by GMR and Delphi-DE. A variety of software modules representing generic MMW-based Forward-looking Radar (FLR) and side-Near Object Detection System (NODS) sensors were to be developed. Included in this task were several issues that must be met in order to achieve the primary objective. Developing the radar models themselves was not enough. The models also had to be integrated into the Multiple Target Tracker (MTT) and Collision Avoidance Processor (CAP) architecture and thoroughly tested to insure that they functioned as desired. In addition, since the primary objective of the simulator was to perform a human factors study to determine how drivers would react to the systems, time was spent adapting the sensor models to the database and developing driving scenarios to insure that the radar modules would properly detect objects and the simulator would activate the warning systems.

Due to the closely related nature of the sensor simulation and the driving simulator, there was a great deal of cooperation between Task 6.2 and Task 6.3. Consequently, this effort was a collaborative effort between the ACAS consortium members of STI, DE/AED, and HRL. By working closely on this complex project, historically thorny integration issues were kept to a minimum. Changes in interface requirements did not cause major delays and technical assistance was freely exchanged between members. At the conclusion of Task 6.2, the following goals were anticipated:

- Fully functional computer model of side zone sensors

- Fully functional computer model of forward zone sensors

- Interfacing of the forward zone sensor model with the MTT and CAP

- Integration of the sensor models with the HRL driving simulator

- Fully developed driving scenarios that would realistically generate warnings

3.11.1   Sensor Modeling and Development

The STI sensor simulation was developed specifically for use in the HRL Driving Simulator (HDS). The purpose of the overall driving simulator was to investigate the relative efficacy of various types of alert systems intended to notify a driver of a potential collision. The sensor model requirements included a generic detection model, real-time run capability interfacing with multiple real-time processes, and conversion of perfect information about simulated objects into quantized and sometimes misinterpreted information about radar targets. This work was attempted in order to create models that would provide the type and quality of information a real radar sensor would. The STI sensor model has met and exceeded these requirements. While there has been considerable emphasis on simplification to provide speed for the real-time simulation, the underlying structure of the model is sound enough that, with minor modifications, this package could also be used as part of a radar evaluation simulation instead of just a human factors simulation.

A functional block diagram of the simulation processes is shown in Figure 3.44. The top row of blocks compose the HDS, the center row is the STI sensor simulation process, and the bottom 2 rows represent the DE/AED MTT and CAP programs.
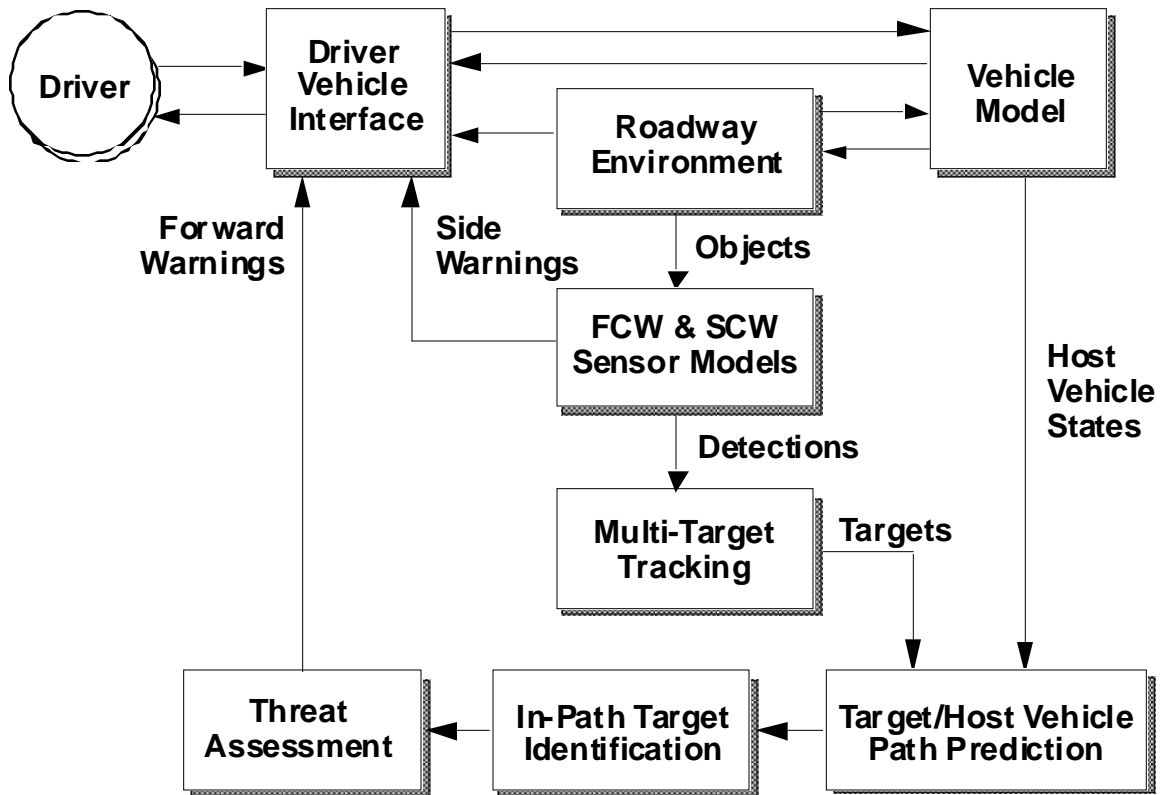
Figure 3.44: Functional Driving Simulator Block Diagram

In the HDS blocks, the driver inputs are transduced by the buck and monitored by a number of Silicon Graphics workstations. These computers also run the vehicle model, update the roadway environment based in part on a scripted scenario, and provide feedback to the driver. The driver feedback consists of the roadway display scene, force-feel on the steering wheel, and auditory cues such as engine noise and vehicle warning sounds. The HDS processes fill a region of shared memory with information about the roadway environment and host vehicle position. This memory is read by the STI sensor process that is running with the MTT on a separate computer. The sensor converts the roadway objects into a list of radar targets and writes this list to shared memory. The MTT reads this list and converts the targets into a list of tracks and then the CAP examines these tracks and determines which of them are "in-path" and whether they represent a threat to the host vehicle.

When the simulator is initialized, all of the objects that the sensor can detect are created and stored in memory for later use. Next the simulator sets up an interrupt driven timing routine that will wake the sensor model up at the correct sample frequency. This way the sensor model acts at the same rate as a real world sensor and will not cause problems with the overall simulation timing. When activated, a function that determines object detection is then executed. Figure 3.45 shows the process that the function goes through each time it is called.
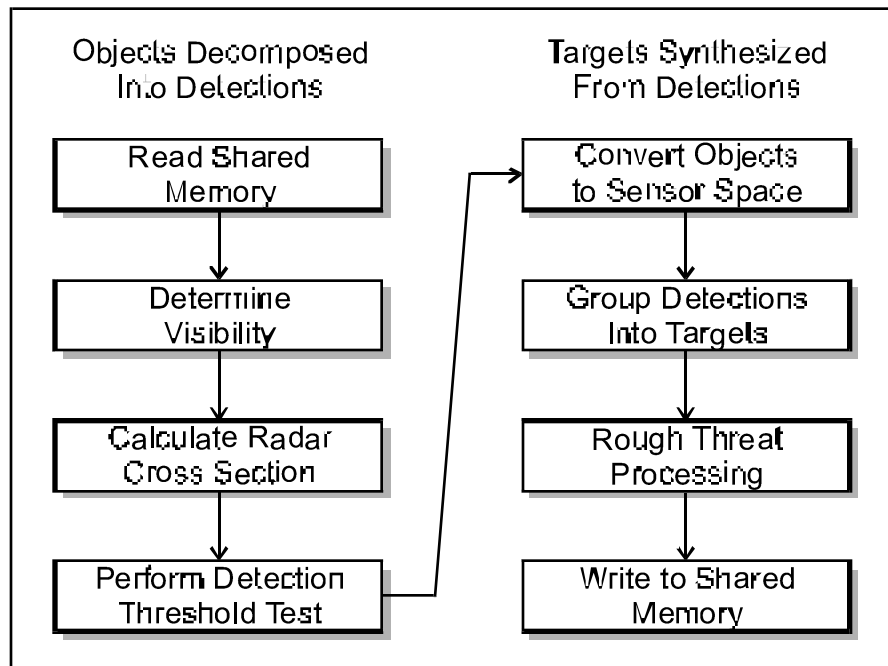
Figure 3.45: Sensor Processing Steps

The first step in the process is to copy the shared memory data structure written by the HDS to a local memory pool that the sensor uses. After the memory is copied, a multi-stage visibility check is performed. Objects that do not fall within the sensor's field of view are ignored. Radar return signals are then calculated for objects that meet the visibility requirements. If an object's return signal is greater than a threshold level, that object is then converted to "sensor space." This process involves determining which of the sensor's beams strike the object. Those that do, create a range bin to store the object's range, range rate, and signal level. If a range bin already contains information for another object at the same range, the information is added together, weighted by signal strength. Once all the visible, detected objects have been converted to detections in sensor space, the process of merging begins. The goal here is to examine the individual detections based on proximity and differential velocity and combine them into targets. These targets are then listed. If more than the maximum number of targets have been identified by the sensor, it will perform a very rough threat assessment and ignore the least likely threats. At this point the target information is written to shared memory for use by the MTT process. Details about how the beams were modeled and how the objects were detected, can be found in the first Annual Report.

At the beginning of the project, one of the objectives was to create the model so that it could easily simulate different sensors. In order to accomplish this feat, the sensor model used a generic process for generating a beam pattern and for obtaining the signal return from the object being detected. These routines were generic and took the form of specific sensors when various parameters that were specific to a desired sensor were defined. These parameters were specified in a parameter file that was read during the simulation's initialization process. Parameters included range, azimuth angle, number of beams, beam width, etc. The above description details the final process that was used to model the sensors within the HDS. However, many problems

and technical challenges had to be overcome before this final fully functional architecture was developed.

During the early stages of the ACAS Program, the challenge was to determine how the suite of algorithms that comprised the MTT and CAP would be implemented. DE/AED already had proprietary routines that were developed for use in their FCW system and implemented on various demonstration vehicles and these routines had previously been evaluated and validated. The original program focus was to have STI create the entire sensor package including the FLR, side NODS, MTT and CAP. This seemed to be a redundant task that would only cause additional problems to occur. After several meetings between STI, DE/AED and HRL personnel, it was decided that rather than have STI try to duplicate the DE/AED proprietary system, DE/AED would modify their existing software and work with STI and HRL personnel so that it would run in the HDS. Although the effort required of DE/AED was considerable, this solution worked well and has assisted in the validation of the real world system. By taking this approach several benefits were derived from this division of software module activities:

• STI would not have to duplicate the already existing DE/AED software efforts and create redundant software, thus saving both time and money.

• It provided commonality between the HDS system and the DE/AED FCW systems and assisted in efforts to validate the simulator.

• DE/AED proprietary data processing techniques would not have to be disclosed in order to provide an accurate simulation.

• It provided an environment where DE/AED could evaluate changes to their software on the HDS system before implementing them in hardware.

Some of the technical challenges encountered were very subtle. Once the simulation was fully integrated, a slight timing irregularity was discovered. The overall simulation consists of many separate programs running at the same time. While theoretically these processes all update in a synchronized way, this is impossible to achieve on a real system. The sensor, the vehicle dynamics model, and the scenario generator are all run on different machines and at different update rates. If any one of these programs iterates for longer or shorter than expected, the data processed by the sensor would be incorrect. The symptom of this problem was erratic velocities reported by the FLR sensor to the MTT process. These irregularities, caused by the fact that the sensor calculates object speed as differential position, resulted in the MTT program behaving unexpectedly. Two changes were made to solve this problem. First, time-stamps were included with the data reported by the driver model and scenario generator. Second, object speed was calculated using a second-order, digital low pass filter.

An important area of investigation for the ACAS Program focuses on how the sensor warning system's false alarm rate will influence drivers. Knowing the point at which drivers begin to ignore the system will set guidelines for minimum system performance. It was, therefore, necessary for the sensor simulation to reliably create false alarms. It was originally thought that the most natural way to create false alarms would be to raise the sensor simulation noise coefficient and create a false sensor detection. Further analysis revealed that increasing the sensor noise level will produce

more detections from the sensor. However, these false detections did not necessarily create false alarm warnings for the driver because the DE/AED MTT and collision warning algorithm suite processes were sufficiently robust so as not to propagate spurious detections identified by the sensor. Therefore, it was decided that the best way to generate false alarms was to simply have the HDS system randomly activate collision warnings at an average specified rate based on a normal distribution.

In order for the simulation to function correctly, the sensor model would have to be able to detect objects in the roadway scene. In order to do this the HDS passes the sensor simulation a list of objects that are capable of being detected. The basic shape of these objects is a rectangular box. It was originally anticipated that once the new database became available, there would be many types of sensible objects including extensive objects such as guardrails. However, a rectangular box shape could not be used to describe something as complex as a curving guardrail. The problem with specifying detectable objects was that they had to be pulled out of the static database and converted into dynamic objects in order to be detected. This approach proved to be extremely time consuming and did not deliver the intended results. Therefore the only objects that were detectable during the simulation runs were interactive vehicles with their basic shapes remaining a rectangular box.

Most of the discussion up to this point has focused primarily on the FLR system. In addition to the FLR a side-looking sensor interface was also developed. The intent of the side-NODS sensor was to alert a driver to the presence of target vehicles traveling in the driver's blind zones. Unlike the FLR sensor package, the side-NODS system had a much simpler architecture. The side-NODS system provides very simple MTT and CAP features. This sensor merely provides a true or false value indicating the presence or absence of a blind spot threat. From a radar perspective, the side-looking sensor is modeled closely on the forward-looking sensor (i.e. objects are turned into range bin detections that are then grouped into targets). When the sensor created a target list an additional stage of processing was used to remove all stopped and oncoming objects. If any targets remained in the list, the side-sensor set a flag in shared memory that instructed the HDS to present a warning alert to the driver.

3.11.2   Simulation Support

The final issue that had to be resolved before the simulation testing under Task 6.3 could occur was to make sure that the simulation's critical events capable of being detected and thus a warning would be presented to the driver. These critical events would have to be designed so that the sensor would be able to detect them and that the MTT would register them as threats, thus triggering the warning. Furthermore, since the critical situations for the side zone and forward zone warnings were completely different, different scenarios were needed for both.

