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Interim Report

Development of Performance Specifications for Collision Avoidance Systems for Lane Change, Merging and Backing

Task 4- Development of Preliminary Performance Specifications

Preface

This is an interim report that presents preliminary performance specifications for lane change, merging, and backing crash avoidance systems. The preliminary nature of the information is reflected, for example, on the fact that the report does not yet provide an estimate of the degree of certainty of the effectiveness of the countermeasure systems.

This report summarizes the work of Task 4, the last task of Phase I of the project. Substantial efforts are still needed for establishing pertinent crash avoidance systems, and for determining their effectiveness and reliability. It is expected that the remaining Phases, II and III, of this project will significantly contribute to the development of the indicated crash avoidance systems, and to the quantification of their effectiveness. The current schedule calls for the completion of this research project in the third quarter of 1997.

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16. Abstract

Preliminary performance specifications which accomplish the functional goals outlined in the Task 2 interim report (shown abridged in Appendix A) are developed for lane change, merge and backing crash avoidance systems (CAS). These preliminary performance specifications are based on analyses of Monte Carlo computer simulations, interactive driving simulator results and the evaluations of the CAS driver-vehicle interface (DVI) by human factors experts. The Monte Carlo simulations utilize travel speed distributions derived from the General Estimates System database and accident scenarios constructed from Crashworthiness Data System hard copy files and police accident reports. The structure and methodology of the Monte Carlo simulations and the interactive driving simulator are discussed in detail. In addition, a description of a sensor model, which provides a means of computing detection probabilities and which was included in both the Monte Carlo simulations and the driving simulator, is included. Using the Monte Carlo simulation, various sensor configurations and parameter fields are investigated for both passenger vehicles and large trucks. Using the interactive driving simulator, various configurations and modalities of the DVIs are investigated in lane change/merge and backing scenarios. The results of these analyses are presented herein.

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0.0 Introduction

The Office of Crash Avoidance Research (OCAR) of the National Highway Traffic Safety Administration (NHTSA) has a multidisciplinary program underway to identify crash causal factors and to study potential IVHS (Intelligent Vehicle/Highway System) technology countermeasures in alleviating various accident types. The US Department of Transportation has provided definitions of a full range of IVHS services (Reference l), and several of these provide the basis for definitions of collision avoidance systems (CASs). Three of these CASs involve augmenting the driver's ability in detecting roadway hazards, and may include semi- or fully automatic control. These systems include: longitudinal CAS for maintaining safe vehicle headways and avoiding rear end and backing collisions; lateral CAS for avoiding lane change, merge and roadway departure collisions; and intersection CAS to deal with hazardous situations occurring in the vicinity of intersections.

As part of the above effort, the Space and Electronics Group of TRW is funded by NHTSA through an Air Force contract to study the CAS for dealing with lane change/merge and backing collisions. This current contract provides for work over three phases to identify conflict scenarios associated with lane change/merge and backing situations, and to propose CAS countermeasures and develop a test bed for demonstrating these countermeasures. Work on Phase I of this contract has concentrated on four tasks: 1) analyze accident data base to identify lane change/merge and backing conflict scenarios; 2) establish functional goals for countermeasures base on results of the accident data base analysis; 3) test existing lane change/merge and backing systems; 4) and finally to develop preliminary performance specifications based on critical factors and models of crash scenarios.

This current report documents the results of the Task 4 work based on computer analysis modeling and simulation. This work was carried out in two parallel efforts. A computer simulation of sensor characteristics and vehicle kinematics was set up to analyze CAS influence on critical situations based on Monte Carlo techniques for sampling distributions of operating characteristics (conflict variables, driver/vehicle response time and amplitude). An interactive driving simulation was also developed using the same sensor model to study driver interaction with a CAS during traffic encounters in driving scenarios emphasizing lane change/merge and backing conflicts.

The above two parallel simulation approaches were designed to address different aspects of the CAS problem. The Monte Carlo simulation was devised to focus directly on critical lane change/merge and backing conflicts, and provide a sensitivity analysis of various driver/vehicle and CAS response characteristics on accident avoidance potential. The driving simulation was conceived to study the CAS driver/vehicle interface (warning displays) and driver reaction to CAS operational characteristics during lane change/merge and backing conflict encounters. Since we had limited control of conflict kinematics in the interactive driving simulation, emphasis was placed on human factors considerations and driver subjective impressions.

The following section of this report (1.0 Background) describes work from earlier tasks on this project and their inputs to the simulation analysis which is the focus herein. Subsequent sections describe the detailed approach and methodology of the simulation approaches and the results of the Monte Carlo analysis and driving simulation experiments. Several appendices give more detailed information on the functional goals, CAS sensor models, and the driving and Monte Carlo simulations.

1.0 Background

The case by case analyses of accident data and police accident reports from the 1992 Crashworthiness Data System (CDS) and the 1992 General Estimates System (GES) suggest that most backing and lane change/merge crashes are due to the driver's being unaware of the potential crash threat posed by the other vehicle, pedestrian/pedalcyclist or fixed object. For this reason, any system which detects the threat and warns the driver with enough lead time to perform corrective action will mitigate the effects of these collisions. Although neither database contains the information on when the driver first perceived the threat, the fact that in less than 8 % of the traditional lane change/merge and backing crashes did the driver even attempt any corrective action indicates that the driver was caught by surprise or did not have sufficient time to respond. It is entirely possible that the threat was never perceived. Many CDS case analyses indicate this.

The warning system must be sufficiently extensive to provide enough time between the warning and the anticipated crash for adequate evasion. Driver reaction times range from a few tenths of a second to a few seconds. The evasion (braking, steering, etc.) also requires another increment of time-before-crash to accomplish the avoidance. The nature of the corrective action is probably instinctive, depending on the perceived threat, such as steering away from a threat in the "blind spot", braking to avoid running into someone/something, or braking and steering in fast-closing circumstances.

In all these cases, the function of the countermeasure system is to warn the driver of imminent danger in a timely manner. Our goal is to analyze the parameters of a crash avoidance system (CAS) to determine the requirements of one which warns the driver with sufficient time to avoid the crash.

The Task 2 report presented the results of the analyses of the crash scenarios and developed a set of CAS functional goals designed to mitigate these crashes. The objective of Task 4 is to further develop and test these preliminary performance specifications for a lane change/merge and backing CAS to achieve each of the identified functional goals (described in Appendix A). Using Monte Carlo simulation techniques, the parameters of the CAS are tested against potential crash scenarios to determine those parameters producing the maximum effectiveness. Using a driving simulation, subjective evaluations of the placement and modality of the CAS display and the CAS activation can be accomplished.

As part of this study, under the Task 3 effort we have evaluated a significant number of existing CAS devices. For the types of accidents investigated here, they fall into three general categories, namely, proximity sensors looking to the side of the vehicle, proximity sensors looking towards the back of the vehicle, and longer range sensors to detect higher speed vehicles approaching from behind the vehicle in an adjacent lane. These devices are attempting to address significant accident types utilizing technology that can be fielded today. They meet only a subset of the functional goals found in Appendix A, but they are the most important ones.

In this task, we will quantify the preliminary performance specifications for these types of CAS, two for lane change/merge collision avoidance and one for backing. Specifically, we will address systems which detect the presence of vehicles in the lane adjacent to the instrumented vehicle and warn the driver if appropriate during a lane change/merge maneuver. Also, there are systems that detect higher closing speed vehicles approaching from behind the instrumented vehicle in the adjacent lane. By turning these systems around to look ahead of the vehicle, then vehicles in the adjacent lane traveling more slowly than the instrumented vehicle can be detected, and the driver can be alerted during the lane change/merge maneuver. (It has been documented that many lane change/merge accidents occur when the maneuvering vehicle is traveling faster than the struck vehicle.) This set of three systems for each side of the vehicle will constitute the lane change/merge CAS whose preliminary performance specifications will be addressed.

This leaves out those systems which warn against drifting accidents, those which explicitly cover simultaneous lane changing by two vehicles, systems which take some form of active control of the vehicle, and those which provide roadway warnings to both the merging vehicle and those potentially in the path of the merging vehicles. The drifting accidents would be better avoided by a lane keeping system that would alert the driver whenever a lane boundary was being crossed while no turn signal was activated. (We are aware of research with video, radar, and passive millimeter wave systems to perform this lateral position control task which is also very useful for navigational systems.) Accidents when two vehicles are simultaneously lane changing are very rare, and we believe that many of them could be avoided by the suite of systems we've considered. Active systems which take control of the vehicle are not included in this study explicitly. Most likely, they would provide the same warning as the systems discussed here. The only difference is that the active systems would take some level of control of the vehicle if the driver

has not responded appropriately to the warning within some predetermined time. Finally, roadway based systems that monitor fixed locations where large numbers of merges take place may some day be considered. For those systems, the sensing range of the traffic detecting segment can be quite short as long as the communication system that provides the appropriate warning to oncoming traffic is correctly placed with sufficient visibility.

With regard to a backing CAS, we will consider the preliminary performance specifications for a system to avoid accidents while backing that involve pedestrians and pedacyclists, fixed objects, vehicles in a parallel path and some slow moving crossing traffic. With regard to a system to warn others of the instrumented vehicle's backing maneuver, we believe that is better left to another study if the suggestion is deemed attractive. The placement of additional backing lights, the utilization of audible warnings as utilized on trucks, and other methods would be addressed. For higher speed crossing traffic, it is a very difficult problem for either the backing vehicle or the one on the crossing path to detect the other. Either a system with an enormous angular field of view (leading to many potential false and nuisance alarms) would be necessary, or a cooperative remote sensing/communication system (like the ones that may be employed at intersections) could be utilized at particularly dangerous sites.

For the classes of CAS described above, the preliminary performance specifications will be addressed in the rest of this report. Generic sys terns will be proposed and evaluated in a statistical and human factors sense against a variety of potential crash situations generated from our analyses of the accident data bases mentioned previously. The collision avoidance potential, defined as the fraction of accidents avoided by utilizing the CAS, will be estimated in our simulations as a function of a variety of parameters to be specified. Ranges of acceptable values will be defined by investigation of the relative variation of collision avoidance potential with these parameters. This is done on a statistical basis utilizing the widely accepted Monte Carlo technique which is discussed in Section 2.3 and Appendices E and F. To gauge the acceptable ranges of display warning positioning, activation, and modality, a driving simulation will be employed where the subjective impressions of a number of naive drivers will be assessed. That driver-in-the-loop simulation tool is described in Section 2.4 and Appendix C.

Monte Carlo simulations are used to study the relative behavior of the percentage of crashes avoided (the crash avoidance potential) when

various system parameters, such as the number of sensors or sensor range or latency time, are varied. Many assumptions are embedded in the Monte Carlo codes which can strongly affect the absolute value of the crash avoidance potential. These include assumptions concerning driver compliance, the nature of the evasive action employed and the passive nature of the other vehicle. The results of the Monte Carlo simulations are to be compared only among themselves as indicators of which sensor configurations and detection pattern parameters may tend to promote better values of the crash avoidance potential than others. As in the case of any theoretical calculation, the results of the Monte Carlo simulations must be considered with this caveat in mind.

The rest of this report is organized as follows. Section 2 delineates our approach to the preliminary performance specification task and briefly describe the tools employed. Each of these approaches is discussed in detail in the appendices. Our methodology which allows us to investigate all the factors discussed in the original statement of work is also presented in Section 2. The results of the numerous simulations performed are contained in Section 3 and the derived preliminary performance specifications are delineated in Section 4 along with conclusions and suggestions for further work.

2.0 Approach and Methodology

2.1 Overview

Two simulation approaches have been applied herein to the study of the efficacy of Crash Avoidance Systems (CASs). The Monte Carlo computer simulation is designed to focus specifically on conflict situations, assuming the driver is not aware of surrounding traffic, and determine whether the CAS alarms assist the driver in avoiding collisions. The Monte Carlo simulation accounts for a distribution of driver response characteristics (i.e. control timing and intensity) and conflict variables (i.e. closing speed and distance) and considers whether the driver responds rapidly enough given an alarm, to avoid an accident. The driving simulation includes the same sensor and processing characteristics as the Monte Carlo simulation, and also driver warning display interface components of lane change/merge and backing crash avoidance systems. Subjects are exposed to driving scenarios with potential traffic conflicts in the interactive simulator, but actual conflicts depend on the driver's situation awareness which is assisted by rear view mirrors as well as the CAS warning displays. In general, the driving simulation approach focuses on the driver's reaction to the CAS warning display formats, and the response of the CAS in traffic situations.

The combination of the Monte Carlo and interactive driving simulator approaches was designed to consider the influence of a range of variables that will impact the general efficacy of CASs. The two simulators dealt with these variables in the follow manner:

2.1.1 Situational Kinematics

This area includes relative distances and velocities between vehicles and absolute velocity of the subject vehicle. In the Monte Carlo simulations, these are sampled from the observed travel speed distributions found in the 1992 GES database and the associated police reports. Since there is no data on the initial gap distances in situations leading to crashes, the initial gap distance is randomly sampled from a uniform distribution.

In the driving simulation scenarios, relative distances and velocities are accounted for as dependent variables . Traffic actions and potential conflicts are programmed into the driving scenarios that presented the full range of distance and velocity effects. These

effects are influenced by traffic behavior, but are not completely controlled because their occurrence depends in large degree on the maneuvering of the subject drivers. Traffic scenarios have been developed to include vehicles that approached from the left and right and may stabilize in the driver's blind spot. Interactive vehicles have been programmed to match the subjects' speed and stay in their blind spot. Interactive vehicles have also been programmed to pass the subject drivers, pull into their lane, then slow down to motivate the drivers to vary their speeds and change lanes. Interactive Roadway situations (gradual lane blocks using barriers and construction barrels) are also programmed to require lane changing on the part of the subject drivers.

2.1.2 Environmental

Light condition is an independent variable that can influence driver visibility of road and traffic conditions. For the purposes of the driving simulation experiment, half the subject population will drive under daylight visibility conditions, and the other half will drive under compromised lighting conditions. The Monte Carlo simulation does not directly address variations in lighting conditions.

2.1.3 Highway/Traffic

Traffic levels are handled as an indenendent variable in the driving simulation scenarios. There are a range of traffic levels programmed to induce various conflict scenarios. The driving scenarios also include horizontal curvature as an independent variable. Traffic scenarios are run on both straight and curved sections of roadway. The sensor models are consistent with a vertical range sufficient to handle any reasonable vertical roadway curvature and at the same time avoid the sensing of overhead objects such as road signs or overpasses. The Monte Carlo simulations consider only the interaction of the SV and a single obstacle per case.

2.1.4 Crash Avoidance System

There are a range of independent variables having to do with the driver/vehicle interface that may influence driver response and reaction to CAS operation. The characteristics of auditory and visual displays are quite pertinent. The driving simulation includes variations in the display interface as indenendent variables. In the Monte Carlo simulation, the CAS detection patterns, system latency and update times are simulation inputs.

2.2 Sensor and System Models

The sensor model, which is used by both simulators, is generic. The probability of detection is calculated for all objects in the scene. Of course, that probability lies between 0.0 and 1.0. After each evaluation of the probability of detection, a random number is generated uniformly between 0.0 and 1.0 and the random number is compared to the probability of detection. If the random number is less than or equal to the probability of detection, a warning is issued. If the random number is greater than the probability of detection, the target is not detected. Since long range sensor models may incorporate velocity discrimination algorithms, these may be included in the long range sensor models as required. Proximity sensors may incorporate range discrimination. This may also be included in the proximity sensor models as required. A more detailed description of the sensor model is found in Appendix B.

The latency time, the time required by the CAS to detect the danger and instruct the driver, is a system parameter which may be varied in both the interactive driving simulator and the Monte Carlo simulation. In the Monte Carlo simulation, the vehicle's response time for counteracting is embedded in the code. In the driver simulator, the driver's perception of longer delays is gauged, and in the Monte Carlo simulation, the degradation of the system's effectiveness with longer latencies is determined.

2.3 The Monte Carlo Statistical Simulation

The ability of the CAS to reduce the number of crashes is investigated through the use of several simulations utilizing Monte Carlo sampling techniques. In this case, such parameters as the maximum lateral and longitudinal extents of the various coverage zones and the allowable latencies of the warnings can be studied by computing the potential relative reduction of crashes by the CAS systems as these geometrical and temporal parameters are varied subject to the assumptions contained in the simulations. (See Appendices E and F.) For lane change/merge simulations, the speeds of the subject vehicle (SV) and the principal other vehicle (POV) are sampled from distributions of the travel speeds of drivers involved in crashes. These distributions are derived from data obtained from 1992 General Estimates System (GES) database. Depending on whether the SV's travel speed is classified as "slow", "moderate" or "fast", the closing speed of the POV is taken from a second distribution, also derived from the 1992 GES database. For backing simulations, the scenario information is derived from police accident

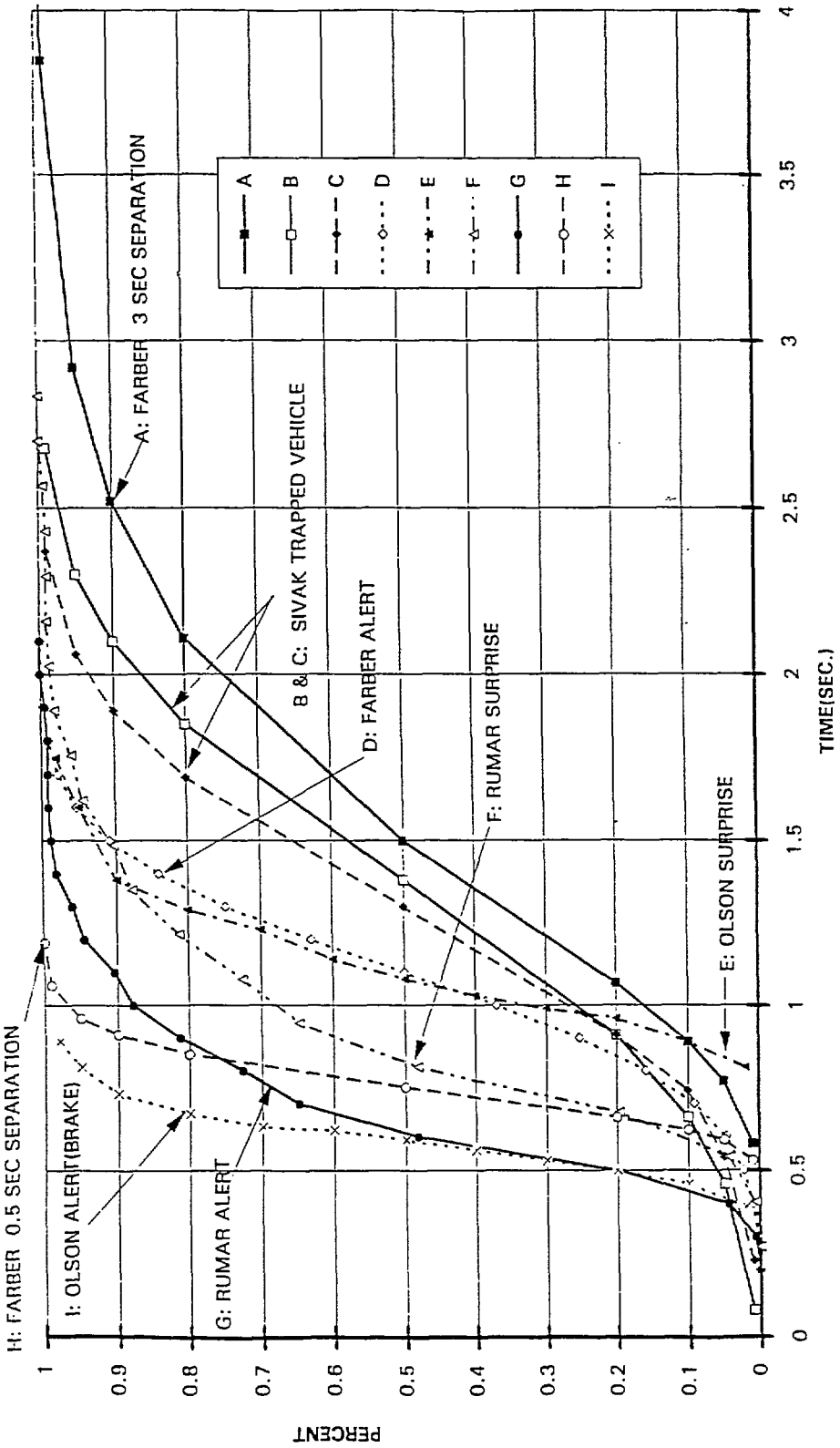
reports (PARs) which formed the basis of the information included in the 1992 GES database.

Monte Carlo sampling techniques are frequently used in evaluating situations in which many variables are drawn from experimentally determined distributions. In these cases, analytical forms of the distributions may not be available, or there may be so many distributions involved in the calculations that the mathematics of an exact solution are intractable. Monte Carlo refers to a technique by which the distributions of a variable is sampled through the generation of a random number. This technique enables the simulation to sample the entire distribution of the variable, for example x, including the “tails” in which only a few cases reside. The entire distribution of x should be sampled because it is possible that the cases represented by the tails of the distribution may strongly affect the results. Neglecting these cases would then lead to erroneous conclusions. In the TRW simulations, Monte Carlo sampling is used to determine the driver’s reaction time and travel speeds and for backing acceleration and the closing trajectories of backing targets. Initial longitudinal gaps are determined by sampling a uniform distribution between preset limits for both types of accidents. The simulations consider only the interaction of the SV and a single obstacle or other vehicle per case. Descriptions of the TRW Monte Carlo simulations are found in Appendices E and F.

In the Monte Carlo simulation, the driver's characteristics must be modeled. The driver’s waiting time between activating the turn signal or putting the vehicle in reverse and initiating the lane change or backing maneuver is considered to be a driver parameter and set at the beginning of the run. Also the maximum intensity of evasive action and the time available for counteracting are embedded in the codes. Reasonable values have been assumed.

Studies have derived several distributions of drivers’ reaction time, t_{react}, as shown in Figure 2-l. (Reference 2) Frequently, the Taoka surprise reaction times have been used. However, it may be argued that a driver of a vehicle equipped with a CAS is not surprised when the CAS delivers a warning, and therefore, the reaction times characterized by Rumar alert reaction times are more appropriate. Also, when a driver is performing a more stressful maneuver such as a lane change/merge or backing up, the driver is more alert and hence the alert driver reaction times distribution may be more appropriate. Simulation runs have been conducted for both sets of reaction times. No information is currently available on the distribution of drivers’ reactions to the CAS warnings or choices of

Figure 2-1. Driver Reaction Time Distributions



evasive maneuvers, if any. These reactions include driver's rejection of the warnings or delay in taking action to verify the threat. The Monte Carlo simulations presented here assume various driver responses as discussed in Appendices E and F. If other driver responses are included or assumed, the results of the simulations could change.

2.4 Interactive Driving Simulator

The driving simulator used in this research is described in some detail in Appendix C. For the purposes of this research CAS features were added to the simulation, including a sensor and processing model as described in Appendix B, and visual and auditory warning displays. The sensor model was set up to respond to all elements in the display scene that were above the ground plane. This included other vehicles as well as traffic control devices such as signs, barriers and construction zone barrels.

The general elements of the simulated CAS and their inter-relationships with the vehicle and driver are illustrated in Figure 2-2. The sensor model detected potential collision threats. Processing provided commands to driver displays which were presented in visual and/or auditory formats.

Figure 2-3 portrays the sensor detection patterns for lane change/ merge and backing CASs. For lane change and merge, sensors provided coverage of the blind spot and rear overtaking zone. Backing sensors included a rear obstacle detection sensor and, in some cases, side looking sensors for crossing path conflicts. After several initial trials, the cross path sensor was omitted due to the high rates of inappropriate nuisance alarms.

The warning displays included arrows that could be presented in the center rear view mirror or a heads-up display (HUD) location at the bottom of the windscreen as illustrated in Figure 2-4. The location of the potential collision was indicated by the arrow direction. Auditory tones were also used as a warning for more severe conflicts. These are generally consistent with the COMSIS guidelines. (Reference 3)

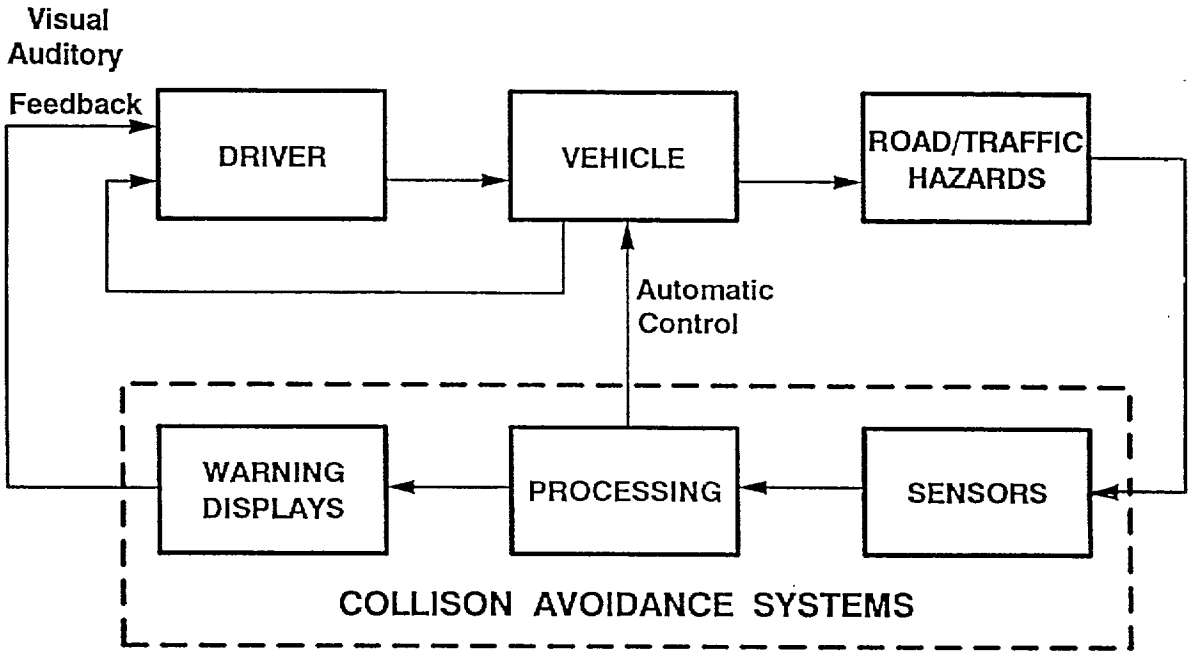


Figure 2-2. CAS Block Diagram

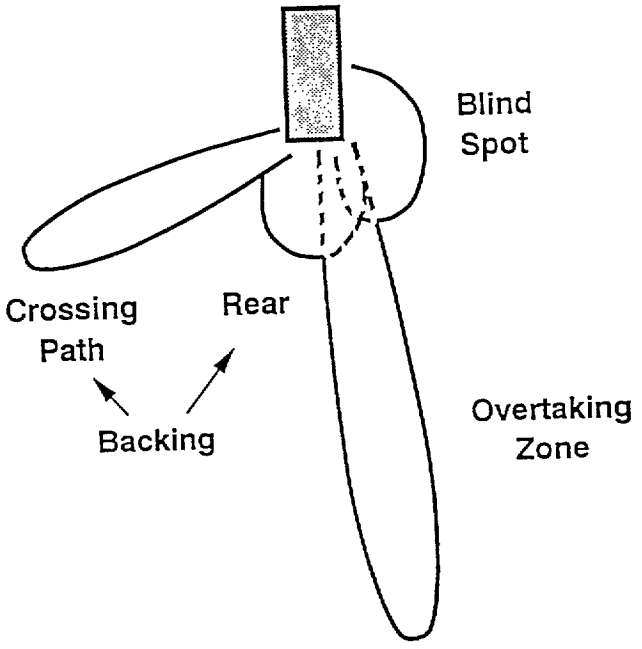


Figure 2-3. Simulator CAS Sensor Coverage

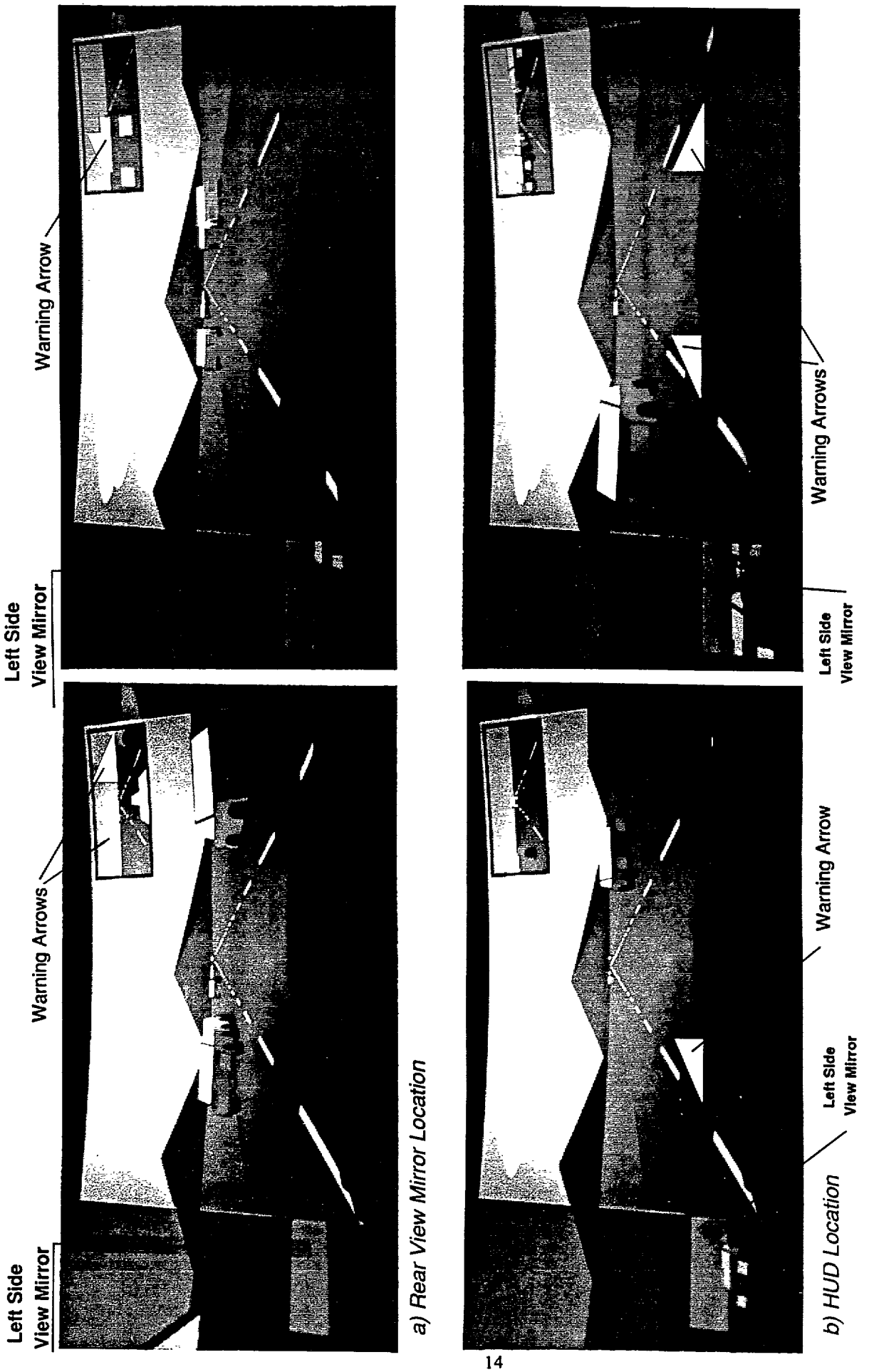


Figure 2-4. CAS Visual Display Warnings

2.4.1. Lane/Change Merge Experiment Methods

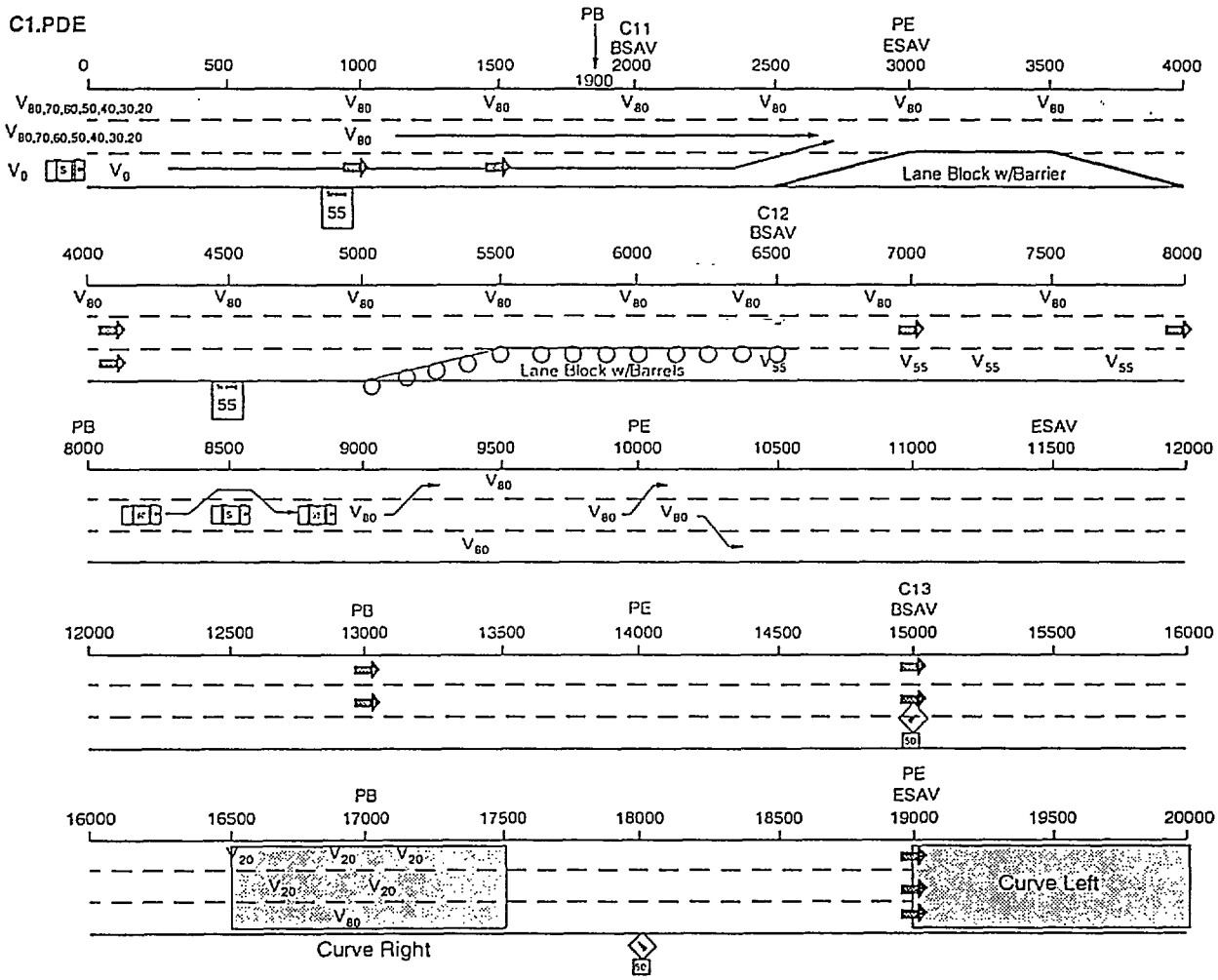
2.4.1.1 Driving Scenarios

Driving scenarios were designed to present traffic situations with potential conflicts. Adjacent traffic was programmed to interact with the subject driver, and situations were created to encourage or force lane changing. Subjects were encouraged to change lanes by having interactive traffic pass them, pull into their lane, then slow down. Drivers were forced to change lanes or merge to the left through the use of lane drops defined by barriers or temporary construction barrel delineators that gradually shut down a lane. Less than one quarter of the merging crashes occur on interstate highways or in interchange areas. Entrance/exit ramps were not modeled.

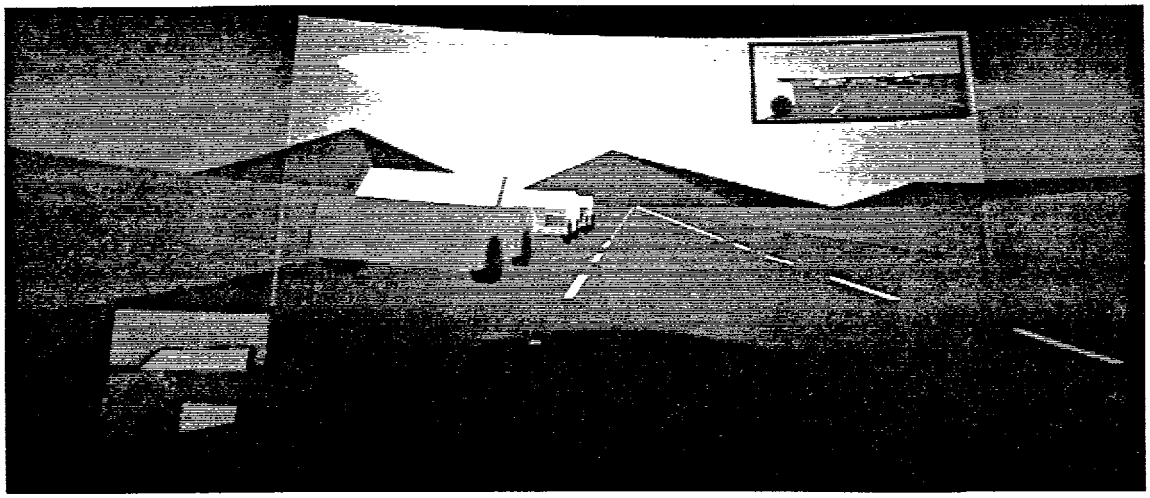
A schematic representation of a typical driving scenario is illustrated in Figure 2-5. Three such 5 minute driving scenario components were prepared then combined into 6 counterbalanced 15 minute scenarios to provide variety in traffic conditions encountered between runs. Figure 2-6 shows several traffic situations involving lane changing. Figure 2-7 shows the use of barriers and construction barrels to encourage merging. Figure 2-8 shows horizontal curvature segments of driving scenarios.

A key objective of the driving scenarios was engaging drivers in encounters which required lane changing and merging. Drivers were positioned prior to conflict situations by lane assignment arrows as illustrated in Figure 2-8-a. Merging was then forced through the use of lane drops created by barriers and construction barrels, and traffic was positioned in the adjacent lane to provide conflicts. Interactive traffic maneuvering was specified relative to the subjects vehicle, so that some control could be exerted over conflicts. For example, an overtaking vehicle could be commanded to stabilize in the driver’s blind spot. Traffic maneuvering could be specified in general, including speed, braking and lane changing.

