Preliminary Assessment of Crash Avoidance Systems Benefits

NHTSA Benefits Working Group

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ERRATA

To

Preliminary Assessment of Crash Avoidance Systems Benefits
NIITSA Benefits Working Group

	Section, Page No	
1.	Synopsis, Pg. i	Line 5 of the third Paragraph. Change 46% to 48%.
2.	1.2.1, Pg. l-l	Line 3. Change 45 1,000 injuries to 928,000 injuries Line 5. Change 1,669,000 **in** 1994 to **2 million** in 1994.
3.	1.51, Pg. l-5	Last 5 lines of Paragraph 1. "Distributions of following time gaps were acquired from a recent ... rural two-lane highway" change to **"Distributions of following time gaps were acquired from a recent on-road field study conducted by the University of Iowa, in conjunction with Frontier Engineering, Inc., which collected data on driver following behavior with and without a rear-end crash warning system. Four collision warning presentations were evaluated in this study. Sixteen drivers participated in this road test that covered 25 miles of two-lane interstates, two-way state highways, and local residential streets."**
4.	1.5.1, Pg. 1-6	Line 1. Change 49.2% to **51%.**
5.	Table l-l, Pg. l-1 1	Row 2, Column 5. "Vehicle speed and joint (range, closing speed) distributions - UMTRI" change to **"Brake reaction times - U. Iowa. Following time gaps - U. Iowa".** Row 2, Column 7. Change 46% to 48%.
6.	2.2, Pg. 2-l	Line 3. Change 2.6 million to 3.14 million Line 5. Change 46% to 48%.
7.	2.5, Pg. 2-3	Whole paragraph. Change "Section" to **"Chapter".**
8.	3.1.1, Pg. 3-l	Line 2. "description of the rear-end crash warning system . . ., definition of the rear-end crash problem . . ." change to **"definition of the rear-end crash problem . . . . description of the rear-end crash warning system . . ."**

9.	Figure 3-1, Pg. 3-4	"Lead Vehicle Stopped" change to **"Lead Vehicle Not Moving"**
10.	3.3.2, Pg. 3-4	Line 2. "... a functions . .." change to **"... a function . .."**
11.	3.6.1.2, Pg. 3-l 1	Line 5. ".. in section 3.2 . . ." change to ". . . in section 3.3.1 . . ."
12.	3.7, Pg. 3-14	F1 andF2 should read "Proportion of **relevant** rear-end crashes . .." After "F2 = ..." add another line **"$E_{ij} = E(S_{ij})$, for simplicity".**
13.	3.8, Pg. 3-16	Line 6. Delete **"(Section 3.3.1)@.**
14.	Table 7-2, Pg. 7-3	Cell for the crash cost of single vehicle road departure. Change 30.9 to 30.7.
15.	Paragraph 5, Pg. 7-6	Line Change 25.5 to 25.6.

Synopsis

The U.S. Department of Transportation's Intelligent Transportation Systems (ITS) program attempts to enhance surface transportation safety, efficiency, and comfort by applying advanced technologies, including information processing, communications, control, and electronics, to transportation. One goal of ITS is to reduce the number of roadway crashes and related fatalities and injuries. Collision Avoidance Systems (CAS) are a focus of ITS research and development.

A wide array of technologies is currently available or being developed as potential countermeasure systems for various crash types. Recent technological advances in sensors, processors, control systems, and advanced displays now allow for the design of crash avoidance systems with increased sophistication, reduced cost, and high reliability. These systems have the potential to significantly improve the collision avoidance capabilities of motor vehicles by assisting drivers in safely carrying out maneuvers to avoid crashes that would otherwise occur.

This document reports on analyses to estimate the impact of crash avoidance systems by using the best available estimates of system performance and driver response. Three types of systems are considered in these analyses. The three crash avoidance systems address three major crash types: (1) rear-end, (2) single vehicle road departure, and (3) lane change/merge. According to 1994 General Estimates System (GES), these three major crash types accounted for about 46% of all police-reported (PR) crashes. Rear-end crash driver warning systems will monitor the forward path of the host vehicle and its relative velocity with respect to the lead vehicle and provide warnings to the driver of a rear-end collision threat. Road departure systems will sense that the vehicle is traveling too fast for operating conditions or is otherwise on a path that will lead to road departure. Drivers will be informed to take appropriate action. Lane change/merge crash avoidance systems will monitor the position and relative velocity of vehicles in lanes adjacent to the host vehicle and advise the driver when it would be unsafe to change lanes.

While potential benefits are expected in these areas, field experience upon which to base such estimates is not available. The combination of the priority of the safety goals, the unavailability of safety estimates, and the programmatic need to project potential benefits led the National Highway Traffic Safety Administration (NHTSA) to convene a task force of Federal staff and support contractors to develop safety benefits estimation methodologies and apply them to these collision avoidance systems. This report presents the findings of the group.

The crash countermeasure system effectiveness and the number of crashes avoided are estimated for each of the crash countermeasure systems, based on the number of crashes experienced annually in the United States and the best research available regarding operation of the collision avoidance systems. The results of this preliminary study are summarizied in the following table. It must be emphasized that many estimates and assumptions were made to develop these results. The results must be considered preliminary in nature pending further research, refinement of potential countermeasure effectiveness estimates, and field experience.

Crash Condition	Total Number of Crashes	Relevant Crashes Addressed by Countermeasures	Effectiveness Estimates for Relevant Crashes	Number of Crashes Reduced
Rear-End Crashes	1.66M	1,547,000	51%	791,000
Lane Change/Merge	0.24M	190,000	47%	90,000
Road Departure	1.24M	458,000	65%	297,000
Totals	3.14M	2,195,000		1,178,000

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Chapter 1 : Executive Summary

1.1 INTRODUCTION

The U.S. Department of Transportation Intelligent Transportation Systems (ITS) program attempts to enhance surface transportation safety, efficiency, and comfort **by** applying advanced technologies, including information processing, communications, control, and electronics, to the driving process. One goal of ITS is to reduce the number of roadway crashes and related fatalities and injuries. Collision Avoidance Systems (CAS), therefore, are a focus of ITS research and development.

A wide array of technologies is currently available or being developed as potential countermeasure systems for various crash types. Recent technological advances in sensors, processors, control systems, and advanced displays enable the development of crash avoidance systems with increased sophistication, reduced cost, and high reliability. These systems have the potential to significantly improve the collision avoidance capabilities of motor vehicles by assisting drivers in safely carrying out maneuvers to avoid crashes.

The benefits that might be associated with effective crash avoidance systems include the avoidance of crashes and the reduction in crash severity, crash-related fatalities and injuries, property damage losses, and crash-caused traffic delays that lead to lost work, wages, or productivity. Additional benefits might also include reduced driver stress, increased driver comfort and satisfaction, and increased highway throughput. This study provides a preliminary estimate of safety benefits of a selected number of crash avoidance systems, in terms of the number of crashes that might be avoided. A major feature of this study in the use of experimental data as the basis of estimating probability of a collision when driving without the assistance of a collision avoidance system and the corresponding probability when driving with a collision avoidance system. These estimates of collision likelihood are combined with other information about usage and types of collisions to estimate benefits.

1.2 TARGET CRASHES

The crash avoidance systems under consideration address three major crash types: (1) rear-end, (2) lane change/merge, and (3) single vehicle road departure. According to the 1994 data from the General Estimates System (GES), these three major crash types accounted for about 46% of all police-reported (PR) crashes. In all cases, estimates are presented of the number of unreported crashes. The number of unreported crashes is included for illustrative purposes only and are not considered in the quantitative benefits estimates.