The critical events were designed to produce specific driver responses and included:

Side Zone:

1. Lane merging due to obstacles in the driver's path

2. Expressway lane changes

3. Evasive maneuvering due to actions of other vehicles interacting with the driver's vehicle

4. Lane changes in traffic as other vehicles pass and turn into the traffic lanes

Forward Zone:

1. Quick vehicle stops in front of the driver's vehicle

2. Lane change maneuvers where another vehicle performs an unsafe lane merge

3. Vehicle performing unsafe passing and veering into oncoming traffic

4. Vehicles pulling into oncoming traffic unexpectedly and in front of the driver's vehicle

5. Vehicles making unsafe turns in front of the driver's vehicle

A complete description of each critical event can be found in the Task 6.3 – Experimental Results report. Between 4 and 6 of these critical events were combined with a handful of benign events and other interactive events (traffic signals, stop signs and normal traffic) to form a complete scenario. For both the side and forward zone studies a total of 12 scenarios were created. The experimental design was setup so that only 9 scenarios would be used but because of possible problems with the simulator, 3 additional scenarios were created in case subjects had to be re-run.

During the process of creating the critical events, each individual critical event was tested by itself using on "off-line" procedure provided by the scenario development software. When it looked like the event was performing as planned, the next step was to drive "on-line" through the event using the simulator. Finally when a scenario was completed, a final drive through the entire scenario was performed. During each step of this process iterations on the event's performance were made, until finally they performed as desired. The amount of time that was required to create these scenarios was greatly under estimated (creation and checkout took more than 8 months) and this caused a huge delay in the simulation testing schedule. Before the actual testing could be performed, some preliminary runs were conducted with test subjects and final adjustments were made to the scenarios based on subject comments.

At the completion of the scenario development, the sensor parameters were set and all of the critical events did a good job of producing a warning. However because of the scenario software architecture, the critical events had to be designed around a relatively constant speed and were based on the speed limit in the area of the database where the event was occurring. Subjects were instructed to try and drive the speed limit, however, if a subject travels very fast or slow through the desired area, the events may not work as well as they were designed too. This is an unfortunate occurrence that could not be avoided.

3.11.3 Accomplishments and Future Directions

During this task, many different problems and issues were encountered, and handled. The generic sensor models that were created are general enough that they can be used in other applications besides this one. Therefore, this phase of the contract can be considered successful and we were able to get more out of it then initially expected. The following major accomplishments and program objectives were realized:

- Developed generic side sensor model that allowed for variable characteristics,

- Successfully integrated the side sensor model into the driving simulator,

- Developed generic forward sensor model that allowed for variable characteristics,

- Successfully interfaced the forward sensor model with the MTT and CAP and integrated it all into the driving simulator architecture,

- Created driving scenarios that successfully triggered the warning systems so that test subjects would be presented with the desired warning alerts.

The sensor simulation was created to perform human-factors studies using a real time, driver-in-the-loop simulator. Therefore, some assumptions have been made to simplify and speed processing. Even so, the changes required to turn this simulated sensor model into a more accurate, batch mode simulator would be minor. As future revisions are made to the MTT and CAP, this sensor model could be used to simulate object detections before the systems are actually implemented on a vehicle.

Incorporating the STI sensor package into an existing simulation should be quite simple from an interface point of view. Since it is designed to run as a standalone process, reading data from shared memory, it requires virtually no support during operation. Instead of using shared memory, the sensor could read data from a global object pool structure that the simulation had written. This data could even be created ahead of time and written to disk. The output of the sensor simulation is currently an array of targets suitable for processing by the Delphi-DE/AED MTT program. The actual structure used to contain this information is proprietary to Delphi-DE, but there should be no problem creating a suitably different way to pass the sensor output targets from the sensor to the simulation. Other changes that would add accuracy to the simulation include integration of a beam lobe-shape function across the sensed object silhouette, and more complete coordinate transform that allows for target objects to pitch and roll.

3.12 Driver-Vehicle Interface Studies (Task 6.3)

The primary objective of this task was to conduct simulation studies that would allow us to evaluate the warning interfaces using a driving simulator located at the HRL Laboratories, LLC (HRL), in Malibu California. As part of the task, a fully interactive, fixed base driving simulator was to be developed and equipped with a model of a collision avoidance system. After the completion of the simulator, human subjects would be tested and asked to evaluate various warning systems that they experienced during their test runs. Both objective and subjective data would be collected and analyzed, and a final report discussing the experimental results was to be written.

A secondary objective of the task was to select 2 side-zone and 2 forward-zone warning systems that would be used later during the Task 6.4 closed course testing. As part of task 6.3 work plan, various aspects of the closed course testing were to be designed and a vehicle test plan describing the closed course testing was to be prepared.

The research consisted of two separate and individual simulation studies. The first study dealt with a side zone warning system that was designed to assist drivers making lane change maneuvers in traffic. The warning system provided information to the driver as to whether or not another vehicle was located in their blind zone as they tried to safely negotiate a lane change. The second study consisted of a forward zone warning system that was designed to detect potential head on collisions while traversing through traffic. The warning systems provided information to the driver, warning of other vehicles that the driver could potentially collide with. During each phase of the study only a single warning system was used, and the subjects only needed to concentrate on the specific system being tested. Additionally, the scenarios were designed so that the focus was on the system being tested and the critical events that occurred were designed to specifically activate the intended system

To achieve our goals during this endeavor, a systematic approach had to be employed where the eventual success of each step was partially based on the previous steps taken. These steps included:

- Develop experimental test plan for simulation driver-vehicle interface approach.

- Design auditory and visual warnings based on Task 6.1 activities, and determine requirements for tactile warnings.

- Develop a human-in-the-loop fixed-based driving simulator to evaluate driver warning systems.

- Evaluate preferred warning interface method to warn drivers of hazardous events in a realistic human-in-the-loop driving simulator.

- Conduct human factor experiments that enable subjects to drive in a variety of realistic environments with programmed scenarios.

  1. Record performance data and gather subjective data.

  2. Analyze performance and subjective data.

  3. Provide evaluation of preferred warning.

- Write a vehicle test plan for the Task 6.4 closed course testing.

- Write a report documenting the Task 6.3 experimental results.

3.12.1   Simulator/Simulation Development

Since there were 2 phases to the simulation study, a test plan had to be devised for both. For the side zone tests, the warning systems were designed to inform a driver that there was a vehicle located within a certain zone next to their vehicle. Therefore, the simulation study needed the capability to have vehicles enter and exit the side zones while the test subject was trying to execute a lane change maneuver. The forward zone

warning systems were designed to detect a threat that the driver could potentially run head on into. Thus, the simulation study had to be designed so that vehicles could blindly pull in front of the subject's vehicle so that the subject's reactionary responses could be measured. From these definitions numerous critical events that would put the subjects into the desired situations were defined and eventually used in the simulator (all events are shown in the Task 6.3 - Experimental Results document).

In Task 6.1, studies were performed to determine which combinations of warning system components would best convey the desired information to the driver. From this work, a final set of warnings was determined for both phases of the simulation testing. The necessary hardware was purchased and integrated into the simulator and all software that was required to control the warnings was written. In the end, there were a total of 8 warning systems that would be tested during each phase of the study. There are some common components such as a Head Up Display (HUD), auditory tone, and tactile feel that appear in multiple combinations. These were the best components and they have been matched in different combinations to see how well they work together. For the forward systems, an additional component was added that dealt with false alarms. Since we did not want to mention to the subjects that there would be false alarms, we dubbed these cases as using a sensitive sensor that would pick up more activity than the normal sensor would. The false alarms that were used were randomly generated false positive readings. They were issued during simulation runs based on a mean time and deviation from a standard distribution. The warning systems used were list in Table 3.17.

Table 3.17: Warning Systems Used in the Simulation Runs.

Side Warning Systems:	Forward Warning Systems:
Head Up Display (HUD)	HUD + Audio + Normal (sensor)
Visual icons in side mirrors	HUD + Tactile feel + Normal
Visual icons in rear view mirror	HUD + Audio + Tactile feel + Normal
Visual icons in both mirrors	Audio + Tactile feel + Normal
HUD + Audio	HUD + Audio + Sensitive
Visual icons in side mirrors + Audio	HUD + Tactile feel + Sensitive
Visual icons in rear view mirror + Audio	HUD + Audio + Tactile feel + Sensitive
Visual icons in both mirrors + Audio	Audio + Tactile feel + Sensitive

Each of these warnings was built into the simulator's architecture and could easily be called from a menu displayed on the main computer console.

In the initial stages of development certain criteria needed to be met in order for the simulator to elicit the driving responses desired and to immerse the test subjects into as real a driving environment as possible. The following components were deemed necessary in order for the simulator to adequately mimic the desired driving tasks:

- Driving buck including interactive steering, throttle and brakes,

- Accurate vehicle dynamics model,

- High resolution, wide field of view display with 6 different out the window views,

- Sensor/Collision avoidance processor (CAP) software and warning displays,

- Sound effects and steering feedback,

- Secondary task event,

- Realistic image database,

- Scenario control and scene generation software.

Based on these general requirements, the driving simulator was built and is comprised of several different independent components acting in unison. A complete simulator configuration is shown in Figure 3.46, and includes a complex arrangement including multiple computers, image generators, driving buck and software. All of these components as well as the image database were employed to generate the driving environment.
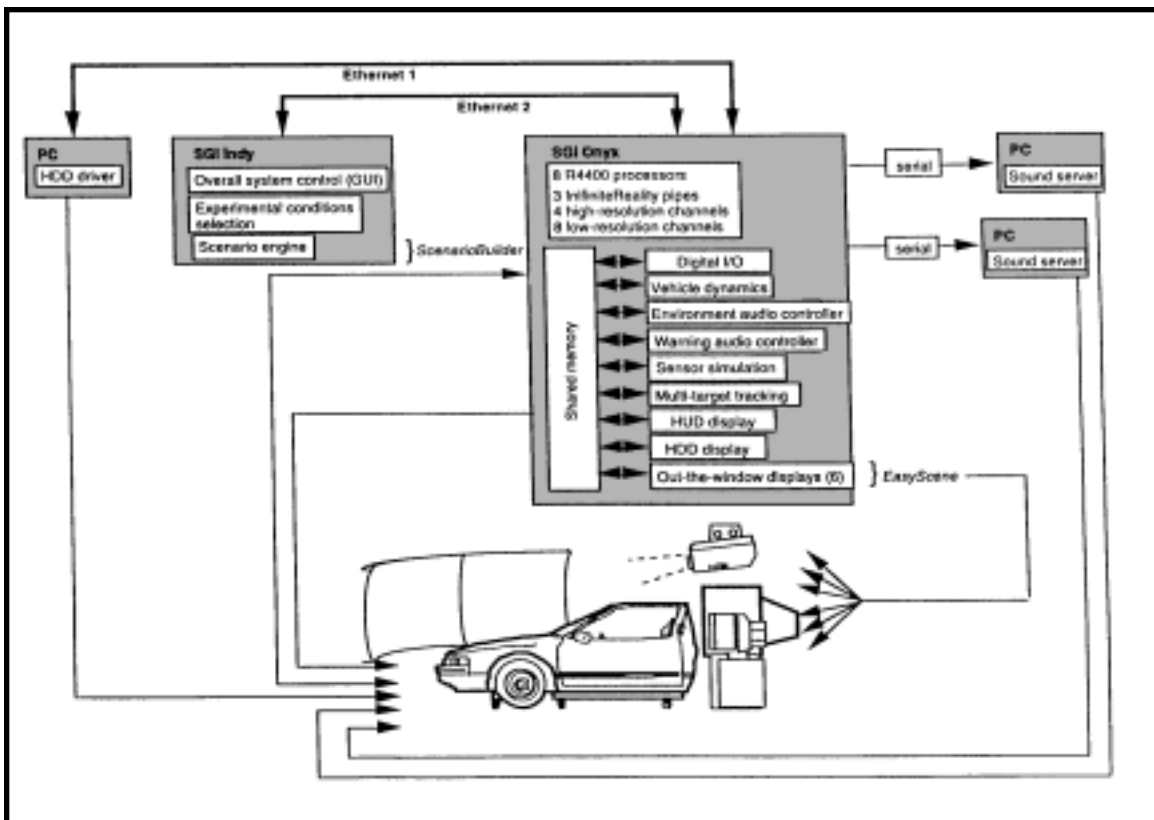

Figure 3.46: Final Driving Simulator Configuration

To provide for interactive controls and appropriate surroundings a complete driving buck was designed and built. This included steering wheel, throttle and brake pedals, and turn signal indicators that the subjects used to enter their control inputs. These inputs were then sent to a high fidelity vehicle dynamics model so that the vehicle behaves consistently with the subject's inputs. Additionally, the seats and mirrors were fully adjustable allowing the subject to configure the buck for optimum comfort and viewing.

To display the graphics in real time and coordinate the entire simulator's activities, 2 Silicon Graphics Incorporated (SGI) computers were used that communicated with each other using an Ethernet connection. The nature of the side zone study dictated that the subject be able to view as much of the scene as possible. Therefore, 6 separate views of the database were displayed during each simulation frame. Three of these views were used to present the forward scene that is viewed outside the windshield. This provided a 165-degree field of view and was displayed using high-resolution overhead projectors projecting onto a toroidal screen. The remaining 3 views were used to display images that could be viewed in the vehicle's mirrors. The images were displayed using monitors positioned so that the images were reflected using the driving buck's mirrors.

Since the basic simulator was built on a fixed platform, the subjects received no motion cues during operation. Other cues were provided to heighten the driving experience. The first was roadway sound effects. These effects included engine rpm noise, providing the subjects with some audio feedback based on speed and acceleration. In addition, a torque motor was added to the steering system so that as the subject steered the vehicle the steering wheel would respond and the subject would receive propioceptive feedback through their arms. This provided an additional cue based on how the vehicle was cornering.

Before any driving could be done, a few more things were needed, a database to drive through, a software package to display the visual scene, and software to control all of the interactive portions of the simulator. The database was designed to provide a complex and multi-facetted scene to drive through. The final database design contained 4 distinctly different roadway sections that provided urban, suburban, rural, and freeway driving. This allowed the subjects to experience all types of driving conditions. The database also contained a wide variety of scenery, traffic control devices and roadways. Scenery included buildings in the urban section, houses and trees in the suburban section, farmhouses and trees in the rural section, and bridges in the freeway section. Traffic control devices such as stop signs and signal lights, and roadway signs can be found throughout the database. The roadways that were built into the database include 2, 4, and 6 lane sections.