Figure 2-5. Schematic of Typical Simulated (Lane Change/Merge) Driving Scenario

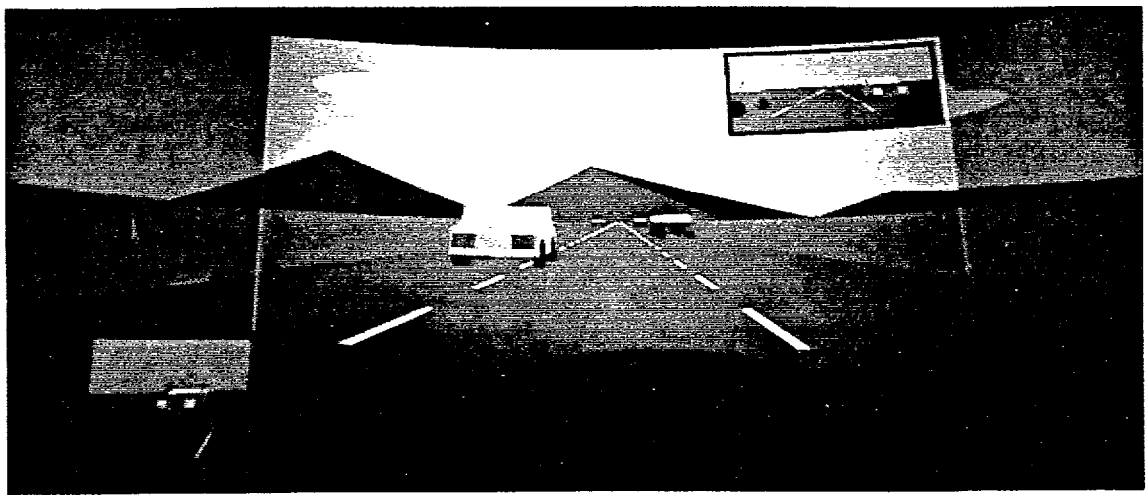


The subject vehicle (simulator) or SV is denoted by S on the schematic. The SV begins this sequence stopped in the right lane. A number of vehicles (denoted by V) of various speeds are passing in the two lanes to the left. After 2500 ft., the SV is forced to merge left by a lane blocking barrier which continues for 1000 ft. After the barrier, there is free driving until the right lane is again blocked, this time by barrels. The driver is forced to merge left. After the barrels, there is again free driving but with interactive traffic. In the case shown, the first interactive vehicle follows the SV, changes lanes to the left and passes the SV and then changes lanes to the right to move to the center lane in front of the SV. The second and third interactive vehicles also approach from the rear, changing lanes to the left and to the right to pass the SV. Meanwhile, the first interactive vehicle (which is now directly in front of the SV) begins to slow. The driver of the SV is thus encouraged to change lanes but must do so safely while other traffic is moving past him on the right and left. After another period of free driving, the road curves to the right and then later to the left. During the curves, the driver must contend with traffic (not interactive).



a) *Vehicle in Blind Spot*

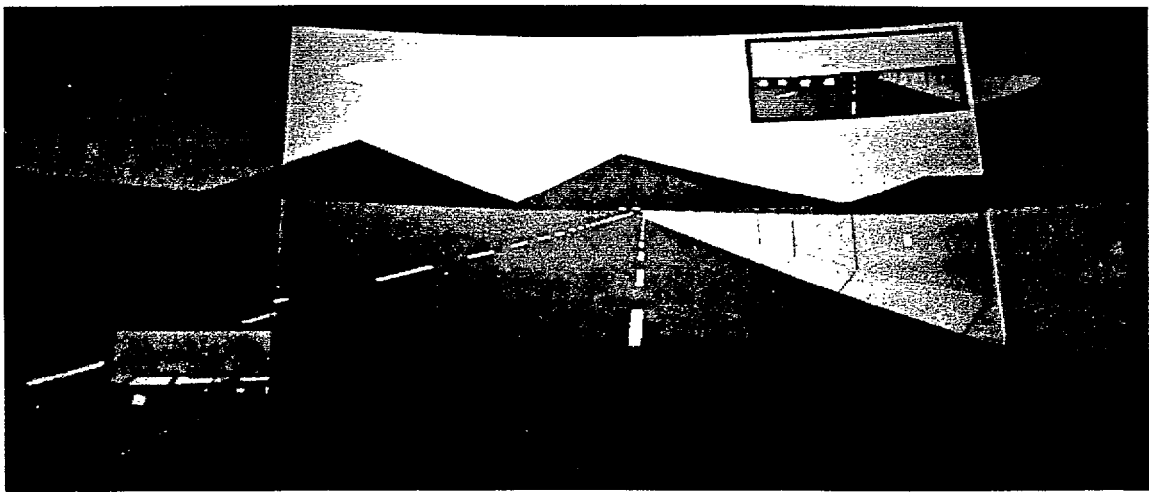
b) Safe Lane Change



c) Lead Vehicle Changing Lanes

Figure 2-6. Lane Change/Merge Driving Scenario:
Lane Change Situations

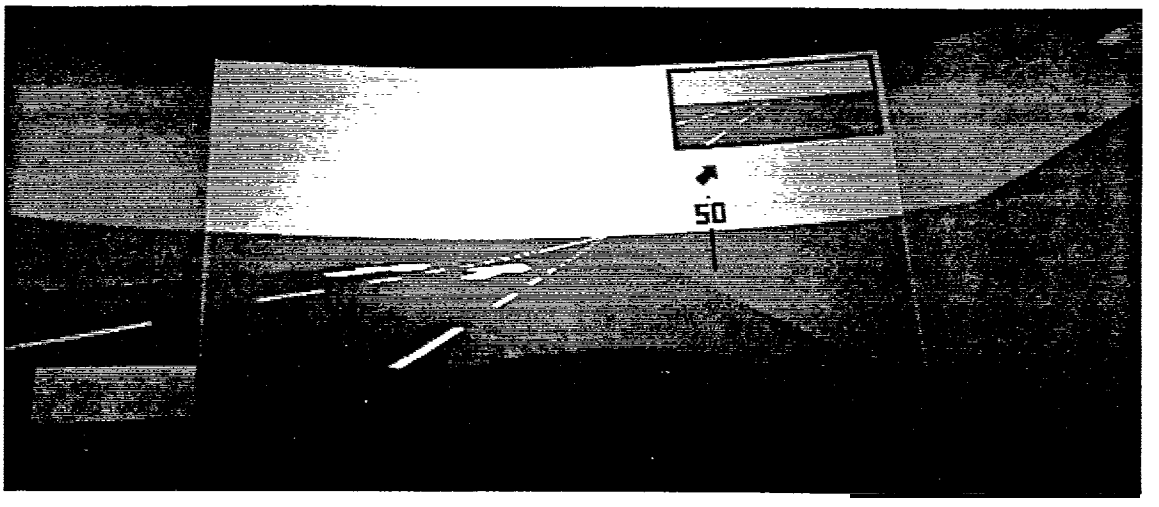
a) Barrier Forced Merge



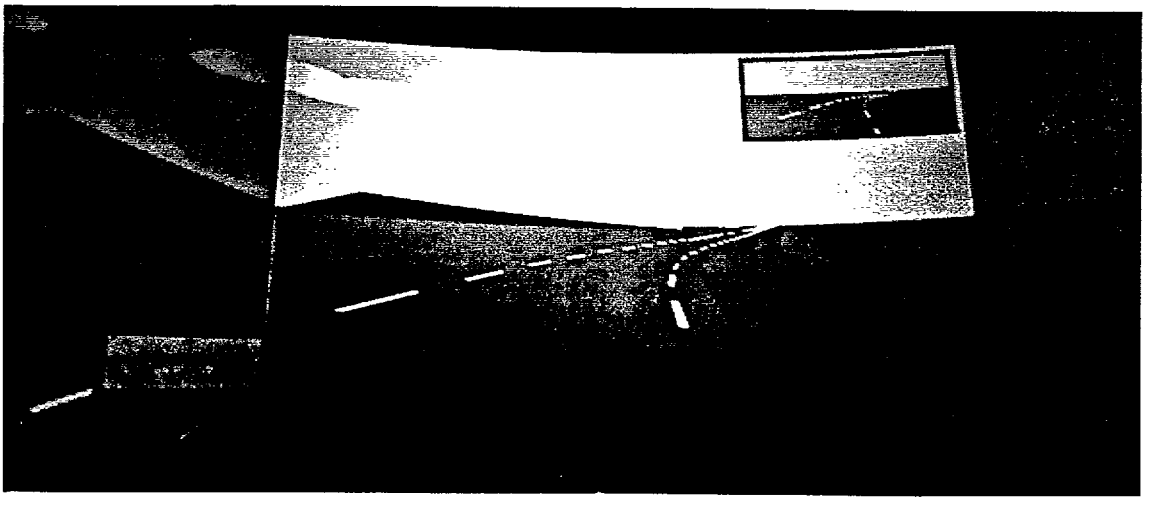
b) Barrier Forced Merge

c) Construction Barrel Forced Merge

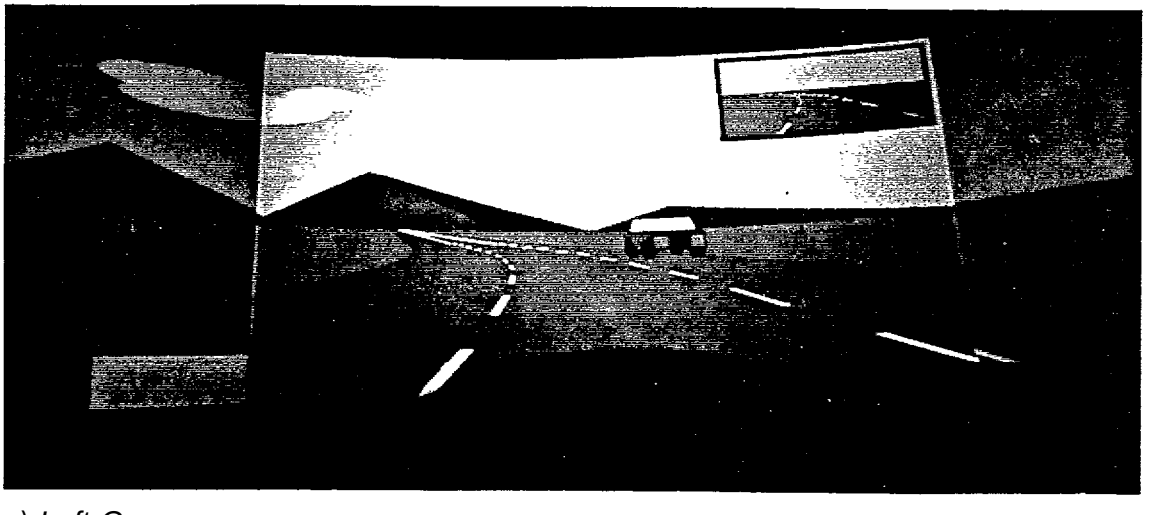
Figure 2-7. Lane Change/Merge Driving Scenario:
Merge Situations



a) Speed Warning Sign + Lane Assignment Arrors



b) Right Curve



c) Left Curve

Figure 2-8. Lane Change/Merge Driving Scenario:
Horizontal Curvature

2.4.1.2 Pilot Experiment

A pilot experiment was conducted to settle various experimental design issues for the formal lane change/merge experiment. The objectives of the pilot experiment were to determine how successfully conflict situations could be controlled, what data might be collected in conflict situations, and what CAS configurations might be presented to each subject. Drivers were exposed to 20 minute traffic scenarios as discussed above. During these drives, subjects were given current information on traffic conflicts via the center rearview and left and right sideview mirrors in addition to the CAS warnings.

After several subject trials, it became apparent that true traffic conflicts were difficult to stage because drivers were obtaining good situation awareness through their rear and side view mirrors. In real life these conflict situations are rare events, and this was true in our simulation even with the staged encounters. Data reduction was carried out on the staged conflict situations to determine what objective measures of conflict severity could be obtained. In these cases we analyzed traffic profiles to determine the proximity of path interactions, but no obvious productive metrics of conflict severity were found.

At this point other approaches were considered but would have required considerable further scenario development and pilot testing. Resources were not available for this effort. Our final approach was to test human factors issues associated with system response and display interface format.

2.4.1.3 Experimental Design

The experimental configurations and variables chosen for analysis are summarized in Table 2-l. System configuration includes whether the alarms are only activated with the turn indicator, or are continuously activated. System response characteristics include false and nuisance alarms and latency due to processing delays. Display variations of the visual warning include the presence and position (center rearview mirror or HUD). Other environmental conditions include time of day (daylight/dusk, or compromised lighting) and roadway curvature.

Crash Avoidance System Warning
- Turn indicator activated
- Continuously activated

Warning Configuration
- HUD visual display plus auditory
- Rearview mirror visual display plus auditory
- Auditory only

Warning System Latency
- Short (0.10 seconds)
- Long (0.50 seconds)

Lighting Condition
- Daylight
- Dusk

Gender
- Femaie
- Male

Table 2-l. CAS Configurations and Experimental Variables for Lane Change/Merge Scenarios

Driver subjective opinion was expected to be the primary results of the experiment. In order to obtain subjective comparison of various system characteristics, each subject experienced all of system configurations listed in Table 2-l.

2.4.1.4 Procedures

Upon arrival at the testing facility, subjects received a short introduction on the experiment. They were given an orientation to the driver simulator and allowed a five minute practice scenario with the CAS warning displays on continuously. Some coaching of the drivers was required in order to ensure desired interaction with the conflict scenarios and transition between conflicts. The necessity for giving some guidance to the driver was due to the limited interaction of the traffic. The guidance provided to the subjects was not unlike that of a passenger/navigator. A fine line was observed by the experimenter, giving an appropriate amount of guidance while trying to keep the driving scenario from becoming artificial.

The experimental design was structured to account for the independent and dependent variables discussed above. Each subject drove scenarios without the system and with the system in various configurations. Subjects drove 15 minute scenarios without the system, and with the system either continuously activated, or activated with the turn signal. These three conditions were counterbalanced between subjects. The display configuration for these 15 minute exposures included visual and auditory alarms with the visual arrow warnings displayed in the HUD position. Subjects were also given 5 minute exposures with the visual arrow warnings in the rearview mirror position, and with auditory alarms only (no visual warning). A final condition included increasing the sensor processing time from 0.10 second to 0.5 second (See page 21.).

Data collection consisted of questionnaire responses. The questionnaire is given in Appendix D. The beginning of the questionnaire on background was administered when the subject reported for testing. Some responses were collected after the major 15 minute scenarios were completed and again after exposure to each 5 minute scenario. The final responses were collected at the completion of the session.

2.4.2. Backing Experiment Methods

The backing CAS was enabled whenever the driving simulator was shifted into reverse gear.

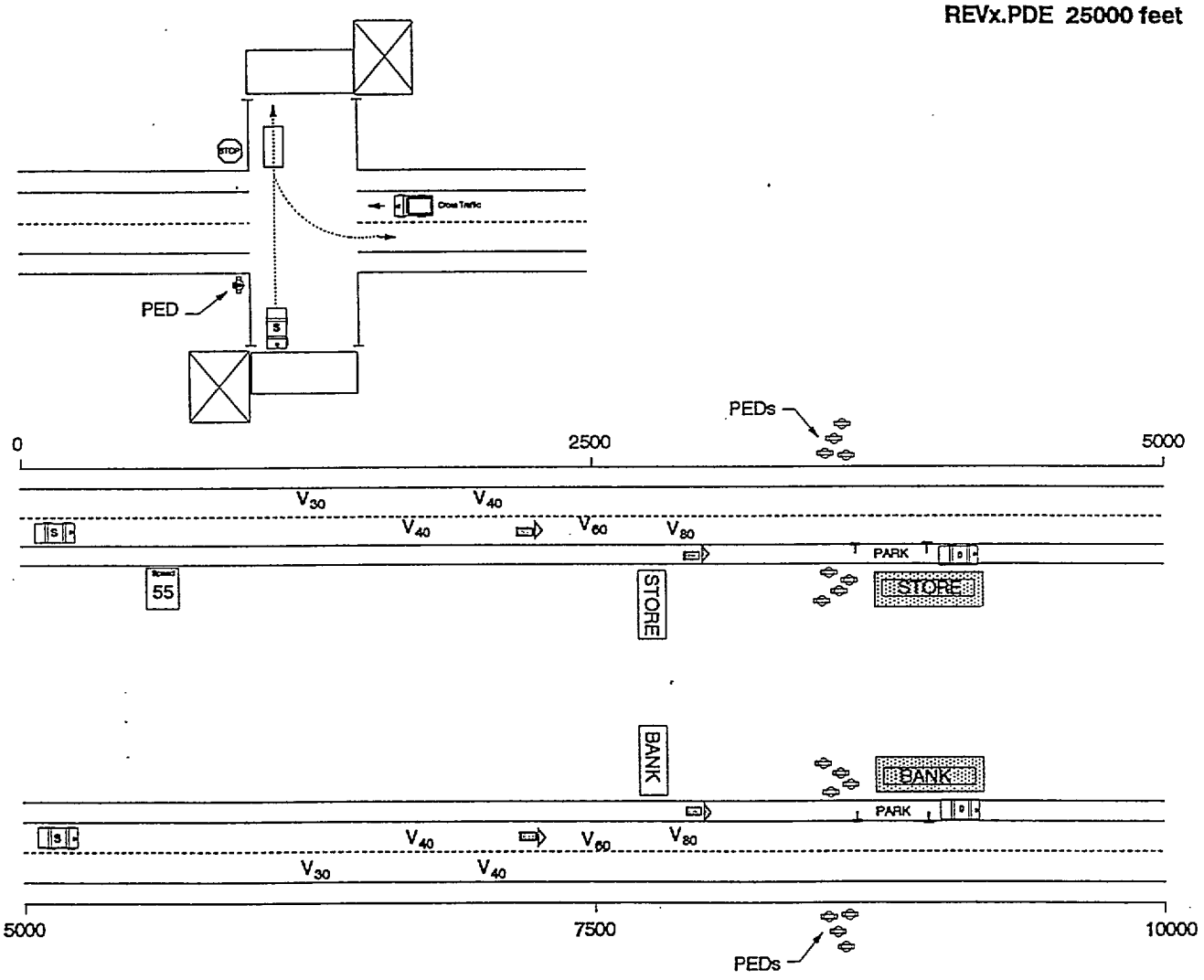
2.4.2.1 Driving Scenarios

Driving scenarios were designed to require driver backing while confronted with pedestrians and cross traffic. A schematic representation of a typical scenario is illustrated in Figure 2-9. The driver started by backing out of a driveway and was immediately confronted with a pedestrian and cross traffic. Once on the main route, the drivers were then required to stop at stores and banks and park behind a parked vehicle. To continue on, the driver then had to back up sufficiently to pull out around the parked vehicle ahead. During backing the driver was confronted with pedestrians crossing the street, and was also faced with merging into oncoming traffic when pulling out to continue the drive.

Figure 2-10 shows a scene at the beginning of the driving scenario where the driver has backed up across the street from the starting point. Drivers were instructed to back. up until the stop sign was visible, then proceed to turn onto the route for the remainder of the drive. Figure 2-11 shows a lane assignment arrow indicating the preferred lane for the driver to travel in during a particular sequence of the scenario. Signs would announce an upcoming required parking point as shown in Figure 2-12. Drivers were then instructed to pull into the parking lane as shown in Figure 2-13, and park directly behind a vehicle parked in front of the building. Figure 2-14 shows the driver approaching a required parking place.

When the driver pulled up to a stop behind a parked vehicle they were then instructed to back up while avoiding potential pedestrian conflicts as shown in Figure 2-15. Pedestrians can be seen in the center mounted rear view mirror and the driver’s side view mirror. Backing conflicts could also be seen in the passenger side view mirror. Figures 2-14 and 2-15 also show the rearview mirror warning arrows for the backing CAS which were the same as the rear view mirror arrows used for the lane change/merge CAS. Auditory beeps could also accompany the arrows.

Figure 2-9. Schematic of Typical Simulated Driving Scenario with Backing



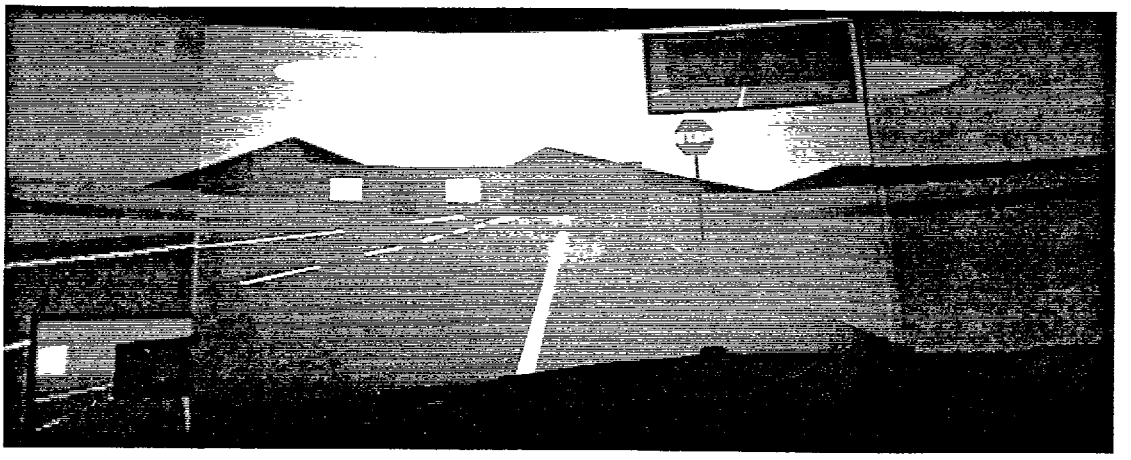


Figure 2-10. Beginning of Backing Scenario: Backing out of a Driveway and Across Street

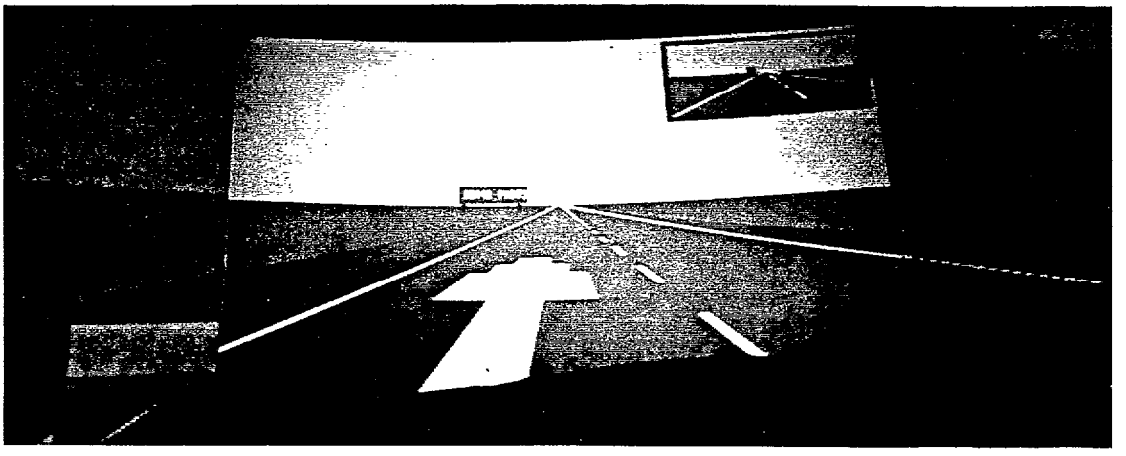


Figure 2-11. Lane Assignment Arrow to Indicate Preferred En Route Lane Prior to Upcoming Stop

Figure 2-12. Sign Indicating Upcoming Required Stopping Location

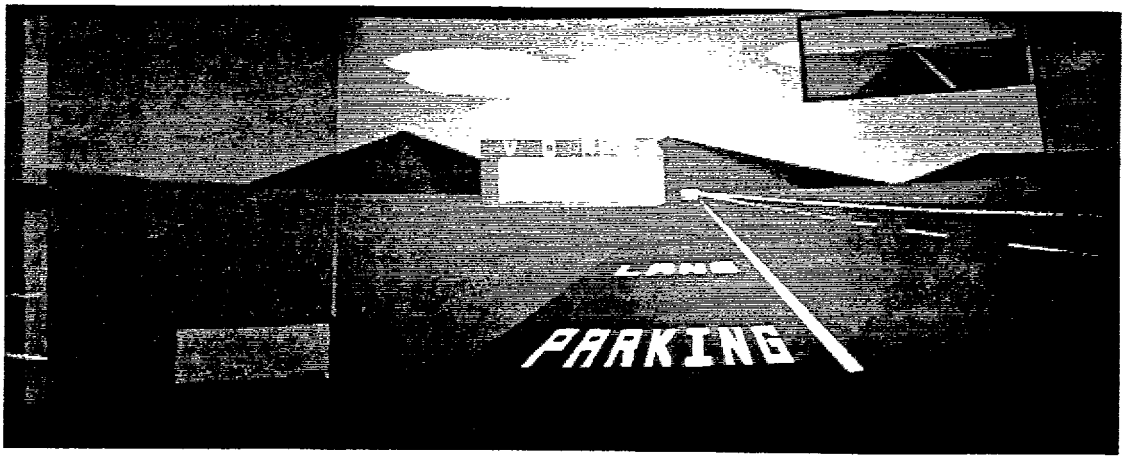


Figure 2-13. Driver Approaching Required Stopping Location in Parking Lane

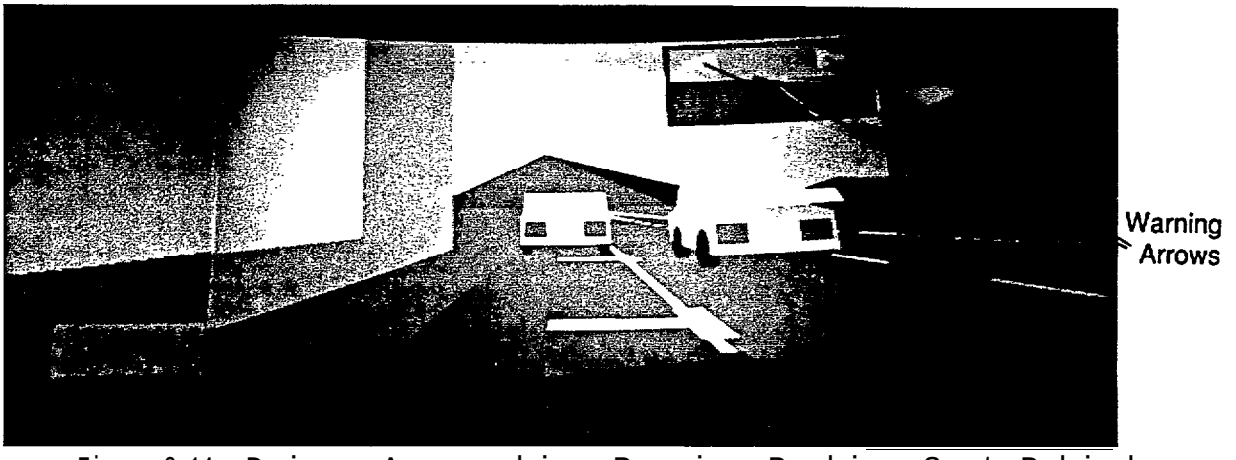


Figure 2-14. Driver Approaching Require Parking Spot Behind Previously Parked Vehicle (CAS Warning Arrows in Mirror)

Figure 2-15. Driver Preparing to Back Up in Parking Space With Pedestrian Conflicts (CAS Warning Arrow in Mirror)

2.4.2.2 Experimental Design

For the backing phase of the driving simulator experiment, a total of twelve subjects were used. Since these subjects had participated in the first phase of the experiment in testing the CAS in forward-driving, they were already familiar with the CAS and the driver simulator. Six subjects were assigned to a daylight condition, and six subjects were assigned to a dusk (compromised) lighting condition.

Each subject drove four 5 minute driving scenarios under various CAS conditions as summarized in Table 2-2. The order of presentation of these conditions was randomized and balanced between the twelve subjects. The driving scenarios were composed of several stopping opportunities which were grouped into separate subroutines as discussed in Appendix C. These were then combined in twelve different procedures.

Table 2-2. CAS Configurations and Experimental Variables for Backing Scenarios

<u>Crash Avoidance System Warning</u>
- Arrows and auditory
- Auditory only

<u>Warning Latency</u>
- Short (.10 seconds)
- Long (50 seconds)

<u>Lighting Condition</u>
- Daylight
- Dusk

<u>Gender</u>
- Female
- Male

2.4.2.3 Procedures

Upon arrival, subjects were given a brief explanation of the purpose of the backing experiment and asked to fill out the first portion of the backing subjective questionnaire (Appendix D). They were then escorted to the driving simulator and given training time to become accustomed to the backing driving scenario. All subjects had previous experience with the simulator in the lane change/ merge experiment. Since the purpose of this experiment was to test the CAS while the simulator is in reverse gear, subjects were instructed to put the simulator in reverse as soon as the situation warranted to give them maximum exposure to the CAS under reverse conditions. The lane change/merge CAS was activated when the vehicle was in forward gear. For this reason, subjects were told to pay attention to the CAS when the simulator was in reverse, so that subjective measures would be based on the CAS in reverse, rather than the cumulative perception of the CAS in forward and reverse. After subjects felt comfortable with their performance and how the simulator and CAS worked, the experiment was started.

Subjects drove in the simulator for approximately 40 to 45 minutes, divided into four randomized scenarios during which each CAS condition was presented. After each of the scenarios was completed, subjects were given a set of questions to answer. At the end the fourth scenario, they were given a set of questions to answer asking them to compare the different CAS configurations, rate the CAS as a whole, and give their general opinions about the CAS. Subjects were then paid and thanked for their participation and dismissed.

3.0 Results

3.1 Results Derived from the Monte Carlo Simulations

3.1.1 The Crash Avoidance Potential

To study various CAS configurations, it is necessary to develop a figure of merit which may be derived directly from the results of the Monte Carlo simulations. The crash avoidance potential (CAP) is defined as follows:

$$CAP = \frac{\text{Number of crashes (no sensor)} - \text{Number of crashes (with sensor)}}{\text{Number of crashes(no sensor)}}$$

$$= \frac{\text{Crashes prevented by the sensor}}{\text{Number of crashes(no sensor)}}$$

These terms are defined within a specific context which is described as follows: First, a given number of cases (for example: 3000, 6000 or 10000) are run without any warning system. From the output of the simulation, the "number of crashes (no sensor)" is determined. This number depends on the total number of cases run and, for lane change/merge crashes, includes both lane changer striking and struck cases for sideswipe, angle and rearend collisions. With no CAS in place, no lane changes are aborted and no safe returns to the original lane are accomplished. For backing crashes, all scenarios result in crashes with no CAS in place. Then the same number of cases is run with the CAS in place. The output of the simulation indicates the new total number of crashes. The difference between this new number and the original number of crashes (no sensor) represents the number of crashes prevented by the CAS. This is compared to the original number of crashes (no sensor) in the CAP. The CAP is bounded by 1.0 for the perfect CAS which prevents all crashes. As mentioned before, the many assumptions embedded in the Monte Carlo codes can strongly affect the absolute value of the crash avoidance potential. Therefore, the relative crash avoidance potential is defined as an aid in setting preliminary performance specifications. This is done as follows:

- For each crash classification, the highest value of CAP calculated by the Monte Carlo simulation for that classification is identified.
- Then the ratio of the calculated CAP to this chosen value is plotted for each CAS configuration as a function of the parameter studied.

This ratio is denoted by $(CAP)_R$ and described as the "relative crash avoidance potential".

A discussion of the statistical uncertainties in the calculation of the CAP and the choice of the number of cases to be run may be found in Appendix E. The value of the CAP is influenced more by the underlying assumptions in the model than by the uncertainties caused by the statistical nature of the model. However, comparisons of the values of the CAP may be useful to suggest relative improvements. For the lane change/merge simulations, since the SV speed distributions and the closing speed distributions are different for lane changes to the right and lane changes to the left, the relative CAP is frequently calculated for both directions of lane change.

3.1.2 Lane Change/Merge CAS for Passenger Vehicles

Generally, the Rumar alert driver reaction times were used for the lane change/merge simulations. POVs traveling in the same direction as the SV were generated in the center of the adjacent lane in the interval from 40 meters in front of the SV to 40 meters behind the SV. The longitudinal displacement of the POV, as measured from the front bumper of the SV, was sampled from a uniform distribution over this interval. Since the driver of the SV should not depend on evasion maneuvers initiated by the POV to prevent the crash, the POV was modeled as a passive vehicle which maintained its speed while the SV maneuvered.

As the range of the system is changed, the beam width and alignment of the sensor detection pattern are adjusted to cover the 12-foot wide adjacent lane at that range.

Since rearward looking and proximity CAS provide no warnings for vehicles in front of the SV, it may be more appropriate to consider the relative CAP derived with no SV rearend striking crashes (LCM8 crashes) in the total numbers of crashes with and without the CAS. Therefore, for these cases the relative CAP is calculated both including LCM8 crashes and without LCM8 crashes.

In general, 3000 cases were generated in each simulation run. The statistical uncertainties as calculated with equation E-15 ranged from about 16 to 20 % for low calculated values of the CAP (values on the order of 0.4) to only a few percent for high calculated values of CAP (those on the order of 0.8 or higher.)

For lane change/merge CAS, the highest value of the CAP calculated by the Monte Carlo simulation (passenger vehicles, Rumar driver reaction

times) was 0.958 for the CAS configuration shown in Figure 3-8 with long-range sensor ranges of 100 ft. The values of the relative crash avoidance potential, $(CAP)_R$, are the values of the CAP as calculated by the simulation divided by 0.958, as described on page 29.

3.1.2.1 Single Detection Pattern CAS

The simplest CAS consists of one sensor system for each side of the vehicle. A single long range sensor is shown schematically below in Figure 3-1.

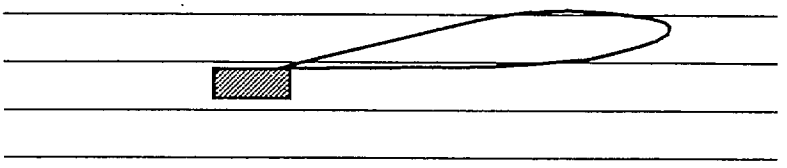


Figure 3-1. Long Range Sensor Detection Pattern

Figures 3-2.a and 3-2.b show the relative crash avoidance potential, $(CAP)_R$, for one long range system mounted on the rear bumper pointing rearward to cover the adjacent lane. For both lane changes to the right and to the left, the $(CAP)_R$ reaches a maximum at CAS ranges greater than 60 feet. For lane changes to the right and to the left, these maxima are 0.44 and 0.50 respectively. For lane changes to the right and to the left, the maxima calculated excluding LCM8 crashes are 0.45 and 0.51 respectively for a long range sensor range of 100 ft.

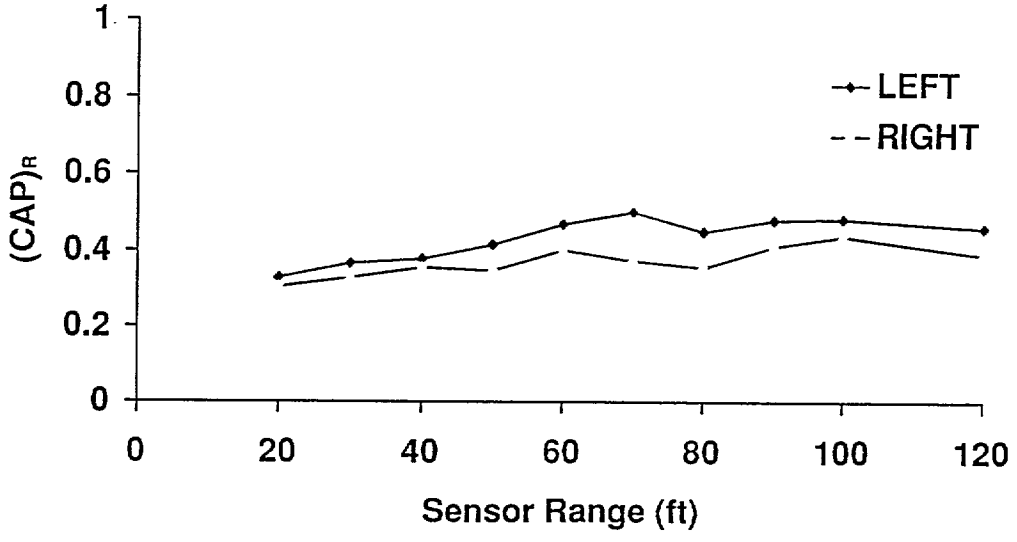


Figure 3-2.a. $(CAP)_R$ of a Single Rearward-Looking Sensor, Rumar Reaction Times, LCM8 Crashes Included

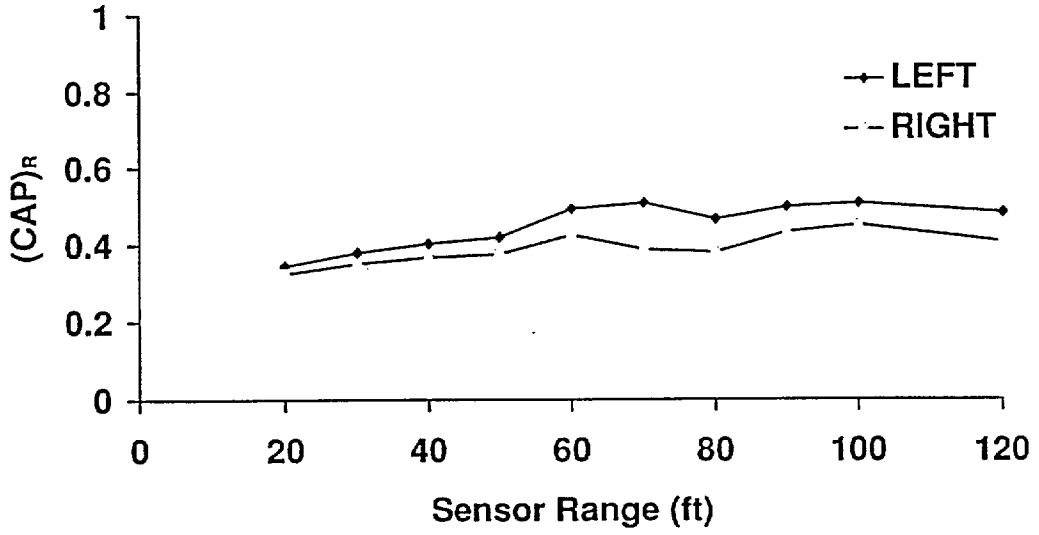


Figure 3-2.b. $(CAP)_R$ of a Single Rearward-Looking Sensor, Rumar Reaction Times, LCM8 Crashes Excluded

The values of the $(CAP)_R$ are roughly constant throughout the ranges of the long range sensor beyond 60 ft.