1.2.1 Rear-End Crash

This crash type occurs when the front of a subject vehicle (SV) strikes the rear of a leading principal other vehicle (POV), both traveling in the same lane. According to 1994 GES, there were approximately 1,660,000 PR rear-end crashes. These crashes accounted for about 45 1,000 injuries, including 1,160 fatalities. In addition, the number of non-PR rear-end crashes is estimated at about 1,669,000 in 1994. This crash type comprises two major precrash scenarios: a) where the lead vehicle was moving(usually decelerating), and b) where the lead vehicle was not moving for a period of time. The lead vehicle moving and lead vehicle not moving precrash scenarios accounted for about 72% and 28% of PR rear-end crashes, respectively.

1.2.2 Lane Change/Merge Crash

In this crash type, the SV driver attempts to change lanes and strikes, or is struck by, a POV in the adjacent lane. In 1994, there were approximately 244,000 lane change/merge (LCM) PR crashes. LCM crashes accounted for 277 fatalities and approximately 52,000 injured people. In addition, there were about 400,000 non-PR LCM crashes in 1994. Lane change/merge crash avoidance system technology that will provide coverage of the adjacent lanes, both beside and to the rear of the SV, to help prevent driver lane change decision errors for four subtypes of lane change crashes: Sideswipe Striking, Sideswipe Struck, Angle Striking, and Angle Struck. These four lane change crash subtypes account for an estimated 78 percent of all lane change/merge crashes. Thus, the target crash size of the lane change/merge crash avoidance system is about 190,300 PR crashes, This implies that 244,000 - 190,300 = 53,700 crashes would not be addressed by the lane change/merge crash avoidance system technologies described.

1.2.3 Single Vehicle Road Departure Crash

This crash type refers to a vehicle leaving the roadway as a first harmful event. This crash type does not include road departures resulting from a crash with another vehicle. In 1994, there were approximately 1.238 million PR single vehicle road departure (SVRD) crashes. About 540,000 people were injured in SVRD crashes according to 1994 GES. These crashes were also associated with 13,330 fatalities according to the 1994 fatal accident reporting system (PARS). In addition, there were about 1.437 million non-PR crashes derived from a conservative estimate for the year 1994.

The longitudinal road departure countermeasure system mitigates SVRD crashes caused predominately by excessive speed on curved roadways and loss of directional control on roadways with a shoulder, excluding involved drivers with a blood-alcohol content over 0.09. Thus, the system applies to about 13.3% or 165,000 SVRD crashes caused by excessive speed on curved roadways and to about 12.9% or 160,000 SVRD crashes caused by alert drivers losing directional control on roadways with a shoulder. Consequently, the longitudinal road departure countermeasure system has the potential to alleviate about 26.2% or 325,000 PR SVRD crashes.

The lateral road departure countermeasure system is designed to prevent crashes caused primarily by driver inattention and driver relinquishing steering control due to drowsiness. In addition, the system is assumed to apply only to crashes that occur on roadways with a shoulder. About 6.1% or 76,000 SVRD crashes were caused by driver inattention on roadways with a shoulder. Driver relinquishing steering control due to drowsiness on roadways with a shoulder accounted for about 4.7% or 58,000 SVRD crashes. Therefore, the target crash size of the lateral road departure countermeasure system is about 10.8% or 134,000 PR SVRD crashes.

1.1.3 BENEFITS ESTIMATION METHODOLOGY

The direct benefit associated with crash avoidance systems is the reduction in number of crashes as defined by:

$$B = N_{wo} - N_w = SE * N_{wo} \tag{1.1}$$

where :

B = Benefit defined in terms of number of crashes reduced

N_{wo} = Number of target crashes without any CAS intervention

N_w = Number of target crashes with CAS intervention

SE = Proportion of crashes that occur without the system that are prevented using CAS

In controlled conditions where equal populations of vehicles equipped with CAS and not equipped with CAS operate under similar situations, benefits could be directly measured from field experience. During all stages of development ranging from the early concept phase to full deployment, benefits can be estimated by calculating a system effectiveness from experiment and analysis as:

$$SE = MP*U* \sum_{\substack{all \\ situations}} p(S)*E(S) \tag{1.2}$$

where :

MP = Proportion of CAS market penetration

U = Utilization of CAS during target crash hazard

S = Distinct crash situations

$p(S)$ = Probability that a crash will be of a particular crash situation

$E(S)$ = Effectiveness of a driver using CAS in preventing a crash in a given situation

In order to develop an estimate of benefit at the current early stage of CAS development, a number of simplifying assumptions are requited. The utilization term includes a number of factors including usage, reliability, and driver compliance which are assumed to be unity (100%) for the first order analysis performed for this report. Utilization also appears outside of the summation, implying that all components of utilization are assumed to be independent of the crash situation. Thus, both market penetration and utilization were set at unity for the calculations made in the report. Effectiveness of the CAS in a specific situation is defined as the proportion of accidents that occur without CAS support that could be avoided by a driver using a CAS.

Although the proportions of CAS penetration into the vehicle market (MP) and CAS usage (U) are assumed to be 1.0 in this study, it should be noted that drivers may disengage a CAS due to a high frequency of alarms, especially nuisance alarms. Another potential effect of nuisance alarms is that drivers may keep the CAS on but take longer time to react. In this study, the effects of nuisance alarms on driver behavior are not considered for lack of empirical data

Generally, the CAS effectiveness in a given situation is expressed mathematically as:

$$E(S) = 1 - \frac{P_w(S)}{P_{wo}(S)} \tag{1.3}$$

where :

$p_W(S)$ = Probability of a crash in a given situation with a CAS

$p_{WO}(S)$ = Probability of a crash in a given situation without a CAS

For purposes of the assessment of effectiveness in this report, estimates of these crash probabilities can be determined from experimental data on driver performance with and without the use of a CAS when available and from analytical techniques or computer simulation methods such as the Monte Carlo method when experimental data are not available.

1.4 DESCRIPTION OF CRASH AVOIDANCE SYSTEMS

At present, NHTSA has projects to develop performance specifications for solutions to several motor vehicle collision problem areas. Among them are rear-end, lane change/merge, and single vehicle road departure collisions. Four vehicle-based crash avoidance systems were selected from three of these projects. Specifically, preliminary safety benefits were estimated for rear-end crash driver warning systems, lane change/merge crash avoidance systems, and two types of road departure systems (longitudinal road departure countermeasure systems and lateral road departure countermeasure systems). These particular systems were chosen based on their technical maturity and the availability of system prototypes. Moreover, experimental data on driver/system performance for these systems have already been gathered via limited on-road and driving simulator tests.

1.4.1 Rear-End Crash Driver Warning System

This system monitors the forward path of the host vehicle and provides warnings to the driver if the headway to a lead vehicle presents a potentially dangerous situation. The driver/system interface consists of a graphical visual display and an auditory voice warning. As the lead vehicle comes closer to the host vehicle, the graphical display increases intensity and color to convey urgency. When the gap reaches a critical threshold based on distance and speed, a digitized voice ("brake") warning is issued to the driver.

Preliminary results related to autonomous/intelligent cruise control are included as Appendix C.

1.4.2 Lane Change/Merge Crash Avoidance System

This system detects targets left or right up to 90 feet behind and along the full length of the host vehicle in adjacent lanes. If there are no indications of lane change start (e.g., turn signals are not used or the vehicle has not begun moving toward the adjacent lane), the system presents an easily-detectable visual "alert" whenever and for as long as there is an object in the sensor coverage zone. If there is an object in the sensor coverage zone and turn signals are activated (or there is some other indication that the vehicle has begun moving toward the adjacent lane), this system provides the driver with a visual, auditory, or haptic "warning" to augment the visual alerts.