After the final database configuration was determined an independent company that specialized in 3D modeling and database development was hired to build the final database. Unfortunately, they took much longer than expected to deliver the final model and multiple iterations had to be created before the final database was accepted. This created some delays in the testing schedule because the final scenario development could not be completed until the scenarios could be tested on the final database.

In order to display the database on the screen, a software package was needed. After researching the various options for the computer system that would be running the software, a decision was made to use the *EasyScene™* software package. This decision was made in part because *EasyScene™* was supposed to be compatible with another software package, *ScenarioBuilder™* that could control the interactive elements of the simulator (signal lights and vehicles). Unfortunately, there were several problems with this configuration and once again the simulation test schedule slipped.

The most serious simulator problems involved a latency between the host vehicle and other vehicles in the roadway display. This latency was caused by a communications problem between the *ScenarioBuilder™* and *EasyScene™* software packages. The manifestation of this problem was that the interactive vehicles that were being displayed would appear jittery (not smooth from one frame to the next) and thus would be visually unpleasant and possibly affect the data being collected. To correct this problem HRL personnel obtained source code from the vendors and made modifications to offset the effects. However, although these modifications did greatly reduce the effects, they did not eliminate them completely. Other problems also occurred such as non scripted vehicles appearing in the display scene, scripted events not occurring on cue, and some data collection glitches. All of these were continuously handled as the need arose.

In addition to the problems with the simulator and its software, there were a couple of general problems that had to be overcome in order for the study to be conducted. The first was obtaining the subjects that would be tested, second was dealing with a large percentage of dropouts due to simulation sickness problems, and third deals with data collection and analysis.

The initial intention was to obtain as many subjects as possible from with the HRL facility. Unfortunately, because of scheduling conflicts, the response from HRL personnel was very low. Next, college students were recruited from local colleges, but this too did not result in as many subjects as was need to complete both studies. Finally, ads were placed in the newspaper in hopes of drawing additional subjects. We were able to obtain the number of subjects desired, but had great difficulty getting them to show up on schedule if at all.

When subjects did show up, they were trained and then allowed to drive the simulator. While driving the simulator many subjects became ill due to the simulator's configuration and lack of motion. In some cases the subjects were able to continue and eventually finish an entire set of runs, and in other cases, they had to be dropped from the program. This resulted in lost simulator time and caused large delays in the test schedule. To help accelerate the schedule, subjects that participated in the side zone study were also asked to participate in the forward zone study. A total of 12 subjects completed both studies.

The final major obstacle that had to be overcome dealt with the data collection and analysis. During the simulation runs, approximately 10 to 20 percent of the critical events failed to be activated. Therefore, when all of the data was collected, there were holes caused by the missing data. This meant that additional analysis tricks had to be employed to try and make sense out of the objective data that was collected. In addition, the data files that were created contained a data stamp from every frame of the

simulation run, thus creating data files that were around 4 MB (compressed, uncompressed about 50 MB) in size. This required a great deal of time and effort in order to extract the critical data and analyze it. To help speed the data process, software was written that would go into the data files and attempt to extract the critical information that we were looking for. Unfortunately, due to the unpredictability of human drivers, the data analysis could not be easily automated and therefore a good portion of it had to be analyzed by hand.

Even with the problems that were being experienced, a decision was made to run some preliminary tests and see if using the simulator was still a reasonable undertaking. During these tests, subjects were enthusiastic about the possibility of these systems being available in the future and did not seem to have any major concerns about the simulator's problems. Therefore, the full simulation testing program was launched. Details about the test matrices, scenarios, subject training and paperwork can all be found in the Task 6.3 Experimental Results document.

3.12.2   Side Sensor Simulation Study

The actual side simulation tests began in February and ended in June of 1997. A total of 36 subjects (20 male and 16 female) were tested. Their ages ranged from 18 to 58 years and there were representatives from a wide range of age groups. Since gender and age effects were not being considered, the use of more male than female subjects and the predominance of middle aged subjects was not a concern.

Subjects were required to complete 9 separate drives through the roadway database, with each run consisting of a different scenario and warning condition. During each run data about the vehicle's position and motion and the subject's reactions was collected. Additionally a questionnaire requesting subject ratings and comments was also completed at the end of each individual run. All of this data was then analyzed and some conclusions were drawn.

Using the objective data that was collected directly by the simulator, a multivariate analysis was performed to see if the warning conditions that the subjects were experiencing had any significant effect on the way they reacted. For the multivariate analysis the independent variables were the warning condition and the critical event, subjects were treated as a repeated measure. The initial dependent variables that we were planning to investigate included, Time To Collision (TTC), Time To Avoidance (TTA), reaction times and collisions. However, due to problems with the simulator and the interactive vehicles it was controlling, none of these variables were used. TTC and TTA (both based on range and range rate) were unreliable because of the jittery motion of the interactive vehicles as they approached the subject's vehicle. From one frame to the next, the TTC and TTA would go from minuscule to infinity, because the vehicle would be 2 meters away, then 5 meters away, then 2 meters away. Reaction times were also desired but for the side zone study they were inconclusive due to the nature of the events. Only a couple of events required braking, and subjects were not forced to steer so they could take as long as necessary to change lanes, thus making reaction times meaningless. The number of collisions were inconclusive due to non-scripted vehicles appearing in the driving scene and subjects occasionally colliding with them. However

less than a couple of dozen crashes did occur during testing which was low and usually the crash involved a vehicle in front of the subject, not in the blind zone.

Since none of the initial dependent variables provided useful data 2 new ones were tried. The first was the minimum range at lane change, and the second was simply the minimum range. The minimum range at lane change was a measure of how far apart the subject's vehicle and the blind zone vehicle were when the subject fully committed to the lane change. This is described in more detail in the Task 6.3 report. The minimum range was simply the minimum range between the 2 vehicles while the warning alert was active.

The multivariate analysis showed that the critical event that was used had a highly significant effect on the data, and failed to show any statistically reliable effects due to warning condition. This can be easily seen in Figure 3.47, where we see the mean minimum range to lane change values as a function of critical event and warning condition. The mean values follow a definite trend based on the critical event, but for each critical event, the warning conditions are scattered sporadically. This is probably due in large part to the drivers' responses to the simulation scenarios, which was reasonably evident while observing the experiments. The side zone scenarios did not contain explicit hazards that the subjects must respond to. Instead, the subjects had the option of observing situations in their mirrors, and not maneuvering until adjacent traffic was clear. Therefore, these results do not give a clear indication of a human factors distinction between the alarm conditions. A complete data analysis is contained in the Task 6.3 report.

Even though the objective analysis did not provide significant results, the subject data that was collected did. The subjective data was comprised of 2 parts. First the subjects responded to general questions about each individual warning system (the complete questionnaire can be found in the Task 6.3 report). In general these questions asked the subjects to rate the various aspects of the warning system on a scale from 0 to 6. The second part of the subjective data was obtained at the completion of each subject's participation in the study. At this point they were asked to rank the various systems from 1 (best) to 8 (worst) and to provide any comments on the individual systems.

The subjective data illustrated that there was a definite tradeoff between system effectiveness and system annoyance. In general the systems that were rated the most effective also were rated the most annoying, and vice versa. When the subjects were asked to rank the systems from best to worst, the systems that tended to be the visually least annoying were rated best. These results are shown in Figure 3.48 where the average results from several different questions are displayed. In general, these results show that the side systems were effective at getting the subject's attention, especially with the auditory warnings (warning conditions 5-8). But at the same time, the subject responses show that the systems could be annoying and that the systems with the auditory warnings were the most annoying. It is interesting to note that in general the less effective a system seems to be the less annoying it is.

At the completion of the study, subjects were asked to rank the various systems from best to worst. Using these rankings and a weighting scheme that assigned a value to each individual rating, a total composite rating was determined. These final

ratings showed that all 4 conditions with the auditory warnings were rated best and the system using icons in the side mirrors combined with the auditory was rated best. With warning systems where no auditory tone was used, the system with icons in the side mirrors was rated best.

Some general comments from the subjects explained that the side view mirrors were the best visual warning because they did not appear in the driver's sight lines and were therefore less distracting than the icons in the rear view mirrors or the HUD. Unlike the HUD, they also provided a clear indication of which side of the vehicle that the threat was located on. The auditory warning was definitely the most effective component at getting the subject's attention, but was also the most annoying component and had the potential to become extremely annoying on long drives and in heavy traffic.
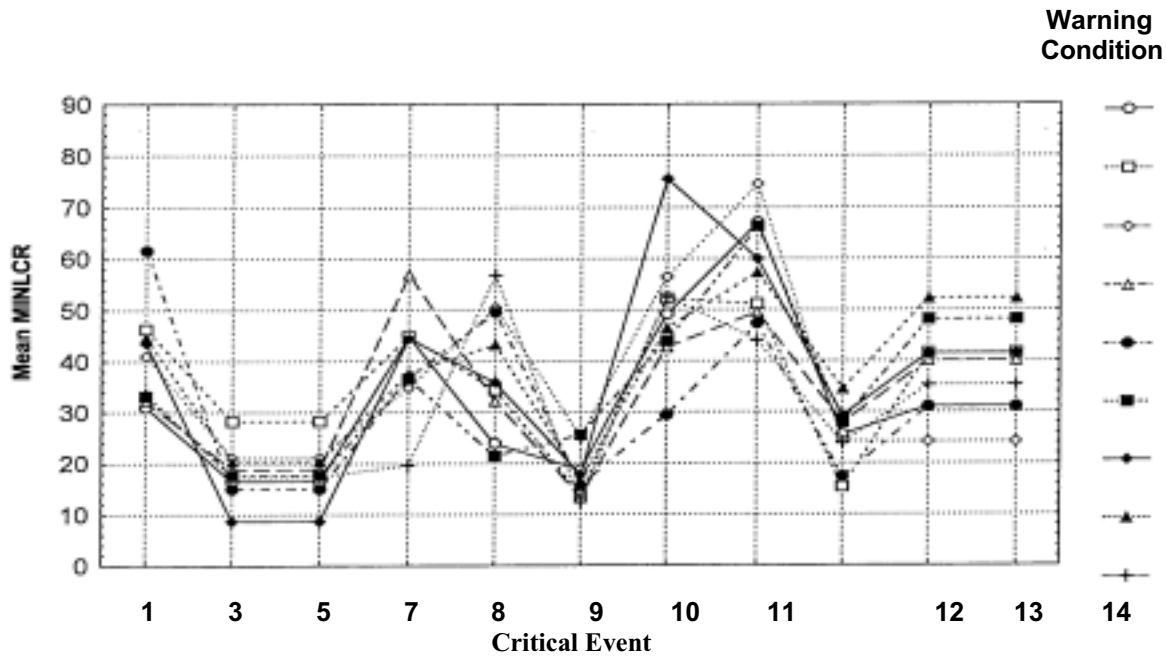
Figure 3.47: Mean Minimum Range to Lane Change.

(a) How effective was the alert at getting your attention?
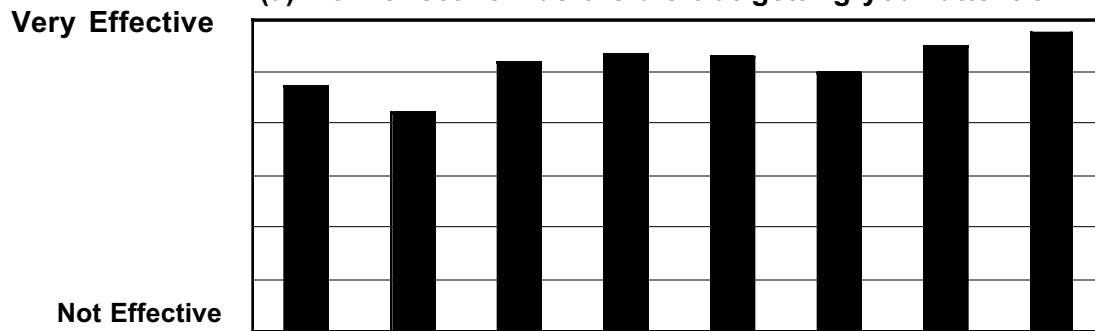
(b) How annoying was the alert?

Figure 3.48: Mean Subject Responses to Post Run Questions

3.12.3   Side Sensor Simulation Summary

Although the objective data collection and analysis did not yield fruitful results, the subjective data based on post run questionnaires provided data that was very useful. The following conclusion were drawn based on the data that was collected:

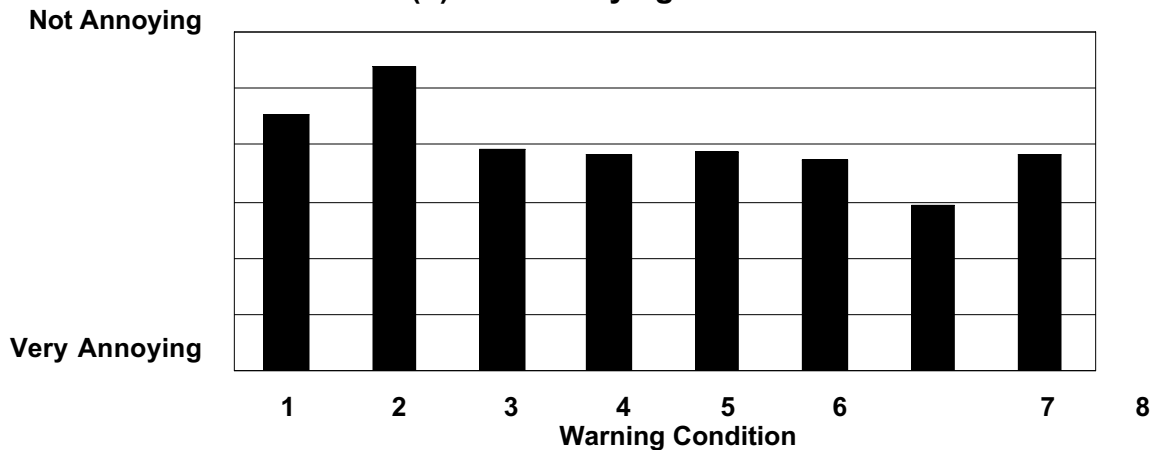- Subjects tended to rate the systems that were visually less annoying and less distracting higher than systems that grabbed their attention each time. Basically, the subjects did not like to see warnings all the time and preferred to have to make a conscious effort to see the warning and then act upon it.

- Auditory warnings provided the best method of attracting the subject's attention, however, they also proved to be annoying and would need adjustments.