A single proximity sensor system with a circular detection pattern mounted on the vehicle proved even less effective. This is shown schematically below in Figure 3-3.

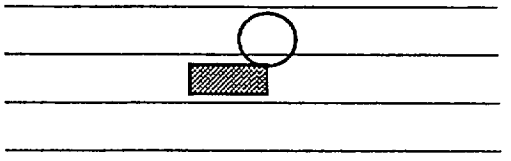


Figure 3-3. Circular Detection Pattern of Proximity Sensor

A proximity sensor with a circular detection pattern 4.5 meters in diameter was placed on the rear bumper (as shown above), on the front fender and at the mirror location. The mirror location provided the best value of $(CAP)_R$, which was 0.42 including LCM8 crashes or 0.44 without LCM8 crashes. This system also prevents less than half of the crashes prevented by CAS configuration shown in Figure 3-8.

The conclusion of the single sensor studies is that the CAS detection area must be more extensive than that provided by either the proximity or long range sensor system alone.

3.1.2.2 Two Detection Pattern CAS

Several combinations of two detection patterns (long range plus proximity) were simulated. In some cases, both proximity and long range transmitter/receiver units were collocated. In others, the units were separated. In still other cases, two proximity sensors were separated. These simulations were performed for lane changes to the right using the Rumar alert reaction times. The results of the Monte Carlo simulations are discussed below.

3.1.2.2.1 Collocated units

SeveraI Monte Carlo simulations were run for the long range and proximity sensors collocated on the rear bumper as shown below.

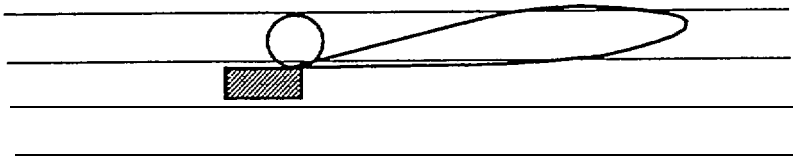


Figure 3-4. Long Range and Proximity Sensors Mounted on the Rear Bumper

The results are summarized in Table 3-l below.

Range for long range detection pattern	$(CAP)_R$ including LCM8 crashes	$(CAP)_R$ excluding LCM8 crashes
40 feet	0.48	0.49
50 feet	0.48	0.52
60 feet	0.48	0.54

Table 3-l. $(CAP)_R$ as a Function of Range for 2 Collocated Sensors

The results of the simulations, even excluding LCM8 crashes, indicate that these configurations would prevent at most about half of the crashes prevented by CAS configuration shown in Figure 3-8.

3.1.2.2.2 Separated Units

Configuration 1: Long range and one proximity sensor on rear bumper and second proximity sensor on front fender as shown below.

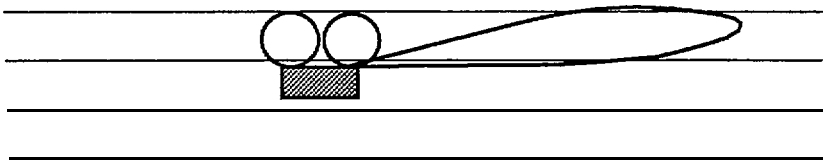


Figure 3 -5. Long Range Sensor and Proximity Sensor on Rear Bumper with Second Proximity Sensor on Front Fender

The range of the long range sensor was either 50 or 90 feet. The boresight angles and locations of the two proximity sensors were varied to optimize coverage.

Long Range Sensor Range(ft)	Boresight angle of forward proximity sensor	Boresight angle of rear proximity sensor	$(CAP)_R$ (with LCM8 crashes)	$(CAP)_R$ (no LCM8 crashes)
50	135°	90°	0.68	0.71
50	90°	90°	0.66	0.68
50	90°	135°	0.66	0.68
90	90°	90°	0.73	0.76
90	135°	90°	0.73	0.77

Table 3-2. $(CAP)_R$ as a Function of Range and Alignment for 2 Separated Sensor Systems

The results of the Monte Carlo simulations, even excluding LCM8 crashes, suggest that these configurations prevent about three quarters of the crashes, but only when the sensors have a very long range.

Configuration 2: Two crossed long range sensors, the forward looking sensor located on rear bumper and the rearward looking sensor on front bumper as shown in Figure 3-6 below.

This appears to be one of the more successful configurations. The results of the Monte Carlo simulations for lane changes to the right are shown in Figure 3-7 for a number of ranges. The effect of placing the

rearward looking sensor on the front fender and the forward looking

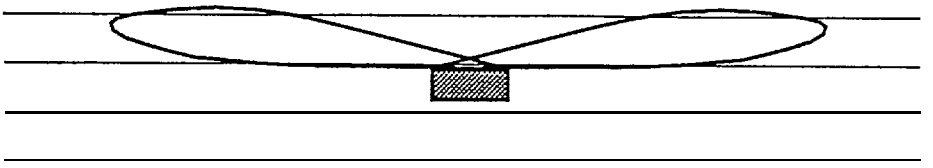


Figure 3-6. Crossed Long Range Sensors

sensor on the rear bumper is to provide coverage from both sensors of the adjacent lane in the area next to the SV. Since there is a forward looking sensor in this configuration, the effects of LCM8 crashes are included.

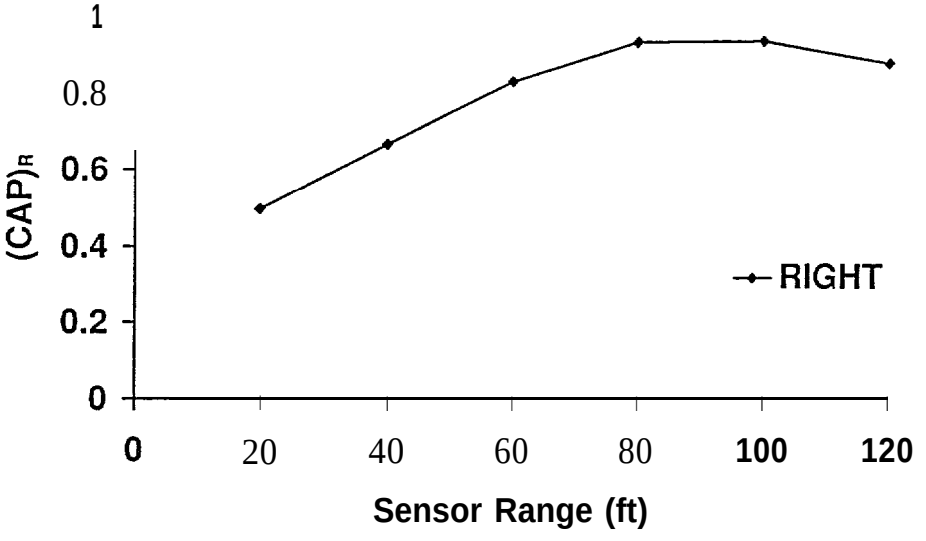


Figure 3-7. $(CAP)_R$ for a System of Crossed Long Range Sensors, Rumar Reaction Times

The conclusion is that this configuration may prevent significantly more of the lane change/merge crashes than the previously described CAS. This is almost as effective as the three pattern CAS discussed below.

3.1.2.3 Three Detection Pattern CAS

The following appears to be a successful configuration of three sensors:

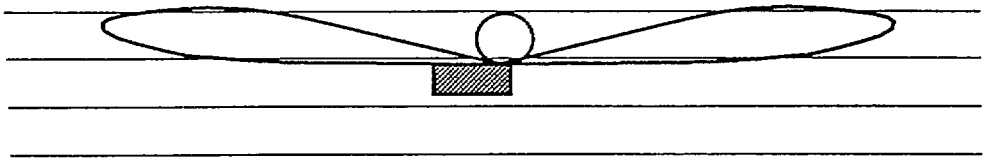


Figure 3-8. Three Sensors Located on Rear Corner: 1 Circular Pattern Proximity Sensor and 2 Long Range (1 Looking Rearward and 1 Looking Forward)

A long range sensor pointing forward covering the adjacent lane, a second long range sensor pointing rearward covering the adjacent lane, and a third proximity sensor with a circular detection pattern. All three sensors were mounted on the rear bumper. This configuration is shown in Figure 3-8 above. The ranges of the long range sensors were taken to be the same.

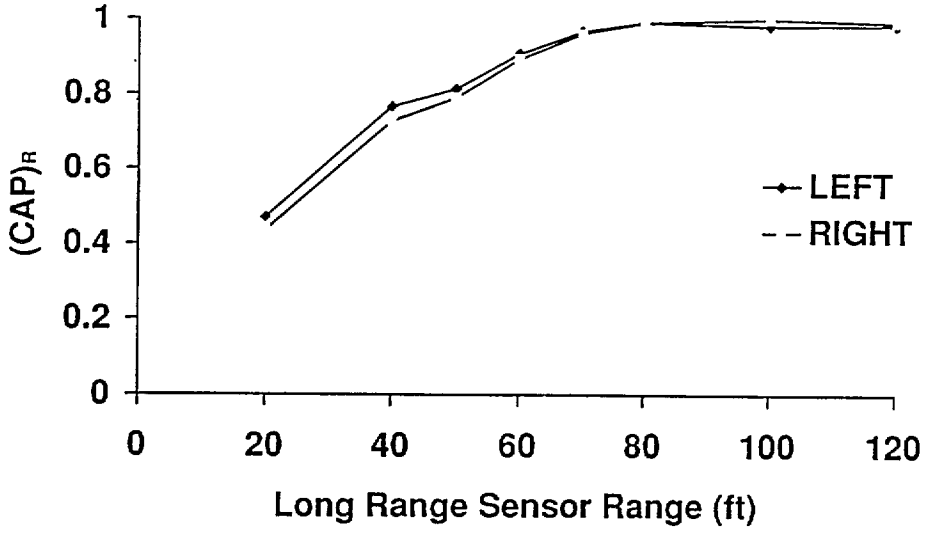


Figure 3-9. $(CAP)_R$ for 3 Sensors (1 Proximity and 2 Long Range) Located on Rear Corner , Rumar Reaction Times

Figure 3-9 shows the $(CAP)_R$ as a function of long range sensor range. Since the comparison value chosen to calculate $(CAP)_R$ (see pages 29 and 30) was taken for this configuration, the maximum $(CAP)_R$ is 1.00 for long

range sensor range of 100 feet, slightly higher than for the crossed sensor configuration discussed above.

3.1.2.4 Parametric studies

As seen in Figures 3-2.a, 3-2.b and 3-9, the $(CAP)_R$ values for lane changes to the left generally were slightly greater than those for lane changes to the right. For the parametric studies which follow, the 3 detection pattern CAS discussed in section 3.1.2.3 above was used. Only lane changes to the right were considered.

3.1.2.4.1 Effects of Reaction Times

As shown in Figure 2-1, the reaction times found by Taoka are somewhat longer than those found by Rumar, sometimes being more than 2 seconds. Typically the reaction times found by Rumar are less than 2 seconds. This may be attributed to the fact that the subject in the Rumar study were expecting a signal at which time they should break. The subjects in the Taoka study were not expecting to take any emergency action. The effects of using each set of reaction times consistently in the Monte Carlo simulations is shown in Figure 3-10.

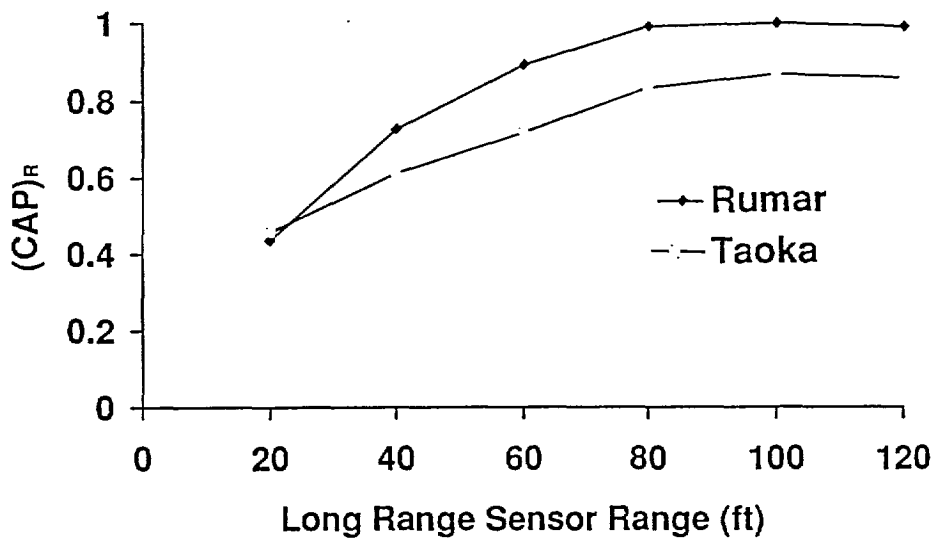


Figure 3-10. Comparison of $(CAP)_R$ Values for 3-Sensor System when Rumar and Taoka Reaction Times are used Consistently

Since both calculations utilized the same CAS configuration, all values of the relative crash avoidance potentials (those calculated using Taoka reaction times and those calculated using Rumar reaction times) have been related to the value 0.958 (as discussed on pages 29 and 30) to allow direct comparison. Longer reaction times similar to those characterized by Taoka may also be appropriate for non-alert drivers. The curves in Figure 3-10 indicate the decrease in $(CAP)_R$ as the reaction times become longer.

3.1.2.4.2 Degraded Vehicle and Driver Performance

In order to characterize the change in performance to be expected when road conditions cause degradation of steering or the driver's condition causes a lengthening of the time required to attain full lateral deceleration, a series of simulations were made using both the Rumar and Taoka reaction times. To simulate the effects of wet roadways, the maximum lateral deceleration was decreased by 30% to 0.28 g, which is consistent with the behavior of the coefficient of road adhesion (Reference 4). To simulate the effect of a drowsy or otherwise non-alert driver, the time required to attain maximum lateral deceleration (see Figure E-2) was increased to 0.55 seconds. In Figures 3-11 and 3-12, the results are compared with the values presented earlier for non-degraded performance.

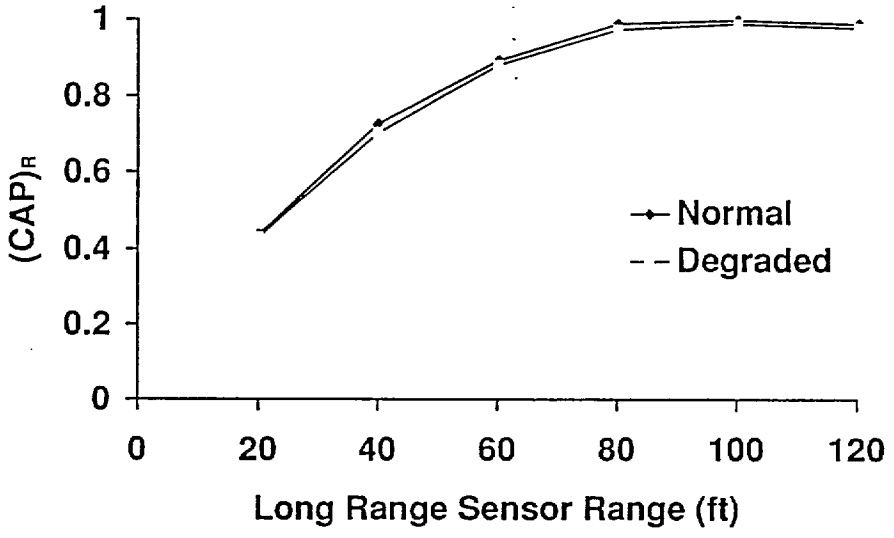


Figure 3-11. Comparison of $(CAP)_R$ Values for Rumar Reaction Times between Those of Normal Performance and those of Degraded Performance

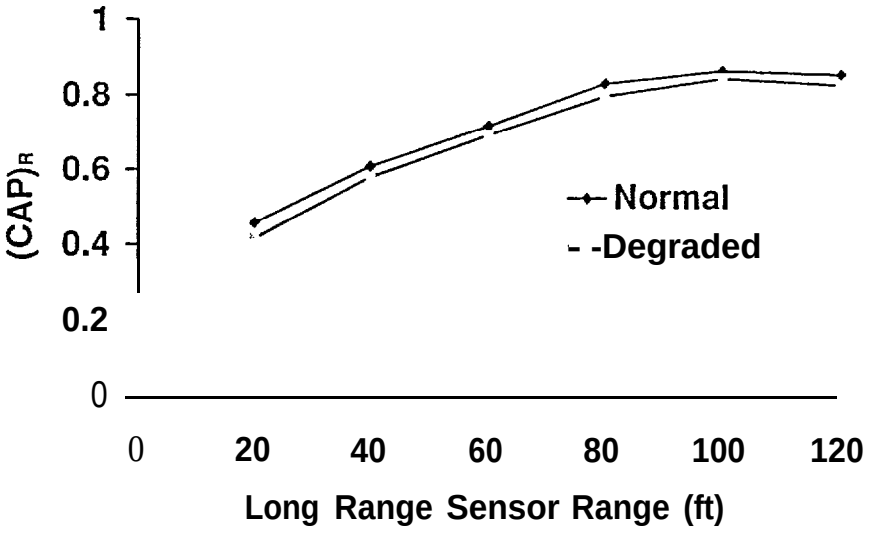


Figure 3-12. Comparison of $(CAP)_R$ Values for Taoka Reaction Times between Those of Normal Performance and those of Degraded Performance

As in the previous section, since both calculations utilized the same CAS configuration, all values of the relative crash avoidance potentials, $(CAP)_R$, have been related to the value 0.958 (as discussed on pages 29 and 30) to allow direct comparison. When the faster Rumar reaction times are used, very little overall degradation of the relative CAP is found. For the slower Taoka times, the degradation is still not severe for this system.

In this Monte Carlo simulation of the lane change maneuver, the dominant interaction between the CAS and the driver is the mechanism in which the CAS alerts the driver of the impending conflict before the vehicle has left its original lane. The lane change maneuver is then aborted by the driver. Degradation of the vehicle maneuvering abilities does not affect the percentage of crashes avoided in this manner. However, it is observed that there are fewer safe returns to the original lane by the vehicles with degraded maneuvering abilities.

3.1.2.4.3 Effects of Increased Latency and Update Times

Usually t_{lat} and the system update time, that is, (1/repetition rate) of the CAS system, are taken to be 0.1 second. This is considered reasonable and achievable. However, simulations were made in which these system parameters were varied up to 0.5 second. In each case, one parameter was varied while the other was held constant.

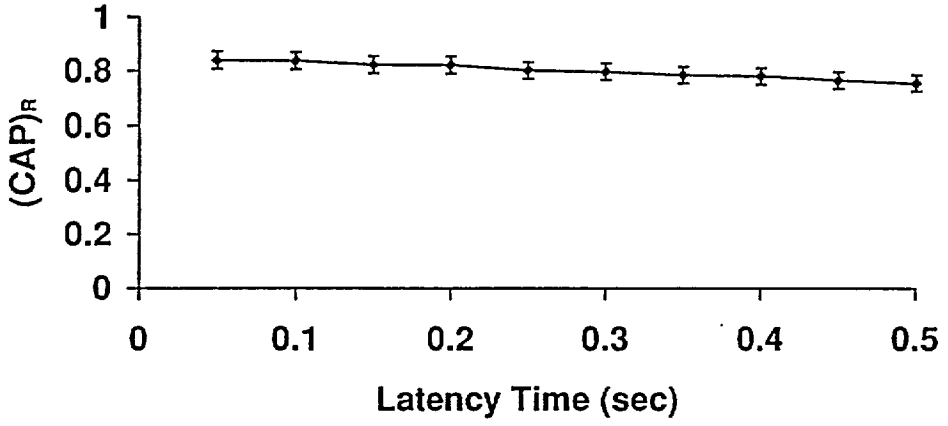


Figure 3-13. $(CAP)_R$ for Various Latency Times for Update Time = 0.1 second

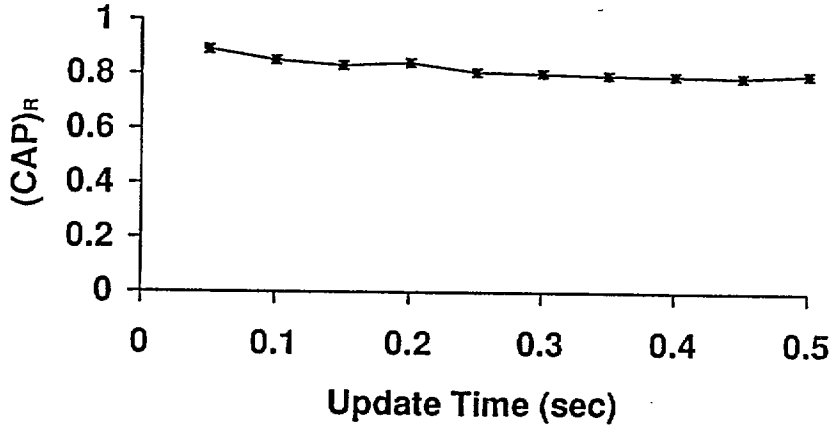


Figure 3-14. $(CAP)_R$ for Various Update Times for Latency Time = 0.1 second

The results are shown in Figures 3-13 and 3-14. In both cases, there was a slight, but not dramatic, decline in the $(CAP)_R$ values over the intervals studied, possibly because the 0.5 s maximum is small compared to the lane change time, t_{lc}, and less than most reaction times, t_{react}.

The upper limits of 0.5 second were chosen for two reasons:

- It is the upper limit of the latency times of systems currently available, and also
- At this time interval, the lag between the appearance of the target in the detection zone and the warning became noticeable.

When latency times on the order of 1.0 second were studied, a significant degradation of the $(CAP)_R$ value (about 25 %) was seen. With either the longer latency times or update times, the SV progresses further into the lane change before the warning, building more lateral velocity and losing the option to abort the lane change maneuver before entering the adjacent lane. Successful return to the original lane is then more difficult.

The statistical uncertainties in $(CAP)_R$ as the latency time was varied was approximately 2 % throughout. The statistical uncertainties in the $(CAP)_R$ as the update time was varied ranged from 3 to 5 %.

3.1.2.5 Conclusions

Based on the Monte Carlo Lane change simulations, the crossed sensor configuration discussed in section 3.1.2.2.2 and 3-sensor CAS discussed in section 3.1.2.3 appear to be the most promising configurations. The crossed sensor configuration requires two separate transmitter/ receiver units on each side of the vehicle, or a total of 4 in all. If the transmitter/receiver can be switched between the various types of patterns generated so that only one transmitter/receiver unit is required in each location, the 3 sensor CAS would require only a total of 2 units, one on each rear corner of the vehicle.

3.1.3 Lane Change/Merge CAS for Trucks

To study the effectiveness of the use of CAS on tractor trailers, two configurations of sensors were simulated. The model for the tractor trailer was 21.1 meters (69 feet) long and 2.6 meters (8.5 feet) wide. (Reference 5) Due to the extreme size and weight of tractor trailer combinations, more time is required to change lanes and to respond to steering input. Also these combinations have many unstable dynamic modes which the truck driver must routinely avoid exciting. For these reasons, the following vehicle parameters were modified:

- The maximum lateral deceleration, A_r, was decreased to 0.25 g.
- The lower and upper limits on the time required for changing lanes, t_{lc}, were increased to 5.0 and 15.0 seconds respectively.
- The time required to attain maximum lateral deceleration, t_{steer}, was increased to 1 .l seconds.

The truck driver is expected to react with a reaction time taken from the Rumar alert reaction time distribution.

For this crash classification (trucks, Rumar reaction times), the highest value of CAP calculated by the Monte Carlo simulation for that classification was identified as 1.000 for the CAS configuration shown in Figure 3-17 with long-range sensor ranges of 100 ft. The ratio of the calculated CAP to this value is plotted for each CAS configuration as a function of the long range sensor range. This ratio is denoted by $(CAP)_R$, the "relative crash avoidance potential". The values of the relative crash avoidance potential, $(CAP)_R$, are the values of the CAP as calculated by the simulation divided by 1.00, as described on page 29. (While the division is trivial, the concept of maintaining the relative crash avoidance potential is not.)

Under these assumptions and with these parameters, the values of $(CAP)_R$ for the two CAS configurations considered appeared to be as good as the best configurations for passenger vehicles. Statistical uncertainties in $(CAP)_R$ were approximately 2 % throughout.

The first configuration, shown in Figure 3-15 below, consisted of 6 proximity sensors with circular patterns mounted along the length of the truck and 2 long range sensors mounted on the front fender and back bumper looking forward and rearward respectively.

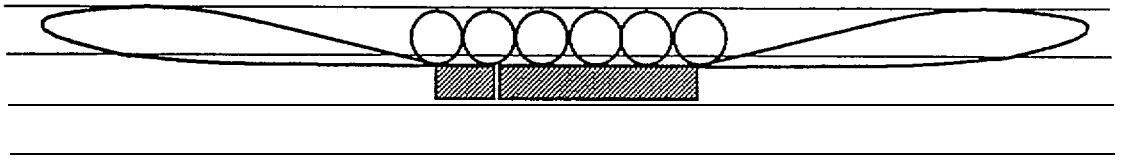


Figure 3-15. CAS Configuration of 8 Sensors Mounted on a Tractor Trailer

The $(CAP)_R$ values as a function of the range of the long range sensors is shown in Figure 3-16 below. For ranges of 30 feet or more, the system reaches its peak performance.

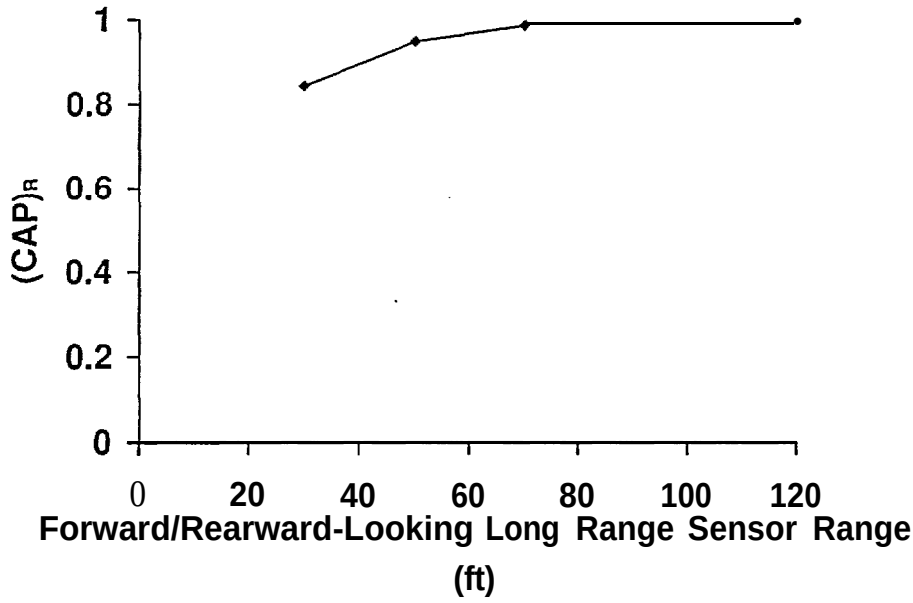


Figure 3-16. $(CAP)_R$ as a Function of the Long Range Sensor -Range for CAS as Shown in Figure 3-15

A second configuration consisting of only 4 sensors on each side was considered. In this configuration, all 4 sensors were long range sensors as shown below in Figure 3-17. Two sensors were crossed to provide coverage of the adjacent lane over the length of the tractor trailer. There was an additional sensor mounted on the front fender looking forward and another sensor mounted on the rear corner looking rearward.

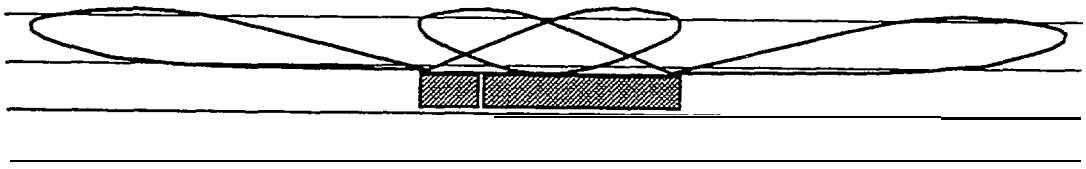


Figure 3-17. Configuration of 4 Long Range Sensors Mounted on a Tractor Trailer

This CAS configuration is as effective as the previous one while using only half the number of sensors. Figure 3-18 shows the $(CAP)_R$ values as a function of the long range sensor range.

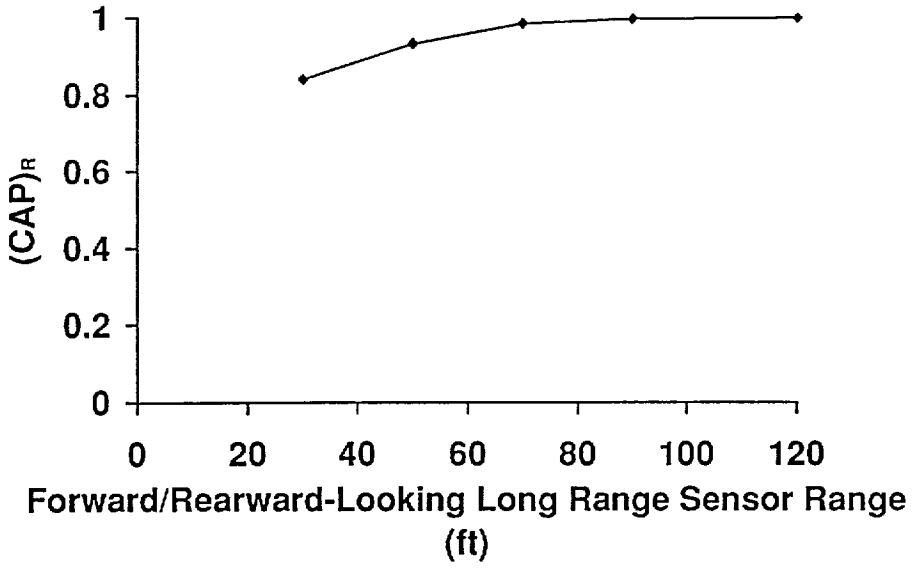


Figure 3-18. $(CAP)_R$ as a Function of the Long Range Sensor Range for CAS as Shown in Figure 3-17

Furthermore, this crossed sensor configuration requires only two separate transmitter/receiver units on each side of the vehicle, or a total of 4 in all. Again, if the transmitter/receiver units can be switched between the various types of patterns generated so that only one transmitter/ receiver unit is required in the rear bumper, this CAS would require only a total of 2 units on each side, one in rear bumper and one in the front fender.

The lane adjacent to a tractor trailer and the space both ahead and behind a tractor trailer can be effectively monitored through the judiciously designed CAS. This conclusion is based on the assumption that the driver is alert, responds promptly and carefully to the warning and does not lose control during the evasion maneuver.

3.1.4 Backing CAS Systems

Approximately 200 police accident reports (PARs) corresponding to backing crash entries in the 1992 GES database were analyzed. Since backing crashes involving pedestrians or pedacyclists may have very serious consequences, all of the entries pertaining to the backing vehicle striking a pedestrian (50 PARs) or pedacyclist (11 PARs) were reviewed. Other categories of backing crashes were sampled. The individual entries of each case in the database were examined, and sample cases were chosen to obtain the maximum relevant data (such as vehicle speeds, etc.). Even so, it was not always possible to obtain all the data desired. Pedestrian speeds were only quantified as standing, walking or running. Vehicle speeds were frequently quoted as "between 1 to 5 mph" or "slow" and so on. Frequently, it was necessary to infer the level of injuries sustained. Based on the assigned weights and our assessment of whether a given crash involved curved path backing or straight path backing, we found that this data indicated that approximately 55 % of backing crashes reviewed involved straight path backing and 45 % curved path backing.

Backing speed distributions were extracted from the available data. These distributions represent the speeds at which the crashes are reported to occur. There was no data on the backing accelerations. Three speed distributions were derived from the raw data: a speed distribution for pedestrian/pedacyclist crashes, a speed distribution for all other straight path backing crashes, and a speed distribution for all other curved path backing crashes. These cumulative distributions are shown below in Figure 3-19.

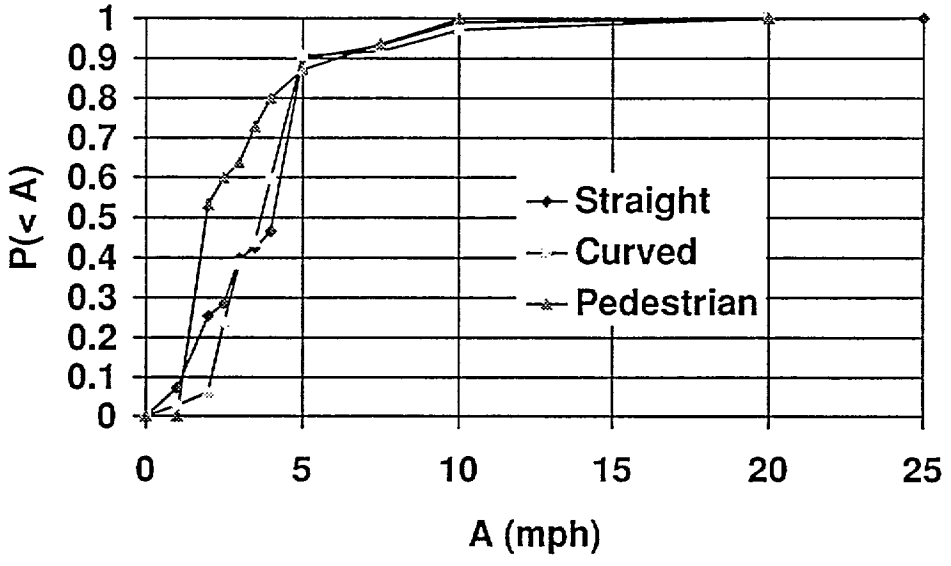
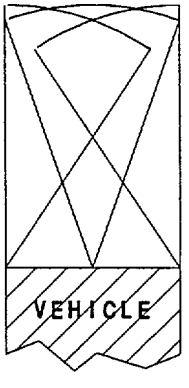


Figure 3-19. Backing Vehicle Speed Distributions

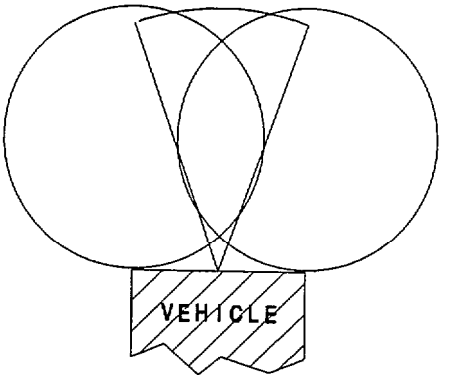
The pedestrian/pedacyclist backing speed distribution is markedly different from the other two, containing a larger percentage of lower travel speeds. This distribution was used in the Monte Carlo simulations involving moving or standing pedestrians or moving bicycles. The curved path and straight path vehicle travel speed distributions are very similar. These were combined for use in the Monte Carlo simulations involving fixed objects or moving vehicles. This latter distribution is designated the "vehicle-vehicle" backing speed distribution.

In the Monte Carlo simulations the backing vehicle's final expected travel speed was found by generating a random number between 0.0 and 1.0 and matching that number to the appropriate cumulative distribution as is described elsewhere. Since no data was available, the backing acceleration was taken from a uniform distribution of accelerations between 0.01 g and 0.09 g.(Reference 5) The. emergency braking deceleration was taken from a uniform distribution of accelerations between (0.7-0.035) g and (0.7+0.035) g.(Reference 5) Since backing is not . the normal driving activity, the Rumar alert driver reaction times were assumed to describe the driver's reaction time. Each simulation contained 3000 individual cases.

Past studies have shown that systems utilizing the pattern of only one sensor pattern do not provide adequate coverage to prevent backing crashes. Two CAS sensor patterns, each requiring 3 separate sensors, were investigated here in some detail. These are shown below in Figure 3-20.



PATTERN #I



PATTERN #2

a) Pattern 1 with a range of 3 m

b) Pattern 2 with a range of 3 m

Figure 3-20. CAS Sensor Patterns 1 and 2

Although the sensors in pattern 1 sometimes sense an obstacle not in the area directly behind the vehicle, they are directed to maximize the coverage of the area directly in the backing path of the vehicle. As the range of the sensors in pattern 1 is extended, the boresight angles and beamwidths are adjusted so that the detection area is limited to that area directly behind the vehicle. As the range of the sensors in pattern 2 is extended, the lateral extent of the pattern also becomes greater. For a range of 5 meters, pattern 2 looks 2.5 meters beyond the side of the vehicle, for a total pattern width of 7 meters. The sensors in pattern 2 look both behind the vehicle and to the sides of the vehicle, which may precipitate many nuisance alarms. Nuisance alarms and the need for side looking capabilities are discussed in subsequent sections.

With the exception of those cases run to test the probability of nuisance alarms, all simulation cases were constructed so that the backing crash is certain without driver intervention (that is, aborting the maneuver before it begins or braking when a detection is made). In the following discussions, the figure of merit is the relative fraction of crashes avoided, $(FA)_R$, which has the same mathematical form as $(CAP)_R$ used previously.

For this crash classification (straight path backing, passenger vehicles, Rumar reaction times), the highest value of the fraction of crashes avoided calculated by the Monte Carlo simulation for a realistic scenario, it is 0.998 for backing CAS configuration pattern 2, 6-meter range, nonzero wait time, and moving pedestrian targets. The ratio of the calculated fraction of crashes avoided to this value is plotted for each CAS configuration as a function of the sensor range. This ratio is denoted by $(FA)_R$, the “relative fraction of crashes avoided”. The values of the relative fraction of crashes avoided, $(FA)_R$, are the values of the fraction of crashes avoided as calculated by the simulation divided by 0.998, as described on page 29. (While the division is trivial, the concept of maintaining the relative fraction of crashes avoided is not.)

The statistical uncertainties in the calculated fraction of crashes avoided are calculated using equation E-15. These statistical uncertainties are generally on the order of 5 % for the systems studied here under the current assumptions.

3.1.4.1 Straight Path Backing

3.1.4.1.1 Pedestrians and Pedacyclists

Based on the analyses of the PARs, pedestrian and pedacyclist crashes were predominantly straight path backing crashes with the pedestrians/pedacyclists approaching the backing trajectory from the side at approximately a 90-degree angle. The pedestrian speed was sampled from a uniform distribution between 2.1 and 5.5 ft/sec, which is consistent with observations reported in References 7 and 8. For pedestrian crashes, the angle of approach was sampled from a uniform distribution between 80 and 100 degrees. (Note: A very highly-weighted curved path backing case did exist but contained little useful data.)

The PARs indicated that the pedacyclist crashes involved bicycles on sidewalks and straight path backing in driveways. For pedacyclist crashes, the bicycle speed was sampled from a uniform distribution between 10.3 and 22.0 ft/sec, which is also consistent with observations reported in Reference 8. The angle of approach was sampled from a uniform distribution between 85 and 95 degrees.