1.4.3 Road Departure Countermeasure Systems

The lateral road departure system detects when the vehicle begins to depart the road. It utilizes data about the dynamic state of the vehicle in combination with information about the geometry of the road ahead to determine if the vehicle's current position and orientation will likely lead to a road departure. If the likelihood of departure exceeds a threshold, a sequence of driver interface functions is triggered to alert the driver of the danger. Data about the vehicle's current position on the roadway and information about the geometry of the road ahead are obtained from a forward-looking vision sensor that tracks lane markings or other features delineating the roadway.

The longitudinal road departure system detects when the vehicle is traveling too fast for the upcoming roadway segment. It utilizes vehicle dynamic state and performance data in combination with information about the current pavement conditions and upcoming roadway geometry to determine the maximum safe speed for the vehicle. If the vehicle's current velocity exceeds the safe speed, a sequence of driver interface functions is triggered to alert the driver of the danger. Vehicle dynamic state information is provided by on-board sensors, and includes vehicle velocity, acceleration, heading, and position on roadway (relative to an upcoming curve). The vehicle performance data include vehicle braking efficiency, center of gravity, cornering characteristics, etc.

1.5 PRELIMINARY RESULTS

The system effectiveness and the number of crashes avoided are estimated for each of the crash countermeasure systems in the following section. The results of this preliminary study are summarized in a Table 1- 1.

1.5.1 Rear-End Crash, Driver Warning System

This system is applicable to "lead vehicle decelerating" and "lead vehicle not moving" mar-end precrash scenarios. Both scenarios were analyzed under dry and wet/icy roadway surface conditions. Monte-Carlo computer simulations were used to estimate the system effectiveness. The analysis of the lead vehicle decelerating scenario incorporated experimental data on driver brake reaction time and following time gaps while driving with and without the system. Distributions of brake reaction times were obtained from a recent study conducted at the University of Iowa's driving simulator which recruited two groups, eight persons each, for each condition between the ages of 18 and 24. This study generalizes the results to the entire population. Driver brake reaction times were gathered at a time headway of 2 sec. The reaction time distributions were modified to account for shorter time gaps. Distributions of following time gaps were acquired from a recent on-road test conducted by the University of Idaho, in conjunction with General Motors, which collected data on driver following behavior with and without a multi-colored headway display. A total of 104 drivers participated in this road test on a Smile, rural two-lane highway.

The analysis of the lead vehicle not moving scenario assumes that drivers in both conditions have the same reaction time to a stationary obstacle in their path. A lognormal distribution of brake reaction time with a mean value of 1.1 sec and a standard deviation of 0.3 sec is adopted based on a "surprise" driver reaction time field study conducted by UMTRI in 1984. This system is assumed to work perfectly up to its range limitation; i.e., it never fails to detect the lead vehicle, never detects the "wrong" vehicle, and always provides accurate speed and distance information. Moreover, drivers with this system never use it as a substitute for their own vigilance. Most important, the effects of nuisance/false alarms were ignored in this preliminary study. Consequently, the effectiveness of the rear-end collision, driver warning system is estimated at 42.0% in the "lead vehicle decelerating" target precrash scenario and at 75.0% in the "lead vehicle not moving" target precrash scenario. Overall, the effectiveness of this system is estimated to be

49.2% of its target crashes. Thus, the number of PR crashes that might be avoided with this system amounts to 791,000 crashes or about 47.7% of all PR rear-end crashes.

1.5.2 Lane Change/Merge Crash Avoidance System

The lane change maneuver involves a decision phase, where the driver gathers information about obstacles to decide whether or not to start the lane change, and the execution phase, where the host vehicle begins the lateral motion to the destination lane. The crash record indicates that lane change crash-involved drivers were largely unaware of the obstacle in the adjacent lane. The lane change CAS concept analyzed in this report has the potential to alert the driver in the decision phase and prevent the execution of the ill-advised maneuver. Decision phase effectiveness estimates are developed from application of reliability theory. Data are taken from GES estimates, assumed frequency of lane changes, assumed nature of the driver-CAS interaction, and field study data gathered on side-object detection systems performance and truck driver behavior on the open highway. Execution phase CAS support is not considered in this report.

For lane change and merge collision avoidance, a highly reliable system was analyzed that will provide an unobtrusive alert when an object is in the sensor coverage zone and a more intrusive warning when the operator indicates intention to change lanes by using a turn signal. For the decision phase the lane change maneuvers, four different modes were described for ways in which drivers may interact with the collision avoidance system. Based on data from experimental studies, estimates of effectiveness of the system consisting of the driver plus the CAS were compared to the current effectiveness of the driver without CAS support. Estimates of the percentage of crashes avoided, for all lane change collisions, range from 8% to 68%. The authors' best estimate of the effectiveness is a reduction of relevant collisions by 47%. This translates into a decrease for all lane change collisions of 37% or about 90,000 crashes annually.

1.5.3 Road Departure Countermeasure Systems

The lateral road departure system is applicable to two precrash scenarios based on driver "relinquished steering control" and "inattention" causal factors. The former scenario addresses mainly drowsy drivers and consists of six circumstances which correlate roadway geometry (curved or straight) and roadway surface condition (dry, wet, or icy/snowy). The latter scenario includes inattentive drivers on curved and dry roadways, and drowsy drivers on straight and dry roadways. As mentioned above, the baseline system effectiveness is estimated at 0.8 for inattentive drivers on dry roadways. This effectiveness value is assumed to be 0.7 for drowsy drivers based on driver mean control-response time under different physiological conditions.

The longitudinal road departure countermeasure system is applicable to two precrash scenarios based on "excessive speed" and "loss of directional control" causal factors. The "excessive speed" scenario comprises nine circumstances which include distinct pair combinations of driver physiological state (alert, had been drinking (BAC 0.09), or inattentive) and roadway surface condition (dry, wet, or icy/snowy). The "loss of directional control" scenario addresses alert drivers only and consists of six circumstances which correlate roadway geometry (curved or straight) and roadway surface condition (dry, wet, or icy/snowy). The system effectiveness of the system in either scenarios for alert drivers on dry roadways is estimated at 0.8. This number comes directly from SVRD crash studies performed at the University of Iowa driving simulator. This assumption of basic effectiveness was made because the longitudinal system employs a more advanced technology and has a much longer preview or anticipation time than the lateral system.

The combined effectiveness of the road departure systems is estimated to be 65% of its target crashes. Thus, the number of police reported crashes avoided would be about 297,000 or about 24% of all police reported single vehicle road departure crashes. For simplicity, the system reliability is assumed to be 1 in all scenarios.

1.5.4 Monetary Benefits of Collision Avoidance Systems (CAS)

The estimated economic costs of motor vehicle crashes in 1994 amounted to $150.5 billion, based on police-reported and unreported crashes. This cost includes, among other factors, the lifetime costs of 40,676 fatalities, 5.2 million people with non-fatal injuries, and 27 million damaged vehicles. Not included in the estimated cost figure are less tangible values associated with factors such as pain and suffering. For rear-end, lane change/merge, and road departure crash types, the estimated economic costs in 1994 were $35.4 billion, $3.5 billion, and $30.7 billion, respectively.

The monetary benefits of CAS were estimated as the total cost savings of motor vehicle crashes prevented. No monetary benefits were estimated for CAS-related crash severity reduction. The analysis of monetary benefits was done for a hypothetical future year when all vehicles in the fleet are equipped with CASs but is expressed in 1994 dollars. The monetary benefits estimate assumed that CAS to address the three crash types are integrated into all vehicles and there are no associated disenefits. By factoring in the effectiveness estimates for each of the three crash types discussed in this report, the cost savings is estimated to be $25.6 billion.