- Subjects did not entirely rely on the warning system and tended to use it as more of a decision making tool than as a foolproof lane change device. However, there is the temptation to develop bad driving habits.

- Subjects thought the yellow and orange triangle icon was synonymous with caution and therefore the warnings were easy to understand, would be easy to learn and would only require minimum training in order to use the system.

- For these warning systems to be usable for a wide range of the population, controls must be included that allow the driver to make adjustments to the light level of the icons and volume for the auditory warning.

- More than 70 percent of the subjects tested would purchase a vehicle with the system if cost was not a factor, and they believed that the systems were understandable, easy to learn and would require little training to use them.

- Objective data for the side zone phase of the study was inconclusive due to subject variability based on the scenarios that were driven.

A secondary objective for this study was to choose the 2 warning systems that would be used in the Task 6.4 Closed Course Testing portion of the contract. Based on the data that was collected and analyzed, the following 2 systems were chosen:

(a)   Icons in the side view mirrors with auditory alert

(b)   Icons in the side view mirrors

The condition with icons in the side mirrors with auditory alert was an easy choice because it finished first overall in the subject ratings and there was a distinct margin between it and the next 3 systems. The second choice of icons in the side mirrors was a little more difficult. The top 4 ranked systems all included an auditory alarm, however it was only triggered when the turn indicator was used and therefore may have been less annoying. In the field test vehicle, the auditory alarm will always be present whether the turn indicator is used or not. Since there was concern over whether having the system on all the time would be too distracting, it was decided that one system would have an auditory alarm and one would not. Since the side mirror system was ranked best with and without the auditory alarm it was the logical choice.

3.12.4   Forward Sensor Simulation Study

The forward simulation tests began in May and ended in August of 1997. A total of 35 subjects (18 male and 17 female) were tested. Their ages ranged from 17 to 55 years and there were representatives from a wide range of age groups. Since gender and age effects were not being considered, the use of more male than female subjects and the predominance of middle aged subjects was not a concern.

Subjects were required to complete 9 separate drives through the roadway database, with each run consisting of a different scenario and warning condition. During each run, data about the vehicle's position and motion and the subject's reactions was collected. Additionally a questionnaire requesting subject ratings and comments was also completed at the end of each individual run. All of this data was then analyzed and some conclusions were drawn.

The forward testing had a couple of additional problems that were not experienced in the side zone study. First, for some reason that could not be readily explained (except for the previously mentioned simulator problems), close to 25 percent of the data either did not get recorded or the events did not occur. This was a much larger percentage than was seen in the side zone study. Second, of the events that did occur, approximately 25 percent of the time, the warnings systems did not issue any alerts. Once again, like the side simulation study, these 2 problems created holes within the database and required additional work to be performed in order to try and make sense of the data collected.

Using the objective data that was collected directly by the simulator, a multivariate analysis was performed to see if the warning conditions that the subjects were experiencing had any significant effect on the way they reacted. For the multivariate analysis the independent variables were the warning condition and the critical event, subjects were grouped into bins based on similar conditions and thus treated as a repeated measure.   The independent variables that were investigated included minimum Time To Collision (TTC based on range and range rate), minimum range, peak steering response, and throttle, brake and steer reaction times. The number of collisions were also desired but like with the side zone study, they were inconclusive due to non scripted vehicles appearing in the driving scene and subjects occasionally colliding with them.

The multivariate analysis showed that the critical event that was used had a highly significant effect on the data, and failed to show any statistically reliable effects due to warning condition. This can be seen in Figure 3.49, where we see the mean throttle time responses for each critical event and warning condition. For each critical event there seems to be a trend in the direction that the throttle times go, but the warning conditions seem to be scattered fairly randomly and were therefore not statistically significant. The unreliability of the data was attributed to the subjects being able to anticipate the coming events and therefore react before any warning could be issued. This also caused the warnings to not be issued because in their anticipation, subjects were able to completely avoid some critical conditions. This observation is evident by looking at the throttle responses shown in Figure 3.49. A negative throttle time indicates that the subject took their foot off of the throttle before a warning was issued. For the majority of the cases, the throttle times were negative meaning that subjects were no

longer accelerating and most likely anticipating a potential problem. The complete data analysis with plots and tables is contained in the Task 6.3 report.

As was the case with the side zone study, the objective analysis did not provide significant results, however the subjective data that was collected did. Once again, the subjective data was comprised of 2 parts. First the subjects responded to general questions about each individual warning system (the complete questionnaire can be found in the Task 6.3 report). In general, these questions asked the subjects to rate the various aspects of the warning system on a scale from 0 to 6. The second part of the subjective data was obtained at the completion of each subject's participation in the study. At this point they were asked to rank the various systems from 1 (best) to 8 (worst) and to provide any comments on the individual systems.

Once again, as was the case with the side zone study, the subjective data illustrated that there was a definite tradeoff between system effectiveness and system annoyance. In general, the systems that were rated the most effective also were rated the most annoying, and vice versa. This is illustrated in Figure 3.50 where mean subject responses to a question about the systems effectiveness at getting the subjects attention and how annoying the system was, are shown. Looking at the 2 plots, you can definitely see that the least effective systems were also the least annoying, and some of the most effective systems were the most annoying. When subjects were again asked to rate the systems from best to worst, 2 of the top 3 choices were the least annoying even though their effectiveness at getting the drivers attention may not have been rated best. In addition, the systems that included false alarms were rated very poorly by the subjects.

In general, comments that were submitted by the subjects, the HUD was the component that was liked best by the subjects. This was because the warning was provided without the subjects having to take their eyes off the road. However, the HUD icon received mixed reviews. Subjects stated that the auditory alert was the best at getting their attention and was also the most annoying part of the system. The tactile feel was liked by a majority of the subjects and when combined with the HUD display it was considered very effective. As for the false alarms, the subjects thought they were confusing and stressful and reduced the overall effectiveness of the system.
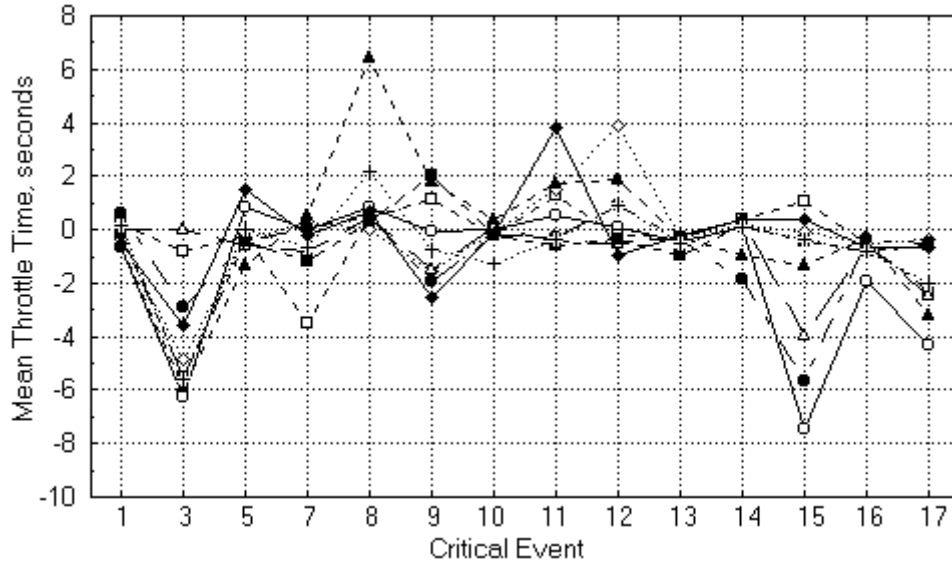
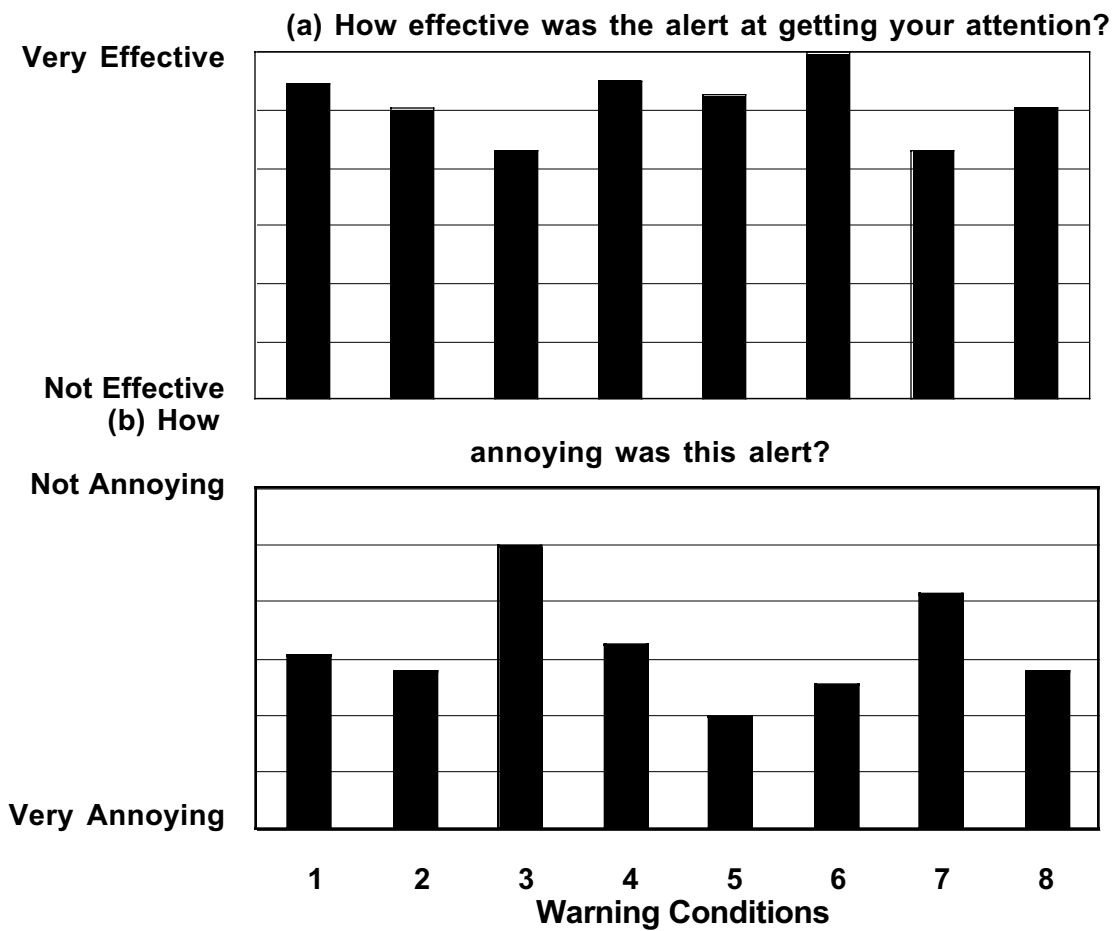**Figure 3.49: Mean throttle response time**

Figure 3.50: Mean Subject Responses for Effectiveness and Annoyance

3.12.5 Forward Sensor Simulation Summary

The primary objective was to investigate how subjects responded to various warning systems and to generate feedback from them about how the warning systems functioned. A statistical analysis of the objective data was performed and overall the warning condition did not reliably influence the data. From all of the data that was collected, the following conclusion were drawn:

- There is a definite trade off between system effectiveness and annoyance, with subjects tending to sacrifice some effectiveness in order to have a less annoying and distracting system.

- Auditory warnings provided the best method of attracting the subject's attention, however, they also proved to be the most annoying part of the system and would need to be adjustable for an actual system.

- The HUD was the most popular of the 3 different components that were tested. Subjects liked the fact that they did not have to take their eyes off of the roadway in order to get a warning. Additionally, the yellow icon that was used was understandable and effective.

- Tactile feel proved to be a good component when combined with the HUD and tended to be less annoying then the auditory warnings.

- Subjects did not exclusively rely on the warning system they were given and used it as more of a tool to keep them informed about what was happening in front of them. To this extent, some subjects were concerned that these systems could lead to poor driving behavior and the creation of very bad habits.

- In order for these systems to be acceptable, false alarms must be eliminated or at least greatly diminished.

- Since the study was performed in fairly light traffic conditions, there was some concern over how annoying the systems would be in heavier traffic situations.

- Approximately 65 percent of the subjects tested would purchase a vehicle with a forward warning system if cost was not a factor, and they believed that the systems were understandable, easy to learn and would require just a little bit of training in order for drivers to use them.

A secondary objective for this study was to choose the 2 warning systems that would be used in the Task 6.4 Closed Course Testing portion of the Project. Based on the data that was collected and analyzed, the following 2 systems were chosen:

1. HUD with tactile feel

2. HUD with tactile feel and auditory alert

The condition with the HUD and tactile feel was chosen because it was rated best in the overall ranking that the subjects submitted. In addition, it was rated as the least annoying during post run questioning, and it has been shown a couple of times that subjects seem to prefer less annoying systems even if they lose some effectiveness.

As for choosing the HUD with tactile feel and auditory alert, this was a little more complex. It was apparent from the data that the second system would be chosen from

either the HUD with tactile feel and auditory, or the HUD with auditory. They tended to be rated fairly evenly by the subjects and finished ahead of the system without the HUD. In the overall rankings, effectiveness ratings and annoyance ratings, they finished almost identical. However, in the distraction category the HUD with tactile feel and auditory was definitely rated better and therefore was chosen. In addition, since the number 1 system included the HUD and tactile, this allows the same system to be tested but with the auditory component added in.

While the scenarios were being designed and tested, a concurrent effort was also conducted to design the events and scenarios that would be used in the Task 6.4 Closed Course Testing portion of the project. During this effort, the test track was chosen, and the critical events that would occur on the test track were designed. In addition, the test matrices and all paperwork that the test subjects would need to complete were also defined. A subject review board approved the final test configurations, thus allowing human subjects to be used during testing. From this effort the Task 6.3 - Vehicle Test Plan report was written and delivered as required. The details about the closed course testing setup can be found in this report.

3.12.6   Accomplishments and Future Directions

During the performance of Task 6.3, many different problems and issues were encountered, and handled. The following major accomplishments and program objectives were realized:

- Designed and built a high fidelity, realistic, real-time, interactive driving simulator.

- Created realistic driving scenarios that were capable of mimicking dangerous real driving situations.

- Designed and conducted an experimental test to collect data on driver's reactions to and perceptions and opinions of, a side zone detection warning system.