The backing speed was sampled from the distribution developed for pedestrian/pedacyclist crashes by means of generating a random number and matching it to the speed distribution. The pedes trian/pedacyclist initial position was calculated to place him/her directly behind the vehicle's back bumper at the moment the vehicle achieved the determined backing speed.

The relative fraction of crashes avoided, $(FA)_R$, for each detection pattern is shown as a function of backing sensor range in Figures 3-21 and 3-22 below.

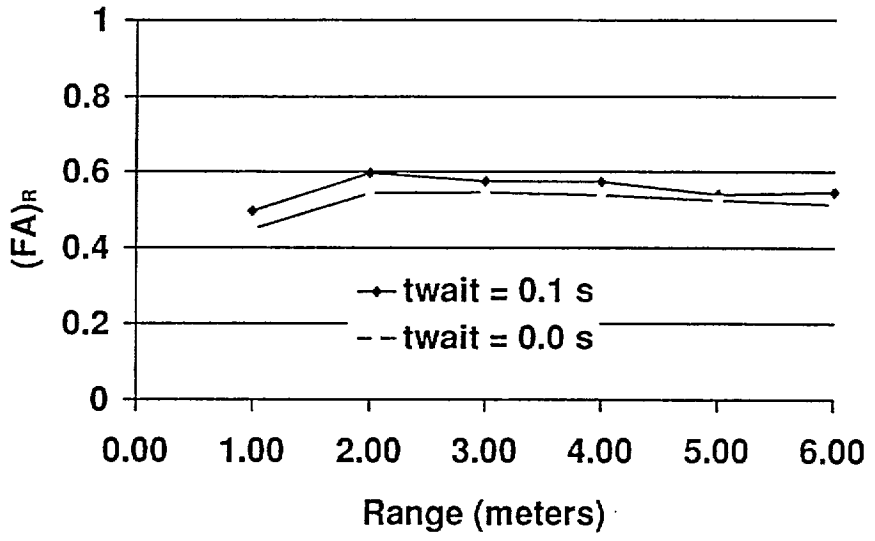


Figure 3-21 Relative Fraction of Crashes Avoided, $(FA)_R$, as a Function of Sensor Range for Pattern 1 for Moving Pedestrians

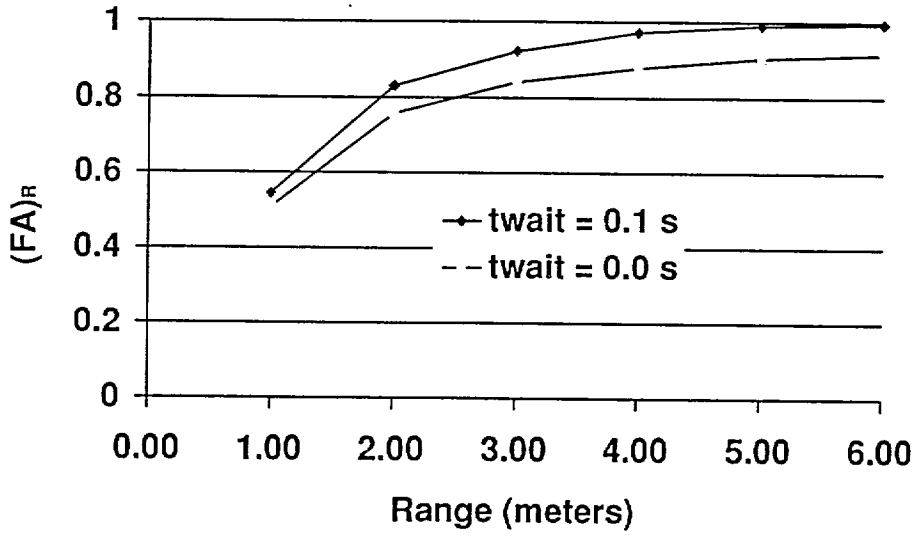


Figure 3-22. Relative Fraction of Crashes Avoided, $(FA)_R$,as a Function of Sensor Range for Pattern 2 for Moving Pedestrians

In the simulation, if the pedestrian or pedacyclist is detected during the period of time t_{wait} before the acceleration has begun, the driver aborts the backing maneuver. If t_{wait} is set to 0.0, then the driver is assumed to begin backing immediately. The results are somewhat different. Figures 3-21 and 3-22 show the $(FA)_R$ values both with and without the opportunity to abort the backing maneuver for patterns 1 and 2. Pattern 2 with its side-looking capabilities was substantially better at preventing moving pedestrian crashes than pattern 1.

Standing pedestrians or fixed objects were distributed uniformly between 0.0 and 10.0 meters behind the vehicle. Simulations were made in which the standing pedestrian or fixed object was located on the vehicle's centerline and also when the positions were randomly located away from the centerline but within the vehicle's path. As expected, the relative fraction of crashes avoided was slightly higher when the "target" was on the centerline, possibly due to the triple redundancy in detection patterns. Figure 3-23 shows the relative fractions of crashes avoided, $(FA)_R$, for each sensor pattern as a function of range for the case of standing pedestrians.

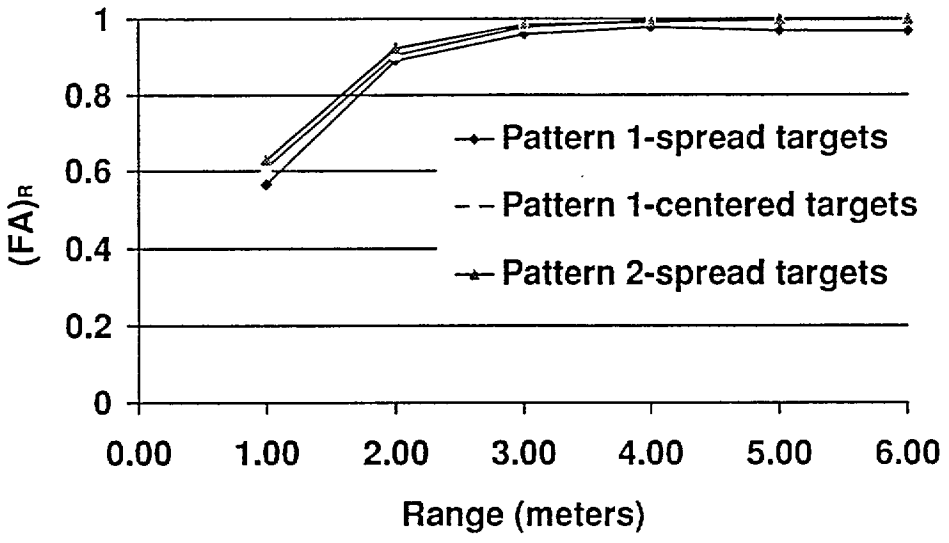


Figure 3-23. Relative Fraction of Crashes Avoided, $(FA)_R$,as a Function of Sensor Range for the Case of Standing Pedestrians (t_{wait} = 0.1 sec)

Finally, Figure 3-24 indicates the efficacy of the backing sensors against bicycle crashes. Pattern 1 was totally ineffective, not preventing any crashes and pattern 2 was only somewhat effective. Neither pattern is

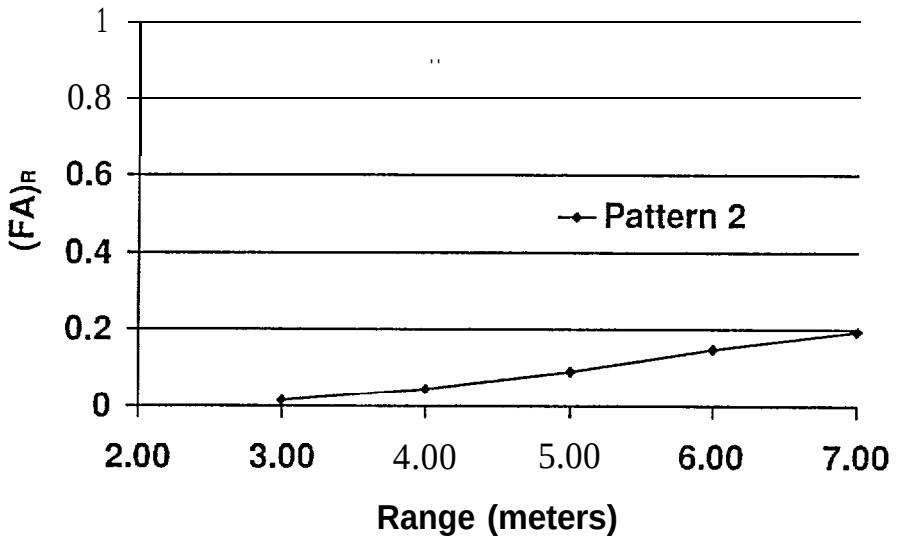


Figure 3 -24. Relative Fraction of Crashes Avoided, $(FA)_R$, as a Function of Sensor Range for Bicycle Crashes

very effective against this kind of crash. In turn, this suggests that even pattern 2 would be only minimally effective against cross traffic crashes.

The most important conclusions which may be drawn from these simulations are as follows:

- A time delay before the initiation of the backing motion provides the opportunity for the driver to abort the backing maneuver before it begins. This time delay could be included into the vehicle's response when placed in "reverse" gear. In this manner, at least one detection cycle could be performed before the backing motion is initiated.
- For slowly approaching targets such as walking pedestrians, pattern 2 with its side-looking capabilities is much more effective than pattern 1.

3.1.4.1.2 Fixed Objects

Fixed objects were distributed uniformly between 0.0 and 10.0 meters behind the vehicle and were randomly positioned across the width of the vehicle. The backing speed distribution for vehicle-vehicle crashes was used in this case. For sensor pattern 1, effectiveness was evaluated both with and without a delay time, t_{wait}. Here there is very little difference. Figure 3-25 shows the relative fractions of crashes avoided, $(FA)_R$, for each sensor pattern as a 'function of range.

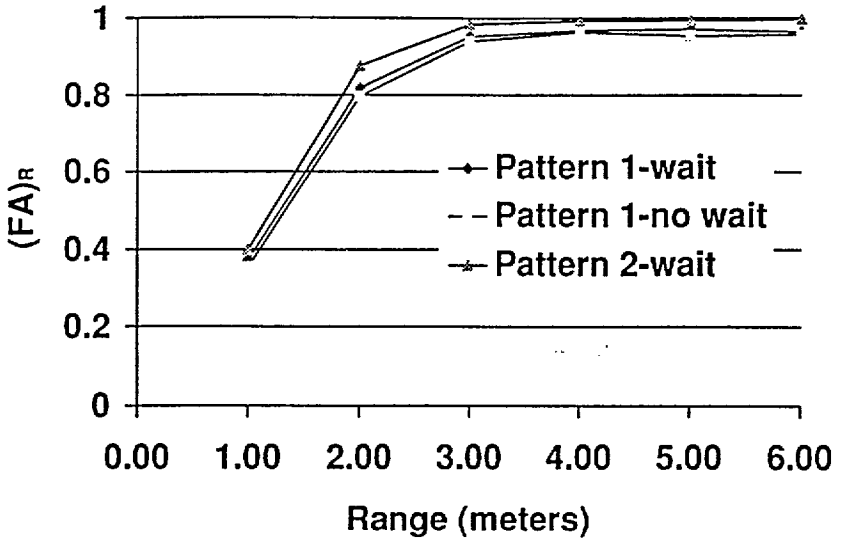


Figure 3-25. Relative Fraction of Crashes Avoided, $(FA)_R$, as a Function of Sensor Range for Fixed Objects Located Directly Behind the Vehicle

3.1.4.1.3 Nuisance alarms

Nuisance alarms are defined as alarms generated by objects which pose no risk of collision to the backing vehicle but are detected by the backing vehicle's CAS nonetheless. They are not noise-induced false alarms, since the object does truly exist within the detection pattern. Nuisance alarms or the potential for nuisance alarms (e.g., garbage cans set near but not in the driveway) may distract the driver or cause the driver to discount a valid alarm caused by another source. However, as discussed in Section 4, a well-designed CAS should be able to discriminate against these detections. To test the potential for nuisance alarms, fixed targets were located out of the SV's path, but in locations where detection was possible. In the first case, the target was placed 0.5 meters beyond the side of the vehicle to simulate a close miss. Then the target was placed 1.0 meter beyond the side of the vehicle. Although this is not "far" in the usual sense, it is out of the danger zone for stationary objects. The percent of cases in which the target was detected is shown for each sensor pattern in the Table 3-3 as a function of pattern range below (assuming no sophisticated discrimination capability for nuisance alarms).

Range (m)	Pattern 1 (close)	Pattern 2 (close)	Pattern 1 (far)	Pattern 2 (far)
1.0	74.0 %	96.9 %	0.0 %	0.0 %
2.0	13.7 %	98.9 %	0.0 %	94.3 %
3.0	0.0 %	99.6 %	0.0 %	97.4 %
4.0	0.0 %	99.7 %	0.0 %	97.8 %

Table 3-3. Percent of Nuisance Alarms for Straight Path Backing

As is obvious from the table, the more extensive pattern 2 produces far more nuisance alarms in most situations than pattern 1.

3.1.4.2 Curved Path Backing

Curved path backing occurs in many situations, for example:

- when the SV backs out of a driveway turning through an arc to align itself with cross traffic moving at an angle,
- when the SV backs out of a parking place turning through an arc to align itself with traffic moving at an angle, or
- when the SV backs around a corner on the roadway, possibly to correct an inappropriate turn.

In each case, it is characterized by moving in an arc. In uninterrupted curved path backing, the vehicle begins by straight backing until the backing speed chosen from the distribution is reached. Then, when that speed is reached, the vehicle begins a quarter circle turn at a constant speed. At the end of the turn, the vehicle begins a moderate planned braking and brakes until the speed is zero. In all of the curved path backing simulations, the backing speed distribution for vehicle-vehicle crashes was used. In the simulation, the POV begins at an initial position calculated to bring it to the subject vehicle's back bumper when the turn is completed. The POV's speed is chosen from a given range, for example, 1 to 5 mph, 5 to 15 mph, or, for fixed vehicles, 0 mph. At some point on the SV's path, the CAS detects the presence of the other vehicle and the driver begins a forceful braking. The case continues until a safe stop is effected or a crash occurs. If the space between the vehicles is less than 1.0 second headway based on the POV's speed, this is considered a crash also. A diagram of curved path backing is shown in Figure 3-26.

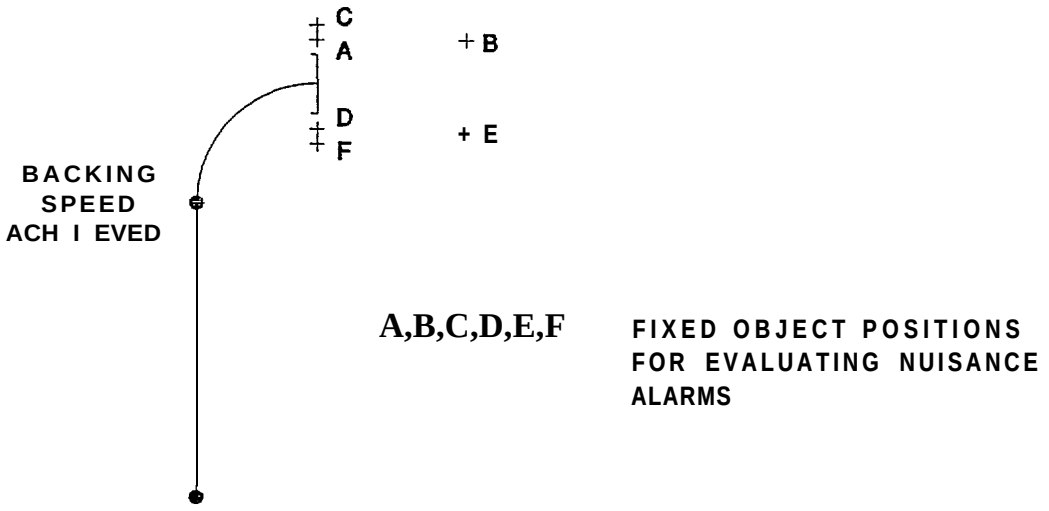


Figure 3-26. Diagram of Uninterrupted Curved Path Backing

For this crash classification (curved path backing, passenger. vehicles, Rumar reaction times), the highest value of fraction of crashes avoided calculated by the Monte Carlo simulation was identified as 0.979 for the backing CAS configuration pattern 2 with a 6 meter range with a stationary vehicle at the end of the quarter circle path. The ratio of the calculated fraction of crashes avoided to this value is plotted for each CAS configuration as a function of the sensor range. This ratio is denoted by $(FA)_R$, the "relative fraction of crashes avoided". The values of $(FA)_R$ are the values of the fraction of crashes avoided as calculated by the simulation divided by 0.979, as described on page 29. (While the division is trivial, the concept of maintaining the relative fraction of crashes avoided is not.)

3.1.4.2.1 Fixed Objects

A fixed object (speed = 0.0) was positioned behind the backing vehicle at the end the quarter-circle arc backing segment. The object was assumed to be the size of another vehicle. Figure 3-27 shows the relative fraction of crashes avoided of each pattern as a function of range.

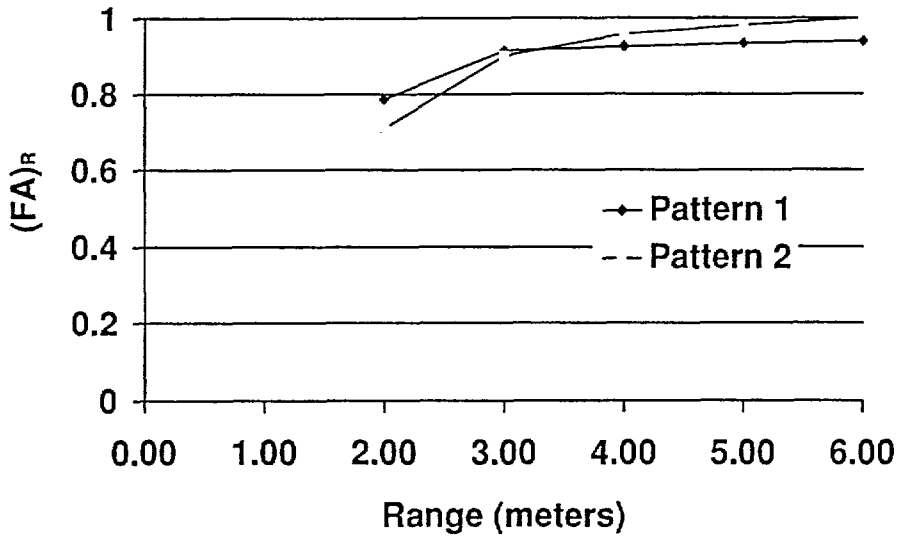


Figure 3-27. Relative Fraction of Crashes Avoided, $(FA)_R$, as a Function of Sensor Range for Fixed Objects in Curved Path Backing

3.1.4.2.2 Moving Vehicles in Transport

For the CAS sensor patterns 1 and 2, the results of curved path backing simulations in which the POVs have slow, moderate and fast speeds are shown in Figures 3-28 and 3-29. "Slow" is defined as from 1 to 5 mph, "moderate" from 5 to 15 mph, and "fast" from 15 to 30 mph.

Both patterns perform relatively well against slow and moderate cross traffic speeds, and neither pattern performs well against fast cross traffic. In all cases, pattern 2 is somewhat more effective than pattern 1. Since the initial positions of the cross traffic are well out of the sensor's range at the beginning of the backing, the existence of an initial delay time, t_{wait} is immaterial.

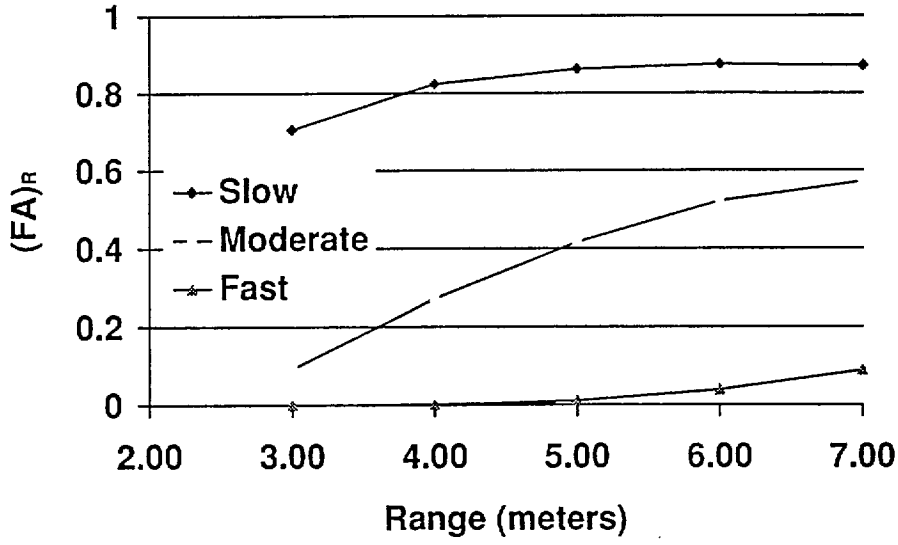


Figure 3-28. Relative Fraction of Crashes Avoided, $(FA)_R$, as a Function of Sensor Range for Pattern 1 with Cross Traffic in Curved Path Backing

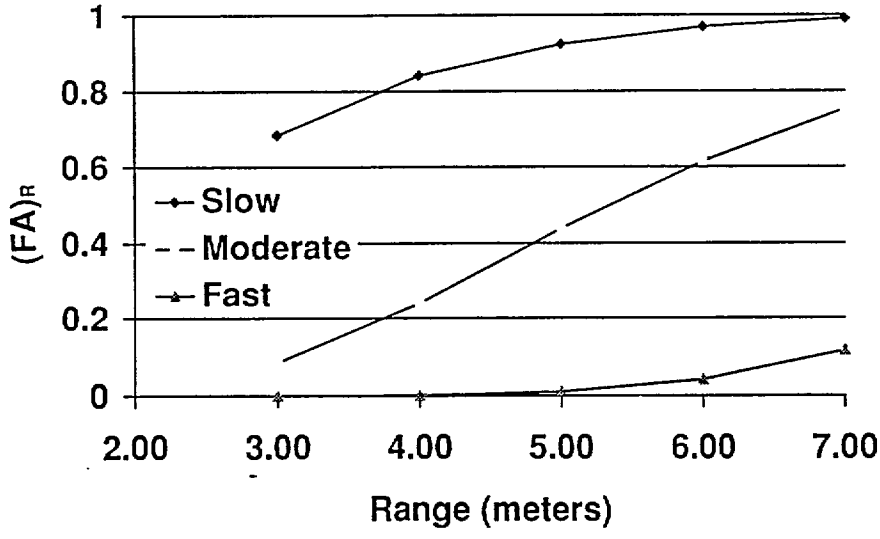


Figure 3-29. Relative Fraction of Crashes Avoided, $(FA)_R$, as a Function of Sensor Range for Pattern 2 with Cross Traffic in Curved Path Backing

3.1.4.2.3 Nuisance alarms

To test the potential for nuisance alarms, fixed targets were again located out of the SV's path, but in locations where detection was possible. In the first case, the target (a simulated parked car) was placed in three locations on the outside edge of the arc beyond the side of the vehicle to simulate a close miss. Then the target was placed in three locations on the inside of the arc again beyond the side of the vehicle. These locations are shown in Figure 3-26 as (A,B,C) and (D,E,F) respectively. Locations B and E are one vehicle length (5 meters) beyond locations A and D. These targets were out of the collision danger zone. The percent of cases in which the target was detected is shown for each sensor pattern in the tables below.

Range (meters)	A	B	C	D	E	F
3.0	100.0 %	0.0 %	27.1 %	0.0 %	0.0 %	0.0 %
5.0	100.0 %	0.0 %	100.0 %	0.0 %	0.0 %	0.0 %

Table 3-4. Percent of Nuisance Alarms for Curved Path Backing for Sensor Pattern 1

Range (meters)	A	B	C	D	E	F
3.0	100.0 %	6.0 %	9.3 %	100.0 %	6.4 %	58.0 %
5.0	100.0 %	55.2 %	100.0 %	100.0 %	55.8 %	100.0 %

Table 3-5. Percent of Nuisance Alarms for Curved Path Backing for Sensor Pattern 2

As before, the more extensive pattern 2 has a much higher potential for nuisance alarms.

3.2 Results Derived from the STI Interactive Driving Simulator

3.2.1 Lane Change/Merge

Data collection consisted of driver subjective opinions as reported in the lane change/merge subject questionnaire in Appendix D, section A. The questionnaire data were organized into a spreadsheet file and analyzed. Since each driver evaluated several CAS configurations, the number of observations recorded in response to each question varies and does not sum to the total number of drivers in the study. In the following figures, the "Q" number shown on each histogram corresponds to the question number in the lane change/merge subject questionnaire.

3.2.1.1 Subjective Impressions

A number of questions were asked regarding system configuration.

After driving the simulator one or more times with a CAS latency time of 0.1 sec, the subject drove the simulator with the latency time adjusted to 0.5 sec. Then the subject was asked to indicate how the alerting system responded in this instance compared to the times before. Three potential answers were available: faster (required less time for the alerting system to come on when a car was in the blind spot), no difference, or slower (required more time for the alerting system to come on when a car was in the blind spot. Subjects generally perceived no difference. The responses are summarized in Figure 3-30.

Figure 3-31 summarizes subject response when asked whether they preferred the CAS to be continuously activated or turn signal activated. The subjects responded in favor of turn indicator activation.

When the subjects were asked whether the CAS gave them adequate notice of vehicles in their blind spot, a majority of the agreed that they were give adequate warning. Figure 3-32 summarizes these responses.

Subjects drove with the visual warnings (arrows) displayed either in the center rearview mirror or as HUD. Afterward, the subjects were asked which location was preferred. Figure 3-33 shows that there was a preference for the HUD location.

Regarding whether the auditory alarm only condition (no visual) had any effect on driving experience, Figure 3-34 shows that subjects overall were mixed in their response.

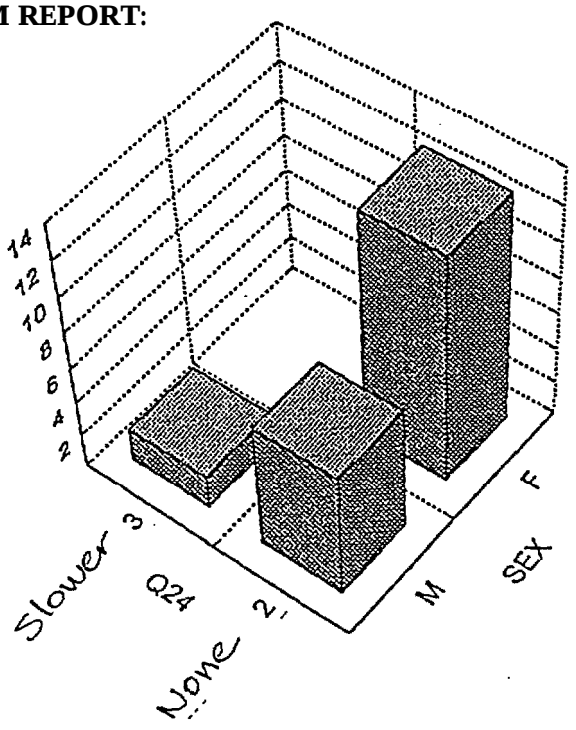


Figure 3-30. Perceived Difference Between Slow (0.5 sec Latency Time) versus Normal (0.1 sec Latency Time) CAS Response (See Appendix D, page D-6.)

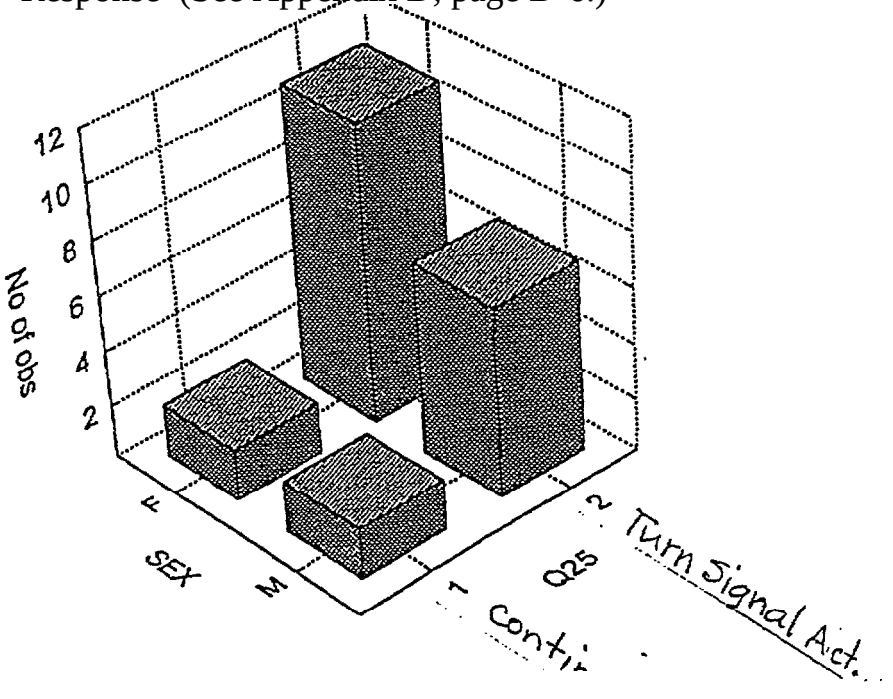


Figure 3-31. Responses Indicating Preference for Turn Signal Activated over Continuously Activated CAS Warnings

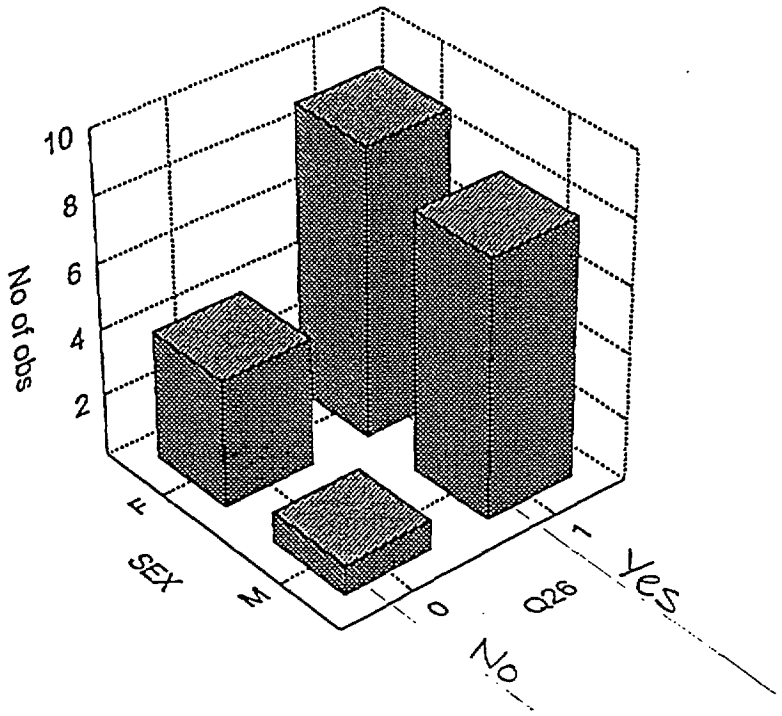


Figure 3-32. Adequacy of Notice of Vehicles in the Blind Spot

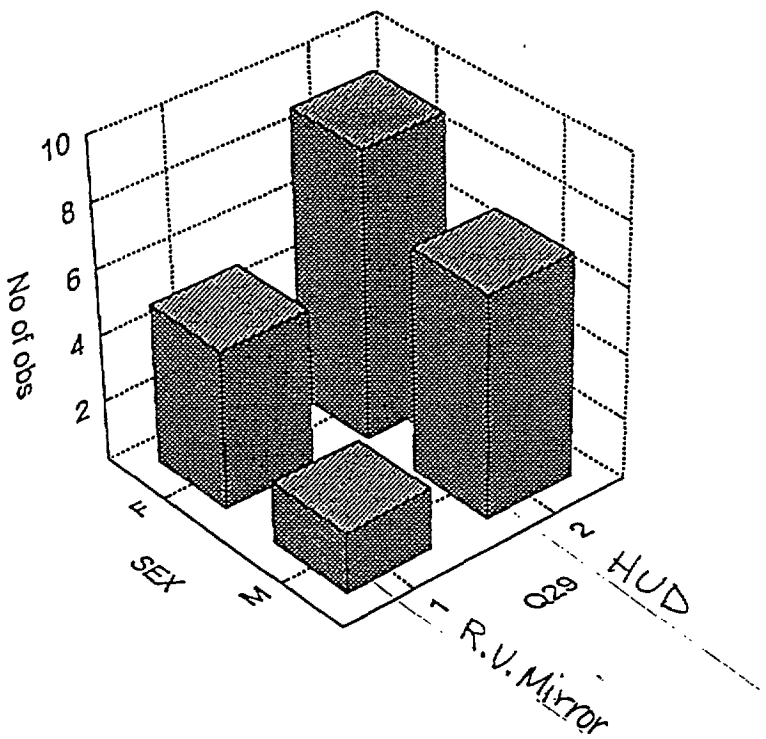


Figure 3-33. Preference for Visual Display Location

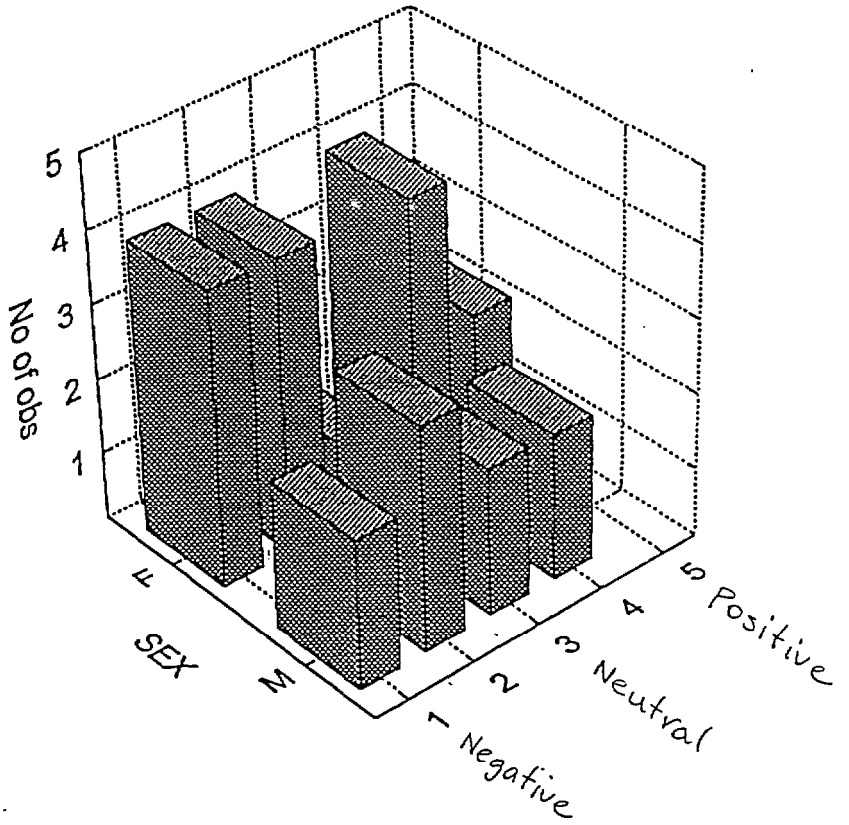


Figure 3-34. Subject's Evaluations the Effect of the Auditory Only Warning Display

Table 3-6 gives a summary of the free form responses elicited in the subject questionnaire. A majority of the subjects think the CAS is a good idea and would prefer a HUD visual display. Regarding the auditory display, some subjects found the "beeps" annoying in the always-on condition and a few found them annoying overall. Some subjects found the "beeps" alerted them to the visual display, while others thought they should be speed dependent or capable of being turned on and off. In general, the auditory display seemed to cause a varied reaction amongst subjects, and is probably prone to significant variation in individual reaction.

CAS in General;	Number of Responses
Like it/think it is a good idea.	15
It is annoying/irritating.	4
Overkill/did not like it when barrels/barriers/signs set off alarm.	2
Gave her extra security while driving.	1
Did not give enough time for him to respond.	1
Visual Display Location	
Don't like them in rearview mirror; diverts from or competes with attention to the road,	8
Like them in rearview mirror; this is where they look to change lanes anyhow.	3

Auditory Display:	Number of Responses
Very annoying in "always on" condition	5
Beeps w/o arrows bad; does not inform what side the other car is on.	5
Annoying overall.	4
Would like different tone.	4
Beeps alerted them to look for the arrow(s).	3
Beeps should be speed dependent or be capable of turning on and off.	2

Turn-signal activated vs. Always on:	Number of Responses
Always on -- annoying/would tune it out or would disconnect it.	4
Turn signal -- encouraged her to use her turn-signals more overall.	1

Table 3-6. Results of Open-Ended Question Summary (Note: Not all subjects responded to every topic. Therefore, the sums of the numbers of responses differ from topic to topic.)

3.2.1.2 Discussion

During the experiment, there were a number of trends and facts about subjects' behavior, opinions, and performance that were of interest. With regards to the CAS, most subjects felt that the concept of a device alerting them to drivers in their blind spot was a good idea. Subjects overall preferred the condition in which the CAS went off only when the turn signal is activated. When the CAS was going off continuously, subjects became annoyed and eventually "tuned it out" according their comments. Most preferred the visual display (arrows) in the center of the windshield as a HUD rather than an indicator in the rear view mirror. Arrows in the center of the windshield were preferred because this is in the general location where drivers maintain visual vigilance most of the time. Arrows in the rear view mirror diverted subjects' attention from the activity in front of them, and imposed upon them the need to constantly monitor the rear view mirror. The tone of the beep was somewhat annoying also. Some gave comments that a chime would be more pleasing. Others commented that they would not want to hear or would not be able to hear a beep at all. Overall, subjects did not like the auditory display only condition.

Subjects encountered a number of accidents due to the non-interacting nature of surrounding traffic. The driving scenarios were designed to provide lane assignment arrows to avoid unintended conflicts. Accidents were typically the result of being out of position in a particular portion of the driving scenario. There was a fine line in the scenario design and experimenter interaction between positioning subjects for an upcoming event while still allowing subjects to have control and make decisions about their driving.

Out of the twenty eight subjects (pilot subjects included), four felt some degree of simulator sickness. Two felt slightly nauseous and/or dizzy at times during the experiment, one got moderately dizzy and had to take a break and step outside, and one got physically ill. This one subject, however, arrived at the facility not feeling well initially, and was susceptible to getting sick even before the experiment began. This experiment was begun with the concern that the wide angle display would result in a high incidence of simulator sickness. This was found not to be the case, and simulator sickness was not felt to have influenced the major objectives of the experiment.