A cost-benefit analysis was conducted to determine the break-even point for per-vehicle CAS costs. Based on the assumptions described in the report, the break-even point is estimated to be $1500. Cost reductions below this value yield cost-benefit ratios greater than 1:l. Thus, it would appear that CAS development effort should strive to keep consumer cost of these systems per vehicle to below $1500.

1.5.5 Potential Benefits Adjustment Issues

System effectiveness caveats and attenuation factors are summarized below:

1.5.5.1 Caveats to Rear-end Crash Avoidance Results

General simplifying assumptions. The analyses assumed full fleet penetration, full CAS usage, 100 percent CAS reliability perfect driver compliance via execution of fully controlled braking maneuvers, and no change in driver data gathering behaviors or risk compensation. These are simplifications and the true state of affairs will undoubtedly differ in at least some respects.

Assumed independence among modeling parameters. The Monte Carlo simulations used independent combinations of parameters (excepting driver reaction time and initial time headway between lead and subject vehicle). Correlated parameters may yield different outcomes.

Relationship between driver reaction time and time headway. It was assumed that driver brake reaction times will be shorter given shorter time gaps assumes that the subject vehicle driver is, in fact, aware of the gap. The target population of drivers are, however, by definition inattentive to the rear-end crash hazard, at least momentarily.

Driver reaction tune (RT) budgets. A fixed driver reaction time "budget" of 0.9 seconds was used in the analysis yet many drivers will not respond that quickly.

Point at which SV driver becomes aware of the crash hazard. The assumption that neither CAS-supported drivers nor drivers without CAS support will ever respond at greater than a pre-calculated distance, d_0 feet, is a simplification that will likely differ in real-world settings.

Feasibility of assumed evasive braking maneuvers and secondary crash consequencs. Secondary crash consequences (e.g., chain reaction crashes) resulting from evasive maneuvers are not addressed in this (or any other) effectiveness estimation.

Lead vehicle deceleration distributions The lead vehicle decelerations for rear-end crashes were assumed to follow distributions like those observed at intersections on dry and wet pavements, decelerations may differ in other settings, e.g., on the open roadway.

Time headway distribution The time headway data was taken from an on-road study in which the test participants followed a confederate vehicle they knew was part of the study. Thus, the observed behavior with the CAS may not be similar to behavior that would occur when the driver is alone, in his or her own vehicle, driving under time pressure, etc.

Time headway distributions and crash-involved drivers. Crash-involved drivers may adopt shorter time gaps even in the face of CAS technology.

Assumed driver brake reaction times for rear-end LVD scenerios The driver brake reaction time (RT) distribution used were from simulator studies whose results may differ from those that would arise in real-world driving situations.

1.5.5.2 Caveats to Lane Change/Merge Crash Avoidance Results

Limitations of the Decision-Execution Phase Concept. For certain crash scenarios there may be no "decision" at all.

The importance of specific CAS features. The effectiveness of a CAS will depend on the specifics of its implementation (driver interface design, sensor performance, processing speed, etc.).

The importance of crash circumstances. The effectiveness of a CAS will depend on the specifics of the crash circumstances to which it is targeted. Factors such as vehicle-to-vehicle separation, lane change aggressiveness, and recovery maneuver acceleration levels are important characteristics of hazardous conditions even though they are probably not sufficient to predict crash avoidance.

The potential non-representativeness of archival driver performance data. Even simple modeling efforts of effectiveness make use of human performance data that may differ from the performances of crash-involved drivers (e.g., error-prone theory).

The similarity in response of modeled versus actual performance. The experimental paradigm used in collecting data for effectiveness or benefits estimation must be carefully considered. Test participants, driving scenarios, and experimental tasks can produce results that differ from real world experience.

Modes of Driver-[redacted]eraction There is little published information on the relative frequency of each of several possible DriveriCAS interaction modes (Driver-only checks for obstacles, CAS-only checks, CAS + Driver check in Series, CAS + Driver check in Parallel). Thus, the necessary information to make a somewhat accurate preliminary estimate of CAS effectiveness is lacking.

CAS Driver Interface Design In application, there are many challenges to conveying necessary and sufficient CAS information reliably to the driver. The design of the driver interface will therefore be crucial to the effectiveness of the CAS as a whole.

Driver Workload or Distraction. The performance of a CAS may be degraded by distractions both inside and outside the vehicle. Driving scene distractions and attentional demands may take the driver's attention away from the CAS display and thus decrease its effectiveness. In-vehicle distractions such as cellular phone use, car radio use, other ITS devices, or other passengers may similarly compromise the performance of a CAS that, when evaluated without such real-world distractions, appears more promising.

Open-loop Behavior. Many human behaviors are performed automatically and without much conscious attention. Such behaviors include habits or over learned behavior patterns that, once the performer's intent is set, are performed in an open-loop fashion, i.e., without attentional checks or control during their execution. Such open-loop behavior may not be easily broken by CAS alerts or warnings.

Perceptual filtering of CAS Alerts Frequent CAS alerts or warnings may be ignored because people routinely filter out extraneous (situationally defined) sensory inputs to avoid being overwhelmed by what otherwise would be ". . ..one great blooming, buzzing confusion".

False or nuisance alarms. There has been much concern raised over the impact of false or nuisance alarms on driver compliance with a CAS alert or alarm. Some of the negative consequences that may arise: CAS is turned off, CAS display is turned down, the driver takes longer to react, or the driver does not comply at all.

Indiators of Driver Intent A CAS should be intelligent enough to discern the driver's intent (e.g., intent to change lanes, lane change start) though this is difficult to do. If available, such indicators might selectively alter the drive alerts or warning (e.g., thresholds, presentation mode, stimulus magnitude, etc.).

Driver Individual Differences. Age, perceptual-motor skills differences, risk-taking differences can all affect the driver's response to CAS technology. Similarly, the CAS warning algorithm must be sensitive to both the time and distance budgets available for crash avoidance and to vehicle control stability. For instance, a lane change/merge CAS will not be effective if its warnings startle the driver to attempt an unsafe evasive maneuver.

1.5.5.3 Caveats to Roadway Departure Results

Lack of operational system Given that no operational system exists, results of a simulator study were used for effectiveness estimates. The simulator study, however, was an exploratory study, conducted to assess several combinations of CAS concepts (e.g., interface alternatives, algorithms) and involved a relatively small sample of test participants and a limited number of driving scenarios. Extrapolations to effectiveness at-large should be approached with caution.

Roadway departure crash circumstances. Limited information is available about crash situational characteristics that must be better understood to support CAS design and benefits estimation.

Crash countermeasure specifics and their impacts. Effectiveness rates will be influenced by CAS specifics such as driver-system interface, false alarm rates, nuisance alarm rates, and so forth.

Such factors will influence driver acceptance which in turn, influences market penetration. These unknowns limit the ability to provide cogent effectiveness estimates.

Additivity of benefits and system integration Benefits for the road departure CAS concepts of curve warning and lane departure on a straight roadway were added together. However, the two system concepts may have combined effects that differ from the additive effects assumed in the analysis.

1.5.5.4 Caveats to the Monetary Benefits Results

Carry-over of limitations on individual CAS effectiveness estimates. The limitations and caveats associated with CAS-specific effectiveness estimates will affect the quality of the monetary benefits estimates in which they are used.

Full Market Penetration Assumption. Full market penetration of CAS technologies may be very difficult to achieve. Even if it is achievable, this will take several years, during which time the benefits will likely be less than predicted.