- Designed and conducted an experimental test to collect data on driver's reactions to and perceptions and opinions of, a forward zone detection warning system.

- Designed the experimental test plan for the Task 6.4 Closed Course testing portion of the project.

- Produced the deliverable report, Task 6.3 – Vehicle Test Plan.

- Produced the deliverable report, Task 6.3 – Experimental Results.

All of the desired objectives of this task were met. Unfortunately, because of the various simulator problems and the scenarios not being constrained enough, the objective data that was collected did not provide statistically significant results. This is a phenomenon that is not uncommon when dealing with human subjects who are very adept at adapting to their given situation. In this regard we can say that based on the initial expectations, less was accomplished than was expected. However, the subjective results that were obtained from the subjects provided incredible insight into the system usage and should be considered a major benefit and accomplishment for this task.

In hindsight, the experimental results show that several things could be improved upon in order to obtain more consistent and reliable data in future studies. Improved communication between software packages would have provided a more reliable simulator and would have allowed all of the desired data to be collected. Also, an improved secondary task that forced the subjects to take their eyes off of the roadway scene for an extended period of time would have added additional realism and would have put the subjects into the types of dangerous situations that the warning systems were designed to eliminate. Both of these should be considered in future simulation tests.

The major emphasize of this study was to see how drivers reacted to a warning that they were given during dangerous driving situations. The data collection and reduction focused primarily on how the subject reacted and their overall opinions of the system's effectiveness and annoyance. Now that we have some idea in these areas, additional work needs to be performed to see if subjects can "blindly" recognize the warnings that they are given. In addition, work needs to be performed in order to determine the warning cues that are best at conveying the necessary information to the driver when the driver has had no training and knows nothing about the system.

3.13 Closed-Course Testing (Task 6.4)

The focus of this task was to conduct closed course testing using human subjects driving a vehicle equipped with working warning systems. From the test data collected, the accuracy and reaction time of driver responses was to be evaluated. Two separate closed course tests were to be conducted using a side zone warning system and a forward zone warning system. In order to successfully complete the task, several different issues had to be addressed. First, a test vehicle had to be equipped with the desired warning systems. This feat was accomplished under Task 2.3, but a few additional modifications had to be made in order to use the vehicle during this portion of the project. Second, a suitable test track had to be procured and a potential subject population obtained. Finally, the closed course testing had to be conducted and all of the data that was obtained (both objective and subjective) had to be reduced, analyzed, and documented.

The actual closed course testing consisted of two separate and individual studies. The first study dealt with a side zone warning system that was designed to assist drivers making lane change maneuvers in traffic. The warning system provided information to the driver as to whether or not another vehicle was located in their blind zone as they tried to safely negotiate a lane change. The second study consisted of a forward zone warning system that was designed to detect potential head on collisions while traversing through traffic. The warning systems provided information to the driver warning of other vehicles that the driver could potentially collide with. During each phase of the study only a single warning system was used, and the subjects only needed to concentrate on the specific system being tested. Additionally, the scenarios were designed so that the focus was on the system being tested and the critical events that occurred were designed to specifically activate the intended system.

At the completion of Task 6.4 the following objectives were to be reached:

- Work out all the necessary logistics so that the closed course testing could be conducted,

- Conduct both side zone and forward zone closed course tests,

- Reduce and analyze the data that was collected,

- Compare the data to the simulation results obtained during Task 6.3,

- Produce and deliver the final report documenting the test results.

3.13.1   Closed Course Testing Preparation

Before any of the actual closed course testing could be conducted a few issues had to be resolved so that the tests could be conducted safely. This entailed modifying the DE/AED "Gold Car", setting up the data collection protocols, obtaining a test track, and adjusting the critical events so that they could be used on the test track that was chosen.

The "Gold Car" is a Cadillac that is equipped with multiple warning systems. For our purposes it had to have both a side zone and forward zone warning system. The warning systems include the sensor, Multiple Target Tracker (MTT), Collision Avoidance Processor (CAP), and the final warnings that were presented to the subjects. The installation of the warning systems occurred on another task; however, a couple of additional modifications had to made. For safety, a hand brake was installed as part of the front passenger's seat. This was installed so that the experimenter that was riding in the car during testing could attempt to avoid potential collisions by applying the brakes. The other modification involved a control box that was designed so that the experimenter could easily control every component of the warning system.

During the initial phases of the Task 6.4 design, there was a concern involving changing the warning conditions during the actual test runs. The solution was to build a control box. The box tied directly into the computer system and allowed the experimenter to toggle various components of the system on and off. For example, the audio portion of the alarm could be activated so that the driver could hear it, or could be deactivated so that no auditory alert was presented. All of this could be controlled by simply setting a toggle switch to either the on or off position. As the test schedule proceeded, the experimenter could easily configure the next run without even leaving the passenger seat. This meant that the entire set of runs for each subject could be conducted without stopping the car (if that was what the subject desired).

The next critical issue that had to be overcome was the data collection. This was handled using an on board laptop computer system. The laptop computer was directly linked to the CAP using a serial communication connection. While the tests were being conducted, the information that was being collected and analyzed by the CAP was also stored on the laptop computer. Using a program that was supplied by DE/AED and another written by STI, the data could then be dissected and the critical information retrieved and stored into spreadsheets for subsequent data analysis using the statistical analysis program *Statistica™*.

During the "Gold Car" configuration, a concurrent effort was being directed to find a test track that was suitable for conducting the closed course testing. This presented quite a problem because there were several definite characteristics that were required. Because of the nature of the events that would be occurring during the test runs, the track had to be sealed off so that no other traffic (besides our test vehicles) would be present. In addition, the track also had to have multiple lanes and long straight-aways. These constraints were necessary because there would be passing involved and vehicles interacting with the test vehicle at long distances. Several different test tracks were considered including the General Motor's (GM) Desert Proving Grounds in Mesa, Arizona, and the California Transportation Department's Automated Highway System test facility near San Diego, California. Unfortunately, due to high costs, security restrictions, and scheduling problems, neither of these facilities as well as others that were considered could be used. Finally, the use of the test track at the GM Technical Center was approved.

The test track at the GM Technical Center is approximately 2.6 miles long with roughly 1 and .8 mile straight sections that lead into wide curves on either end. The track was reserved for exclusive use (6 hours a day) for both of the tests that would be conducted. Finally, for the entire length of the test track, there were 2 lanes of traffic so that passing would not be a problem.

Having the testing located at the GM Technical Center also eliminated another potential problem, obtaining subjects. No matter where the testing was to be conducted, there were going to be problems with the subject population. These problems included having a large enough population so that the 24 required subjects could participate, scheduling the subjects so that they would fit into the proposed test schedule, and obtaining permission so that the subjects could be given access to the test facility. The GM test track eliminated these problems because the size of the work force at the Technical Center was large and subjects were able to easily schedule test runs around their work schedules, and they all had access to the facility. In addition, a GM representative was able to handle the entire subject scheduling on site, thus greatly reducing the workload that would be required if the scheduling was being conducted from across the country.

With the test track facility secured, the final step was adjusting the critical events that would be occurring during testing so that they would work on the test track. As part of the Task 6.3 effort, a test plan was designed and delivered to a review board. The review board approved the test plan and therefore no deviations from the plan would be acceptable. However, we were allowed to make the test plan fit the test track that was being used. The details of the final test plan can be found in the document "Task 6.3 – Vehicle Test Plan".

One of the objectives of the Task 6.3 simulation study was to determine the 2 warning systems that would subsequently be tested during the Task 6.4 Closed Course Testing portion of the project. This meant that the 2 best side warnings and 2 best forward warnings would be instrumented on the "Gold Car" and used during the tests. The systems that were tested were:

Side Warning Systems:	Forward Warning Systems:
Visual icons in side mirrors	HUD + Tactile feel (seat shaker)
Visual icons in side mirrors + Audio	HUD + Tactile feel + Audio

During the actual tests, a laptop computer was being used to collect various information about both the vehicle's and the subject's performance. All of this data was taken directly from the CAP computer at each frame time during the test run. In addition to this objective data, some subjective data was also obtained from the subjects. This data was collected in the form of a post test questionnaire. At the completion of all of their test runs, each subject was required to fill out a questionnaire regarding their impressions of the systems that they had just experienced. Most of the questions required the subjects to rank their impressions on a scale from 0 to 6. Other questions required a Yes or No response, and all of the questions allowed the subjects to add any comments that they felt were necessary. As a final piece of data, the subjects were also asked to choose which of the 2 systems that they experienced, was best. The questionnaires that were used can be found in the report, "Task 6.3 – Vehicle Test Plan".

Because of problems that were encountered when the Task 6.3 simulation studies were being conducted, the closed course testing could not be started until June of 1997. In order to conduct the closed course tests, the warning systems that would be tested had to be determined and this was one of the objectives of Task 6.3. Therefore, no closed course tests could be run until the simulation data was collected and analyzed. This unfortunate occurrence created a huge delay in the overall project schedule and was primarily responsible for the schedule running way over the initial estimates.

In hindsight, after all of the test were completed (both side and forward), it was easy to go back and notice several general problems that occurred during testing. The first and most important issue was safety. Although the reason the tests were conducted was to obtain data and driver feedback with the warning systems activated, we could not put the subjects in extreme danger and therefore the tests were less realistic than normal driving. There were 2 reasons for this, first we did not want any of the subjects or experimenters to get injured, and second since we only had one test vehicle we did not want to damage it and take the risk of not being able to conclude the testing. Therefore, the tests that were conducted had reduced realism in order that they would be conducted safely.

In order to comply with the desired safety requirements, only the test vehicle and one other vehicle that the test vehicle could interact with were on the test track. There was no defined secondary task to try and distract the subjects as they drove, allowing the subjects the ability to constantly check their mirrors and scan the entire field of view. This caused a perception problem with the subjects because although the warnings were given for the events that they experienced the overall experiment did not sufficiently mimic real life. The events themselves were reminiscent of real life events but they were conducted in a controlled environment and the subject's were able to partially anticipate the events. This in turn caused problems with the statistical data analysis because you

never knew if the warning caused the subjects to respond or if simple visual observations resulted in their responses.

Subjects were able to anticipate events due in part to the test track that was used. At first the test track seemed fine because the types of events that were scripted to occur only required a continuous track, with at least 2 driving lanes and a long straightaway. However, in hindsight the number of lanes became a limiting constraint that reduced what we were able to do with the chase vehicle. For example, in the side zone study, the subject always knew which side the chase vehicle was going to be on and therefore could partially anticipate what was going to happen. By having at 3 lanes on the test track, the chase vehicle could be on either side and becomes harder to keep track of.

3.13.2   Side Sensor Closed Course Testing

The side zone closed course tests were conducted during the last 3 weeks in June. A total of 24 subjects (22 male and 2 female) participated in the testing. Their ages ranged from 28 to 59 years with the majority of the subjects in the 40 to 50 year old category. Since gender and age effects were not being considered, the use of predominately middle aged male subjects was not a concern.

As is detailed in the vehicle test plan document, subjects were requested to complete 36 laps around the test track, with every 3 laps consisting of a different speed (40 or 50 mph) and warning condition (no warning, icons in mirror, or icons with audio). Each of these combinations was repeated once giving a total of 12 scenarios. As the subject drove the test track, a chase vehicle would continually move in and out of the test vehicle's blind zone, thus causing the warning system to activate. The system was activated 8 times during the 3 laps that comprised a scenario. Because a total of 36 laps were driven and the subject was required to complete the post testing questionnaire, a total of 3 hours was required to test each subject. Therefore, a total of 3 weeks were necessary to check out the vehicle and test track, and to conduct the entire study.

It is important to note that the warning system was not active during the side zone testing. There was a major concern that the test vehicle and chase vehicle would have to be extremely close in order to activate the system. Since there was only a single test vehicle, and the possibility for a mishap was high, a decision was made to activate the warnings manually using the control box instead of the live system. This was done by scripting the side scenarios so that a critical event (vehicle in the side zone) would occur at a certain time during the test run. During these critical occurrences, the chase vehicle would move close to the vehicle but not close enough so that if the test vehicle suddenly changed lanes the 2 vehicles would collide. At the same time, the experimenter inside the test vehicle would activate the warning. When the subject began changing lanes the experimenter would then deactivate the warning. This setup worked well and the testing occurred without any potential collisions occurring.

As part of the original plan, a mechanical side mirror was also going to be used during testing. In these cases the mirror would display an image of a car in the side mirror with and without the warning icon. The idea for this mirror came about during the safety discussions, however once the mirror was built and tested, a decision was made not to use it. There were 2 basic reasons for this decision. First, initial subjects that

drove the test vehicle with the mirror did not think is was very realistic and therefore they ignored it. Second, in order to use the mechanical mirror, it would have to be continually switched with the real mirror, causing delays in an already tight test schedule and increasing the likelihood that something would break.

The actual tests were conducted with virtually no major problems. The only real problem that was encountered was getting all of the test runs completed during the 3-hour session. Because of some minor computer problems, and some subjects arriving late, not all of the subjects were able to drive the entire 12 scenarios. Every subject ran each of the 6 basic scenarios once, and then it was a matter of driving as many repeat runs as possible.

During each run data about the vehicle's response and the subject's reactions was collected. Using the objective data that was collected directly by the laptop computer, a multivariate analysis was performed to see if the warning conditions that the subjects were experiencing had any significant effect on the way they reacted. For the multivariate analysis the independent variables were the warning condition, the speed and the subjects. The dependent variables investigated were the maneuver time (time to start and complete the lane change), maximum steer angle during the lane change, maximum longitudinal acceleration, maximum lateral acceleration, and the maximum speed differential during the lane change. Since the side-Near Object Detection System (NODS) does not include the capability to measure range and range rate between vehicles, this information could not be analyzed. Furthermore, although reaction times were obtained (for steering and braking) they were not seriously analyzed because of the randomness of the subject's responses. For the side zone tests there was no clear threat and therefore different subjects did different things. For example some subjects were very aggressive and changed lanes quickly when the command was issued. This gives the impression of quick reaction times. However, other subjects continued to drive ahead until the side zone vehicle was clearly behind them and then changed lanes. The differences in these types of behavior make comparing reaction times very difficult.