It is possible that some of the opinions and preferences of the subjects were elicited due to the nature of the driving simulator, and that

in the real world, their opinions and preferences would be different. The simulator may have created a heightened sense of vigilance in the subjects. On the other hand, some subjects said that the arrows were distracting and diverted their attention from the primary task at hand -- maintaining safe driving conditions. It is hypothesized that in the real world, this may be less of an issue than was expressed during the driving scenario,

3.2.2 Backing

Data collection consisted of driver subjective opinions as reported in the backing subject questionnaire in Appendix D, section B. The questionnaire data were organized into a spreadsheet file and analyzed. Since each driver evaluated more than one CAS configuration, the number of observations recorded in response to each question varies and does not sum to the total number of drivers in the study. In the following figures, the "Q" number shown on each histogram corresponds to the question number in the backing subject questionnaire.

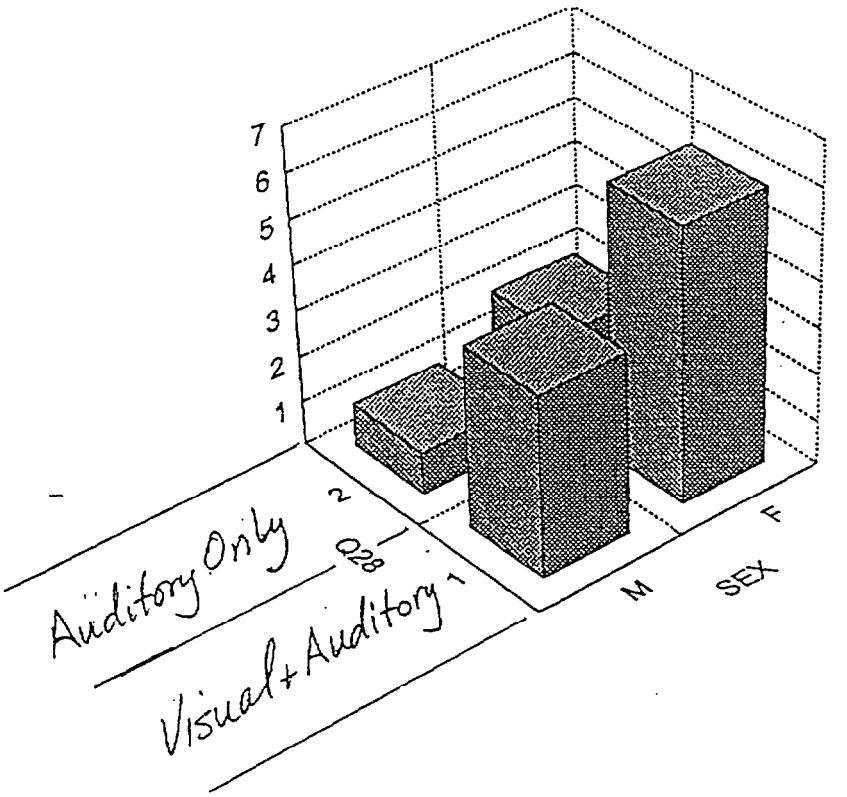
3.2.2.1 Questionnaire Results

After driving the simulator in several configurations, the subjects were asked a series of questions very similar to those described in section 3.2.1 .l. However, since the backing CAS was always activated by placing the simulator in reverse gear, there was no question concerning continuous versus turn signal activated CAS. Also, since there is no universal agreement on the placement and modality of the warning signals of the backing CAS, this aspect was explored in more detail.

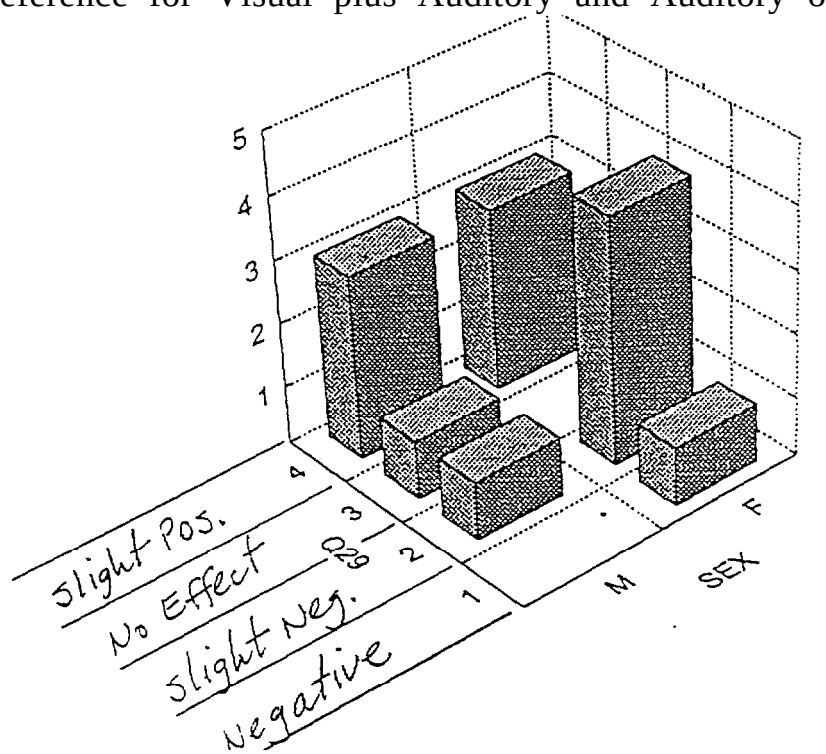
When comparing the latency time of the backing CAS, subjects did not perceive any difference between any of the CAS conditions.

Each driver drove the scenario with two different CAS configurations: one in which both visual (arrows) and auditory (beeps) warnings were activated and one in which only auditory warnings were activated. As shown in Figure 3-35a, when comparing visual plus auditory warnings to auditory only warnings, most subjects preferred‘ the visual plus auditory mode. There was a mixed response, however, to the effect of the auditory only display mode. Some subjects thought auditory only mode had a positive effect while others thought the effect was negative as shown in 3-35b.

Subjects in general thought the CAS gave adequate notice of cars and pedestrians in their blind spot as indicated in Figure 3-36a. Subjects also felt that using the alarm made them feel confident about their ability to drive backward. This is shown in Figure 3-36b. A significant percentage of the subjects noticed the CAS responding to things other than cars and pedestrians (Figure 3-37a). This did have some negative effect on their view of the system as a whole (Figure 3-37b). As indicated in Figure 3-38, when the alarm was activated, subjects in general found the information to be meaningful

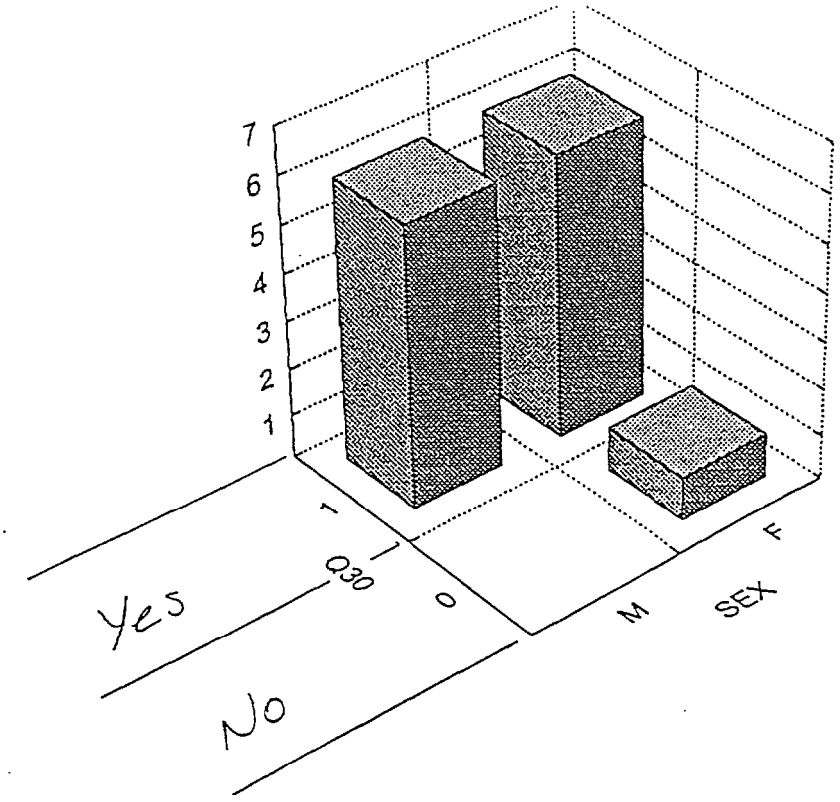


a) Preference for Visual plus Auditory and Auditory only Warnings

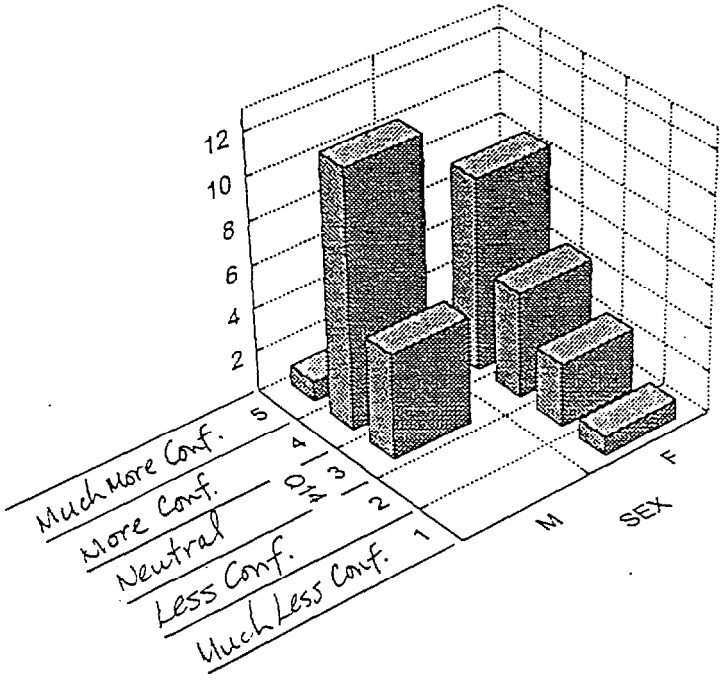


b) Subject's Impressions of the Effect of Auditory Only Warnings

Figure 3-35. Preference for Visual plus Auditory vs. Auditory Only CAS Warning

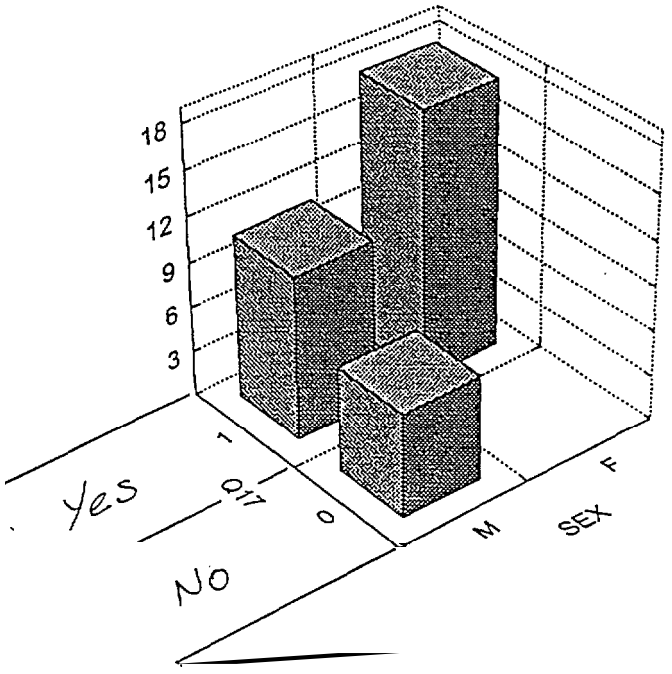


a) Driver's Impression of Adequate Warning of Cars and Pedestrians

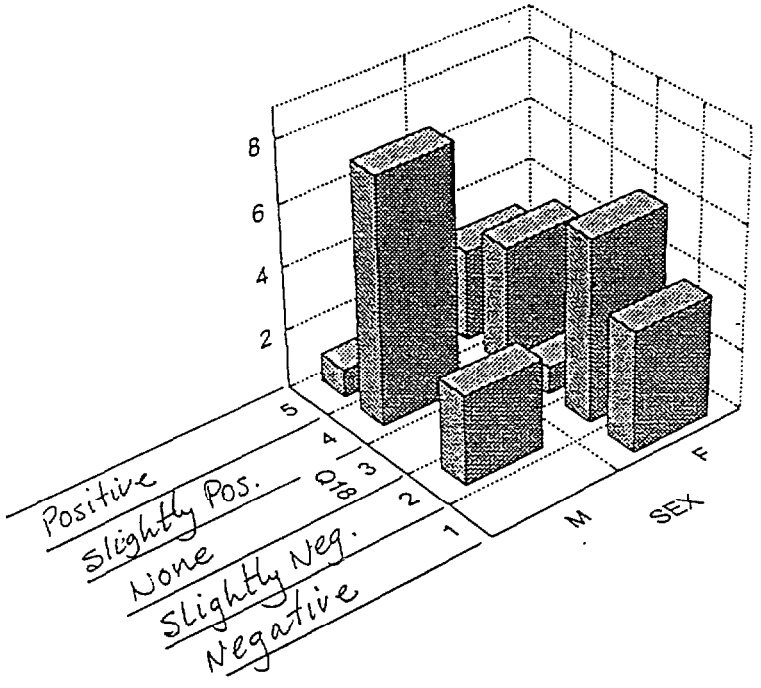


b) Driver's Confidence in Avoiding an Accident

Figure 3-36. Driver's Confidence in Backing CAS



a) Did subject notice warnings not associated with cars or pedestrians?



b) If "yes" on a), what was the influence of this on the overall impression of the system?

Figure 3 -37. Reaction to Warnings not Related to Cars and Pedestrians

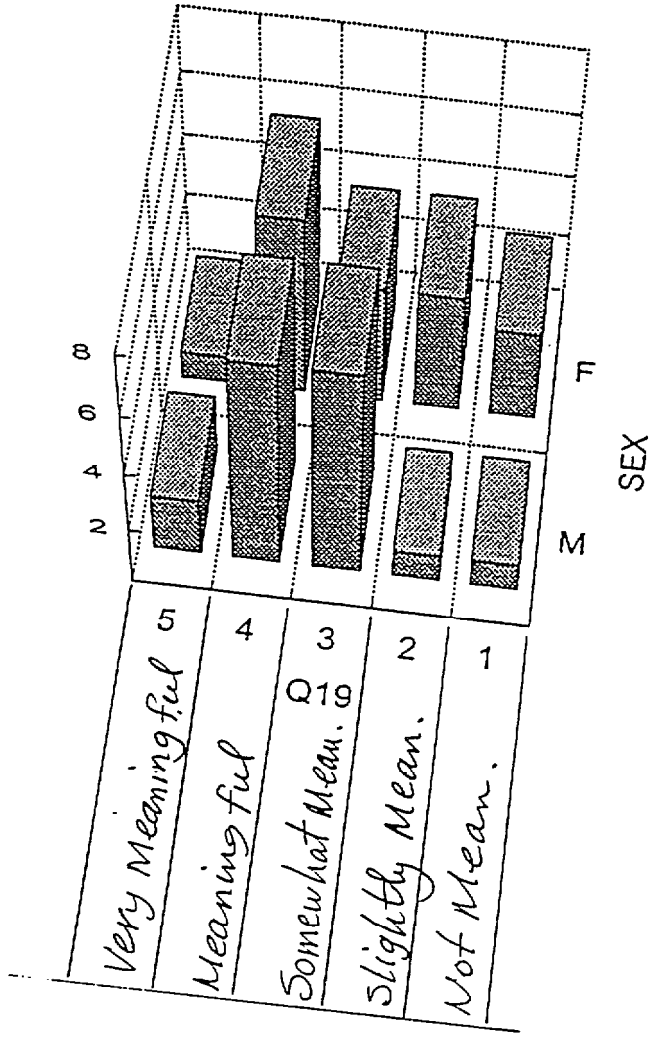


Figure 3-38. Driver's Assessment of the Meaningfulness of Warning Alarms

Subjects in general thought the CAS had too much alarm activity as indicated in Figure 3-39. This result may be due to the active driving scenario that was programmed to challenge the subjects as much as possible.

On the other hand, Figure 3-40 indicates that subjects tended to find their driving positively affected by the visual warning display (arrows), but they had a nominally neutral reaction to these warnings based on the system activity.

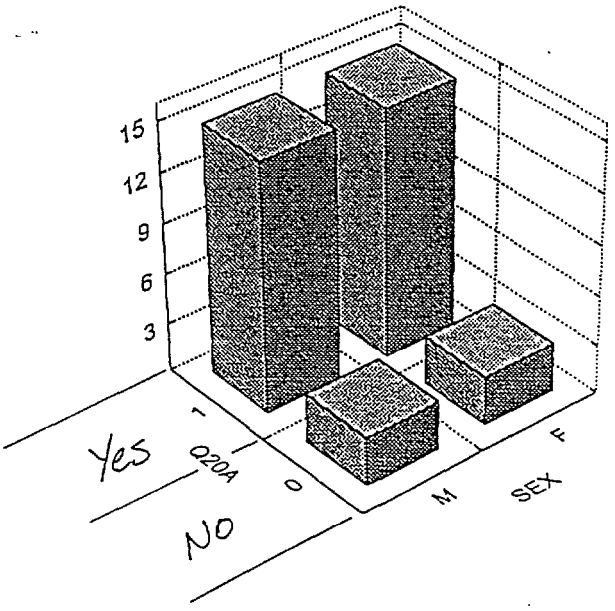
Regarding the auditory warning display, Figure 3-41 shows that reaction was mixed, with the 'beeps' being somewhat annoying.

Regarding the general perceived efficacy of the CAS, Figure 3-42 indicates that most males tended to find the system helpful while females were quite mixed in their impression of the backing CAS. However, in this regard the sample size was not large enough to draw any more definite general conclusions.

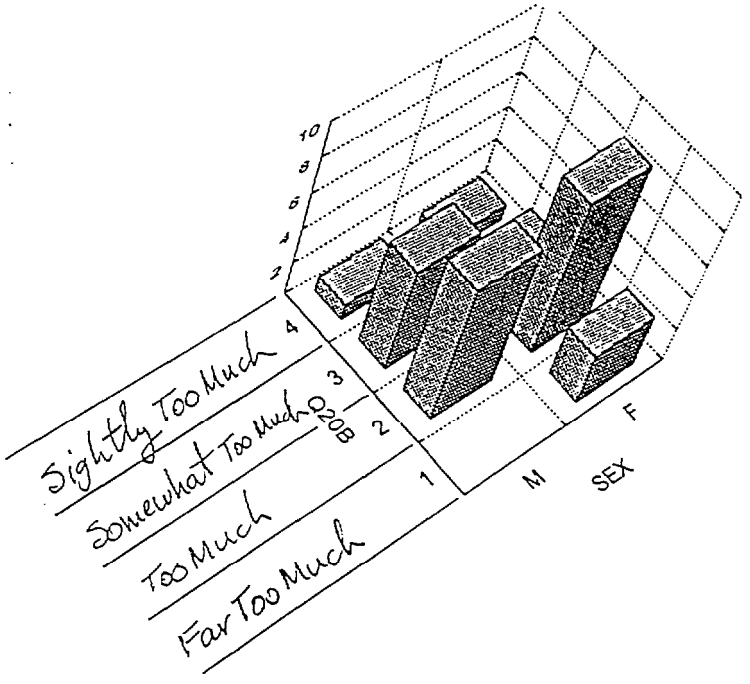
3.2.2.2 Discussion

Subjects found this phase of the experiment to be much easier and to be more enjoyable as compared to when the CAS was tested under forward-driving conditions. The driving scenarios seemed to make more sense, and subjects' interaction with other traffic and the environment in general was more real-world as well as more involving.

For a few reasons, less training in this phase was needed, allowing the simulator interface to become more transparent, which enabled the experiment to go smoother, faster, and make more sense. First, subjects participating in this phase of the experiment had already participated in the forward-driving phase. Second, fewer constraints were necessary on subjects' driving, and those implemented were easily understood. Third, there was much less traffic on the road than in the forward-driving phase.

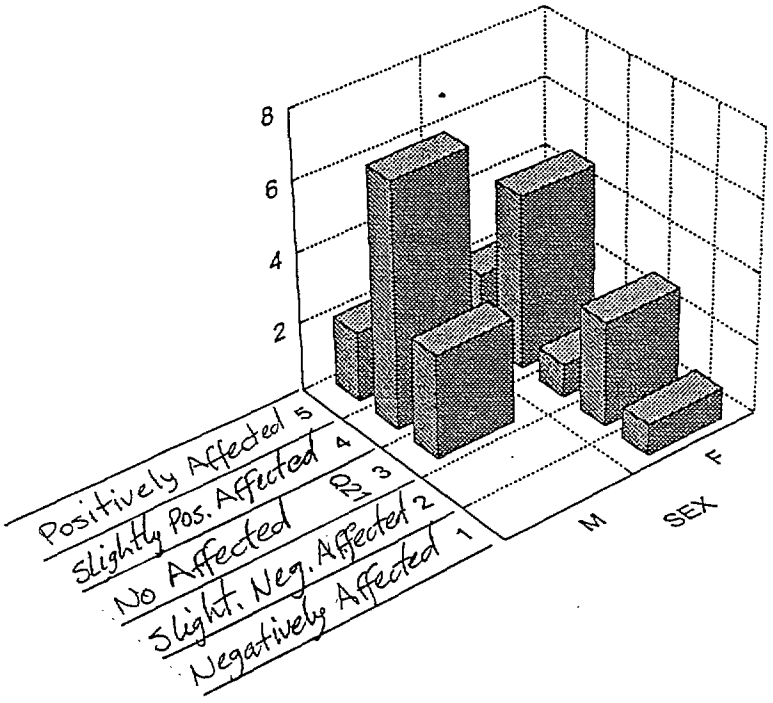


a) Was there too much activity from the warning system?

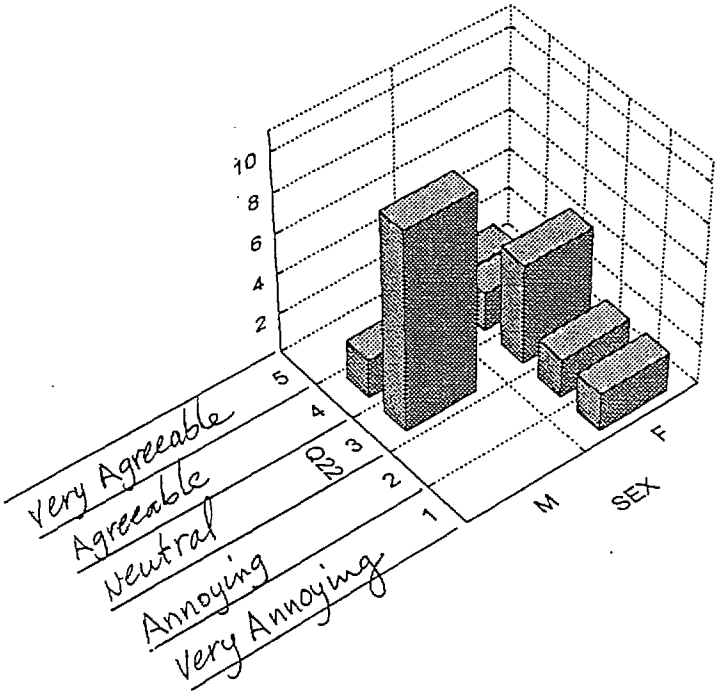


b) If answer to a) was "yes", how much excess activity was there?

Figure 3-39. Driver's Impression of CAS Warning Alarm Activity

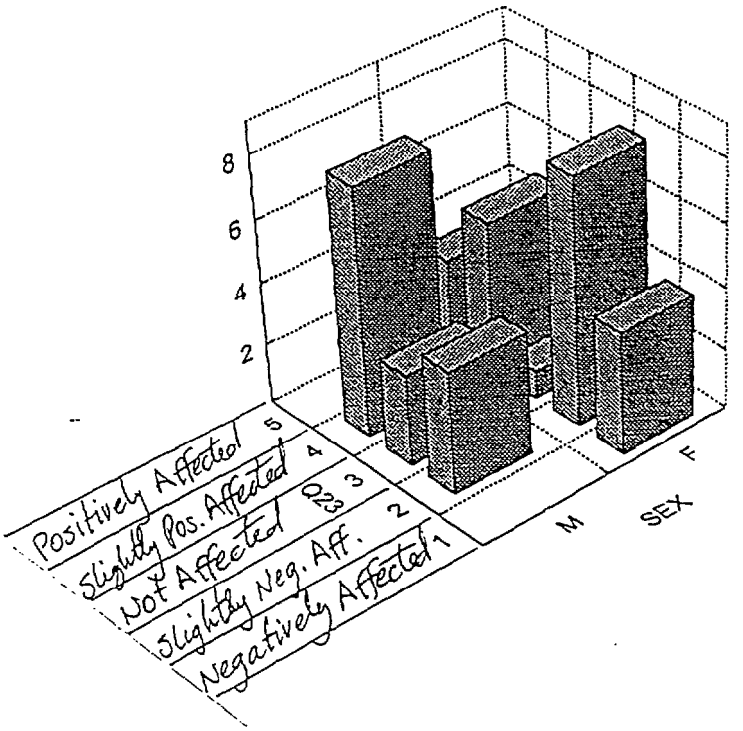


a) Driver's Assessments of the Effect on Driving

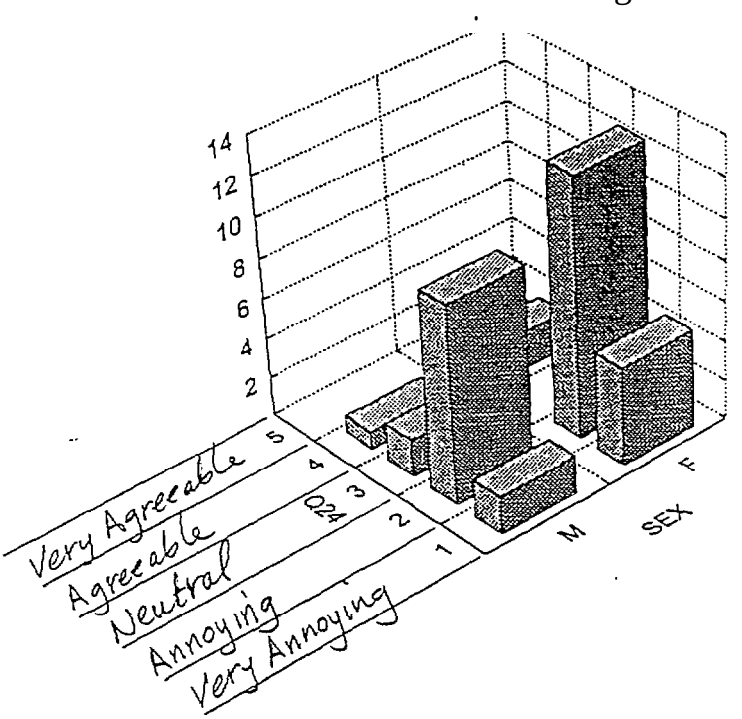


b) Driver's Assessments of the Helpfulness of the Warning Arrows

Figure 3-40. Visual CAS warning alarm (arrows) effect on driving

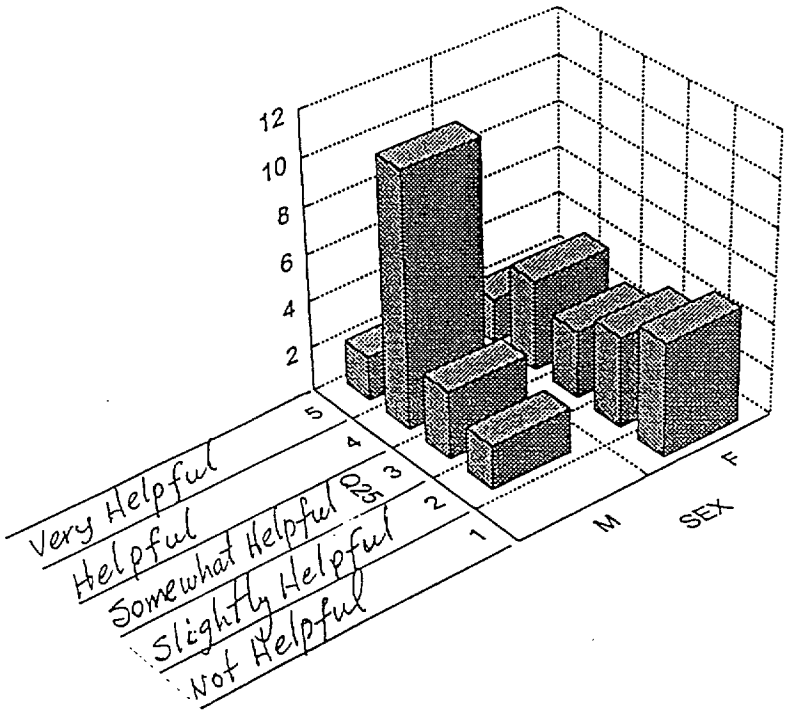


a) Driver's Assessment of the Effect on Driving

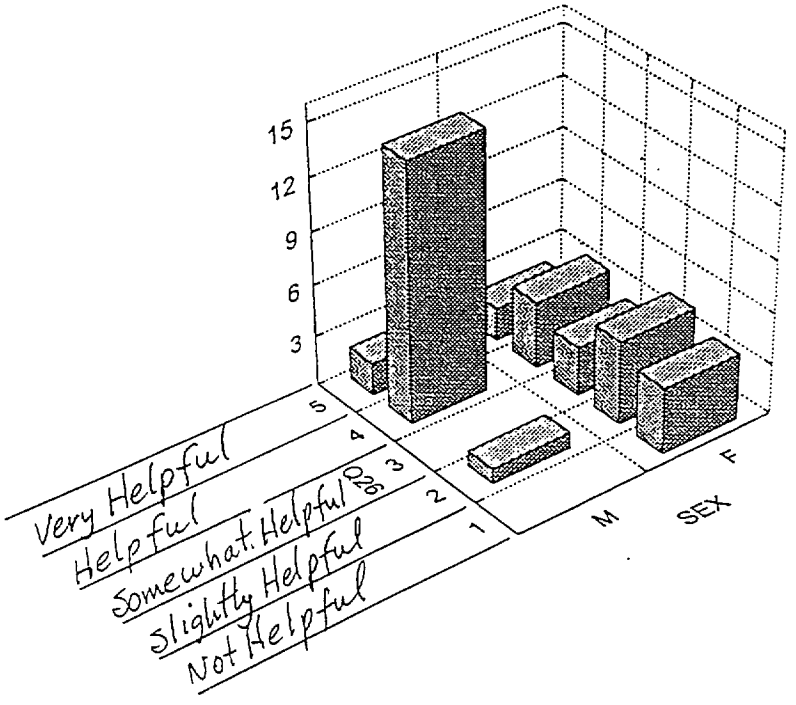


b) Driver's Assessment of the Helpfulness of the Warning Beeps

Figure 3-41. Auditory CAS Warning Alarm (beeps) Effect on Driving



a) Driver's Assessment of the Helpfulness of the CAS in Warning of Objects in Blind Spot



b) Driver's Assessment of Helpfulness in Avoiding Accidents?

Figure 3-42. General Perceived Efficacy of CAS Warnings

Out of the twelve subjects in the backing experiment, not one felt any sort of dizziness or nausea during the experiment, compared to four out of twenty eight from the first phase of the experiment. The driving scenarios were shorter and fewer in the backing experiment which resulted in less total exposure and more frequent breaks. Drivers' responses to the open ended questions are tabulated in Table 3-7.

CAS in general:	Number of Responses
Liked the backing CAS	6
The CAS did not add anything beyond what the mirrors provided	3
CAS would be good when drivers are tired/careless	2
More helpful than when driving forward	1
CAS distracting/dangerous	1
Made them more aware of pedestrians	1

SPECIFIC COMMENTS ABOUT AUDITORY	Number of Responses
Sometimes confusing/distracting	3
Beeps-only condition not effective	3
Would like beeps for reverse driving only	1
Does not like beeps in any condition	1

Table 3-7. Subject Open Ended Comments on Backing CAS (Note: Not all subjects responded to every topic. Therefore, the sums of the nmbers of responses differ from topic to topic.)

3.2.3 General Discussion and Conclusions

The primary purpose of the CAS driving simulation studies was to determine the human factors implications as elicited through an extensive questionnaire given to test subjects. In this light, the experiment was useful in that data were obtained showing representative end-users' opinions and preferences regarding various configurations of the CAS.

Accidents are rare events in the real-world. A significant challenge in setting up the driving scenarios was trying to create conflicts that would increase the likelihood of an accident. It is natural for people to try very hard to avoid accidents. Experience in creating the driving scenarios as well as conducting the experiment has led to some potentially useful observations for future work. Further intelligence on avoiding and flowing around the subject driver would be helpful, subject to realistic maneuvering acceleration constraints (i.e., on the order of 0.6-0.8 g).

On the whole, drivers had a positive response to CAS performance under the display conditions that they preferred.

4.0 Conclusions

4.1 Preliminary Performance Specifications

Based on the results of the driver and Monte Carlo simulations, we have revisited the requirements for the various CAS that were specified in our Task 2 Report. As mentioned in Section 1 of this report, The Background, we have addressed a subset of the systems described in our Task 2 report, namely those which we anticipate could be available by the year 2005 based on our assessment of the status of available technology in the year 2000. This judgment is based on our Task 3 work, where we tested all of the available CAS products that address lane change/merge and/or backing accidents. In Section 4.2 through 4.4 we have reproduced the set of requirements already presented in the Task 2 Report, and have updated those preliminary performance specifications which have been refined and/or defined during the Task 4 effort.

The methodology employed to arrive at these preliminary performance specifications is different depending on which simulation is being employed. For example, the Monte Carlo simulation results define the maximum range of the long range sensors utilized for lane change accident avoidance. Figure 3-9 shows the $(CAP)_R$ as a function of that range. Of course, the actual value of the $(CAP)_R$ displayed depends in a complex way on the many assumptions that have gone into the Monte Carlo simulation. It is not the actual values of the $(CAP)_R$ that are important, but rather the shape of the curve. That shape should be much less sensitive to the underlying assumptions. It appears that beyond a maximum range of 80 ft., the $(CAP)_R$ no longer increases significantly. Although some slight improvement occurs beyond 80 ft., the benefit derived from the increased complexity required to provide longer coverage does not appear to warrant going beyond the 80 ft. range. Thus in the preliminary performance specification for Goals #3 and #4 for the lane change CAS, the maximum range has been set to 80 ft.

When one looks at the results of the questionnaire administered after each session on the driving simulator (see Figure 3-31), it can be seen that the majority of tested drivers preferred that the lane change collision avoidance system's activation be tied to the lane change signal. However, other factors may dictate that at least some portion of the warning display be functioning at all times.

Some general comments will be presented before the specific requirements are discussed. For all the systems, a detection probability of at least 95% at the sensor level for a single look has been specified. This would essentially guarantee detection of all objects in the detection zone since it would be extremely unlikely that missed detections could occur over the entire number of opportunities for detection during an encounter. (The probability of detection is defined for a single detection step which is one or more "looks" at the detection zone coupled with data processing.) The best of the lane change CAS tested have a duty cycle of at least 10 Hz and so numerous detection periods would occur. Of course, a missed detection for one or more periods during the encounter could add to the overall latency of the CAS. This has to be traded against increasing the sensitivity of the detection process to raise the detection probability and at the same time increase the false and nuisance alarm rates which are defined on page 81. We have tentatively specified a false alarm rate of 10^{-6} and a nuisance alarm rate of 10^{-3}. The exact balance between the detection probability and the false and nuisance alarm rates can only be attained through a large number of test drives with a specific CAS and a variety of drivers. An added complication arises in this trade because one driver's warning might be another driver's nuisance alarm.

Human factors testing was performed in conjunction with task 3 by VRTC, and the following indications have emerged. For Side Object Detection Systems (either left side, right side, or both), Table 4- 1 summarizes those indications.

For Rear Object Detection Systems, three items of the advice in Table 4-l are changed. These are as follows:

1. The audio is a more important warning mode than is visual. Except for the problem of hearing impaired drivers, it is not clear that Rear Object Detection Systems require visual warnings.

2. It is not clear where the visual warning display should be located. The recommended Side Object Detection System location of on or near the line of sight to a side view mirror is probably not a good location to place a Rear Object Detection System visual warning display.

3. The system should provide audio warnings only when the vehicle is in reverse gear. If the Rear Object Detection System has a visual warning display, it may be desirable to have this operational all of the time.

1. Should be very simple (from the driver's perspective, not necessarily the manufacturer's!) and straightforward.
2. Provides both audio and visual warnings.
3. Provides no more than two levels of warnings.
4. Provides audio warnings only when the appropriate turn signal is on (or there is some other reason to expect that the driver is about to steer the vehicle to either the left or right).
5. Has two visual displays. These are a driver warning display and a system trouble display.
6. Has the driver warning visual display located on or near the line of sight to the appropriate side view mirror.
7. Has the driver warning visual display indicate presence of an object in the detection zone by turning on a red light and turning off all other lights on this display.
8. Has the driver warning visual display indicate that no object is present in the detection zone by turning on an amber light and turning off the red light.
9. Whenever the system is powered up and functioning properly either the amber light or the red light, but not both, on the driver warning visual display will be on.
10. The system trouble visual display should be integrated with the vehicle's instrument panel. This display should consist of a trouble light that is normally dark. The trouble light should light momentarily when the vehicle is turned on and continuously if a system failure is detected.
11. Allows loudness of the audio display to be adjusted.
12. Allows brightness of visual display to be adjusted. Although they did not work well in the interfaces evaluated, automatic adjustment may be best.
13. Manual loudness and brightness controls should be located on the vehicle's instrument panel.
14. When the controls are used to manually adjust loudness or brightness, the interface should momentarily produce a warning signal so as to provide the operator with feedback about the adjusted level.

Table 4-l. Indications of Desirable Features of a Side Object Detection System and Driver Interface

For Rear Vision Enhancement Systems, a standard television interface appears to work well. This type of interface has the advantage that most people are familiar with it.

4.2 Preliminary Performance Specifications for Lane-Change CAS

4.2.1 Goal #l: Minimal System

Since most lane change/merge collisions involve closing speeds of 15 mph or less, the minimal CAS is a proximity detection system. This CAS is the closest to deployment. Of the seven lane change CAS tested, six addressed this requirement. We have specified the coverage zone based on the length of the vehicle, making it equally applicable for passenger cars and various size trucks.