Self-selected "safe" drivers as CAS consumers. There remains a concern that the types of drivers most willing and able to purchase CAS technologies will represent a portion of the driving population that is relatively uninvolved in crashes. If this arises, it will diminish the benefits realized accordingly because the CAS technologies are not in the hands of the drivers most in need of them.

Crash cost estimate uncertainties. Many extrapolations underlie the crash cost estimates for each crash type. These include crash severity conversions, redistribution of fatalities based on fatality ratios in mass crash databases, adjustments for under counting of crashes, and so on. Since each of these extrapolations introduces some error of estimation, the actual versus predicted crash costs are likely to vary somewhat.

Differential CAS effectiveness. It was assumed in lieu of data that the CAS effectiveness rate is constant across all crash severity categories. If, CAS technologies are especially good at eliminating the more severe crashes, monetary benefits would presumably be greater than if CAS technologies are only able to relieve the lowest-severity crashes of a particular crash type.

Discounting percentage assumed. A discounted rate of 4% per annum was assumed for the monetary benefits estimations. In light of the numerous uncertainties involved, this figure appeared reasonable. However, it is subject to substantial shifts based on the economy.

CAS	Function	Target Crash Size*	Crash Type	Empirical Data**	%E/ Target Crash	%E/ Crash Type	Crashes Avoided*
Rear-End Collision, Driver Warning	Provides warnings if headway to a lead vehicle presents a potentially dangerous situation.	1547 K	Rear -End	Vehicle speed and joint (range, closing speed) distributions - UMTRI	51	46	791 K
Lane Change/Merge Crash Avoidance	Provides alerts/warnings if adjacent vehicles are in left/right blind spot, or otherwise adjacent with host vehicle.	190 K	Lane Change/ Merge	Driver and system performance data - VRTC	47	37	90 K
Road Departure Countermeasures	Recommends safe speed when vehicle is traveling too fast for upcoming roadway curvature. Warns driver when likelihood of vehicle departing the road exceeds a threshold.	458 K	Single Vehicle Road Departure	Data extrapolation - U. Iowa Crash avoidance rates - U. Iowa	65	24	297 K

Table l-l. Crash Reduction Effectiveness Summary

* Police-reported crashes according to 1994 GES.

** Additional data were extrapolated from other human factors and highway traffic studies conducted in driving simulators or on road tests.

Chapter 2 : Introduction

2.1 PURPOSE OF STUDY

The U.S. Department of Transportation's Intelligent Transportation Systems (ITS) program attempts to enhance surface transportation safety, efficiency, and comfort by applying advanced technologies, including information processing, communications, control, and electronics, to the driving process. One goal of ITS is to reduce the number of roadway crashes and related fatalities and injuries. Collision Avoidance Systems (CAS), therefore, are a focus of ITS research and development.

A wide array of technologies are currently available as potential countermeasure systems for various crash types. Recent technological advances in sensors, processors, control systems, and advanced displays now allow for the design of crash avoidance systems with increased sophistication, reduced cost, and high reliability. These systems have the potential to significantly improve the collision avoidance capabilities of motor vehicles by alerting drivers in time to safely avoid crashes.

The benefits that are expected from effective crash avoidance systems include reduced numbers of automobile crashes and therefore reduced consequences such as crash-related fatalities and injuries, property damage losses, and crash-caused traffic delays that lead to lost work, wages, or productivity. Additionally CAS may enable reduced driver stress, increased driver comfort and convenience, higher overall driver satisfaction, and increased highway throughput.

While potential benefits are expected in these areas, field experience is scarce and quantified benefits estimates are not available. The combination of the priority of the safety goals, the unavailability of safety estimates, and the programmatic need to project potential benefits lead the National Highway Traffic Safety Administration (NHTSA) to convene a task force of Federal staff and support contractors to develop and perform initial application of methodologies to estimate anticipated benefits. This report presents the findings of the group.

2.2 PROBLEMS ADDRESSED

CAS considered in this study address several collision types including rear-end, lane change/merge, and road departure. As will be detailed in subsequent sections, these categories collectively total approximately 2.6 million police-reported collisions annually in the U.S. that result in 15,000 fatalities. As a proportion of total crashes, collision types susceptible to improvement using CAS represent 46% of collisions and 36% of fatalities. CAS to reduce the crash types identified above were chosen for this study based on their technical maturity.

2.3 ESTIMATION TECHNIQUES

The underlying foundation of this work is the availability of experimental data. These data have been gathered for a variety of driving situations where drivers did not have assistance from a CAS and then under the same conditions when drivers did have assistance from a CAS. The data are

used to estimate probabilities of collisions in each situation with and without assistance from a CAS. These estimates of collision probability are used to estimate system effectiveness.
The direct benefit associated with crash avoidance systems is the reduction of crashes as defined by:

$$B=Nwo-Nw=SE*Now \qquad (2.1)$$

where :

B = Benefit defined in terms of number of crashes reduced
Nwo = Number of target crashes without any CAS intervention
Nw = Number of target crashes with CAS intervention
SE = Proportion of crashes that occur without the system that am. prevented using CAS

In controlled conditions where equal populations of vehicles equipped with CAS and not equipped with CAS operate under similar situations, benefits could be directly measured from field experience. During all stages of development ranging from the early concept phase to full deployment, benefits can be estimated by calculating a system effectiveness from experiment and analysis as:

$$SE=MP*U*\sum_{\substack{all\\situations}} p(S) * E(S) \qquad (2.2)$$

where :

MP = Proportion of CAS market penetration
U = Utilization of CAS during target crash hazard
S = Distinct crash situations
$P(S)$ = Probability that a crash will be of a particular crash situation
$E(S)$ = Effectiveness of a driver using CAS in preventing a crash in a given situation

The above equation provides a very general framework for estimating collision reduction using CAS countermeasures. For each system considered in this report, specific situations over which collision reduction are expected will be detailed and estimated benefits will be calculated using experimental results and expert judgment. The results of each section will be tabulated to obtain an overall estimate of potential CAS crash reduction for the systems considered.

In order to develop an estimate of benefit at the current early stage of CAS development, a number of simplifying assumptions are required. Market penetration is intended to reflect the proportion of the vehicle fleet with CAS installed.The utilization term includes a number of factors including usage, reliability, and driver compliance which were assumed to unity (100%) for the first order analysis performed for this report Utilization and market penetration appear outside of the summation implying that all components of utilization are assumed to be independent of the crash situation for simplicity. Researchers acknowledge the importance of such factors on CAS effectiveness and attendant benefits. However, because of the lack of information on the factors, both market penetration and utilization were set at unity for the calculations made in the report

Effectiveness of the CAS in both a specific situation and overall is defined as the proportion of accidents that occur with the driver alone that could be avoided by a driver properly using a CAS.

Experience with both vehicle and roadway safety improvements indicates that drivers will adjust their behavior based on new perceptions of safety. Unless otherwise stated, the estimates in this paper make the optimistic assumption that increases in risky behavior are negligible. Likely effectiveness attenuation factors are presented in the general discussion chapter of this report.

2.4 SOURCES OF DATA

Data regarding crash types and crash scenarios are derived from mass databases of crash reports, such as the General Estimates System (GES) as well as a rich literature of collision analysis. Data in these reports, generally based on reports covering crashes occurring between 1991 and 1994, are current. Details of sources and subsets are provided in each of the following chapters. However, it must be acknowledged that mass databases often cannot provide a full accounting of crash circumstances and that causal and contributing factors often must be inferred from limited data.

The data used in the estimation of benefits are derived from a limited number of sources including single vehicle road departure studies performed at the University of Iowa driving simulator, braking reaction time studies performed at the University of Iowa driving simulator, driver reaction field studies performed at the University of Michigan Transportation Research Institute, human reliability performance studies, and a lane change collision avoidance system usage study of professional drivers on public roads. Although some of the studies that are referenced represent excellent research with landmark results, none of them present either highly reliable predictions of human interaction with CAS or extensive usage of CAS by the full user population.