A multivariate statistical analysis was performed on the data and showed that both the speed and warning independent variables had a significant influence on several dependent variables although the interaction of speed and warning only influenced the maximum steering angle variable. The plots in Figure 3.51 show that the visual plus auditory warning condition tends to give the best performance regardless of the speed condition.
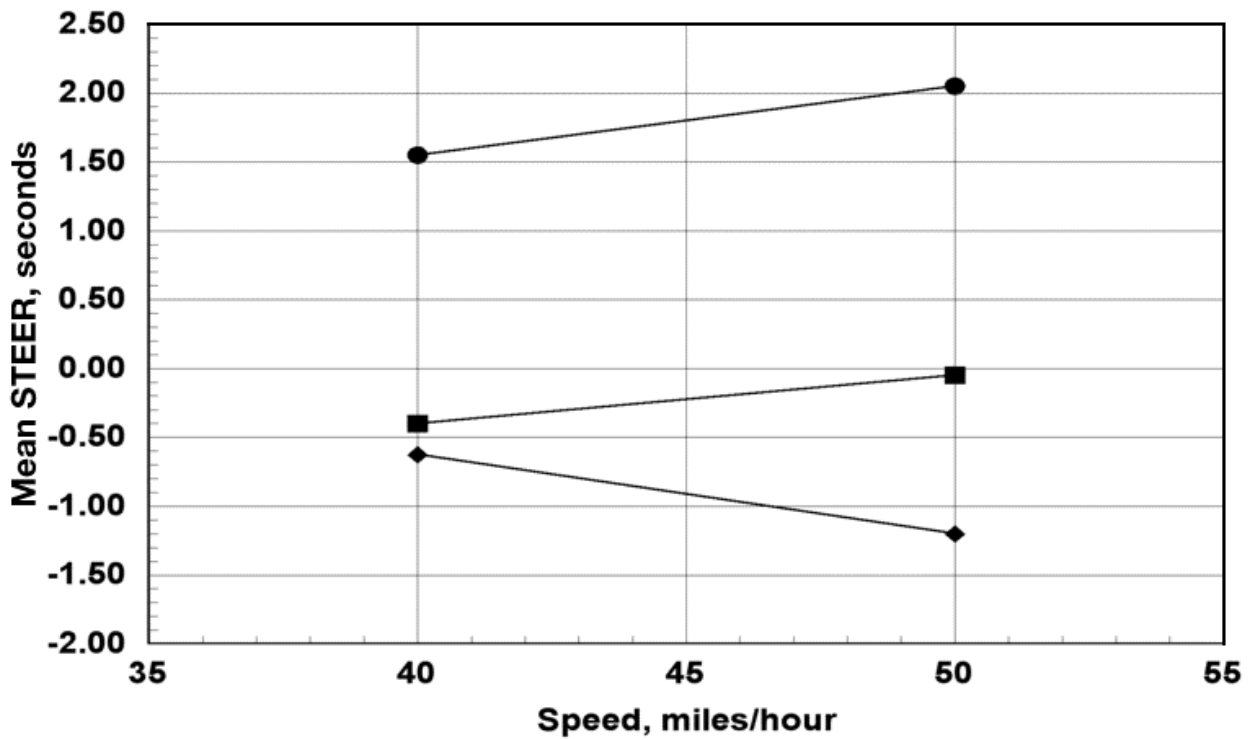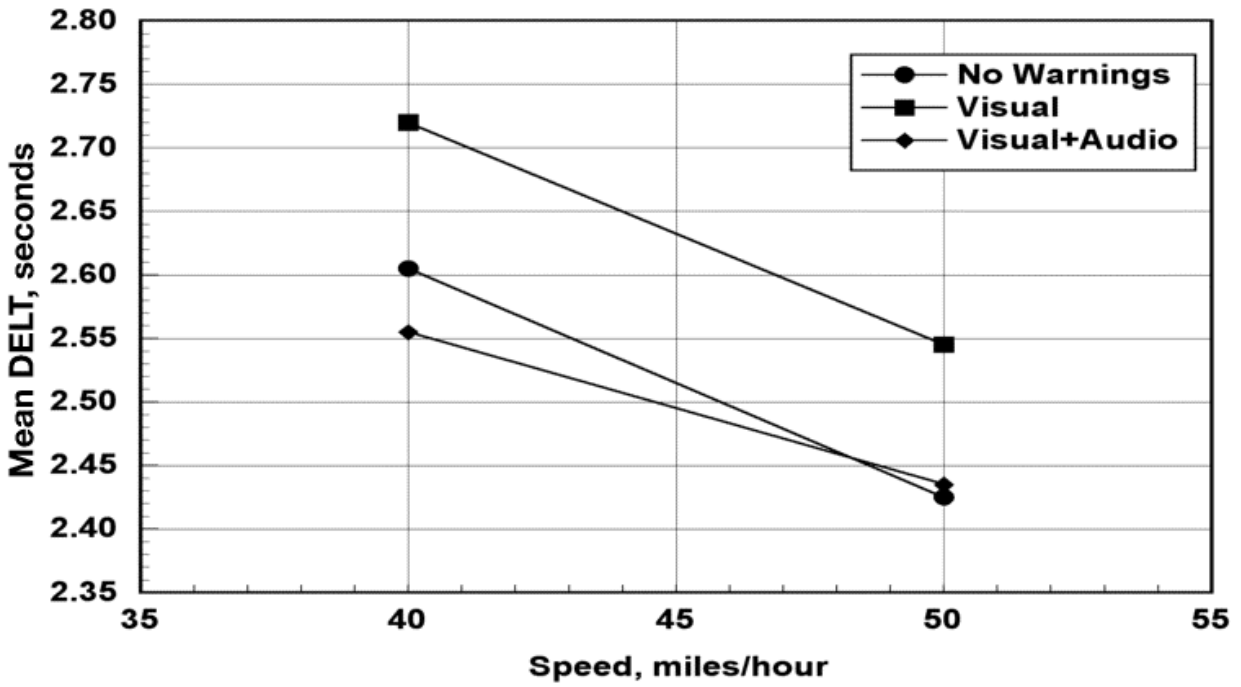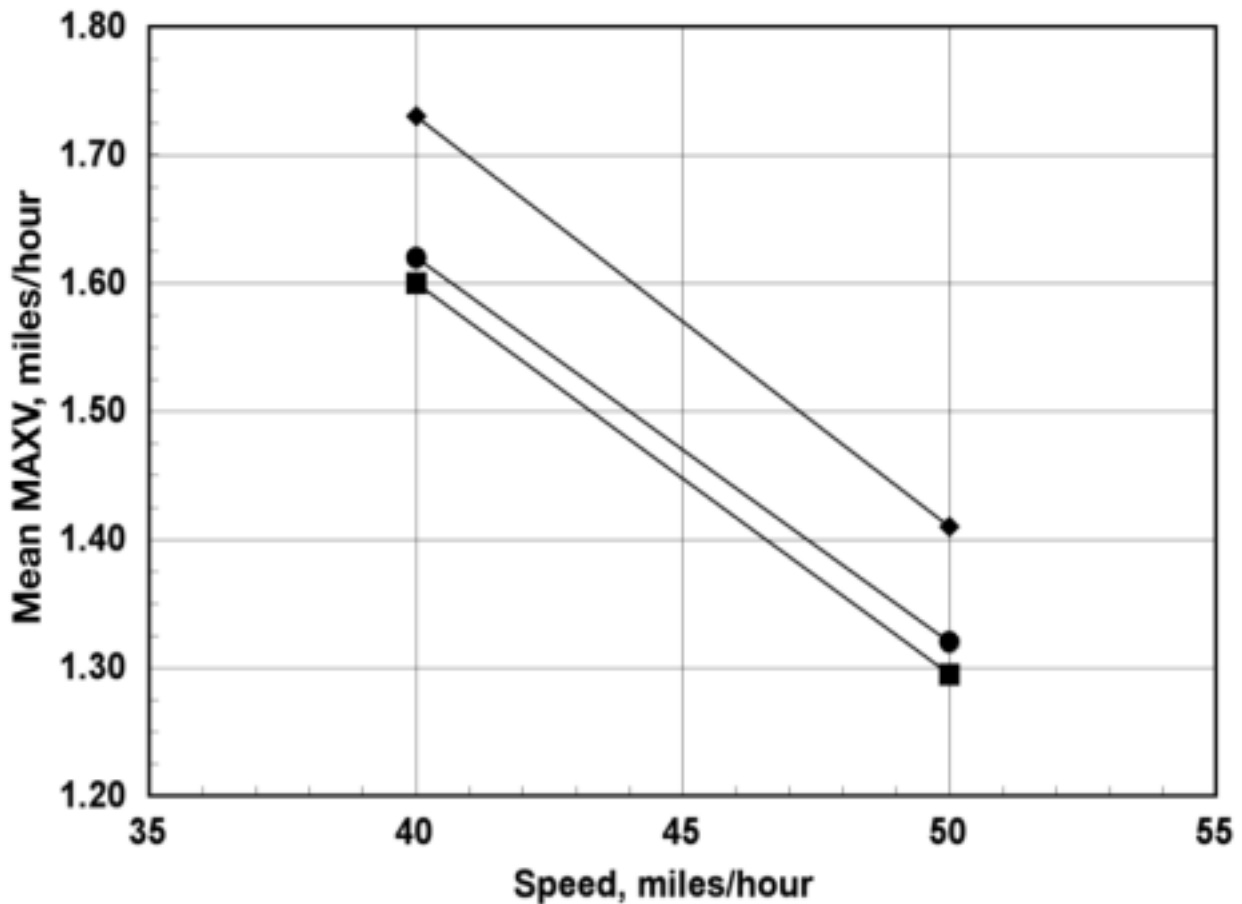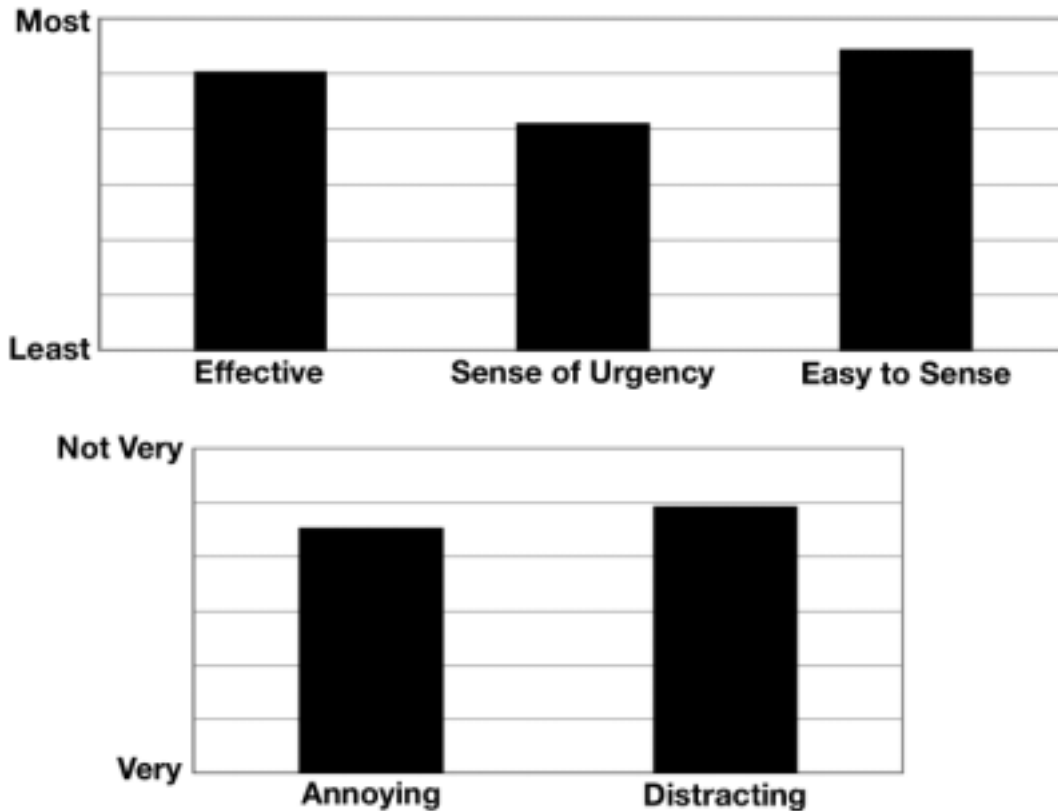
Figure 3.51: Side Zone Mean Subject Responses

Figure 3.51 (Continued): Side Zone Mean Subject Responses

Additionally, the plots in Figure 3.51 provide some insight into what the subject's were doing. In the mean steer response plot, the subjects were inputting larger steering angles (potentially more dangerous) when they had no warnings as compared to when they were receiving warnings. Also, the differential speed plot (MAXV) shows that when the visual alert was combined with the audio alert, the subjects tended to increase their speed during the lane change, putting additional separation between the 2 vehicles and therefore allowing for a safer lane change maneuver. Overall, the visual icons combined with the auditory alert tend to give the best performance.

In addition to the multivariate analysis that was done on the objective data, analysis was also performed on the subjective data that was collected. At the conclusion of each subject's test set, they were required to fill out the post run questionnaire. This was done to obtain a subjective opinion on the warning systems that were experienced. Like the results of the simulation study, subjects perceived the systems to be effective at getting their attention, easy to sense, and good at presenting a sense of urgency. In addition to the system's effectiveness, subjects also found the systems to be annoying. Once again this was a similar response to the simulation study, however, in this case the annoyance factor was less than that reported during the simulation study. These results are shown in Figure 3.52.

Figure 3.52: Subject Perception of Side Zone Systems.

The subject responses indicated that there was a tradeoff between system effectiveness and system annoyance. This was the same as with the simulation study, but once again the annoyance factor was less in the closed course testing than it was in the simulation study. This is evident in the overall response where more than 70 percent of the subjects preferred the system that combined the visual and audio warnings in the same system.

Subject confidence in the systems was good with subjects responding that they had above average confidence that the systems would help prevent crashes from occurring. At the same time, only 30 percent of the subjects stated that they were relying on the systems. This was much lower than the 50 percent that was observed in the simulation study. Most importantly, every subject with the exception of 1, responded that if cost were not an issue, they would purchase a vehicle with a side zone warning system. This is a good indication that the subjects walked away with an overall positive attitude for the warning systems.

While filling out the questionnaires, subjects took the time to write in comments about the systems and the various components that they contained. The visual icons produced mostly positive responses because subjects associated the orange triangle icons with caution, making them readily understandable and easy to learn. A majority responded that it was an effective display that conveyed the necessary information in a clear concise manner. In addition, locating the icons in the side mirrors enforced good driving habits by forcing the driver to check the rear view mirror in order to see the icon.