· Function:	Target Detection within a given zone; Driver alert
· Coverage:	1 lane (12 ft) to left or right in the transverse direction, depending on the lane Change direction indicated; this coverage to extend for the length of the vehicle, more is better; 1 - 10 ft in height
· Size of Target::	Any vehicle allowed on public roadways (pedacycle to truck)
· Target Velocity:	Any allowable (0 to 65 mph)
· Target Acceleration:	Any achievable (-g to +g)
· Number of Targets:	Presence detection of all targets, most likely only one
· Platform (SV) Velocity:	Any
· Platform (SV) Acceleration:	Any
· Measurement Latency:	Less than 0.5 s
· Measurement Accuracy:	2 feet*
· Performance* * :	Probability of Detection: > 99% (TBR) Probability of False Alarm: < 10^{-6} (TBR) Probability of Nuisance Alarm: < 10^{-3} (TBR)
· Interference including EMI/EMC:	Shall not interfere with the operation of other in-board or out-board systems

· Duty Cycle:	On-demand operation with TBD activation mechanism
· Driver Vehicle Interface:	Headup display activated by turn signal or always on visual signals in respective side view mirrors with audio warning tied to turn signals (TBR)

* Measurement accuracy is required to differentiate targets that are within the prescribed detection zone and those that aren't. Given that the minimum dimension of these zones is a lane width (12 ft.), an accuracy of 2 ft is a good compromise between what can readily be achieved (<3 ft.) and what is desired (~ 1 ft.).

** Detection probability here is defined at the system level. It is the cumulative probability of detecting an object in the coverage zone. False alarm is here used as a sensor parameter. It represents the probability that the sensor electronics will generate enough energy internally to trigger the detection algorithm. The nuisance alarm rate is determined by the system performance. It is a function of the sensor design, the effectiveness of the algorithms employed, and the physical interaction of the energy sampled and the surroundings. The level specified is one assumed to be tolerated by the sophisticated driver. It will be reevaluated during Phase III of this program, when extensive testing of a prototype CAS will be performed with our testbed.

4.2.2 Goal #2: Lane Keeping

We have not addressed this system during our Task 4 effort. Although lane keeping monitors may be achievable in the future, no product currently exists which purports to fulfill this requirement. Systems which address the running off the road type accidents may be applicable here.

· Function:	Detect unplanned transverse vehicle motion across lane boundaries and alert the driver
· Measurement Range:	Drift from 2 ft/s - 30 ft/s (TBD)
· Accuracy:	2 ft/s (TBD)
· Vehicle Velocity:	Any

· Special Interface:	Determine if transverse motion is intentional via interface to vehicle steering unit; Synergistic with Driver Alertness Sensor
· Duty Cycle:	Always on in forward gears

4.2.3 Goal #3: Counter-Fast-Approach

The CAS design is extended to detect targets in the adjacent lane with high closing speeds. To do this in a timely manner, it is necessary for the CAS to detect the POV at much longer distances. Also in order to determine whether the target represents a threat to the SV, the CAS must also measure the closing speed of the POV.

Additions/Modifications to 4.2.1:

· Coverage:	Modify - Coverage in the longitudinal direction to 80 ft. (TBR) fore and aft of the SV
· Function:	Add - Longitudinal relative velocity measurement;
· Relative Velocity Range:	+/- 60 mph
· Number of Targets:	One or more per zone
· Measurement Accuracy:	5 ft/s* (TBR)

*This corresponds to about a 5% accuracy on a closing speed of 60 mph and is an accuracy achievable with state-of-the-art systems. However, the requirement is ultimately tied to the detection/ warning algorithm and is design dependent. The relative velocity accuracy is determined by the requirement to determine if another vehicle can potentially be a threat to a planned lane change maneuver. That calculation must allow for the variations in the lane change times from driver to driver and situation to situation and for the unmeasured acceleration (if any). (Reference 9) A relatively large safety cushion in the algorithm that utilizes the measured range and velocity to determine a warning would allow for reasonable uncertainties in those measurements (2 ft and 5 ft/sec, respectively).

4.2.4 Goal #4 Counter-Convergence/Situational Awareness

This goal is designed to alert the driver of the SV during the course of lane changing of a potential conflict due to the presence of

vehicle(s) initially two lanes over to either its left or right which are also executing lane change maneuvers into the same lane. Due to the more complex velocity and range calculations required and to the need of tracking multiple targets, it is unlikely that this system can be realized by the year 2000.

Additions/Modifications to 4.2.1 and 4.2.3:

· Coverage:	Modify - 2 Lanes to the left or right of the SV in the transverse direction; 80 ft. (TBR) fore and aft of the SV in the longitudinal direction
· Function:	Add - Transverse relative velocity measurement
· Measurement Accuracy:	5 ft/s for relative longitudinal velocity; TBD ft/s for relative transverse velocity (sample value: 5 ft/s)
· Concept of Operation:	TBD; At one extreme: a Situational Awareness System can be functional at all times, detecting vehicle targets, measuring their velocity relative to the SV and predicting their trajectories relative to the SV - a warning signal will be issued upon imminent danger; At the other extreme: a Counter-Convergence System can be activated on demand and the driver of the SV will postpone lane-change until the System declares it is safe to do so
· Duty Cycle:	On-demand operation with TBD activation mechanism

4.3 Preliminary Performance Specifications for Merge CAS

4.3.1 Goal #l Driver Advisory/Warning

The fact that a majority of merge crashes occur on non-interstate trafficways where there is no traffic control indicates the need to heighten the state of awareness of drivers as they approach a merge situation in the roadway. To accomplish this goal, changes in the roadway, posted passive and active signs, and modifying the merge lanes and ramps are proposed.

• Function:	Provide warning to drivers approaching a merge site of the possibility of merging traffic; Provide warning to drivers performing a merge of potential conflict with through traffic
· Concept of Operation:	Roadway advisory system ranging from simple warning signs to complex vehicle detection and velocity measurement warning systems
· Vehicle Interface:	Via warning display on the roadway visible to the drivers or via direct communication link to a receiver onboard the vehicle which in turn issues . a warning to alert the driver

4.3.2 Goal #2 Merging Aid

The same requirements as for 4.2.3 apply but with additional requirement for

· Coverage:	Modify - Coverage in adjacent lanes to include lanes that intersect the merging lane at angles up to 15 (TBD) degrees

4.4 Preliminary Performance Specifications for Backing CAS

The goal of the backing CAS is to enhance the awareness of the driver of the presence of obstacles, both animate and inanimate, at rest or in motion, in a zone to the rear and to the side of the vehicle in a timely fashion so that preventive action may be undertaken. The CAS should be activated automatically whenever the SV is put in reverse gear.

4.4.1 Goal #l Rear Obstacle Detection - Minimal System

The minimal system is designed to warn of the presence of stationary or slowly moving targets behind the SV.

· Function:	Target Detection and Warning
· Range:	13 ft. (TBR) (See e.g. Figure 3-25) to the rear of the vehicle in range; Minimally, width of vehicle in azimuth*; Height of vehicle in elevation
· Target Size:	From small child to large vehicles or fixed objects
· Target Number:	All targets within range
· Target Motion:	0 - 5 mph
· Performance:	Probability of Detection: > 99% (TBR) Probability of False Alarm: $< 10^{-6}$ (TBR) Probability of Nuisance Alarm: $< 10^{-3}$ (TBR)
· Concept of Operation:	Near Zone detection of obstacles
· Duty Cycle:	Operational on demand when SV is put in reverse gear
· Vehicle Interface:	Can be interfaced with vehicle braking or transmission systems to introduce a delay before the onset of backing motion; this delay is long enough to test for the presence of a target and warn the driver before motion is initiated, thus allowing the driver the option to abort the backing maneuver before motion begins
· Driver Vehicle Interface:	Visual warning display visible in rear view mirror and/or auditory warning

*Pattern 1 coverage extends over the width of the vehicle and avoids many nuisance alarms. Pattern #2 is much more effective against accidents involving moving obstacles, but it produces many more nuisance alarms. It has an azimuthal extent of 19 ft. for a typical passenger vehicle. (See Figure 3-20 on page 46.)

4.4.2 Goal #2 Rear Obstacle Detection - Advanced System

Additions/Modifications to 4.4.1:

This goal pertains to the CAS mounted on the backing vehicle. It is designed for the mitigation of transverse, high-closing-speed crashes between the backing SV and cross traffic. Due to the long range required to detect cross traffic in a timely manner and complexity of the analysis to determine target velocity and predict the target trajectory, this goal is unlikely to be realized by the year 2000.

• Function:	Presence detection and velocity measurement
• Coverage	Far Zone - 100 ft. (TBD) to the left and right of the vehicle; TBD FOV
• Target Motion:	0 - 45 mph
• Concept of Operation	Far Zone detection of vehicles in transport (range and velocity)

4.4.3 Goal #3 Forward Collision Warning

This system falls outside the purview of the current contract. However, we include key requirements below for completeness. Its goal is to warn the drivers of the (non-backing) vehicles in transport of the impending intrusion of the backing vehicle into its lane of travel. This goal requires a forward looking collision warning system on the non-backing motor vehicle in transport. The range should be long with a wide field of view. In this case, SV is not the backing vehicle. Due to the long range required to detect cross traffic in a timely manner and complexity of the analysis to determine target velocity and predict the target trajectory, this goal is unlikely to be realized by the year 2000.

· Function:	Detect vehicles and pedacyclists in the crossing path of the SV; range and velocity measurement translated into trajectory and time to impact prediction
· Coverage:	100 ft (TBD) range in front of the vehicle; +/- 25 degrees in azimuth
· Size of Target:	Pedacycles to trucks
· Target Velocity:	0 - 15 mph transverse to the velocity of the SV
· Target Acceleration:	TBD
· Number of Targets:	one or more
· Platform Velocity:	0 - 60 mph
· Platform Acceleration:	TBD
· Measurement Latency:	Much less than 1 second (TBD)
· Measurement Accuracy:	Sufficient to predict time to impact; Accurate to about 0.5 second (TED)
· Display Requirement:	Issue warning if target is in collision course with SV; Optional display of safe speed for SV in order to avert collision
· Performance:	Probability of Detection: > 99% (TBR) Probability of False Alarm: $< 10^{-6}$ (TBR) Probability of Nuisance Alarm: $< 10^{-3}$ (TBR)
· Interference including EMI/EMC:	Shall not interfere with the operation of other in-board and out-board systems;
· Duty Cycle:	On-demand operation upon switch activation

4.5 Concluding Remarks

Based on the simulations described, we have been able to further specify several near-term CAS that could be effective in reducing the number and severity of lane change/merge and backing accidents. Based on the limited number of drivers exposed to the simulator, there is some indication of public acceptance for such devices. We know from our testing of currently available systems that no product exists today that can meet most of the derived preliminary performance specifications. However, there are indications that some technologies can provide for robust near-range

detection while also avoiding some fraction of the false and nuisance alarms that plagued the CAS that were available.

Armed with these preliminary performance specifications, we will investigate the technologies available to meet them in the beginning of Phase II of our program. We will then design and build a sophisticated testbed where a number of the most promising approaches can be evaluated to much better quantify the performance specifications in terms of coverage, discrimination, driver interface, interference with other systems, public safety, etc.

5.0 References

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Appendix A: Functional Goals by Crash Type

The following description of the functional goals of the Crash Avoidance System (CAS) has been taken from the Task 2 Interim Report. The goals, which are underlined, are subdivided by crash type. The square brackets enclose a brief preliminary discussion of the CAS required for each case.

A. Lane change crashes

1. To alert the driver of the presence of vehicles in the left and right adjacent lanes (relative to the SV) immediately prior to his/her initiation of lane-change maneuvers.

[The lane coverage should extend at least one car length (15 feet, but preferably longer) to the fore and aft of vehicle.]

2. To alert the driver of vehicle drifting motion across lane. This unintentional transverse movement may be caused either by steering or the lack of steering.

[Counteracting this type of crash may require sensors to monitor lane-keeping. If the vehicle crosses into the next lane with the turn signal enabled (a deliberate act), then the drifting motion warning system should be silent, thus encouraging the use of turn signals.]

3. To alert the driver of the presence of high speed or slow speed vehicles (relative to the SV) in the adjacent lanes immediately prior to his/her initiation of lane-change maneuvers.

[This goal would require longer range fore and aft looking sensors whose signals would be processed to give range rate as well as range.]

4. To alert the driver of the SV during the course of lane-changing of the presence of vehicles initially two lanes over to either its left or right which are also executing: lane change maneuvers into the same lane.

[Ideally this system would warn driver of closing transverse velocities. However, this is more difficult than simply monitoring the adjacent lane for the presence of another vehicle.]

B. Merging crashes

1. To heighten the state of awareness of (non-merging) vehicles as they approach a merge in the roadway.

[To accomplish this goal, changes in the roadway, posted passive and active signs, and modifying the merge lanes and ramps are proposed. The fact* that 91% of all merge crashes (includes angle, sideswipe and rearend manners of collision and both striking and struck) occur on non-interstate trafficways and 65% at locations where there is no traffic control indicate the need for increased awareness.]

* Source: the 1992 General Estimates System database

2. To provide situational awareness to the driver of the merging; vehicle as it enters into the traffic flow, including: presence of vehicles in the merged lane as well as their longitudinal velocities relative to the merging vehicle. The awareness should extend to vehicles both fore and aft of merging vehicle.

[Ideally, the system coverage should extend fore and aft of the merging vehicle, so the driver can better judge the relative distance and speed .]

C Backing crashes

1. To enhance the awareness of the driver of the Dresence of obstacles, both. animate and inanimate. at rest or in motion. in a zone to the rear and to the side of the vehicle in a timelv fashion so that Dreventive action may be undertaken.

[This requires an enhanced driver field of view to the rear and side. . Also there should be a very long range side-looking CAS on left and right sides to warn of fast closing cross traffic vehicles. The CAS should be activated automatically whenever the subject vehicle is put in reverse gear.]

2. To warn pedestrians. pedacyclists as well as drivers of the other vehicles of imminent backing; maneuvers by the SV so that appropriate defensive action mav be taken.

[Backing lights perform this function. For mitigation of high closing speed crashes, this warning should be visible for 100 ft. and possibly should be further enhanced by audible or visible techniques.]

3. To warn the drivers of other motor vehicles in transport of the impending; intrusion of the backing: vehicle into its lane of travel.

[This requires a forward looking collision warning system on the other motor vehicle in transport. The range should be long with a wide field of view.]

Appendix B: Sensor Models

The same sensor model is shared by both simulations. A further discussion of the sensor parameters may be found at the end of this section. Although the following methodology was developed for radar systems, it deals with generic system properties, such as signal-to-noise and detection patterns, and is applicable to active sensor systems.

To describe the model of the sensor, one should begin by discussing the relationship between the probability of detection, the probability of false alarm and the signal-to-noise ratio. Assume that the input noise voltage at the signal receiver is Gaussian distributed, with a mean value of zero and a variance (i.e., rms noise voltage) of Ψ_o. Passing this noise through the receiver's narrowband filter, the probability density of the envelope of the noise voltage output is given by the Rayleigh probability density function

$$P_N(V)dV = \frac{V}{\Psi_o}\exp\left(\frac{-V^2}{2\Psi_o}\right)dV \qquad \text{B-1}$$

When this modulation envelope is passed through an envelope detector, a target detection is considered to have occurred whenever the output voltage envelope exceeds a threshold V_T. Thus the probability of a false alarm due to noise is

$$P_{FA} = P(V > V_T) = \int_{V_T}^{\infty} \frac{V}{\Psi_o}\exp\left(\frac{-V^2}{2\Psi_o}\right)dV$$

$$= \exp\left(-\frac{V_T^{\,2}}{\sqrt{\Psi_o}}\right) \qquad \text{B-2}$$

Note that by raising the threshold voltage, the probability of false alarm may be decreased.

Next, consider a sine-wave signal of constant amplitude A (i.e., a steady-state target model) along with the noise at the input to the filter. The output to the envelope detector now has a probability density function given by

$$P_{S+N}(V)dV = \frac{V}{\Psi_o}\exp\left(-\frac{V^2+A^2}{2\Psi_o}\right)I_o\left(\frac{VA}{\Psi_o}\right)dV \qquad \text{B-3}$$

where $I_0(z)$ is the modified Bessel function of zero order. The probability that the envelope V will exceed a predetermined threshold V_T, which is also the probability that the signal will be detected, is

$$P_D = \int_{V_T}^{\infty}\frac{V}{\Psi_o}\exp\left(-\frac{V^2+A^2}{2\Psi_o}\right)I_o\left(\frac{VA}{\Psi_o}\right)dV \qquad \text{B-4}$$

This probability increases with increasing signal amplitude and decreasing threshold voltage. This is similar to the relation for the probability of false alarm, where P_{FA} also increases with decreasing V_T. These relationships are graphically illustrated in Figure B-1 below.

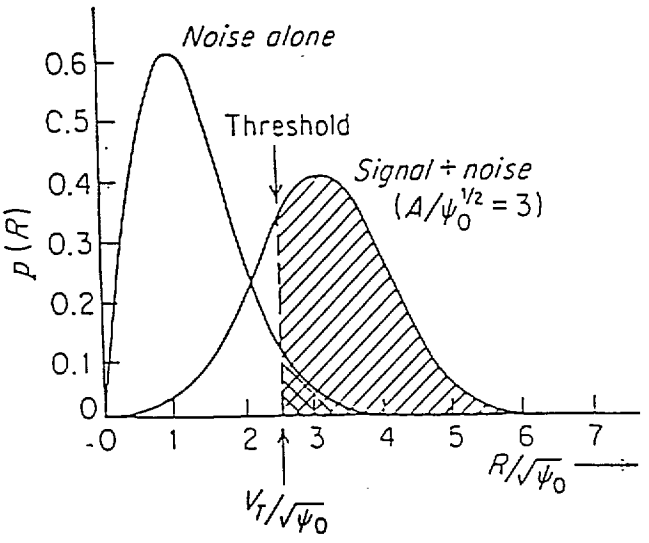


Figure B-1: Probability Density Functions for Noise Alone and for Signal-Plus-Noise, Illustrating the Process of Threshold Detection

The probability density for noise alone is plotted with that for signal plus noise. The cross-hatched area to the right of the threshold voltage and under the curve for signal plus noise represents the probability of detection, while the double cross-hatched area under

the curve for noise alone represents the probability of false alarm. If the threshold voltage is increased to reduce the probability of false alarm, the probability of detection will also be reduced, whereas if the threshold voltage is lowered to achieve a higher probability of detection, the false alarm probability will also increase.

A final expression for the probability of detection, P_D, given by equation 4, involving just the probability of false alarm and the signal-to-noise ratio may be obtained by noting from equation 2 that

$$\frac{V_T}{\sqrt{\Psi_o}} = \sqrt{2\ln\left(\frac{1}{P_{FA}}\right)} \qquad \text{B-5}$$

and that the signal-to-rms-noise voltage ratio, $A/\sqrt{\Psi_o}$, can be written as a ratio of signal power to noise power

$$\frac{A}{\sqrt{\Psi_o}} = \sqrt{2\frac{S}{N}}. \qquad \text{B-6}$$

With this, the probability of detection for a given false alarm probability and signal-to-noise can be written as

$$P_D = \int_{\sqrt{2\ln\left(\frac{1}{P_{FA}}\right)}}^{\infty} \xi \exp\left[-\left(\frac{\xi^2}{2}+\frac{S}{N}\right)\right] I_o\left(\sqrt{2\frac{S}{N}}\xi\right) d\xi \qquad \text{B-7}$$

where the variable of integration, ξ, is $\xi = v/\sqrt{\Psi_o}$ and $d\xi = dV/\sqrt{\Psi_o}$. Although the above expression can be (and has been) evaluated numerically, it is computationally cumbersome.

The signal-to-noise at the receiver due to a vehicle at a given location may be written as

$$\frac{S}{N} = K\frac{P_t G^2 \sigma}{T_o R_{max}^4} \qquad \text{B-8}$$

where $\frac{S}{N}$ = signal to noise ratio, SNR
P_t = transmitted power
G = transmitter/receiver gain

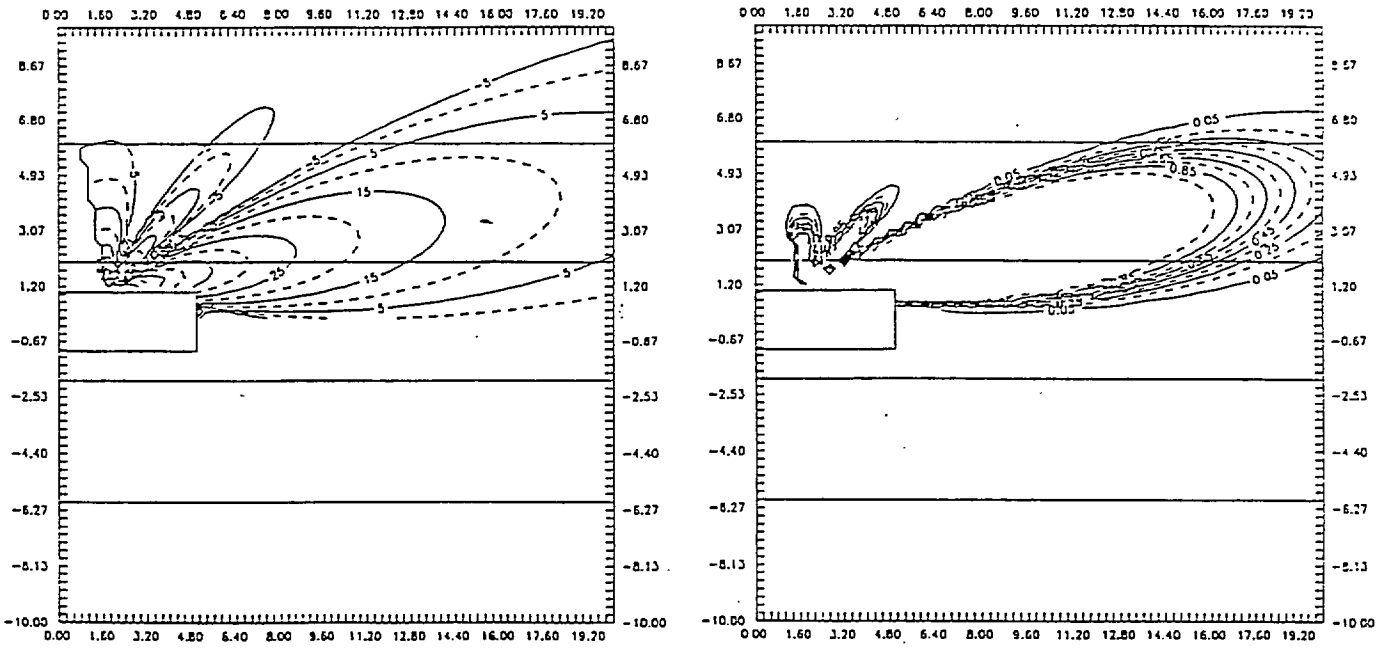
$\sigma =$ cross section
$T_o =$ standard temperature
(used in the definition of noise figure)
$K =$ proportionality constant, specific to the system
$R_{max} =$ maximum sensor range

In general, this expression is appropriate for active systems since the signal-to-noise may be expressed in terms of the transmitted power, a coefficient of proportionality for signal return (a cross section), a detection pattern (the gain pattern), a temperature used in the definition of the noise, and the sensor-to-target distance, R.

The only parameters in this expression which vary over the coverage zone are the gain, G, and R, the distance from the sensor, so that at any location (R,θ) the value of SNR is given by

$$\frac{S}{N} = \frac{S}{N}\bigg|_{R=R_o,\theta=0} \left(\frac{R_o}{R}\right)^4 \left(\frac{G(\theta)}{G(0)}\right)^2 \qquad \text{B-9}$$

In the above expression, $\frac{S}{N}\bigg|_{R=R_o,\theta=0}$ is a normalization constant which must be determined. Having already defined the probability of detection as a function of signal-to-noise and false alarm probability, the problem may be reversed to ask what signal-to-noise level is required to achieve a given probability of detection at a specified range and for a fixed probability of false alarm. This is used to determine the appropriate normalization of equation 9. With this normalization defined, the values of signal-to-noise at any (R,θ) location can be readily obtained. As a function of the Cartesian (x,y) coordinates of a given location, the radial distance from the sensor and the angle from boresight are determined. Using this in equation 9, a value of the signal-to-noise ratio (SNR) is determined on a rectangular grid covering the region of interest. For a radar system using a 20° beam antenna, this gives the SNR coverage map shown in Figure B-2.a. Finally using the previously defined relation for the probability of detection, the values of SNR at each (x,y) location can be converted into values of probability of detection, this for a fixed probability of false alarm. The resulting probability of detection contours are shown in Figure B-2.b below.



(a) SNR Coverage Map for 20° Beam Antenna

(b) Probability of Detection Contours for the Same 20° Beam Antenna

Figure B-2: An SNR Coverage Map is Converted into Probability of Detection Contours

All of the above calculations are done with respect to a local coordinate system centered at the sensor, with the angle from boresight measured in the horizontal plane. The implementation of these calculations has been generalized to allow positioning of the sensor at any location and its aiming in an arbitrary lateral direction.

Velocity discrimination is handled differently by the STI driving simulator and the TRW Monte Carlo simulation. In the TRW simulation, many situations are generated in which the POV is initially completely behind the SV and moving more slowly (negative closing speed) or the POV is completely in front of the SV and moving faster (positive closing speed). Neither case represents a potential crash situation. There are other cases in which the longitudinal gaps and closing speeds are such that these cases evolve in a short time to one of the above cases before the SV detects the POV and begins evasion. These cases are ended and placed in the "no crash" category to minimize run time. This is equivalent to velocity discrimination which eliminates detections in cases where no potential

conflict exists. No further velocity discrimination is done in the Monte Carlo simulation.

The following is a list of key parameters relevant to CAS sensor system modeling and their significance. The following quantities are the keyboard entries used in the TRW Monte Carlo statistical simulations. These are input directly into the models used in the STI driving simulator.

Number of sensors on the subject vehicle: The number of lane change aid sensors to be applied to one side (the right) of the vehicle for lane change/merge simulations or the back for backing simulations. This may be as low as 0 (zero) for running cases designed to test the effectiveness results, or as many as 10.

System update time (l/repetition rate) in seconds.

None of the following parameters are necessary for simulations in which there is no CAS applied to the SV. However, for each sensor to be placed on the SV, the following information is entered.

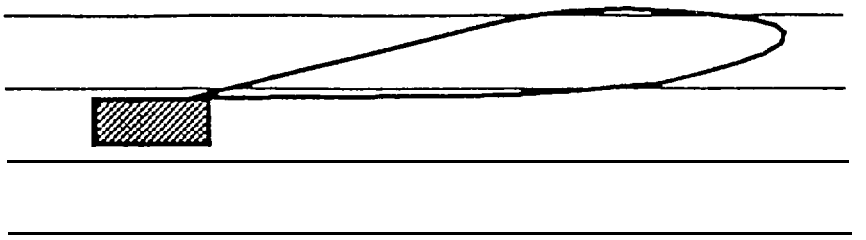
Signal-to-Noise Ratio (SNR) normalization (dB) for coverage map.

Distance (m) at which to normalize SNR.

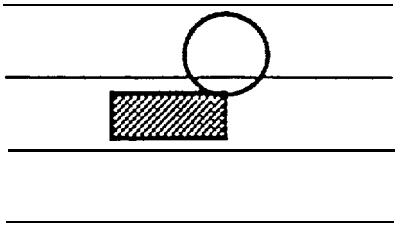
Detection pattern type, as chosen from the following list:

a. Narrow beam long range sensor (example: uniform rectangular aperture)
b. Circular pattern tangent at the sensor location (example: Hertzian dipole)
c. Wide beam proximity sensor, usually rangegated (example: nonuniform (cosine weighted) rectangular aperture)

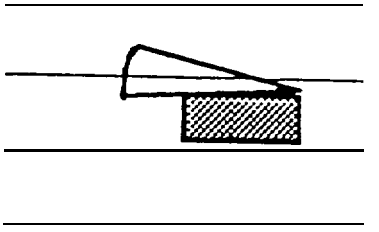
Note: Here, rangegating is a data processing procedure in which signals received from targets located at distances exceeding the rangegate distance are not considered. Examples of these patterns are shown in Figure B-3.



a. Long Range Sensor Pattern



b. Circular Pattern



C. Rangegated Proximity Sensor Pattern

Figure B -3: Schematic Examples of Detection Patterns for Each of the Sensor Types Listed Above

3dB beamwidth (deg) for this pattern (not always required).

Position of sensor as chosen from the following menu:

1. Rear bumper (corner)-right or left side
2. Mirror (1.7 m behind front bumper)-right or left side
3. Front fender (.7 m behind front bumper)-right or left side
4. Center back bumper

Boresight angle (degrees) of beam - 0.0 degree points rearward, along longitudinal vehicle centerline

Desired false alarm probability.

Latency time of the detection system (sec). The latency time represents the time required by the detection system to process the data and present it to the driver.

Appendix C: The STI Driving Simulator

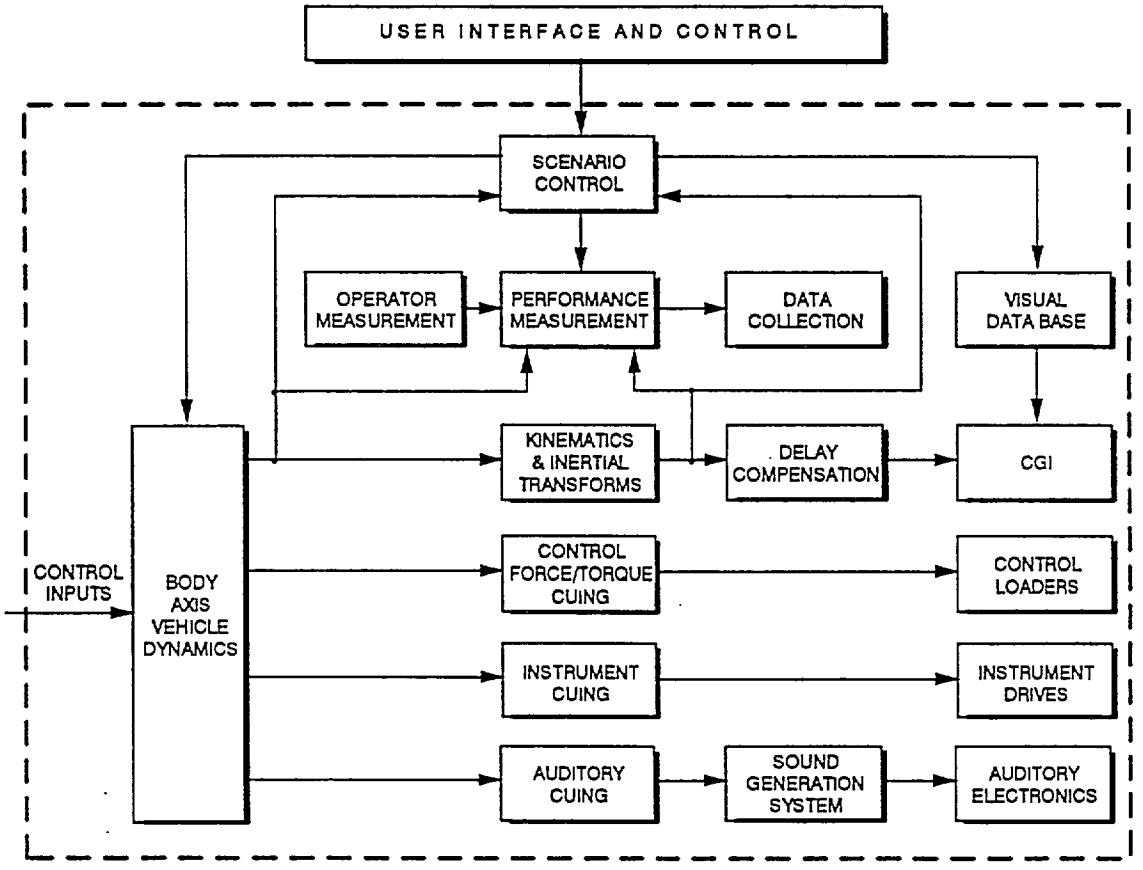
A. Overview

This appendix describes a PC based, interactive driving simulator designed for driver behavior research and to permit rapid prototyping of new systems and vehicle characteristics, cab layouts, etc. Earlier versions of this simulation approach have been used to investigate driver impairment, alertness monitoring and IVHS systems (References. C-l to C-3). This PC based approach is intended to be low cost and permit rapid set up of configurations and experimental conditions and tasks.

The driving simulator includes a car cab, a roadway display projected on screens in front of the cab, speakers for sound effects and auditory displays, torque cueing in the steering system, and a computer system for overall simulator control. The functional capability of the simulator system is illustrated in the Figure C-l block diagram. As indicated in Figure C-l the simulator includes vehicle dynamics, a computer graphics imagery system to produce the roadway display, auditory cueing to produce vehicle and roadway environment sounds, control cueing based on vehicle maneuvering to command steering torque, instrument cueing to drive a speedometer, and elements for controlling driving scenarios, collecting data and calculating performance measurements.

The processing of the simulator cueing feedbacks to the driver were designed to minimize delay and emphasize good fidelity within the limitations of the PC based approach of this simulator. The computational elements of the cueing feedbacks are illustrated in the Figure C-2 block diagram. A simplified model is used to compute the lateral/directional (steering) and longitudinal (speed) vehicle dynamics (Reference C-4). Visual cueing computations include compensation for delays in the computer generated image computations and display frame buffering. The compensation is specified so that no additional delay over real world vehicle response is apparent to the driver between steering control inputs and visual display response. Steering torque is provided by a large torque motor at the end of the steering shaft that is powered by a high band width (50 Hz) current amplifier. Steering torque is commanded from the vehicle dynamics based on maneuvering conditions (lateral acceleration) which provides the subject appropriate proprioceptive cues.

Figure C-1. Interactive Simulator Components



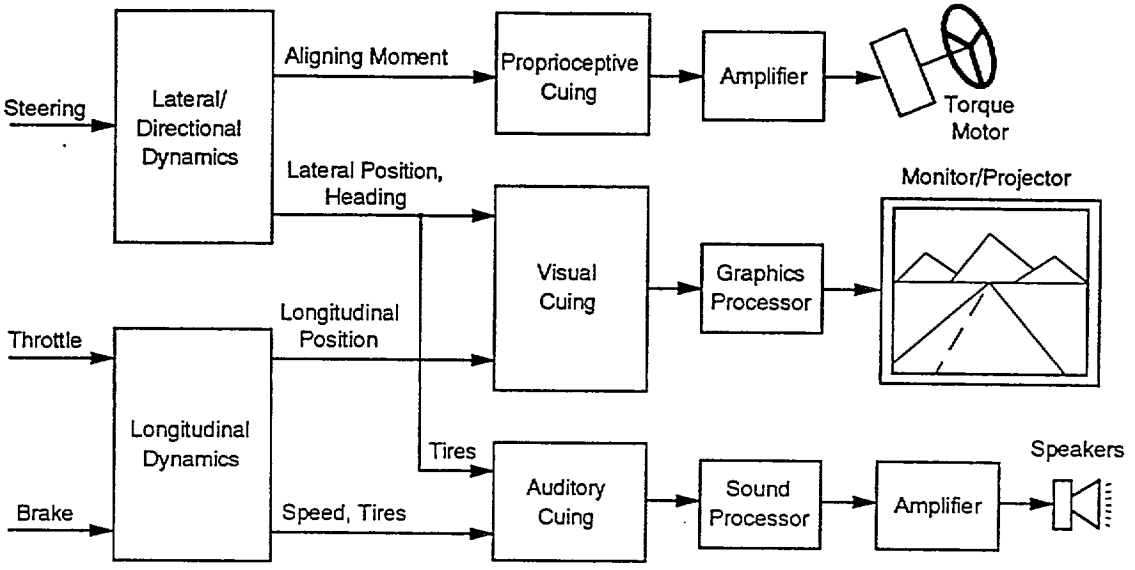


Figure C-2. Vehicle Dynamics and Cuing Commands

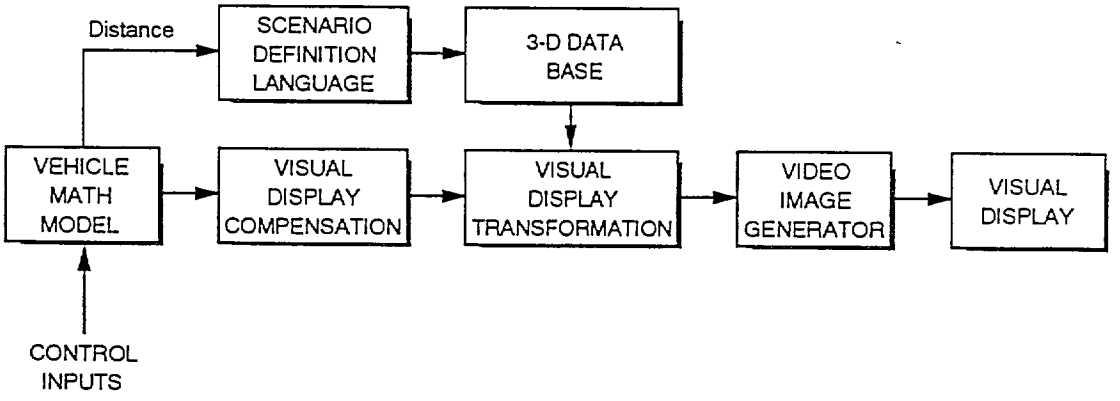


Figure C-3. Computer Image Generation

B. Vehicle dynamics

The vehicle dynamics computations provide the commands for visual, auditory and proprioceptive cuing as illustrated in Figure C-2. The vehicle dynamics used for this project were a relatively simple implementation designed to provide essential steering and speed control response from the driver's point of view and included the following functions:

1. Lateral/Directional (Steering) Control

Basic yaw rate and lateral acceleration response to steering inputs, including understeer and tire saturation effects. Transformations then provide display commands: visual feedback on vehicle orientation and lateral position; auditory feedback on tire screeching under limit performance conditions; proprioceptive feedback via steering torque based on maneuvering conditions.

2. Longitudinal (Speed) Control

Basic longitudinal acceleration and speed response to throttle and brake inputs, including engine power and tire traction limits. Transformations provide display commands: visual feedback on vehicle speed and longitudinal position; auditory feedback on vehicle speed and tire screeching under traction limit conditions.

C Visual Cuing

Transformations are applied to 3-D objects in the roadway scene field of view to create a driver's perspective scene as displayed on a roadway scene display (projector or monitor). Both through-the-windshield and through-the-mirrors perspectives were provided. Visual display lead compensation is also provided to minimize the influence of transport delay in the response of the visual scene to steering commands (Reference C-4). Display transformations process 3-D objects in a display list, as indicated in Figure C-3, to yield a perspective roadway scene. Simplified display transformations, including windowing and Z buffering, have been designed to minimize computational load on the main processor.