2.5 ORGANIZATION OF THIS REPORT

Section 1 of this report presents an executive summary of the report. Section 2 gives an overview of the purpose and content of the report. Sections 3,4, and 5 represent the estimates of effectiveness of mar-end, lane change, and road departure CAS and were authored by leading practitioners in the fields covered. Section 6 summarizes the potential benefits. Section 7 presents a cost benefit analysis for the CAS considered in the document. Section 8 contains issues and assumptions that could affect the accuracy of the results presented and suggests areas for future research.

Chapter 3: Preliminary Safety Benefits of a Rear-End Crash Warning System

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3.1 INTRODUCTION

The purpose of the ***Intelligent Transportation System (ITS)*** program is to enhance all aspects of surface transportation by applying advanced technologies, including information processing, communications, control, and electronics. One major goal of the ITS program is to improve the safety of travel by helping reduce the number of crashes and resulting casualties. A wide array of technologies are currently available as potential countermeasure systems for various crash types. Recent technological advances in sensors, processors, control systems, and advanced displays now allow for the design of crash avoidance systems with increased sophistication, reduced cost, and high reliability. These systems have the potential to significantly improve the collision avoidance capabilities of motor vehicles by assisting drivers in safely carrying out maneuvers to avoid crashes. The benefits that might be associated with effective crash avoidance systems include reduction or elimination of automobile crashes, crash-related fatalities and injuries, property damage losses, and crash-caused traffic delays that lead to lost work, wages, or productivity. Additional benefits might also include reduced driver stress, increased driver comfort and convenience, overall driver satisfaction, and increased highway throughput.

This chapter develops an estimate of the safety benefits of a rear-end crash warning system, in terms of the number of crashes that might be avoided. Experimental data on driver performance with and without the use of such a collision warning system are the primary basis for this assessment. These benefits are also presented in economic terms based on monetary costs of goods and services which must be purchased as a result of motor vehicle crashes such as medical care, vehicle repair services, legal services, etc. In addition, economic monetary costs include the value of both workplace and household productivity lost due to death or injury, the value of travel delay to non-involved motorists, and costs incurred due to workplace disruption when an employee is killed, injured, or delayed (Wang, Knipling, and Blincoe, 1996).

3.1.1 Chapter Outline

This chapter consists of eight major sections which succeed this introduction in the following order: description of the rear-end crash warning system being investigated for the safety benefit estimation, definition of the rear-end crash problem addressed by the subject countermeasure system, delineation of the methodology used for estimation of safety benefits, kinematic modeling of two major rear-end precrash scenarios employed in computer simulations, description of the data elements used as input to computer simulations, derivation of system effectiveness values, computation of preliminary safety benefits, and concluding remarks.

3.2 CRASH PROBLEM DEFINITION

This crash type is characterized by the front of a following vehicle striking the rear of a leading vehicle, both traveling in the same lane. According to 1994 General Estimates System (GES) accident data base, there were approximately 1.66 million police-reported (PR) rear-end crashes.

These crashes accounted for about 928 thousand injuries, including 1,160 fatalities. In addition, the number of non-police-reported crashes was estimated at about 2 million in 1994.

Based on a recent analysis of 135 rear-end crash cases obtained from the 1992 Crashworthiness Data System (CDS) accident data base, ten dynamically-distinct precrash scenarios were identified for the dynamic states of the two vehicles involved in the crash (Frontier, 1994). The results showed that the following vehicle was initially traveling at a constant speed in about 93 percent of rear-end crashes and it was either accelerating or decelerating in the remaining 7 percent prior to the events that led to the collision. Moreover, the lead vehicle was decelerating immediately before the collision in 69 percent of rear-end crashes. Of these cases, the dynamic state of the lead vehicle was listed as decelerating and stopped shortly before impact if a lead vehicle was stopped due to a traffic control device or in order to make a turn on a straight roadway. The lead vehicle was stopped in traffic lane for an extended period of tune prior to collision in about 25 percent of rear-end crashes. In the remaining cases, the lead vehicle was either accelerating or traveling at a constant speed. For the purpose of this assessment of the safety benefits of a rear-end crash warning system, only the rear-end crashes in two major precrash scenarios were considered; one where the lead vehicle was decelerating immediately prior to the collision and one where the lead vehicle was stationary for an extended period of time prior to the collision. In both scenarios, the following vehicle was traveling at a constant speed. The statistical characteristics and causal factors of the two major precrash scenarios and relevant crash sizes that influenced the safety benefit estimation are described below.

3.2.1 Statistical Characteristics of Major Precrash Scenarios

Based on 1994 GES statistics, the lead vehicle decelerating (LVD) and lead vehicle not moving (LVNM) precrash scenarios accounted for about 72 percent or 1.20 million and 28 percent or 465 thousand PR rear-end crashes, respectively. The statistics on "roadway surface condition" and "posted speed Limit" crash characteristics were used in estimating the safety benefits of the rear-end crash warning system. Tables 3-l and 3-2 show the distributions of both crash characteristics for each precrash scenario. Also in 1994 GES, alcohol involvement was cited in 4.3 percent and 2.3 percent of all LVD and LVNM rear-end precrash scenarios, respectively. Moreover, about 13.8 percent of all LVNM rear-end precrash scenarios occurred on curved roadways compared to only 3.2 percent of all LVD precrash scenarios,

Table 3-1. Percent Distribution of Roadway Surface Conditions

Roadway Surface Condition	Lead Vehicle Decelerating	Lead Vehicle NOt Moving
Dry	714	746
Wet/Snow/Ice	28.6	25.4

Table 3-2. Percent Distribution of Posted Speed Limit in MPH

Scen./MPH	≤ 20	25	30	35	40	45	50	55	≥ 60
LVD	1.0	11.0	9.7	26.6	10.9	17.9	5.8	15.5	1.5
LVNM	1.2	11.3	7.8	24.2	11.0	19.3	5.8	18.4	0.9

3.2.2 Causal Factors of Major Precrash Scenarios

The causal factors were identified for each precrash scenario based on the analysis of a 135-case CDS sample conducted by Frontier Engineering (1994). The results were derived from 104 LVD cases and 3 1 LVNM cases and were weighted by the national inflation factor assigned to each case in the CDS data base. In order to closely approximate the national profile, the results were modified based on alcohol involvement rates in the GES data base given above. It should be noted that the CDS data base investigates a nationally-representative sample of about 5,000 PR crashes annually, involving at least one towed passenger car, light truck, van, or utility vehicle. The GES data base, on the other hand, is a nationally-representative survey of nearly 44,000 police accident reports that are gathered from sixty geographic sites and include all vehicle types and crash severities. Table 3-3 lists the percent distribution of causal factors associated with each precrash scenario.

Table 3-3. Percent Distribution of Crash Causal Factors

Causal Factor	Lead Vehicle Decelerating	Lead Vehicle Not Moving
Inattention	455	643
Inattention/Following too Closely	16.2	25
External Distraction	98	124
Poor Judgment	93	80
Drivers vision Obscured	67	12
Alcohol/Drug Involvement	43	23
Too Fast for Conditions	31	00
Internal Distractions	19	41
Disability	1.4	00
Inattention/Too Fast for Conditions	10	00
Encroachment	0.8	5.2

3.2.3 Relevant Rear-End Crash Sizes

The relevant rear-end crashes that can be addressed by the rear-end crash warning system were discerned based on causal factors. Rear-end crashes caused by drunk or momentarily-disabled drivers and by vehicle encroachment situations were deemed unaffected by the countermeasure system. Therefore, the relevant rear-end crashes constitute 93.5 percent or about 1.12 million and 92.5 percent or about 430 thousand PR rear-end crashes of LVD and LVNM precrash scenarios, respectively. It should be noted that the relevant crashes in this analysis do not include single-vehicle crashes which were caused by the subject vehicle attempting to avoid a lead vehicle stopped, slowing, or cruising at a lower speed in its lane of travel, or which involved an animal, pedestrian, pedalcyclist, or object in the roadway.