However, there were concerns about seeing the icons during bad weather or if something was in the passenger seat and thus blocking the view of the passenger side mirror.

As for the auditory tone, subjects stated that it was the most effective alert at getting their attention. This was the same result as was found during the simulation study. As with the simulation study, there was concern about the auditory tone becoming increasingly annoying as time went on and especially in heavy traffic conditions. Subjects responded that the system would have been better if the auditory alert was connected to the turn signal so that it would only activate when the turn signal was used (this was the way the simulation was configured).

Summing up the side zone closed course testing, several conclusions can be drawn:

- The auditory warning was the most effective component at getting the driver's attention, but also has a very high potential for becoming increasingly annoying.

- From both the objective data and subject responses that were collected, the icons in the side mirrors combined with the auditory tone was the better of the 2 systems tested.

- The majority of the subjects said that they would not rely on the systems and that the systems could not replace good driving habits, however it would be a useful tool to provide to drivers.

- The results of the field test study and simulation study were very similar with subjects tending to rate the systems in the same manner (e.g. auditory was the most effective alert and the most annoying, not relying on the systems, etc.).

- The closed course testing responses showed the subjects to be more positive about the systems than during the simulation study. For example, the auditory was annoying, but not as annoying as in the simulator. This indicates that there may have been problems with the simulator setup as far as playing the auditory alert, the alert that was used, the driving display information and so on. Once again this is a positive indicator because although the closed course test subjects had similar opinions as the simulation subjects did, the real systems that were tested produced more positive responses.

3.13.3   Forward Sensor Closed Course Testing

The forward zone closed course tests were conducted during the last 2 weeks in August of 1997. A total of 24 subjects (22 male and 2 female) participated in the testing. Their ages ranged from 24 to 59 years with more than half being over 40 years old. Since gender and age effects were not being considered, the use of predominately middle aged male subjects was not a concern.

As was stated earlier, the warning conditions that were presented to the subjects consisted of a HUD with tactile feel, and a HUD with tactile feel and an auditory alert. The HUD that was used consisted of 4 different symbols that could appear in front of the

driver and inside their field of view. The 4 symbols are shown in Figure 3.53 and consist of:

- Red outline of a stop sign, signifying a severe condition,

- Yellow outline of a triangle, signifying a caution condition,

- Blue outline of a car, signifying a tailgating condition,

- The vehicle's current speed in miles per hour.

The auditory tone that was used had 2 separate components, a beeping sound during cautionary warning conditions and the word "BRAKE" continuously repeated during severe warning conditions. The auditory warnings were played until the threat no longer existed or until the subject pressed the brake pedal. The tactile feel was comprised of a seat shaker. Anytime a threat was detected the seat would shake. The same shaking intensity was used for both cautionary and severe warnings.

As is detailed in the vehicle test plan document, subjects were requested to complete 12 laps around the test track, with each lap consisting of a different speed (40 or 50 mph) and warning condition (no warning, HUD with tactile feel, or HUD with tactile feel and audio). This gives a total of 6 basic scenarios and each of these combinations was repeated once giving a total of 12 scenarios. As the subject drove around the test track, a chase vehicle was used to pull in front of the test vehicle in order to activate the warning system. When the vehicle pulled in front of the subject it would do one of 2 things, either coast along at a slower speed so that the test vehicle would eventually overtake it, or apply the brakes. In addition to these 2 critical events, there was a third event that involved a stationary target and placing the chase vehicle in the other lane to essentially force the subject towards the stationary target. In all cases, the subject was required to take whatever means was necessary to try and avoid a collision.

Unlike the side zone study where the actual sensors were not used, the forward zone study was conducted with a fully active warning system. There was no input from the experimenters except to instruct the subject on which alarm they would be experiencing, what speed they should be traveling at, and which lane they should be positioned in. On each individual lap around the test track, the subject was given a particular speed and warning condition and then would encounter all 3 of the critical events. Because the stationary target was fixed at a certain location on the track, the subjects always encountered it at the same location. The other 2 events (coasting and braking) were mixed in at different times to try and keep the subjects off guard. With the 12 laps plus completing the post test questionnaire, a total of a hour and a half was required to run each subject. Therefore, the testing could be conducted in as little as 6 days if the weather and schedule worked out correctly.
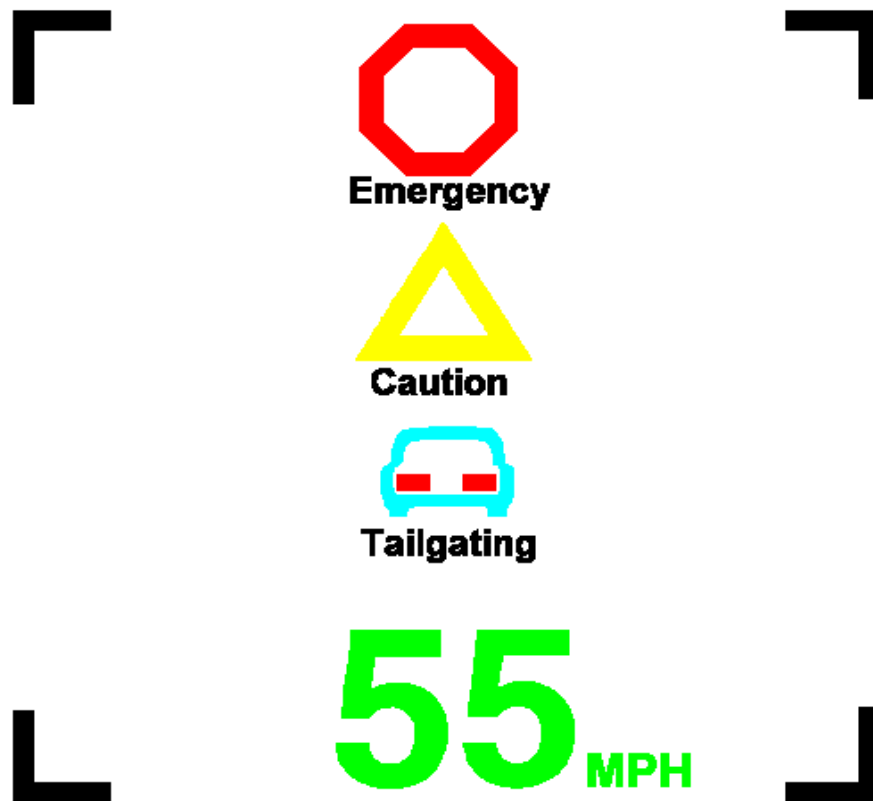
Figure 3.53: Forward Zone HUD Icons

The weather was a major concern because the test track was located in Michigan and the tests were being conducted in August. Since it was possible that the subjects may have to input large quick steering maneuvers and possibly hard braking, it would be far too dangerous to conduct any testing on a wet test track. Fortunately, we were only rained out on 1 day and the rest of the testing was conducted with little interference due to the weather.

The actual tests were conducted with virtually no major problems occurring and each subject was able to complete their entire set of runs. The only problem encountered was a computer-related problem when storing the data at the end of a session. Basically the computer was run continuously during each subject's session. At the end of the session the data was saved to the laptop's hard disk and copied to an external disk at the end of the day. The files would then be checked at the end of the day to see if data was there. For some unknown reason, when conducting the actual data analysis, several of the early subjects had data files that were corrupted. In most cases the data files contained a majority of the data collected, however in a couple of cases less than 30 percent of the data collected was useable. This was not detected in the field because the data at the beginning of the file was fine and passed the initial data checks.

During each run data, about the vehicle's response and the subject's reactions was collected. Using the objective data that was collected directly by the laptop computer, a multivariate analysis was performed to see if the warning conditions that the subjects were experiencing had any significant effect on the way they reacted. For the multivariate analysis the independent variables were the warning condition, the speed and the critical event. The dependent variables investigated were the minimum Time To Collision (TTC based on range and range rate from the CAP), minimum range between vehicles, brake response time, and steering response time. During the simulation testing we also looked at throttle response time, however, this was not available from the CAP so it was not evaluated.

A multivariate statistical analysis was performed on the data and showed that the critical event had a highly significant effect on the data and that neither the warning condition nor speed did. This can be seen in Figure 3.54 where plots of the mean TTC, mean minimum range between vehicles and mean steering reaction time are all shown for each critical event type. The plots show that each of the critical events had a different effect on the variables being plotted. We believe that the warning condition did not have an influence on the variables because of the event diversity and the ability of the subjects to anticipate the events and respond to them in a variety of ways. This was evident in the braking response times (not shown in Figure 3.54) where approximately half of the subjects either did not brake or began braking before the alert was given. This occurrence was independent of the critical event that was being experienced.

Like they did at the end of each side zone session, subjects filled out a questionnaire requesting their opinions about the warning systems that they had just experienced. The results from the questionnaire were similar to those from the simulation study and showed that there was a definite tradeoff between system effectiveness and system annoyance. Subjects thought that the systems were very effective at getting their attention, were very easy to sense and provided some sense of urgency. The only significant difference between these results and the simulation results was that in the simulation study, the subjects responded that the systems provided a better sense of urgency. This may be attributed to more complex situations in the simulator where there was more potential for danger.

Similar to the simulation study, the component that provided the most effective way of getting the subject's attention was the auditory alert. As with all the other testing (both side and forward, and simulator and closed course testing), subjects thought that the auditory alert was annoying and had the potential to become extremely annoying out in every day traffic. This is the case even though the subjects thought that the systems were very effective. These results are shown in Figure 3.55 where once again we see that the systems are rated very high in effectiveness but are also shown to be moderately annoying.
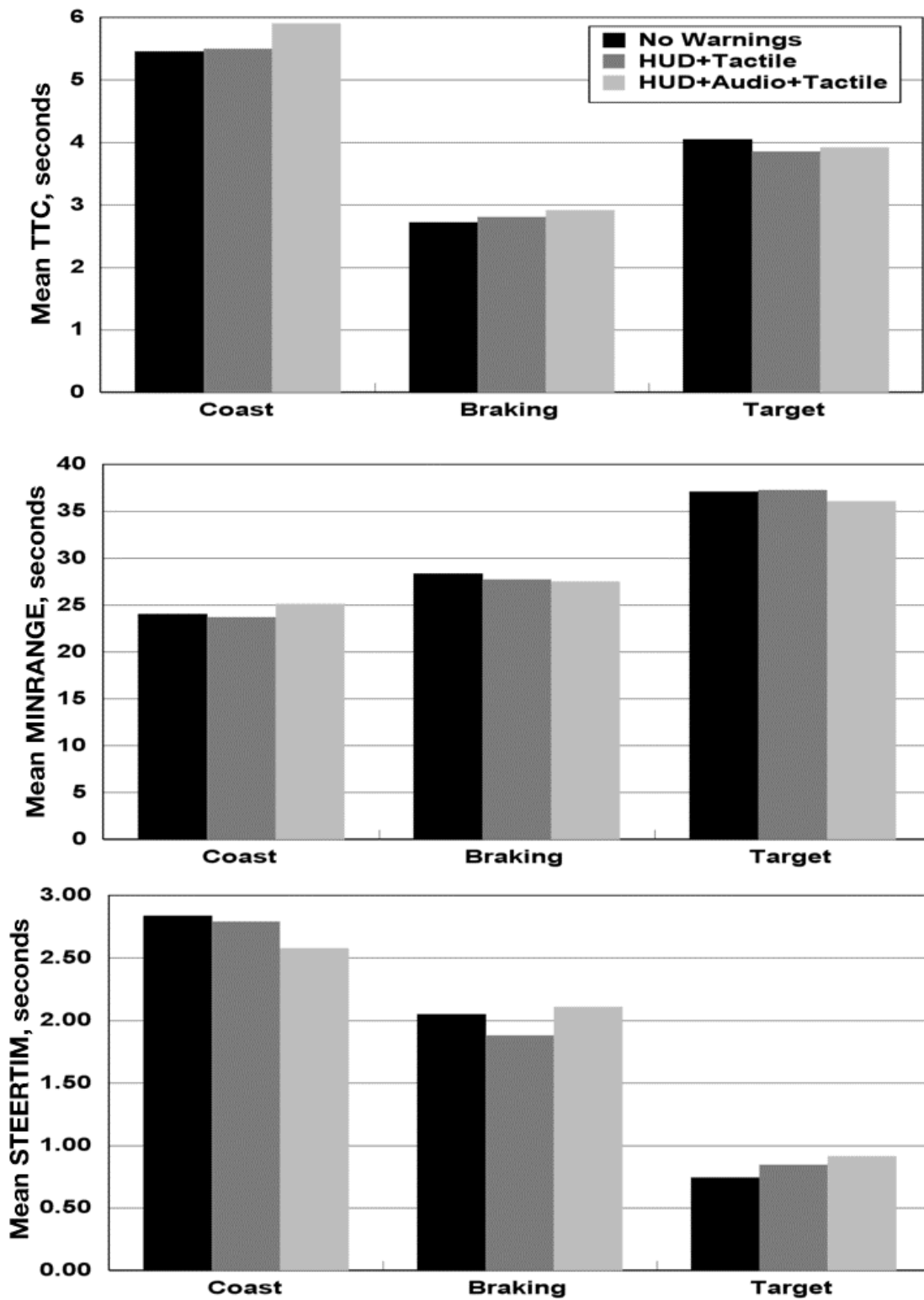
Figure 3.54: Mean Values of Selected Forward Zone Dependent Variables

Some of the other results that were obtained from the questionnaires included 85 percent of the subjects specifying that if cost were not an issue they would purchase a vehicle with a warning system on it. This was a definite increase over the simulation survey where 65 percent of the subjects stated that they would. In general the subjects stated that they had above average confidence that the systems would help prevent crashes from occurring, but only 20 percent of the subjects claimed that they were relying on the system which was almost identical to the simulation results. Finally, the warnings were less understandable then those presented in the simulation study but were still easy to learn and would probably require a minimal amount of training. The lower understandability is attributed to the warnings changing based on either cautionary or severe situations. In the simulator there was only a single warning for all critical conditions.

Finally, the subjects were asked to choose the best system of the 2 that they experienced. Half of the subjects preferred the system that combined the HUD with the tactile feel. A third preferred the system combining the HUD with the tactile feel and the auditory. The remaining said that they would prefer a system with only the HUD. This was not unexpected since over 70 percent of the subjects specifically commented about the HUD's effectiveness and how much they liked it. In fact this was the component that was best liked by the subjects. The main reason for this is because the warning was presented in their field of view, so they did not have to take their eyes off of the roadway scene and this provided more time for them to react. In addition, the HUD icons used in the closed course study were less complex and confusing then the icon used in the simulator and subjects perceived them to be informative and effective.