The 3-D data base is not constrained by a physical map. Instead, the display list is object oriented, and a scenario definition module takes instructions from a scenario file to define objects that

appear in the driver's field of view. Objects can be moved independently of one another in the field of view to permit traffic interactions. Objects or events (e.g., signal timing) in the scenario file can be accessed as a function of either time or distance down the road. The time function is important as it allows control of event timing for decision making situations (e.g., over taking vehicles, gaps in passing vehicle platoons).

1. Scenario Definition Language

The scenario definition language (SDL) allows a random specification of visual data base elements and events to be described in a file as a function of distance down the road. An example is given in Table C-l. Each entry defines the appearance of an object or the start or end of a process at some distance into the scenario. The attributes of objects include the distance from 'the driver at which they appear, size, colors, timing (e.g. traffic speed, traffic maneuvering relative to subject vehicle, etc.). Performance measurement is turned on and off by other commands as indicated in Table C-l. The SDL also allows for the equivalent of subroutines or 'previously defined events' (PDE) as indicated in Table C-l. A PDE is another file of SDL commands which can be called as desired. Attributes for a given PDE can also be left as variables so that, each time it is called, different attributes (e.g. pedestrian walking speed) can be defined. Table C-2. gives an example of a PDE.

2. Roadway Scenes

Typical examples of roadway scenes defined by the SDL are shown in Figure C-4. The roadway scenes are composed of full color polygons defined by the display transformations applied to the 3-D data base. The speed of approaching and lead vehicles can be controlled independently of the simulated vehicle's speed. Vehicles, signs and intersections can be commanded to occur through instructions programmed in a driving scenario file. The roadway display also includes rear and side view mirror scenes of the roadway and traffic as shown in Figure C-4.

Table C-l. Example Scenario Definition File

```
0,ROAD,12,2,1,1,1,10,l0,.3,.3        Two lane road, 12' lns, dash CL
0,PDE,BILLBRD.PDE                    Billboard subroutine
0,PDE,BUILDING.PDE                   'Building subroutine
0,PDE,PEDXING.PDE,5,3                Pedestrian crossing subroutine
50,PDE,RBLDGl.PDE                    Building subroutine
750,PDE,LBLDGl.PDE                   Building subroutine
1000,I,0,500,1                       Cross intersection
1000,CT,500,2,0,0,L                  Cross traffic, collision course
1250,PDE,INTRBLDG.PDE                Building subroutine

3000,BSAV,l,.l                       Save time series, seg. #1
3500,ESAV                            End saving time series, #1
3500,RMSB,l                          Save means and u's, seg. #l
3500,LS,45,1000                      Speed limit 45 mph
3750,PDE,4BLDGS2.PDE                 Building subroutine
3750,V,30,1000                       Lead vehicle ahead, 30 mph
4000,A,30,1000                       Approaching vehicle, 30 mph
4000,RMSE                            End saving means and o's, #1

8000,ROAD,12,3,2,1,1,l0,l0,.3,.3     Three lane road
8010,R,40,1000                       Rt. hand curve warn'ng, 40 mph
8400,UDE2,1000,2,2.5,1,1,1100,2,-1,l
                                     User defined subroutine, barriers.
```

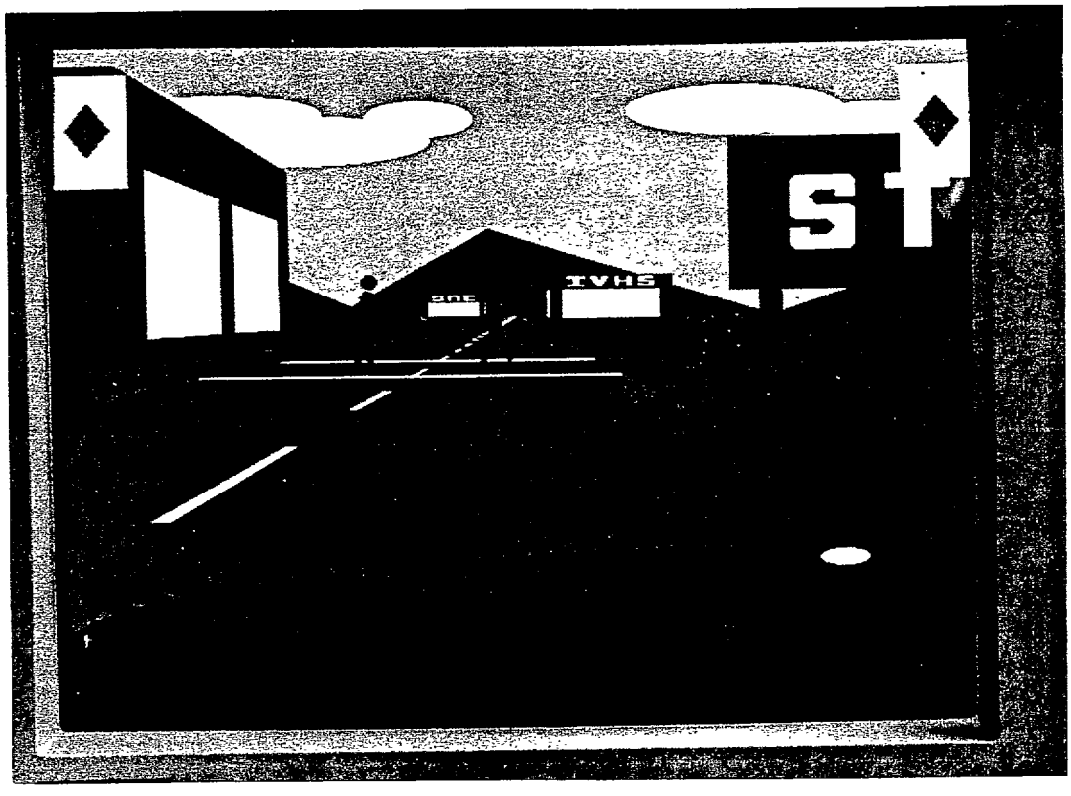
Table C-2. PDE Subroutine Examples

BUILDING.PDE (Building with windows)

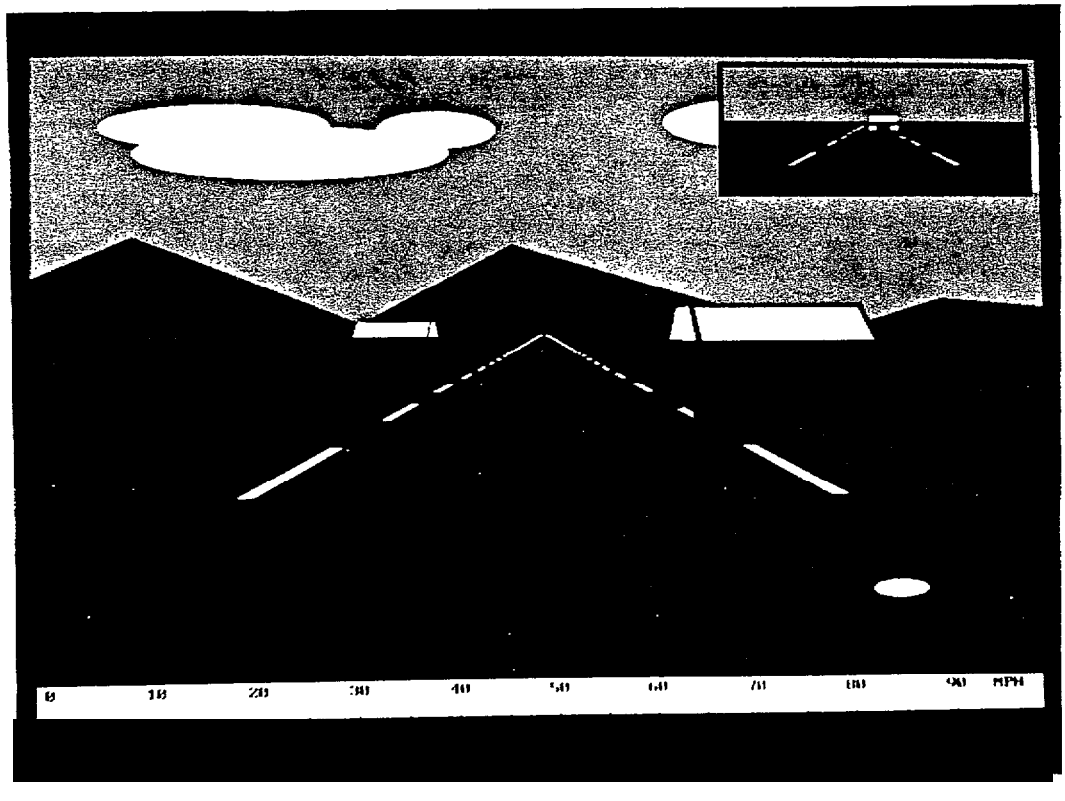
```
0,BLCK,l000,0, -50,20,30,20,50,1,          Building
0,BLCK,l000,0, -45,14,20,12,0,7,           Side window
0,BLCK,1000,5,-20,14,0,12,18,7,            Front window
0,BLCK,1000,27,-20,14,0,12,18,7,           Front window
0,TEXT,l000,0,-47.5,19,25,4,0,15,l,STI,    Side message
```

PEDXING.PDE (Pedestrian crossing)

```
0,TEXT,750,0,1,0,10,30,2,15,23,PED,        Road Text "PED"
0,TEXT,800,0,1,0,10,30,2,15,23,XING,       Road Text "XING"
0,BLCK,990,0, -12,0,24,0,2,15,             Near Xing
0,PED,995,4,@1,-20,L,                      Left Pedest., var. spd.
0,PED,1005,6,@2,20,R,                      Right Pedest., var. spd.
0,BLCK,l0l0,0,-12,0,24,0,2,15,             Far Xing
```



a) Buildings, Signs, Crosswalk, Pedestrians and Secondary Task



b) Multilane Road, Traffic, Rear *View Mirror*

Figure C-4. Example Roadway Scenes

3. Dynamic Objects

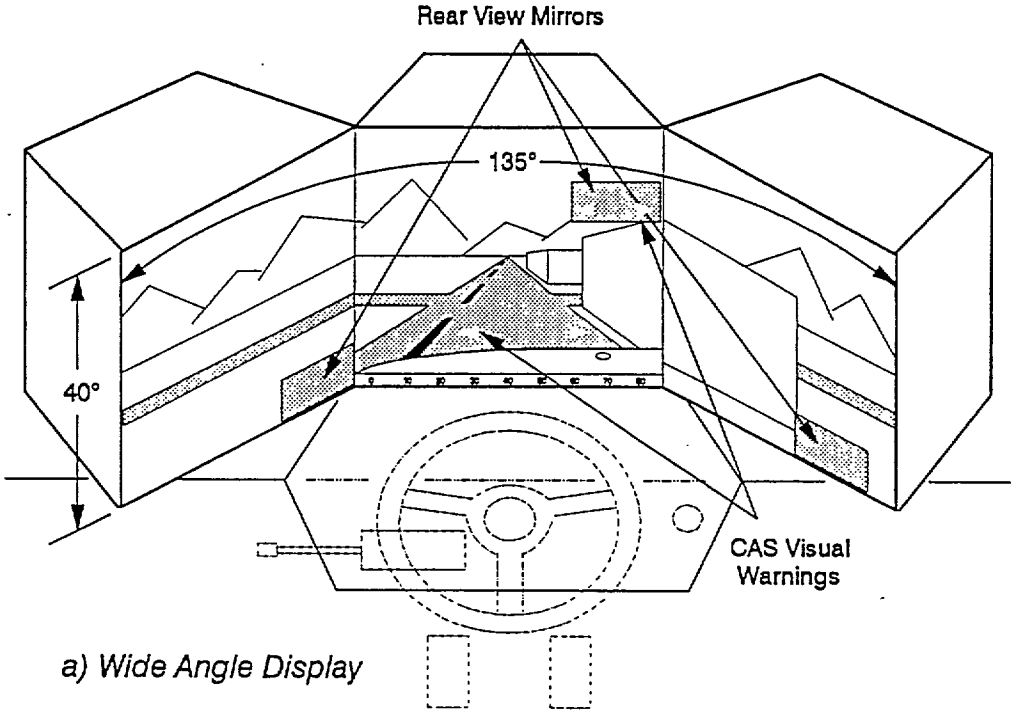
The SDL allows for the control of pedestrian, signal and traffic behavior. Speeds and timing can be specified to allow the manipulation of subject decision making behavior. Traffic movements can be manipulated so that vehicles can pull ahead, move to the subject's lane and brake, or stabilize in the subject's blind spot.

4. Display

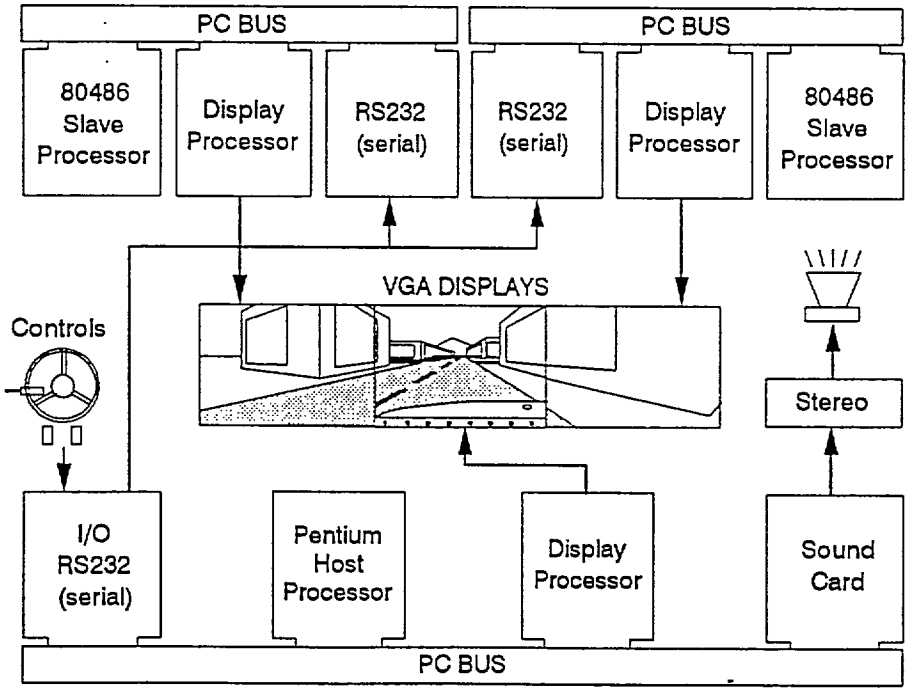
A three screen option was used in this research to give a 135 degree field of view using low cost projection devices. The architecture for this three screen version is shown in Figure C-5. The main processor runs the vehicle dynamics, auditory and proprioceptive cuing and generates the center 45 degree field of view. Two subsidiary processors generate the left and right peripheral 45 degree scenes. All processors run the same scenario definition file, and the peripheral scene viewing angles are offset from the central scene by 45 degrees.

The display scenes are projected on a screen 6 feet in front of the driver as shown in Figure. C-6. The display scene includes the rear and side view mirror scenes which show an accurate, perspective representation of the rear view scene including overtaking traffic. The mirror alignment is such that a blind spot occurs on either side of the subject's vehicle large enough to include an adjacent vehicle. The display projector arrangement shown in Figure C-7 is mounted directly over the drivers head. The center scene is projected with a VGA LCD projection panel and an overhead projector. The peripheral displays are presented with Sony model CPJ-100 video projectors.

Figure C-5. Architecture for Wide Angle, Three Screen Display Configuration



a) Wide Angle Display



b) Computer Architecture

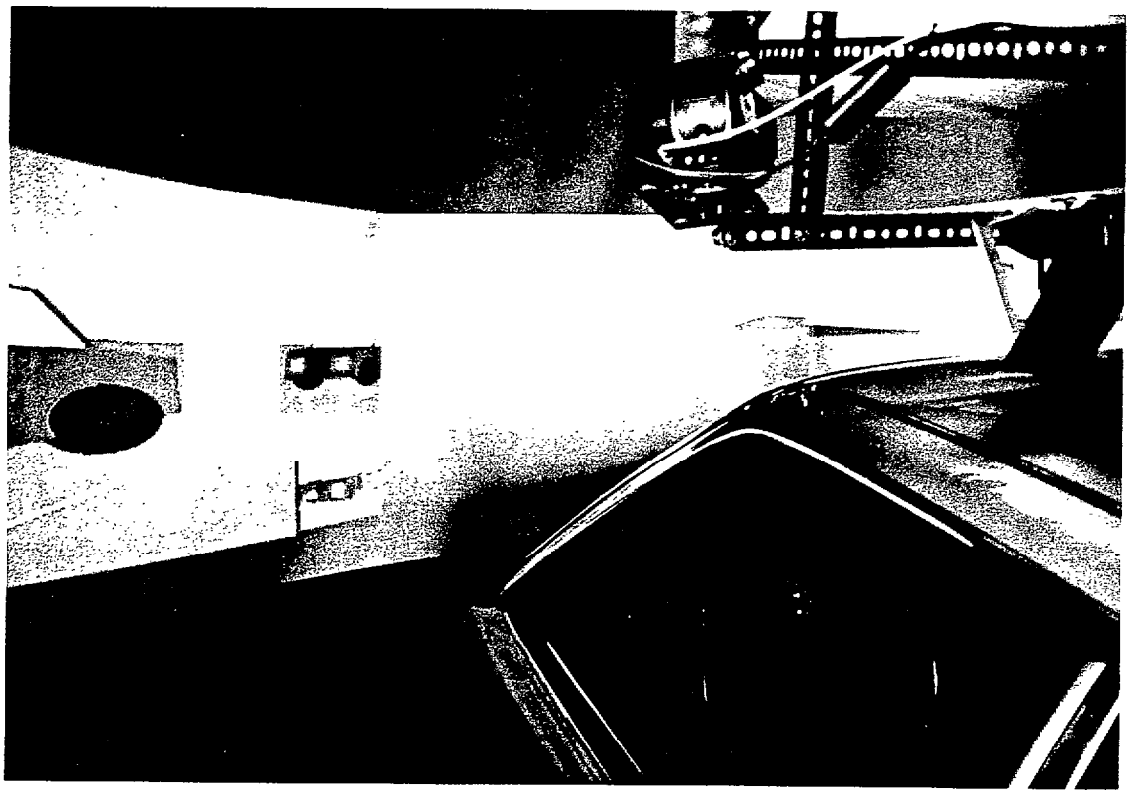


Figure C-6. Projected Display Scene

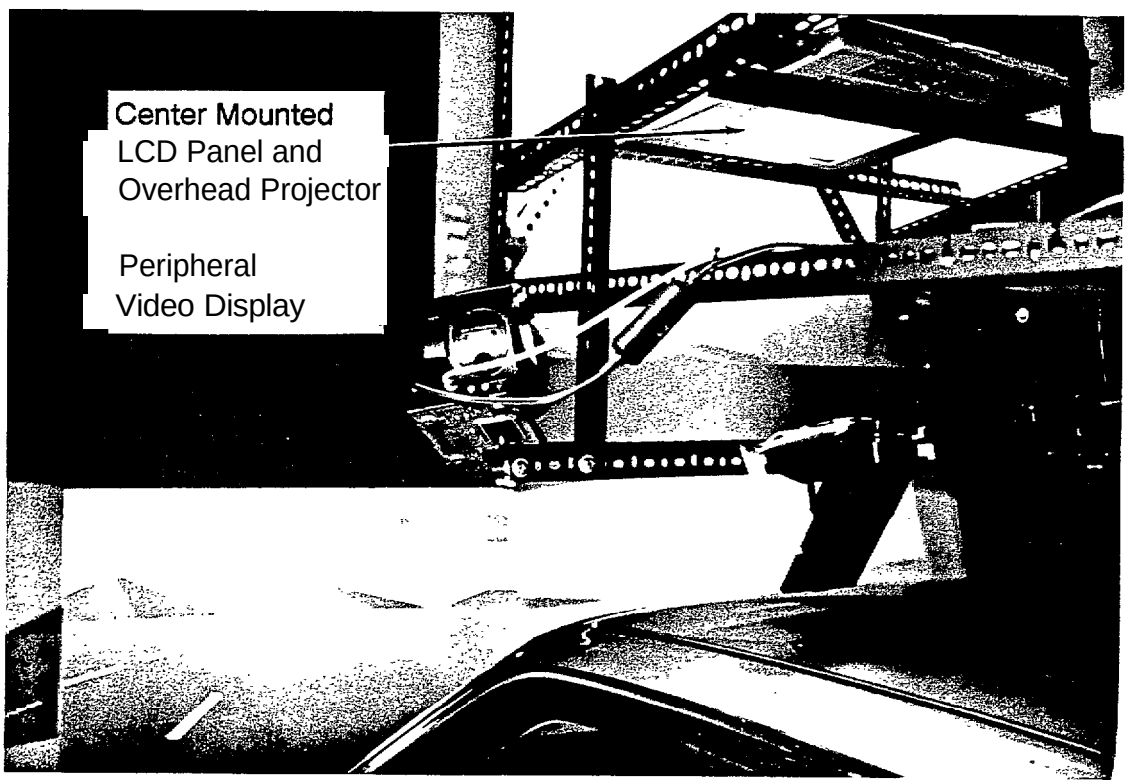


Figure C-7. Roadway Scene Projectors

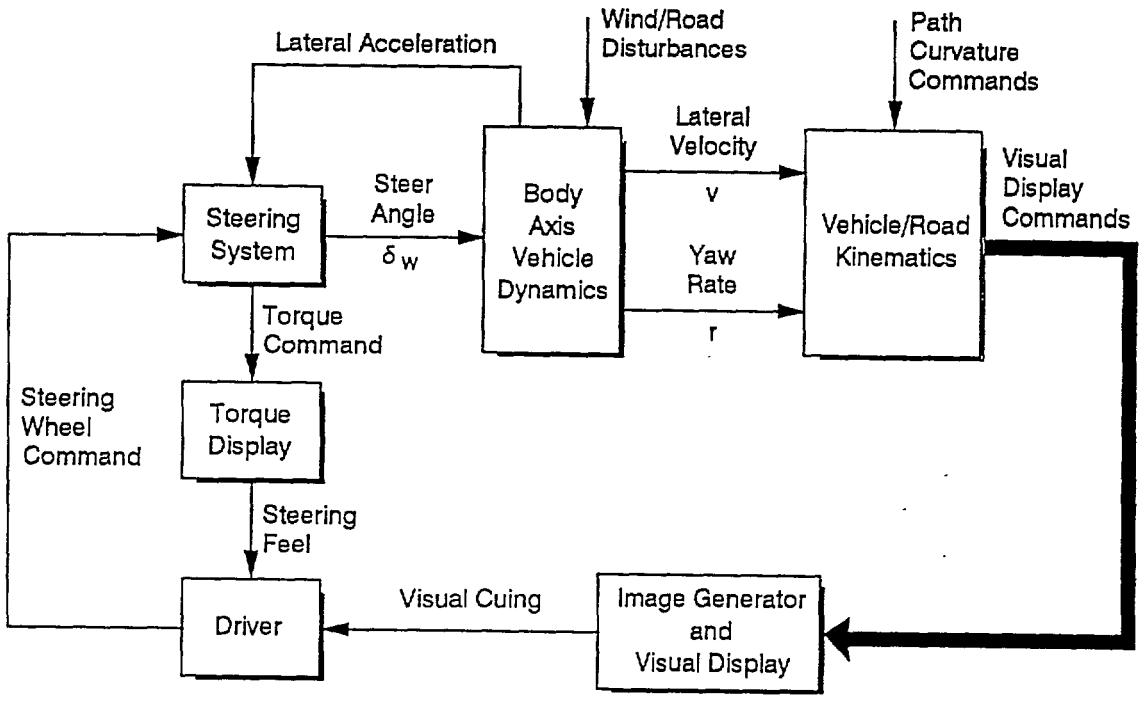
D. Auditory Cuing

Auditory cues are produced by a Sound Blaster compatible card. A combination of auditory effects are commanded by the vehicle dynamics, including engine and wind components, tire screeching, sirens, and collision sounds. The sound card output is amplified and displayed by standard commercial stereo components for a high fidelity rendition. The auditory system permits both synthesis and reproduction of prerecorded sounds. The engine and wind sounds are synthesized while tire screeching, sirens and crash sounds were obtained from sound effect recordings.

E. Proprioceptive Cuing

Steering torque commands are developed. by the vehicle dynamics based on vehicle lateral acceleration which is a close equivalent to the front axle side forces which provide steering aligning moments. The torque command drives an electrical power amplifier which provides current to a torque motor as indicated in Figure C-8. This closed loop approach is a standard simulation control loading technique that has been described previously for driving simulation (Reference C-5). The closed loop response of the torque motor/amplifier combination is quite linear with a bandwidth on the order of 50 Hertz which was originally designed for on-center handling work.

Figure C-8. Steering Torque Feedback to Driver



F. Data Collection

Performance measures include own vehicle maneuvering and relative measures with respect to adjacent traffic as summarized in Table C-3. Own vehicle maneuvering includes the steering and speed control variables. Curvature, heading and lane position error measures relate to steering performance, and speed measures relate to speed control. Variables relative to other vehicles include relative position and velocity and whether the crash avoidance system has responded to a given vehicle.

<u>Steering Control</u>
Curvature deviation
Lateral acceleration
Heading deviation
Lateral lane deviation
<u>Speed Control</u>
Longitudinal acceleration
Speed
<u>Adjacent Traffic</u>
Lateral and longitudinal relative position
Lateral and longitudinal relative velocity
CAS visual and auditory state

Table C-3. Performance Measure Variables

APPENDIX C REFERENCES

C-l. Stein, A.C., et al., "The Use of Low-Cost Driving Simulation to Detect Impaired Drivers," IMAGE VI Conference Proceedings, Scottsdale, AZ, July 1992.

C-2. Allen, R.W., et al., "An Experimental Study of Driver Alertness Monitoring," Paper 508, Systems Technology, Inc., Hawthorne, CA, Sept. 1994.

C-3. Mollenhauer, M.A., et al., "The Effects of Sensory Modality and Information Priority on In-Vehicle Signing and Information Systems," Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting, Oct. 1994.

C-4. Allen, R.W. and Rosenthal, T.J., "Meeting' Important Cuing Requirements with Modest, Real-Time, Interactive Driving Simulations," SAE Paper 940228, Society of Automotive Engineers, Warrendale, PA, Feb. 1994.

C-5. Allen, R.W. and Weir, D.H., Analysis of Man-in-the-Loop Performance Measurement Technology for Crash Avoidance Research, NHTSA Report DOT HS 806 718, US Depart. of Transportation, Washington, DC, 1984.

Appendix D : Subject Questionnaires

A. Lane Change/Merge Subject Questionnaire

Please answer the following questions as honestly as possible. Your answers have NO BEARING on the amount of money you will receive today!

Date: _____ Subject Number: _____

1) How old are you?

_____

2) What is your profession?

_____

3) How many years have you had your driver's license?

_____

4) How many accidents have you been involved in (regardless if they were your fault or not)?

_____

5) How many of those accidents involved you or someone changing or drifting into another lane?

_____

6) To what degree do you use your mirrors when driving?

____ constantly (skip to question 8)
____ often (skip to question 8)
____ sometimes
____ seldom
____ rarely

7) Can you explain why you do not use you mirrors often or constantly (for example, do you just look over your shoulders more)?

_____
_____
_____
_____
_____
_____

8) To what degree do you use your turn signal when it would be required of you to do so?

_____always
_____ most of the time
_____ sometimes
_____ seldom
____ rarely

9) How awake or tired are you right now?

____ very awake
____ awake
____ in-between
____ tired
____ very tired

10) How many hours sleep did you have:

last night _____
the night before _____
the night before that _____

11) How many hours has it been since you last ate?

_____

STOP!

Subject # _____ Condition_____

12) Overall, how tense or relaxed were you during the driving event?

____ very tense
____ tense
____ in-between
____ relaxed
____ very relaxed

13) How confident or unsure were you in your ability to avoid getting into an accident?

____ very confident
____ confident
____ neither confident nor unsure
____ unsure
_____ very unsure

14) Were there any instances in which you noticed other things besides cars that would set the alarm off?

____ no (go to question 16)
____ yes -- what were they? _____

15) What kind of effect, if any, did this have on your view of the system as a whole?

____ positive
____ slightly positive
____ none
____ slightly negative
____ negative

16) When the alarm turned on, how meaningful was that information to you (i.e. did it matter much to you)?

____ very meaningful
____ meaningful
____ somewhat meaningful
____ slightly meaningful
____ not at all meaningful

17) Was there too much activity in terms of the alarm?

____ no (skip to next question)

____ yes (answer below)
- ____ far too much activity
- ____ too much activity
- ____ somewhat too much activity
- ____ slightly too much activity

18) How positively or negatively affected was your driving by the presence of the alerting arrows (their physical presence, not the "beeps")?

____ positively affected
____ slightly positively affected
____ not affected
____ slightly negatively affected
____ negatively affected

19) How agreeable or annoying were the arrows (regardless if they affected your driving ability or not)?

____ very agreeable
____ agreeable
____ neutral
____ annoying
____ very annoying

20) How positively or negatively affected was your driving by the "beeps?"

____ positively affected
____ slightly positively affected
____ not affected
____ slightly negatively affected
____ negatively affected

21) How agreeable or annoying were the "beeps" (regardless if they affected your driving ability or not)?

____ very agreeable
____ agreeable
____ neutral
____ annoying
____ very annoying

22) How helpful was the complete alarm (arrows plus beeps) in alerting you to drivers in your blind spot?

____ very helpful
____ helpful
____ somewhat helpful
____ slightly helpful
____ not at all helpful (did not make a difference)

23) How helpful was the complete alarm (arrows plus beeps) in preventing you from having an accident?

____ very helpful
____ helpful
____ somewhat helpful
____ slightly helpful
____ not at all helpful

Subject # _____

24) Please indicate how the alerting system responded in this instance compared to the times before.

____ faster (it took less time for the alerting system to come on when a car was in my blind spot)

____ no difference

____ slower (it took more time for the alerting system to come on when a car was in my blind spot)

Subject # _____

25) There were two different configurations in which the alerting system informed you of drivers in your blind spot. Please indicate which of the ways you preferred (mark one).

____ the alarm went off AT ALL TIMES
____ the alarm went off ONLY WHEN I USED THE TURN SIGNAL

26) Do you feel the alerting system gave you adequate notice of vehicles in your blind spot?

____ yes
____ no

27) In terms of amount of activity during the driving scenario, how did driving the simulator compare to actual driving on a highway?

_____
_____
_____
_____

28) Any other comments?

_____

_____
_____

Subject # _____

29) Please indicate which of the two locations of the alerting arrows you liked the most in terms of helpfulness and effectiveness.

____ REARVIEW mirror
____ CENTER of windshield

30) What effect, if any, did the alarm condition with beeps and no arrows have on your driving performance?

____ positive effect
____ slight positive effect
____ no effect
____ slight negative effect
____ negative effect

B. Backing Subject Questionnaire

Please answer the following questions as honestly as possible. Your answers have NO BEARING on the amount of money you will receive today!

Date: _____ Subject Number: _____

1) How old are you?

_____

2) What is your profession?

_____

3) How many years have you ‘had your driver’s license?

_____

4) How many accidents have you been involved in (regardless if they were your fault or not)?

_____

5) How many of those accidents involved you or someone changing or drifting into another lane?

_____

6) To what degree do you use your mirrors when driving?

____ constantly (skip to question 8)
____ often (skip to question 8)
____ sometimes
____ seldom
____ rarely

7) Can you explain why you do not use you mirrors often or constantly (for example, do you just look over your shoulders more)?

_____

_____

_____

_____

8) To what degree do you use your turn signal when it would be required of you to do so?

____ always
____ most of the time
____ sometimes
____ seldom
____ rarely

9) How awake or tired are you right now?

____ very awake
a w a k e
in-b e t w e e n
t i r e d
____ very tired

10) How many hours sleep did you have:

last night _____
the night before _____
the night before that _____

11) How many hours has it been since you last ate?

_____

STOP!

Subject #_____ Condition_____

12) Overall, how tense or relaxed were you during the driving event?

____ very tense
____ tense
____ in-between
____ relaxed
____ very relaxed

*** When answering the following questions, please answer in reference to only those times when you were in REVERSE GEAR, traveling BACKWARDS.

13) How confident or unsure were you in your ability to avoid getting into an accident or hitting a pedestrian?

____ very confident
confident
neither confident nor unsure
unsure
- - very unsure

14) Please indicate how using the alarm made you feel about your ability to drive backward.

____ much more confident
____ more confident
____ no effect
____ less confident
____ much less confident

15) To what degree, if at all, did you use the alarm to help you drive backwards safely?

____ used it every time (skip to question 17)
____ used it the majority of the time (skip to question 17)
____ used it sometimes (skip to question 17)
____ used it seldom
____ used it never

Subject # _____ Condition _____

16) Please explain, if you can, why you used the alarm either seldom or never to help you drive backwards safely?

_____
_____
_____
_____ _____

17) Were there any instances in which you noticed other things besides cars and pedestrians that would set the alarm off?

____ no (go to question 19)
____ yes -- what were they? _____

18) What kind of effect, if any, did this have on your view of the system as a whole?

____ positive
____ slightly positive
____ none
____ slightly negative
____ negative

19) When the alarm turned on, how meaningful was that information to you (i.e. did it matter much to you)?

____ very meaningful
____ meaningful
____ somewhat meaningful
____ slightly meaningful
____ not at all meaningful

20) Was there too much activity in terms of the alarm?

____ no (skip to next question)

____ yes (answer below)
____ far too much activity
____ too much activity
____ somewhat too much activity
____ slightly too much activity

Subject # _____ Condition_____

21) How positively or negatively affected was your driving by the presence of the alerting arrows (their physical presence, not the "beeps")?

____ positively affected
____ slightly positively affected
____ not affected
____ slightly negatively affected
____ negatively affected

22) How agreeable or annoying were the arrows (regardless if they affected your driving ability or not)?

____ very agreeable
____ agreeable
____ neutral
____ annoying
____ very annoying

23) How positively or negatively affected was your driving by the "beeps?"

____ positively affected
____ slightly positively affected
____ not affected
____ slightly negatively affected
____ negatively affected

24) How agreeable or annoying were the "beeps" (regardless if they affected your driving ability or not)?

____ very agreeable
____ agreeable
____ neutral
____ annoying
____ very annoying

25) How helpful was the complete alarm (arrows plus beeps) in alerting you to objects in your blind spot?

____ very helpful
____ helpful
____ somewhat helpful
____ slightly helpful
____ not at all helpful (did not make a difference)

Subject #_____ Condition_____

26) How helpful was the complete alarm (arrows plus beeps) in preventing you from having an accident or hitting a pedestrian?

____ very helpful
____ helpful
____ somewhat helpful
____ slightly helpful
____ not at all helpful

Subject #_____

27) Please indicate how the alerting system responded in this instance compared to the times before.

____ faster (it took less time for the alerting system to come on when a car was in my blind spot)

____ no difference

____ slower (it took more time for the alerting system to come on when a car was in my blind spot)

Subject # _____

28) There were two different configurations in which the alerting system informed you of cars and pedestrians in your blind spot. Please indicate which of the ways you preferred (mark one).

____ when the alarm was comprised of ARROWS AND BEEPS.
____ when the alarm was comprised of BEEPS ONLY.

29) What effect, if any, did the alarm condition with beeps only have on your driving performance?

____ positive effect
____ slight positive effect
____ no effect
____ slight negative effect
____ negative effect

30) Do you feel the alerting system gave you adequate notice of cars and pedestrians in your blind spot?

____ yes
____ no

31) In terms of amount of activity during the driving scenario, how did driving the simulator compare to actual driving on a highway?

_____
_____
_____
_____

32) Any other comments?

_____
_____
_____

Appendix E: The TRW Lane Change/Merge Monte Carlo Simulation Code

A. Simulation Variables

Monte Carlo refers to a technique by which the distributions of a variable is sampled through the generation of a random number. The cumulative distribution of a variable x, $P(x \leq A)$, is the percentage of the total population for which the variable x is less than or equal to the quantity A. $P(x \leq A)$ ranges from 0.0 to 1.0 when plotted as a function of A. To sample the distribution of x, a random number, R, is generated between 0.0 and 1.0. The value of R is matched to the value of $P(x \leq A)$ and the appropriate value of A1 corresponding to $P(x \leq Al) = R$ is extracted. For that particular case, the value of x is set to Al. Since R may be any number between 0.0 and 1.0, Al may take on any allowed value of x. This technique enables the simulation to sample the entire distribution of the variable x, including the "tails" in which only a few cases reside. The entire distribution of x should be sampled because it is possible that the cases represented by the tails of the distribution may -strongly affect the results.

This code has been designed to be used in parametric studies of lane change/merge crashes. One or more of the system and scenario parameters may be varied to determine the effect on the crash avoidance potential.

This code can be used for either lane changes to the right or lane changes to the left. These may represent different cases since

1. the sensor detection pattern on the left (driver's) side may differ from that of the sensor on the right side, and further,
2. the distribution of closing speeds of the vehicles on the left side differs from the distribution of closing speeds of the vehicles on the right side. This latter is probably due to the tradition of slower vehicles keeping to the right-hand lanes and faster vehicles keeping to the left-hand lanes on multilane trafficways. For this study, sensor detection patterns are assumed to be the same on both sides of the vehicle.

The closing speed distributions are taken from the GES reported speeds of vehicles involved in police reported lane change/merge crashes. Unfortunately, between **two** thirds to three quarters of the cases contain insufficient data to calculate the

estimated closing speeds. For this reason, when the speeds which are supplied are used, it is necessary to make the further assumption that they represent the missing data as well.

Since there is mirror image symmetry about the longitudinal center line of the lane changing vehicle, the code has been written for one kinematic scenario. That is, the vehicle changing lanes moves to the right. The sensor system (one or more sensors) is positioned at the appropriate position(s) on the right side of the vehicle, that is, rear bumper, front bumper, side-view mirror, etc. This is taken as being on the right hand side. The pattern is input appropriate to that sensor and the distribution of closing speeds is specified for either the right or left side. The principal other vehicle (POV) is generated in the lane adjacent to and on the right hand side of the lane changing vehicle (subject vehicle or SV) with the closing speed (either positive or negative) taken from the distribution specified in the input.

After specifying whether the lane change is to the right or to the left, the total number of cases to be considered in this particular run is specified. Next, the sensor(s) specifications and locations are entered. The transmitter/receiver patterns include the following which are shown schematically in Figure B-3 in Appendix B.

a. Narrow beam long range sensor (example: uniform rectangular aperture)
b. Circular pattern tangent at the sensor location (example: Hertzian dipole)
c. Wide beam proximity sensor, usually rangegated (example: nonuniform (cosine weighted) rectangular aperture)

Rangegating is a data processing procedure in which the return signals received from targets located at distances exceeding the rangegate distance are not considered.

After the sensor parameters (see Appendix B for a listing) including the sensor positions, the system latency and repetition rate are entered, the the code begins to generate a series of scenarios, each of which runs to its conclusion before the next is begun.