Each major precrash scenario was analyzed under "dry" and "wet/snow/ice" roadway surface conditions. As a result, the rear-end crash problem is broken down to a tree structure shown in Figure 3-l in order to estimate the safety benefits of the rear-end crash warning system. The distributions of "posted speed limit" and causal factors were considered the same for both roadway surface conditions in the safety benefit estimation.

3.3 SYSTEM DESCRIPTION

The rear-end crash warning system under study is based on preliminary specifications described for "Driver Warning Systems" by Frontier Engineering, Inc., as part of a project to develop performance specifications for ITS rear-end crash countermeasure systems. The rear-end crash warning system monitors the forward path of the host vehicle and provides warnings to the driver if the speed differential and headway to a lead vehicle present a potentially dangerous situation.

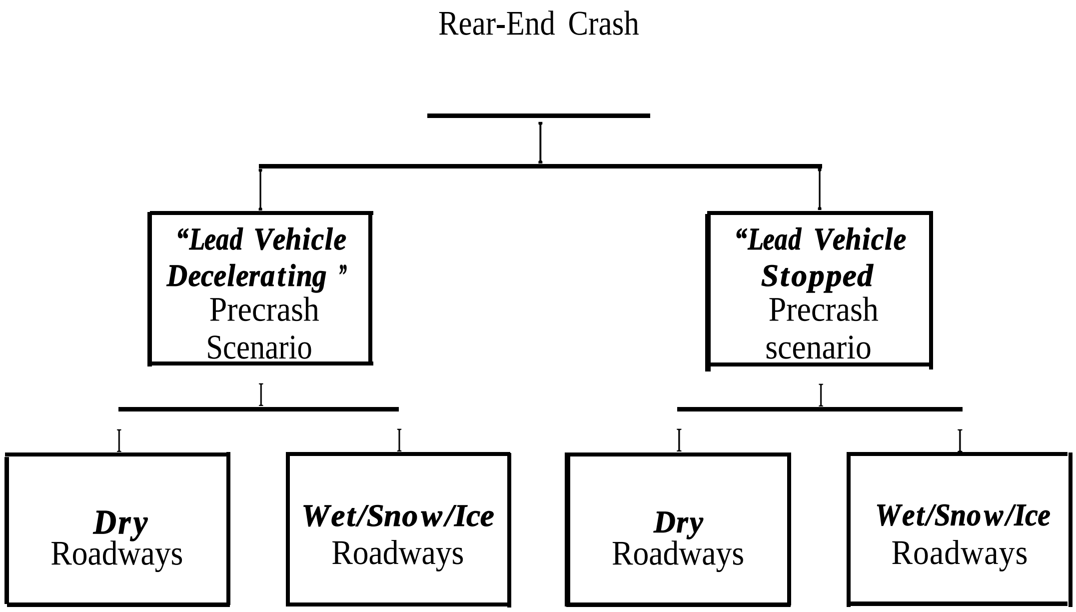

Figure 3-l. Rear-End Crash Problem Breakdown

This section briefly describes three main functional elements of the system: driver/system interface, decision-making logic, and forward-looking sensor.

3.3.1 Driver/System Interface

The driver/system interface consists of a visual display and an auditory voice warning. The display presents a graduated series of messages that get progressively more strident as the time-to-collision (TTC) decreases. At a predetermined value of TIC, the driver will hear an auditory warning: “Look Ahead”. If the driver fails to brake, the verbal message changes to “Brake!” (Iowa, 1995).

3.3.2 Decision-Making Logic

The driver graduated warning described above is updated continuously by comparing the actual gap measured by the system’s forward-looking sensor to a functions such as following warning distance:

$$D_W = \frac{v_F^2 - v_L^2}{2 * 0.35g} + vF * Tr + 6.6 \tag{3.1}$$

where :

Dw = following warning distance (ft)
vF = speed of the following (host) vehicle (ft/sec)
vL = speed of the leading vehicle (ft/sec)
g = acceleration due to gravity (32 (ft/sec 2)
Tr = time delay assigned to each warning level (sec)

Tr indicates the time delay in seconds assigned to each warning level (green, yellow, and red bars) of the system display (Frontier, March 1995). For instance, if the measured gap is less than orequal to ***Dw*** evaluated at ***Tr*** = 0.9 second, then the digitized voice "Brake" warning is issued to the driver and the red area of the visual display flashes on and off. Equation 3.1 is applicable to both LVD and LVNM scenarios. When the lead vehicle is stopped, the equation can be slightly simplified, as will be discussed in Section 3.5.2.

3.3.3 Forward-Looking Sensor

The forward-looking sensor has a target acquisition range of 130 m (427 ft) and provides information to the driver at ranges down to approximately one meter (3.28 ft) (Frontier, June 1995). The sensor measures range and range rate between the host vehicle and the vehicle ahead of it. The speed of the lead vehicle is determined using measurements of range rate and host vehicle speed. The analysis in this chapter assumes that the errors associated with measured range, range rate, and host vehicle speed are negligible.

3.4 BENEFITS ESTIMATION METHODOLOGY

The number of motor vehicle rear-end crashes that might be avoided with a rear-end crash warning system can be estimated as follows:

$$Na = Nwo - Nw = Nwo * SE \qquad \textbf{(3-2)}$$

where :

Na = Number of rear -end crashes that can be avoided using a rear - end crash warning system
Now = Number of rear - end crashes that occur without using a rear - end crash warning system
Nw = Number of rear - end crashes that occur with rear - end crash warning system intervention
SE = Total system effectiveness

The term ***SE*** is estimated as follows:

$$SE=MP*U*\left(\sum_{i=1}^{2}\left(\sum_{j=1}^{2} p(Sij)*E(Sij)*Fi\right)\right) \qquad \textbf{(3.3)}$$

where :

MP = Proportion of countermeasure market penetration

U = Proportion of countermeasure usage during crash hazard

$p(S_{ij})$ = Probability of a crash occurring under circumstance j given prccrash scenario i

$E(S_{ij})$ = Estimate of countermeasure effectiveness in precrash scenario i under circumstance j

F_1 = Fraction of a relevant precrash scenario i to the rear end crash size

Based on rear-end crash statistics presented in Section 3.3, the relative size of the relevant LVD precrash scenario (F1) is about 0.673 while the relative size of the relevant LVNM precrash scenario (F2) is about 0.259 with respect to all PR rear-end crashes. Using the statistics of the roadway surface conditions given in Table 3- 1, ***p(S11) = 0.714, p(S12) = 0.286, p(S21) = 0.746,*** and ***p(S22) = 0.254.*** System market penetration, MP, and system usage, U, are assumed to be unity in this analysis.

The effectiveness, E(Sij), is expressed mathematically as (Krishnan, 1983; Wolf and Barrett, 1978):

$$E(S_{ij}) = 1 - \frac{P_w(S_{ij})}{P_{wo}(S_{ij})} \qquad (3.4)$$

where :

$p_w(S_{ij})$ = Crash probability of a vehicle with the rear - end crash warning system in precrash scenario i under circumstance j

$p_{wo}(S_{ij})$ = Crash probability of a vehicle without the rear - end crash warning system in prccrash scenario i under circumstance j

The equation for effectiveness takes into account the countermeasure system hardware reliability and the probability of driver compliance with system warnings in a relevant pm-crash scenario ***i*** under circumstance ***j***.