Subjects had mixed feelings about the tactile feel. Most of the positive responses indicated that it provided a clear message about what was going on and would be perfect if their eyes were not on the roadway. However, some subjects thought it was unnecessary and therefore distracting. Another major concern was how well it would work on rough roadways and would the driver be able to feel it.

As for the auditory tone, it was very effective at getting the subjects attention, but as the runs progressed it became increasingly annoying. This was especially true during false alarms. Subjects voiced concerns about the auditory alert in noisy areas such as construction zones and some also objected to the use of the word "BRAKE" for the severe warning. In these cases, subjects observed that braking might not necessarily be the correct response in all situations.
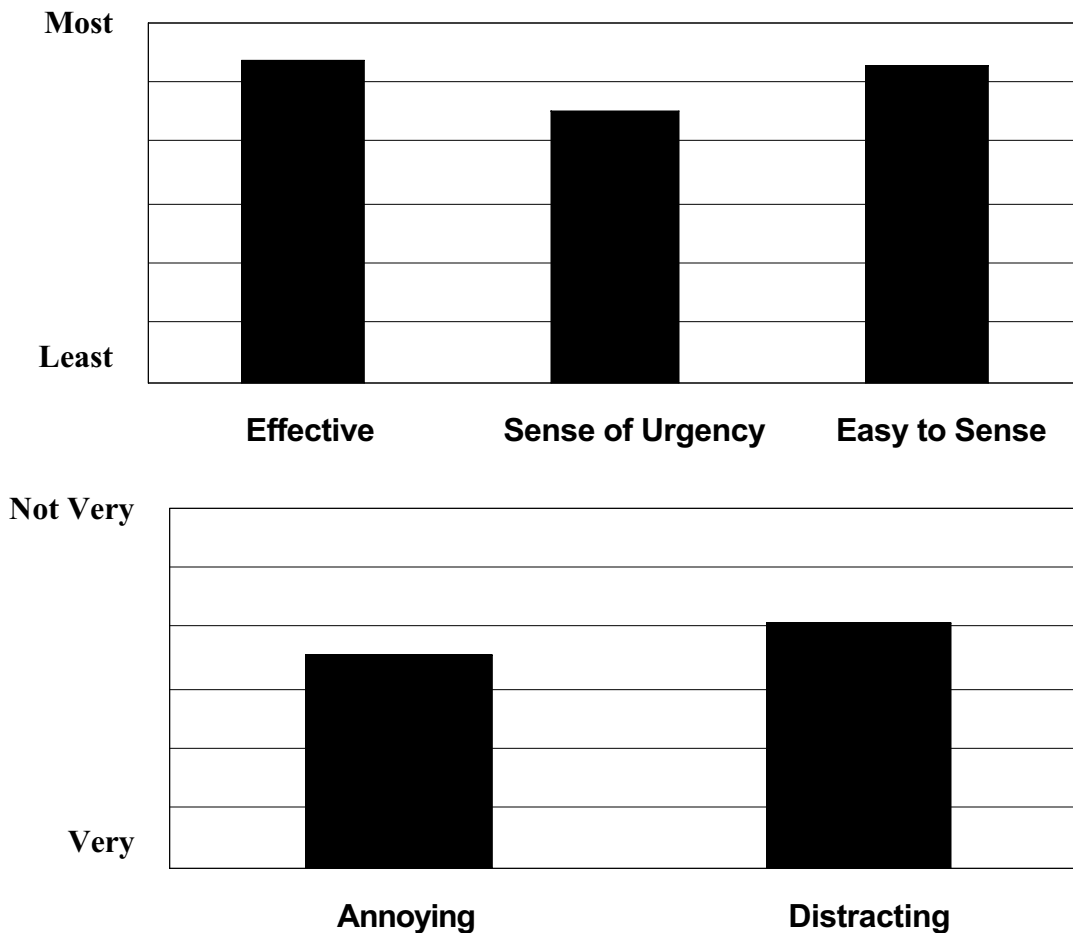
Figure 3.55: Subject Perception of Forward Zone Systems

A subject that has not really been discussed up to this point but is very important and therefore warrants its own special attention deals with false alarms. Over 80 percent of the subjects complained about false alarms that occurred during their test runs. This was by far the dominant response on the questionnaires. When we say false alarm what we mean is the system detecting something and warning the driver and the driver does not perceive it as a danger. During this testing there were several places along the test track were a false detection may have triggered the system to present a warning to the driver. For example, in one of the curves between the straight sections of the track there was a guardrail that caused a false alarm to be triggered. Even though the guardrail is a potential threat (if you go straight you will hit it) the driver sees it as a false alarm because they are steering through the curve and they do not perceive the guardrail as a threat. After the subjects received several of these false alarms, they started to become annoyed and this reduced the overall effectiveness of the systems because they are no longer sure if the system is reliable. As was stated above, this was the most dominant response and could cause drivers to not use the system. The general consensus was that the false alarms must be greatly reduced for these systems to ever become useful to the average driver. It should also be noted that negative responses to the false alarms were more prominent in the closed course testing than in the simulation study.

Summing up the forward zone closed course testing, several conclusions can be drawn:

- False alarms are a major concern because they are annoying and reduce the perceived effectiveness of the systems and they must be reduced before drivers will accept the systems.

- Overall the HUD was the best component that the subjects experienced.

- Auditory warnings are still the most effective way of getting the driver's attention but continue to be perceived as the most annoying component with the potential for further annoyance in actual traffic.

- Many subjects thought the systems would be great for situations where their eyes are not on the road.

- Comparison between the simulation study and closed course study show similar results were obtained in both. In general, the data trends were the same even if the magnitudes of the various data were not exactly the same.

3.13.4   Accomplishments and Future Directions

During the performance of the work required to complete Task 6.4, several different problems and issues were encountered, and handled. The following major accomplishments and program objectives were realized:

- The "Gold Car" was configured so that data could be easily collected during the test runs, the warning systems could be easily switched on the fly, and the experimenter could have some control over the vehicle during critical phases of the testing,

- Side zone closed course testing was conducted and the data analyzed,

- Forward zone closed course testing was conducted and the data analyzed,

- During data reduction and analysis the data was compared with the data obtained during the task 6.3 simulation runs,

- Produced and delivered the final report documenting the test results ("Task 6.4 – Experimental Results")

In general, all of the desired goals for this task of the project were met. However, because of the safety issues that were raised and the limited capability to constrain the driver and force them to do what we wanted, the objective data that was collected did not provide overwhelming statistically significant results. As with the simulation study, this is a result of human subjects adapting to the situations that we were presenting and based on our initial expectations, less was accomplished with the data than was originally expected. However, once again, the subjective results that were obtained from the subjects provided incredible insight into the systems and should be considered a major benefit and accomplishment of this task.

Work needs to continue on improving the MTT and CAP so that false alarms can be minimized. With today's sensors being good enough to detect lots of objects in the

vehicle's path, it is necessary to try and reduce the number of false detections that are presented to the driver.

The major emphasize of this study was to see how drivers reacted to a warning that they were given during dangerous driving situations. The data collection and reduction focused primarily on how the subject reacted and their overall opinions of the system's effectiveness and annoyance. Now that we have some idea in these areas, additional work needs to be performed to see if subjects can "blindly" recognize the warnings that they are given. In addition, work needs to be performed in order to determine the warning cues that are best at conveying the necessary information to the driver when the driver has had no training and knows nothing about the system.

Some of the data collection and critical event problems could definitely be improved if the driver were distracted in some way while driving during critical situations. By taking their eyes off the road, the driver is letting the warning system take over for them and thus a situation is created where the system does what is intended to do, provide assistance to a non-attentive driver. A better secondary task such as adjusting the radio, or having to do something in the back seat of the vehicle could accomplish this task. Any future controlled testing should examine the secondary task problem thoroughly before the tests are conducted. In addition to trying to take the driver's eyes off the road, adding additional interactive traffic and more lanes would greatly increase the realism of the task and force the driver to concentrate on more than just a single vehicle.

Since it is basically impossible to conduct every situation in a closed and controlled environment, placing test vehicles equipped with the warning systems out into every day real traffic situations would be the best course of action. This would allow subjects to evaluate the systems in a realistic way by taking them into heavy stop-and-go traffic, high speed traffic, over rough roadways and construction zones, and on curves and hills. By doing this, a true indication of effectiveness versus annoyance can be obtained.

Section 4
Program Conclusions

The Automotive Collision Avoidance Systems (ACAS) Development Program was formed to further investigate collision warning technologies. The program was originally set up to run for two years but several unexpected delays in simulator development caused the program to be extended for almost one extra year. Therefore, it turned into a three year program, with activities beginning in January 1995 and ending in October 1997. The main objective of the program, to provide a focused approach to accelerate the commercial availability of a portfolio of select high-value key fundamental collision warning countermeasure technologies/systems, was largely accomplished. Progress was made in improved manufacturing processes and accelerated technology development activities. As a result of this program, the gap between R&D and the deployment of new technology in the real world of driver-vehicle-highway systems was substantially bridged. As a matter of fact, this program provided a great deal of new knowledge concerning the influence of new technological capabilities on pertinent aspects of the driving process.

The program activities were accomplished through a cooperative arrangement between the U.S. Government and the program consortium, whose membership is comprised of both industry and academic participants. Financial support for this Program was provided by both the U.S. Government and program consortium members. The U.S. Government financially sponsored this activity through the Defense Advanced Research Project Agency (DARPA), in accordance with the goals of the Technology Reinvestment Program (TRP). The U.S. Government also actively participated in the ACAS Program activities, through NHTSA, which administered the ACAS Program on behalf of the U.S. Government.

The ACAS Program has laid a solid foundation towards the implementation of a comprehensive collision warning system, which is capable of detecting and warning the driver of potential hazard conditions in the forward, side, and rear regions of the vehicle. Performance requirements of the major components of the CW system, such as long range forward-looking detection sensors (radar or optical, short range side and rear detection sensors, and a lane detection vision-based were investigated. Finally, the effectiveness of a variety of warning cues were also studied. The results of this program have generated new insights for how the CW system should be configured and deployed.

The results demonstrated during this program have been broad, varied, significant, and very encouraging. For example, a varied and extensive analysis of crash data has been carried out in order to focus the system requirements of an integrated collision warning system. Several demonstration vehicles, equipped with the rudimentary capabilities of a forward collision warning system, have been designed, developed, constructed, and successfully demonstrated. These vehicles demonstrated the viability of the baseline system architecture. Additionally, remarkable progress has been achieved in the individual development of strategic

technologies/systems/components, in such areas as: active sensors (i.e., radar, laser and vision), algorithm/software development (i.e., collision warning processing components), and human factors. For instance, the linearity of a FMCW radar has been improved by an order of magnitude while the development unit cost has been reduced by a factor of three. The production unit cost is projected to be reduced by a factor of five. A significant improvement in sensor reliability was also achieved (zero field returns versus 20% prior to the ACAS program).

The collision warning processing algorithm suite matured as evidenced by the dramatic reduction of false alarms and missed detections. Besides the conventional Path algorithm, a new approach, Scene Tracking, was investigated, producing initial promising results. All MMIC radar transceivers were demonstrated with good system performance in numerous "over the road" tests, the design repeatability was demonstrated by multiple successful wafer runs, and the reliability of the design was verified through environmental tests. On the human factors front, a wide field of view (4.5 x 3.0 degrees) Head-Up Display (HUD) was developed with high brightness and excellent image quality. It was used for simulator studies as well as for limited test track studies. Several human factors studies were conducted either through use of a simulator or in actual driving to determine the best visual and auditory warnings for an effective collision warning (CW) system.

Although substantial gains in knowledge of the CW systems was achieved during the program, there is more work yet to be done. System performance to cost trade-offs is a never ending battle. The real world traffic environment is so varied that it is extremely difficult to make the system free of false alarms. In the future, the system development should take advantage of sensor fusion to increase its robustness. There is also the need to carry limited field operational tests to gain a more thorough understanding of the requirements, functions and societal impact of this technology. Because of the safety impact, any potential adverse operational and safety-related issues should be identified, analyzed, and addressed while the technology is still in the early stages of product development. This is possible only in real world driving situations.

Appendix A

Glossary of Acronyms

1D	An Array with only 1 vertical element (linear array)
2D	An array with 2 vertical elements (two dimensional array)
ACAS	Automotive Collision Avoidance Systems Development
AED	Automotive Electronics Development (A Delphi Delco Electronics Systems' Advanced Engineering Group located at Malibu, California)
CAP	Collision Avoidance Processor
COTS	Commercial Off-The-Shelf
CW	Collision Warning
DAS	Data Acquisition System
DC	Direct Current
DE	Delphi Delco Electronics Systems
Delphi-DE	Delphi Delco Electronics Systems
DFMA	Design For Manufacturing & Assembly
DVI	Driver-Vehicle Interface
FCW	Forward Collision Warning
FDDT	Finite Difference Time Domain
FEM	Finite Element Method
FLR	Forward-looking Radar
FMCW	Frequency Modulated Continuous Wave
FOV	Field-of-View
GM	General Motors Corporation
Gold Car	Delco Cadillac Demonstration Vehicle
GUI	Graphical User Interface
HBT	Hetero-junction Biploar Transistor
HDD	Head Down Display
HDS	HRL Driving Simulator
HEM	HE Microwave
HRL	HRL Laboratories, LLC (used to be Hughes Research Laboratories)
HUD	Head Up Display
I/O	Input/Output
LO	Local Oscillator

MB	Megabytes
MMIC	Microwave Monolithic Integrated Circuit
MMW	Millimeter Wave
MPH	Miles per hour
MTT	Multiple Target Tracker
NHTSA	National Highway Traffic Safety Administration
NODS	Near Object Detection System
PC	Personnel Computer
PCM	Process Control Monitor
R&D	Research and Development
RDS	Rear Detection System
RF	Radio Frequency
Rx	Receiver
SDS	Side Detection System
SGI	Silicon Graphics, Incorporated
STI	Systems Technology, Inc.
T/R	Transmit / Receive
TTA	Time To Avoidance
TTC	Time To Collision
Tx	Transmitter
UC-Davis	University of California at Davis
VCO	Voltage Controlled Oscillator
VSWR	Voltage Standing Wave Ratio

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