Calculations are done in metric units. Therefore, distances in feet and speeds in mph are converted to meters and meters per second respectively.

B. Embedded characteristics

1. Scenario generation

The initial lateral separation is considered to be a constant, 3.66 meters. This corresponds to both vehicles being in the centers of their respective lanes, each lane having a width of 3.66 meters.

The gap between the SV and POV is defined as the longitudinal distance from the front bumper of the SV to the front bumper of the POV, with a positive gap indicating that the POV is somewhere behind the SV. A negative gap indicates that the front bumper of the POV is somewhere in front of the front bumper of the SV. The initial gap distance is randomly generated from a uniform distribution between any two limits. This interval may be changed (but not without recompiling the source code) and may extend beyond the front of the SV.

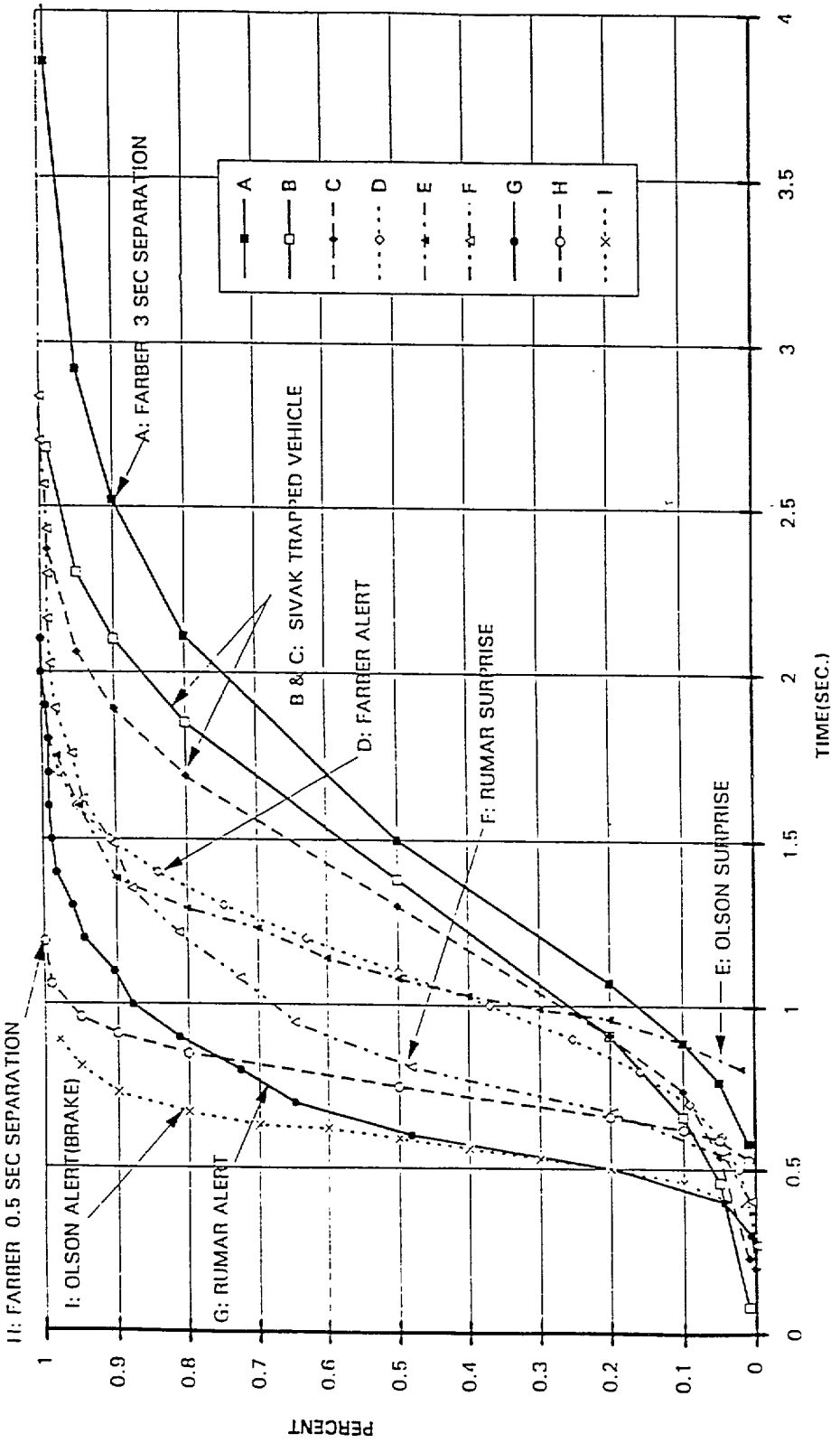
2. The Subject Vehicle (SV)

The subject vehicle is, by definition, the vehicle performing the lane change or merge maneuver. The vehicle type of the SV (passenger vehicle, truck, etc.) is implicit in the vehicle's size and the positioning of the sensors. At present, the SV is assumed to be 5 meters long and 2 meters wide (a passenger vehicle) except when trucks are explicitly under discussion.

The SV travel speed v_1 is generated from the observed distribution of SV speeds in crashes of all vehicle types involving changing lanes to the specified side. A random number between 0.0 and 1.0 is generated and matched by means of a table lookup to the cumulative distribution of percentiles of SVs with speeds less than v_1 as a function of v_1. The table chosen for the table lookup depends on the direction of the lane change. The SV travel speed is then classified as slow ($\leq$ 20 mph), moderate (20 < speed $\leq$ 50 mph) or fast (> 50 mph). This classification is used later to generate the closing speed of the POV.

The time required for the SV to complete the lane change, called T_{lc}, is generated from a uniform distribution between the limits of 2.0 and 10.0 seconds for passenger vehicles and between 5.0 and 15.0 seconds for tractor trailers.

Figure E-1: A Compilation of Cumulative Distributions of Drivers' Reaction Times



The driver's reaction time, t_{react}, is taken from the graph of either Rumar's alert driver reaction time of Taoka's surprised driver reaction time. As described previously, it is found by means of generating a random number and a table lookup or calculation of the reaction time.

This interval, t_{wait}, represents the time between the driver's activation of the turn signal which enables the CAS and the beginning of lateral motion. At present the delay time is 0.2 seconds.

Finally, the vehicle reaction time, $t_{vehicle}$, is taken to be 0.1 second, independent of the system involved. This represents the interval between the steering input and the turning of the wheels.

3. The Principal Other Vehicle (POV)

At present all POVs are considered to be passenger vehicles and the POV dimensions are those of a passenger vehicle. If other types of POVs were to be considered, these dimensions may be linked to the type of POV being characterized and adjusted accordingly. At present, the SV is assumed to be 5 meters long and 2 meters wide (a passenger vehicle).

The POV closing speed is determined by means of a random number and subsequent table lookup. When the travel speed of the SV was determined, it was also characterized as slow, moderate or fast. Depending on this determination, the POV closing speed is taken from one of three possible tables: POV closing speeds when SV speed slow, POV closing speeds when SV speed moderate, or POV closing speeds when SV speed fast. These tables were taken from data in the GES for these conditions and contain both positive and negative closing speeds. It is the combination of the randomly generated initial gap distances and closing speeds which samples all of the possible lane change scenarios.

For cases in which the SV does successfully complete the lane change in front of or behind the POV, there is still the possibility of a rearend crash. Therefore, there is assumed to be a second reaction time, trear, of 1.0 second. If the SV has completed the lane change leaving the POV with less than 1.0 second of headway time, the POV is assumed to rearend the SV (causing an LCM4 type crash). This crash is counted in the statistics as a separate category of crash. If the SV completes the lane change behind the POV with less than 1.0

second headway time, the SV is assumed to rearend the POV (in an LCM8 type of crash). These are counted in the statistics as separate categories.

Finally, it should be noted that the POV is essentially passive. Although the SV may undertake evasive maneuvers or modify its relative speed, the POV undertakes no evasion maneuvers, nor does the POV modify its closing speed. It must be assumed that if the SV does complete its lane change in front of the POV with more than 1 second of headway, the POV will modify its trajectory as dictated by good sense to avoid the crash.

C The Battelle Model of Lateral Motion during Lane Change

The kinematic model for the lane change suggested by the Battelle and CALSPAN report "Analysis of Lane Change Crashes" (Reference E-1) has been adapted for use in the TRW Monte Carlo statistical simulation.

The lane change maneuver begins at time t = 0 with zero initial lateral velocity and zero initial lateral displacement (or lateral distance traveled). If the lane change maneuver proceeds without interruption, the lateral acceleration a(t) is given by

$$a(t) = \frac{2\pi W}{\tau_{LC}^2} \sin\left(\frac{2\pi}{\tau_{LC}} t\right) \qquad \text{(E-1)}$$

where W is the lateral lane change width (total expected lateral displacement) and τ_{LC} is the time required to complete the lane change. Although a distribution of W has been observed, in this simulation, W is constant (12 feet). The time required to complete the lane change, τ_{LC}, is randomly sampled from a uniform distribution between 2 and 10 seconds for passenger vehicles and between 5 and 15 seconds for tractor trailers. Although lane change times longer than 10 seconds have been observed, most lane changes are expected to be significantly faster. At time t, the lateral velocity, V(t), is given by

$$V(t) = \frac{W}{\tau_{LC}} \left[1 - \cos\left(\frac{2\pi}{\tau_{LC}} t\right) \right] \qquad \text{(E-2)}$$

and D(t), the lateral distance traveled since the initiation of the lane change, is given by the following.

$$D(t) = W\left[\frac{t}{\tau_{LC}} - \frac{1}{2\pi}\sin\left(\frac{2\pi}{\tau_{LC}}t\right)\right] \qquad \text{(E-3)}$$

Equations (E-1), (E-2) and (E-3) describe the lateral motion of the SV until the beginning of the evasion maneuver. Figure E-2 which follows, is taken directly from the reference E-1 and shows this maneuver as well as the acceleration profiles.

The evasion maneuver is described by a trapezoidal acceleration model with a maximum recovery acceleration value A_r which the driver does not exceed. At time $t = t_2$, the full recovery acceleration $-A_r$ is achieved. This is also shown in Figure E-2. Evasion is initiated at $t = t_1$. If the lateral acceleration at t_1 is a_{01}, the lateral acceleration for the first phase of recovery is given by

$$a(t_1 < t < t_2) = a_{01} - k(t - t_1) \qquad \text{(E-4)}$$

for times $(t_1 < t < t_2)$. If the interval $t_{steer} = (t_2 - t_1)$ is specified, the value of k is found to be

$$k = \frac{a_{01} + A_r}{t_{steer}} \quad . \qquad \text{(E-5)}$$

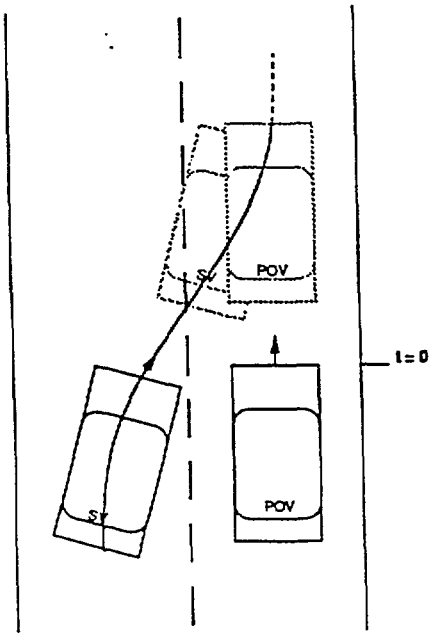
At present, the full lateral recovery acceleration, A_r, is 0.4 g for passenger vehicles and 0.25 g for tractor trailers under normal driving conditions. For passenger vehicles the time required for the transition of the acceleration t_{steer} is 0.4 seconds for normal driving. For degraded driving conditions, such as wet roadways, Ar is 0.28 g and t_{steer} increases to 0.55 seconds . For tractor trailers under normal conditions, t_{steer} is 1.1 seconds.

If the lateral velocity and displacement at t_1 are V_{01} and D_{01} respectively, then during the interval $(t_1 < t < t_2)$ the velocity and displacement are given by

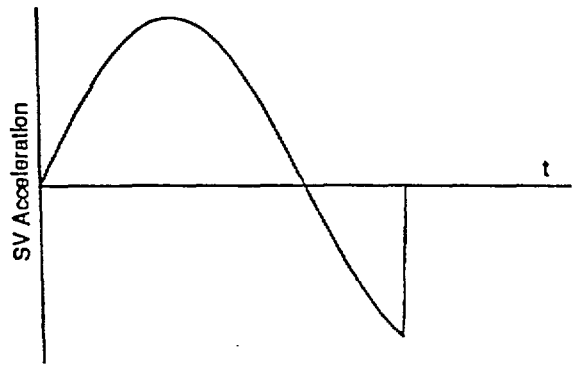
$$V(t_1 < t < t_2) = V_{01} + a_{01}(t - t_1) - k(t - t_1)^2/2 \qquad \text{(E-6)}$$

$$D(t_1 < t < t_2) = D_{01} + V_{01}(t - t_1) + a_{01}(t - t_1)^2/2 - k(t - t_1)^3/6 \qquad \text{(E-7)}$$

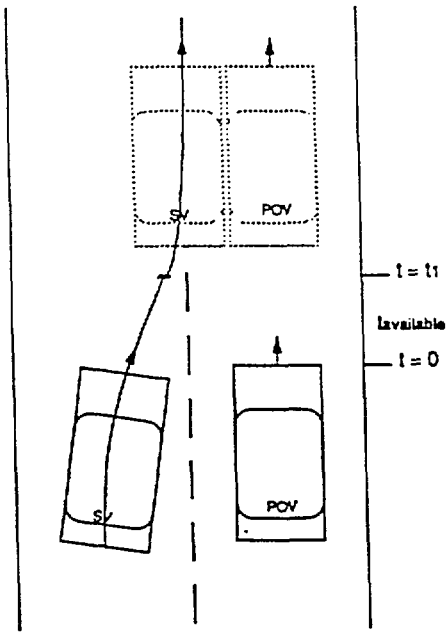
Figure E-2. The trajectory and Acceleration Profile of SV With and Without Crash Avoidance



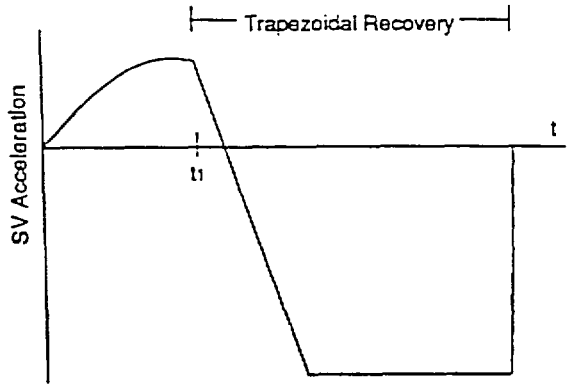
Trajectory *Without* Collision Avoidance Action



Acceleration Profile *Without* Collision Avoidance



Trajectory *With* Collision Avoidance Action



Acceleration Profile *With* Collision Avoidance

At time t2, the lateral acceleration reaches -Ar. If the velocity and displacement at time t = t2 are denoted by V02 and D02, then for times t > t2, the lateral velocity and displacement are given by

$$V(t > t2) = V02 - Ar(t - t2) \qquad \text{(E-8)}$$

$$D(t > t2) = D02 + V02(t - t2) - Ar(t - t2)2/2 \qquad \text{(E-9)}$$

The full lateral recovery acceleration is continued until the vehicle regains the original lane, at which time that simulation case ends with a “safe return”.

D. The Time Sequencing and the Driver Choices

After the scenario has been set up for the case, the scenario runs by means of increasing the time in well defined steps.

After turning on the lane change indicator, the driver is assumed to wait for the interval twait seconds before initiating the lane change. During that time the longitudinal gap between the SV and POV increases/decreases by an amount equal to (t_{wait}*closing speed) and also the CAS checks for possible detections. Detections during this time before the lateral motion has been initiated cause the lane change maneuver to be abandoned (lane change aborted). After t_{wait} has elapsed, the simulation time becomes 0.0 seconds and there is a new value of the gap distance is calculated as described above. At and following time = 0.0, the following actions are taken:

If the situation is such that the POV is behind the SV (no longitudinal overlap) and going more slowly than the SV (POV closing speed < 0.0),

or

if the POV is in front of the SV (no overlap) and going faster than the SV (POV closing speed > 0.0),

then

there is no possibility of a crash. The INOCRASH flag is set along with a flag which indicates whether the POV is in front of or behind the SV, and the program goes to the “no crash ending” for that case.

Otherwise, the following steps are repeated throughout the program until the case is terminated by a “crash ending” or a “no crash ending”:

1. If the scenario has not ended with the “no crash ending” or the “crash ending”, then the relative positions of the POV and SV are calculated for this time and checked for “physical overlap” which indicates that a crash had occurred. At time = 0.0, no crash can occur since the POV and SV are generated separated by a lane width. The check is part of the routine sequencing. If a crash is detected, the program proceeds to the “crash ending”. If no crash is detected, then the positions are checked to see if the scenario has evolved into a “no crash case” as described above. If so, then the program proceeds to the “no crash ending”. If not, the SV position is checked to see if the SV has completed the lane change. If so, then the program proceeds again to the “no crash ending”. (It should be noted that a small number of these “successful lane change - no crash endings” become rearend, striking or struck, crashes when the headway distance between the SV and POV is calculated during the “no crash ending” sequence. These are removed from the “successful lane change - no crash ending” and tabulated accordingly as crashes.)

2. If the case has not exited to an ending at this point, the signal-to-noise is calculated averaged over the dimensions of the POV, for each of the sensors specified. (If this is a test case with no sensor installed, this section is omitted.) This probability of detection is compared with a random number generated by the program. If the random number is less than the probability of detection, a “detection” is declared. If not, the program continues to the next step which is to increment the time by a repetition period and return to the beginning of step 1 above.

3. If a “detection” is declared, the time in incremented by the driver’s reaction time, the system latency time, t_{lat}, and the system reaction time, $t_{vehicle}$. During this interval, the SV and POV are considered to proceed as before and the position of the POV and the lateral displacement of the SV are updated. If the SV has nearly completed the lane change (< 60 cm from the center of the lane into which the SV has changed), the SV driver decides to ignore this warning. The SV driver’s reaction time is subtracted, the vehicles are returned to their relative positions before updating, and the new updates are calculated while the SV continues the lane change just as he was doing. This results in a small number (usually 0, but sometimes as many as 3 or 4 in 3000 cases) of LCM4 crashes (lane-changing vehicle rearended). The sequence begun in step 1 is

repeated until the case exits to a “crash ending”, a “noncrash” ending or to the evasive maneuver section of the program.

4. When the driver begins the evasion maneuver section of the program, the kinematics of the vehicle are dictated by the Battelle model of the evasion maneuver. In the time interval t_{steer}, the lateral acceleration which has been progressing on a sine curve abruptly changes (linearly) from its positive value at (detection time $+ t_{react} + t_{vehicle} + t_{lat}$) to a constant negative value, -Ar. The position of the POV and lateral displacement of the SV are calculated for time steps equal to the repetition period. After each update, the positions are checked for physical overlap (a crash). If a crash is detected, the program exits to the crash ending. If no crash is detected, then the positions are checked to see if the scenario has evolved into a “no crash case” as described previously. If so, then the program proceeds to the “no crash ending”. If the program has not already gone to an ending, then the lateral displacement is checked to determine if the SV has returned to the original lane. If so, then the program goes to the noncrash, safe return ending. The program repeats the procedure in this step until an ending is reached for the case, updating the times and positions at each repeat.

The numbers of crashes (striking or struck as determined by relative positions), noncrash scenarios, aborted lane changes, safe returns, successful lane changes and LCM4 (SV rearend struck) and LCM8 (SV rearend striking) crashes are updated and printed in summary form in a log file which may be inspected after the simulation is completed. It is possible to make the log file in various degrees of detail, but in general only the sensor characteristics and the final summary are used. Two other data files may be created: one summarizing the characteristics of the vehicle pairs which crash and the other summarizing the characteristics of all of the vehicle pairs generated in the simulation. For example, these characteristics may include closing speed, initial gap distance, SV driver reaction time and SV speed. By comparing these files, it is possible to contrast the characteristics of the crashed vehicles with those of the general population.

E. Uncertainties due to the Statistical Nature of the Calculations of the Crash Avoidance Potential Within the Monte Carlo Framework

As discussed previously, the value of the crash avoidance potential (CAP) is influenced more by the underlying assumptions in the model than by the uncertainties caused by the statistical nature of the model. However, comparisons of the values of the CAP may be useful to suggest relative improvements. This section provides a method for estimating the uncertainties in the relative values of the CAP due to the statistical nature of the Monte Carlo simulations.

As defined and discussed in section 3.1.1, the CAP is given by

$$CAP = \frac{\text{Number of crashes(no sensor) - Number of crashes(with sensor)}}{\text{Number of crashes(no sensor)}}$$

$$= \frac{\text{Crashes prevented by the sensor}}{\text{Number of crashes(no sensor)}} \qquad \text{(E-10)}$$

If N_2 = Number of crashes(no sensor)
N_1 = Number of crashes(with sensor)
X = CAP

then the CAP is simply written

$$X = \frac{N_2 - N_1}{N_2} \qquad \text{(E-11)}$$

and $$\ln(X) = \ln(N_2 - N_1) - \ln(N_2). \qquad \text{(E-12)}$$

The magnitude of a variation in X, δX, caused by variations in N_1 and N_2 (given by δN_1 and δN_2 respectively) is given by

$$\frac{\delta X}{X} = \frac{\delta(N_2 - N_1)}{(N_2 - N_1)} - \frac{\delta N_2}{N_2} \qquad \text{(E-13)}$$

This approach breaks down for the ineffective CAS sensor, for which $N_1 \approx N_2$ (no crashes are prevented) and $X \approx 0.0$. However, outside of this region, the upper limit of $\delta(N_2 - N_1)$ is

$$\delta(N_2 - N_1) \leq \delta N_2 + \delta N_1 , \qquad \text{(E-14)}$$

and $$\frac{\delta X}{X} \leq \frac{\delta N_2 + \delta N_1}{(N_2 - N_1)} - \frac{\delta N_2}{N_2} \quad . \qquad \text{(E-15)}$$

This may be used to calculate the statistical uncertainties in the CAP, δX. The variations in N_2 and N_1 are assumed to be given by

$$\delta N_2 = (N_2)^{1/2} \text{ and } \delta N_1 = (N_1)^{1/2}$$

respectively. As $N_1 \Rightarrow 0$ (all crashes are prevented), $(\delta X/X) \Rightarrow 0.0$, indicating the statistical uncertainties become very small. Figures E-3 and E-4 show the CAP values calculated for two CAS configurations and for simulations containing 100, 300, 600, 1000, 3000, 6000, 9000 and 10,000 cases with the statistical uncertainties in the CAP. The configurations chosen were the three-sensor configurations described in section 3.1.2.3 and shown in Figure 3-8, the first having a long range sensor range of 50 feet and the second having a long range sensor range of 20 feet. As can be seen from these figures, simulation runs containing 1000 cases or less have large statistical uncertainties. Also the statistical uncertainties associated with the less effective CAS were larger in general than those associated with the more effective CAS.

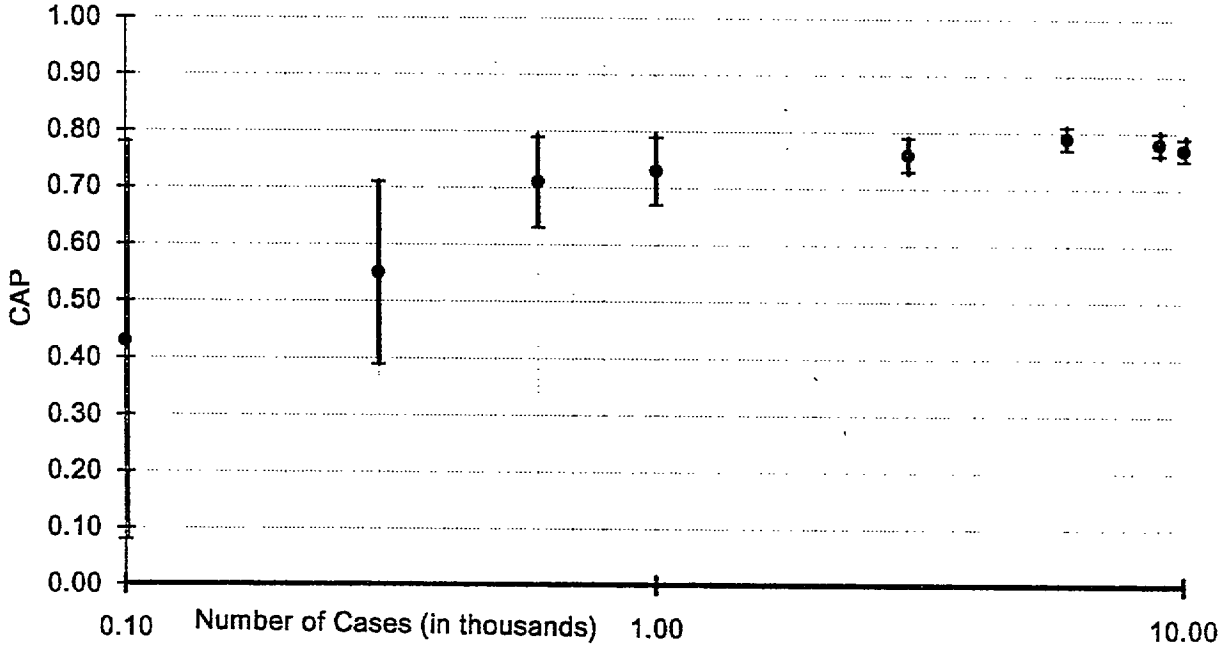


Figure E-3. CAP with Statistical Uncertainties for the 3-Sensor Configuration shown in Figure 3-8 with a Long Range Sensor Range of 50 feet as a Function of the Number of Cases in the Simulation Run

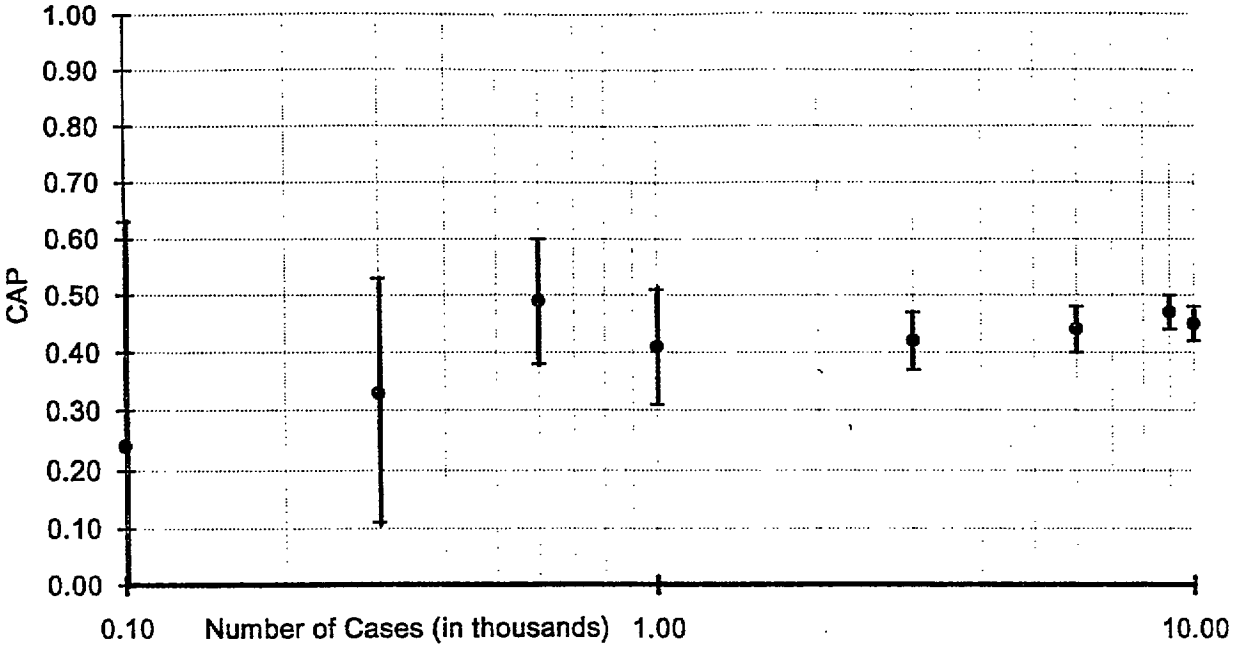


Figure E-4. CAP with Statistical Uncertainties for the 3-Sensor Configuration shown in Figure 3-8 with a Long Range Sensor Range of 20 feet as a Function of the Number of Cases in the Simulation Run

A typical simulation run of 3000 cases was chosen as little improvement was seen for longer case runs.

Finally, the CAP values were calculated using both 3000 and 6000 cases in the simulation runs of the CAS shown in Figure 3-1, which consists of a single long range sensor for three ranges of 20, 30 and 60 feet. There is agreement between the values derived from the 3000 case runs and the 6000 case runs. LCM8 crashes were included in the crash totals. The statistical uncertainties range from 11 to 20 % of the CAP. The agreement indicates that 3000 cases are sufficient for computing the values of the calculated lane change/merge CAP in the Monte Carlo simulations. This is a rather small value of the CAP. The percentages of the statistical uncertainties become smaller as the value of the CAP increases.

References:

E-1. Chovan, John D., L. Tijerina and G. Alexander and D. L. Hendricks, "Analysis of Lane Change Crashes", Omni Task RA 1039 - Intelligent Vehicle/Highway System (IVHS) Program (Contract No. DTRS-57-89-D-00086), U.S. Department of Transportation, October, 1993.

Appendix F: Description of the TRW Backing Simulator

The specifics of the backing simulations are discussed in detail in section 3.1.4. The curved path and straight path backing simulations were handled separately. Each simulation run consists of a large number of individual cases over which the statistics are collected. In the backing simulations, each case results in a backing crash. Therefore, the effectiveness of any CAS is measured by the fraction of crashes avoided.

Only two detection patterns of the CAS sensors were studied. Each utilized three sensors. These are shown in section 3.1.4. One sensor pattern was concentrated in the area directly behind the vehicle while the second pattern covered an area both behind and to the side of the backing vehicle.

Since the consequences of striking a pedestrian while backing can be extremely serious, striking a pedestrian during straight path backing was the first category of backing crash to be modeled. With modifications, this simulation was generalized to investigate other types of straight path backing crashes.

In the backing simulations, all cases begin with a definite crash scenario. Since the “fraction of crashes avoided” used to evaluate backing CAS has the same form as the “crash avoidance potential”, equation E-15 of section E of Appendix E may be used to compute the statistical uncertainties due to the use of the Monte Carlo simulation, where N2 equals the total number of cases run.

A. Straight Path Backing

Straight path backing occurs backing from a driveway or on the roadway and backing from and into parking. The backing trajectory is straight and consists of an acceleration phase and deceleration phase after the detection or warning. If there is no warning, the acceleration phase ends at a preset speed VI, after which the vehicle continues for a preset distance. The constant velocity phase may not exist for some choices of accelerations. The accelerations and speeds are determined by Monte Carlo processes.

The undisturbed backing course is determined by the following:

a, the initial backing acceleration

v 1, the constant speed at which time (tl) the initial backing acceleration goes to zero

t1, the time at which the initial backing acceleration goes to zero

Ar, the braking deceleration

t2, the time at which the backing deceleration begins

These are defined case-by-case.

The backing acceleration is sampled from a uniform distribution of accelerations between 0.01 g and 0.09 g (where g = 32.0 ft/sec/sec). The backing acceleration varies from case to case within the simulation.

The speed v1 is derived through the use of a Monte Carlo process in which the observed distribution of vehicle speeds for pedestrian or vehicle-vehicle crashes (based on the speed estimates contained in the PARs) is sampled.

All targets (pedestrians, pedacyclists, vehicles) are considered to be a point targets, but the location is varied for each case. The initial position is calculated so that, for the target's speed and direction, the target arrives at the center of the vehicle's back bumper at the same time and place that the vehicle reaches the speed v1.

For fixed targets (standing pedestrians or fixed objects) with a speed of 0, the distance behind the vehicle and lateral position are varied from case to case.

Moving targets are assumed to approach the SV from a given angle phi (approximately 90 deg) at a given speed. The angle phi is measured with respect to the vehicle's backward velocity. The angle phi is sampled from a uniform distribution between 80 to 100 degrees.

For pedestrians, the approach speed, taken from the GES data gathered in Arlington, VA, was defined only as walking, running, or unknown. For the scenario of straight path backing and striking a pedestrian, this was walking. Since many of the victims of backing crashes were very young or very old, the walking speed distribution

was extended to include slower walking speeds than the observed sidewalk walking speeds.

Calculations are done in metric units. Therefore, distances in feet and speeds in mph are converted to meters and meters per second respectively.

Evasion is modeled in the following way. After the detection is made, the vehicle continues for the time interval (t_{react} + t_{lat}). The time interval t_{react} contains the driver reaction time while the driver assesses the data and moves his/her foot to the brake pedal and a system reaction time of 0.1 sec. This latter corresponds to the time required for the braking signal to get from the pedal to the brake pads. The time interval t_{lat} is the time for the data processor to process the data and convert it into a detection warning. During this interval the vehicle continues with its original acceleration. Then, the rearward acceleration of the vehicle decreases abruptly from +a or zero, if v1 has been reached, to - A,.

After this interval, the deceleration stabilizes' to -A, -and remains -A, until the vehicle stops or there is a crash. A, is sampled from a uniform distribution between 0.65 g and 0.75 g, that is, between 6.486 and 7.169 m/sec/sec.

At present the vehicle is considered to be a standard passenger vehicle 2.0 meters wide and 5.0 meters long.

Driver's reaction time, t_{react}, is sampled from Rumar's alert driver's reaction times, since the driver is not totally surprised by the warning during backing.

In the simulation code perfect driver compliance has been assumed, that is, the driver always brakes after his reaction time upon receiving the warning. However, it is possible that the driver will sometimes look around to see what triggered the alarm. This is a driver option which is investigated in the STI simulation.

The following scenarios were studied with the Monte Carlo straight path backing simulation. Based on the analyses of the PARs, pedestrian and pedacyclist crashes were predominantly straight path backing crashes with the pedestrians/pedacyclists approaching the backing trajectory from the side at approximately a 90-degree angle. Standing pedestrians or fixed objects were distributed uniformly between 0.0 and 10.0 meters behind

the vehicle. Fixed objects were distributed uniformly between 0.0 and 10.0 meters behind the vehicle and were randomly positioned across the width of the vehicle. Finally, to test the potential for nuisance alarms, fixed targets were located out of the SV's path, but in locations where detection was possible, such as 0.5 meters beyond the side of the vehicle to simulate a close miss and 1.0 meter beyond the side of the vehicle. Although this is not "far" in the usual sense, it is out of the danger zone for stationary objects.

B. Curved Path Backing

Curved path backing is discussed in detail in section 3.1.4.2. Curved path backing may occur in many situations, for example:

- When the SV backs out of a driveway turning through an arc to align itself with cross traffic moving at an angle,
- When the SV backs out of a parking place turning through an arc to align itself with traffic moving at an angle, or
- When the SV backs around a corner on the roadway, possibly to correct an inappropriate turn.

In each case, it is characterized by moving in an arc. A diagram of curved path backing is shown in Figure F.l below.

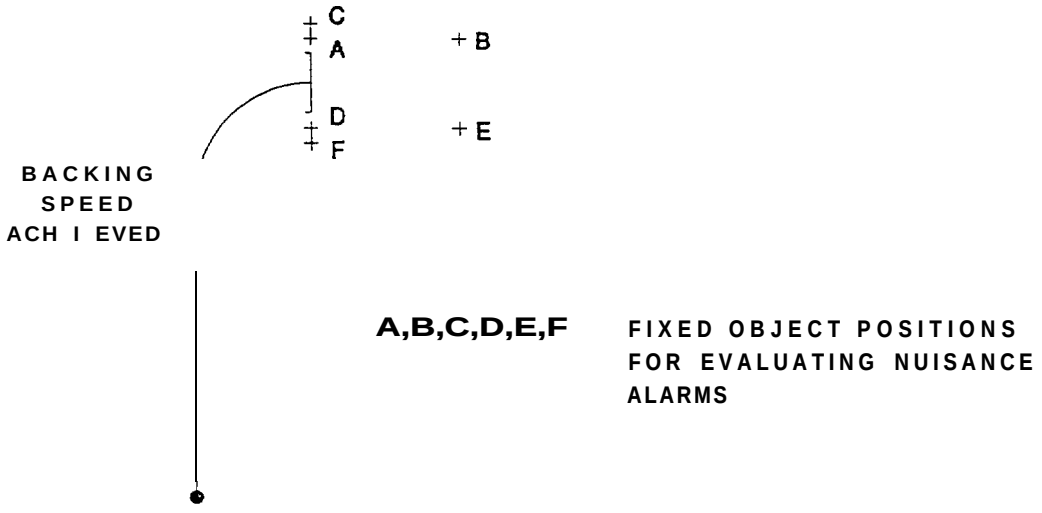


Figure F-l. Diagram of Uninterrupted Curved Path Backing

In uninterrupted curved path backing, the vehicle begins by straight backing until the backing speed chosen from the distribution is reached.

Then, when that speed is reached, the vehicle begins a quarter circle turn at a constant speed. At the end of the turn, the vehicle begins a moderate planned braking and brakes until the speed is zero. In all of the curved path backing simulations, the backing speed distribution for vehicle-vehicle crashes was used. In the simulation, the POV begins at an initial position calculated to bring it to the subject vehicle's back bumper when the turn is completed. The POV's speed is chosen from a given range, for example, 1 to 5 mph, 5 to 15 mph, or, for fixed vehicles, 0 mph. At some point on the SV's path, the CAS detects the presence of the other vehicle and the driver begins a forceful braking. The case continues until a safe stop is effected or a crash occurs. If the space between the vehicles is less than 1.0 seconds headway based on the POV's speed, this is considered a crash also.

The following scenarios were examined:

A fixed object (speed = 0.0, assumed to be the size of another vehicle) positioned behind the backing vehicle at the end the quarter-circle arc backing segment.

A motor vehicle in transport (POV) whose speed and direction cause it to arrive in the area behind the backing vehicle at the end of the quarter-circle arc backing segment. The POVs have slow, moderate or fast speeds defined as "slow" from 1 to 5 mph, "moderate" from 5 to 15 mph, and "fast" from 15 to 30 mph.

Nuisance alarms, or fixed targets placed in locations out of the collision danger zone to simulate a close miss. (These locations are shown in Figure F.1 as A,B,C and D,E,F.)

Again, in this simulation code, perfect driver compliance has been assumed, that is, the driver always brakes after his reaction time upon receiving the warning.