In addition to the assumption of unity for system usage and market penetration, this analysis assumes the following:

- The system works perfectly up to its range limitation; i.e., it never fails to detect the lead vehicle, never detects the "wrong" vehicle, and always provides accurate speed and distance information.
- Drivers always brake in response to warnings from the rear-end crash warning system even though in actuality some drivers may steer or both brake and steer to avoid a rear-end crash.
- The effects of nuisance alarms on driver behavior are considered negligible. These effects might include disengaging the countermeasure system due to a high frequency of nuisance alarms, taking a longer time to react, or simply becoming annoyed.
- Driver risk compensation is negligible.

Drivers do not use the system as a substitute for their own vigilance when attending to the driving task.

Estimates of crash probabilities can be obtained by use of computer modeling and simulation to extrapolate experimental data on system and driver performance with and without the use of the rear-end crash warning system. Computer modeling and simulation is a technique to approximate values of a crash probability in a certain scenario under various circumstances since it allows the extrapolation of experimental results of driver/system performance from very limited experimental conditions to a wider range of conditions. Monte Carlo simulation is an appropriate method for obtaining estimates of the crash probability, which requires models of the driving environment under study and statistical distributions for each variable in the models (Hahn and Shapiro, 1967). This method has also been referred to as synthetic or empirical sampling where many trials are run for each condition by selecting a random value from each of the distributions at each trial to determine whether a crash occurs. Consequently, a crash probability can be obtained from:

$$p(S_{ij}) = \frac{\text{no. of crashes in scenario } i \text{ under circumstance } j}{\text{no. of encounters (trials) in scenario } i \text{ under circumstance } j} \quad (3.5)$$

3.5 KINEMATIC MODELING OF MAJOR PRECRASH SCENARIOS

The models of the LVD and LVNM rear-end precrash scenarios are built using kinematic representation of vehicle movements and simple time delays to incorporate driver, countermeasure system, and vehicle brake actions. These models determine if a crash occurs for some given initial conditions and identify the appropriate variables.

3.5.1 Lead Vehicle Decelerating Rear-End Precrash Scenario

Initially, both the following and lead vehicles were traveling at a constant speed at various relative rates prior to tbe following vehicle's driver recognizing the critical precrash event. In this scenario, the critical event is created when the lead vehicle starts to brake at various deceleration levels. After some time delay, the driver in the following vehicle responds to lead vehicle deceleration by braking hard to avoid a rear-end crash. Drivers without the rear-end crash warning system react after observing the brake lights of the lead vehicle, while drivers with the system react after observing the brake lights of the lead vehicle or noticing the system warning alarm, whichever occurs first.

A crash occurs in this scenario when the difference between the stopping distances of the lead and following vehicles is greater than the gap between the two vehicles when the lead vehicle braking was initiated. In this analysis, this crash is counted only if the relative speed between the two vehicles at impact was over 5 MPH. This crash criterion was adopted in order to account for rear-end crashes that cause any vehicle damage. The parameter d_c is expressed mathematically as follows:

$$d_c = \frac{v_F^2}{2 * a_F} - \frac{v_L^2}{2 * a_L} + v_F * t_R \quad (3.6)$$

where

d_C = Difference between stopping distance of lead and following vehicles

v_F = Following vehicle speed before onset of braking

v_L = Lead vehicle speed before onset of braking

a_F = Following vehicle deceleration

a_L = Lead vehicle deceleration

t_R = Time delay of following vehicle

Time delay of the following vehicle is defined as:

$$t_R = t_D + t_B \tag{3.7}$$

where

t_D = Driver reaction time from onset of lead vehicle braking until brake pedal is depressed

t_B = Vehicle braking delay required for vehicle to reach maximum deceleration level

It should be noted that the countermeasure system time delay is included in t_D in case the driver of the equipped vehicle reacts to the system warning instead of the lead vehicle brake lights. According to a study conducted in 1990 (Schweizer, Parosh, Lieberman, and Apter 1990), it was found that driver reaction time in this particular scenario increased with the following gap (d_H). This effect of short driver reaction times for small gaps was explained by the increased attention that drivers had towards the lead vehicle. Based on this finding, this analysis utilizes a driver reaction time as a function of time gap, t_H, where $t_H = d_H/v_F$.

The LVD rear-end precrash scenario was simulated using the Monte Carlo method under dry and wet/ice/snow roadway surface conditions for discrete values of following vehicle speed, v_F ranging between 20 and 60 MPH, in a 5 MPH step. For each value of v_F a total of 100,000 Monte Carlo trials were run to estimate a crash probability in which random numbers were picked from statistical distributions of the variables a_F, a_L, v_L, t_D and d_H. Data distributions of these variables are described in Section 3.6.

3.5.2 Lead Vehicle Not Moving Rear-End Precrash Scenario

Initially, the following vehicle was traveling at a constant speed and the lead vehicle was stopped in its traffic lane for a long period of time. As the following vehicle approaches the stopped vehicle, the driver in the following vehicle recognizes the obstacle in the travel lane and responds to this critical event by braking hard to avoid a tear-end crash. In this scenario, drivers without the rear-end crash warning system react after observing the brake lights of the stopped lead vehicle, while drivers with the system react after observing the brake lights of the lead vehicle and/or noticing the system warning alarm.

A crash occurs in this scenario if the stopping distance of the following vehicle is greater than the gap between the two vehicles when the lead vehicle was observed to bc not moving in the traffic lane. In this analysis, this crash is counted only if the following vehicle speed was over 5 MPH at the moment of collision. This crash criterion was adopted in order to account for rear-end crashes that cause any vehicle damage. The stopping distance of the following vehicle is expressed mathematically as follows:

$$d_S = \frac{v^2_F}{2*a_F} * t_R \tag{3.8}$$

where :

d_s = Stopping distance of the following vehicle

v_F = Following vehicle speed before onset of braking

a_F = Following vehicle deceleration

t_R = Time delay of following vehicle to begin braking

The variable t_D represents driver reaction time from the moment the driver of the following vehicle observes the stopped vehicle in his/her path until the moment the brake pedal is pressed. Vehicle braking time delay, t_B, accounts for the time it takes the vehicle to reach its maximum deceleration level. A recent human factors study examined the last moment at which drivers considered braking must commence in order to avoid a rear-end collision with a vehicle stopped in their path (Hirst and Graham, 1994). Drivers were found to start braking earlier when the lead vehicle was seen at a longer gap. Results of other research studies have shown that when approaching a stopped vehicle, drivers start braking at less safe distances the higher the vehicle speed (v_F), resulting in excessive and higher deceleration levels (a,) than normal in order to avoid a rear-cnd crash (Graham and Hirst, 1994; Kuge, Ueno, Ichikawa, and Ochiai, 1995). It should be noted that drivers in these studies, unlike those involved in a LVNM rear-end crash, were very attentive to the driving task Using Table 3-3 statistics on crash causal factors, about 89 percent of all relevant LVNM rear-end crashes involved drivers who were not paying attention to the driving task As a result, the system effectiveness of the rear-end crash warning system was estimated by assuming that all drivers with and without the system were inattentive and reacted by braking hard immediately after they observed the stopped vehicle.

In this analysis, drivers ***with*** the system are assumed to initiate their braking reaction at the onset of the warning alarm to brake which is issued at the following warning distance, D,, as derived from Equation (3.1):

$$D_w(ft) = \frac{v_F^2}{2*0.35g} + v_F*0.9+6.6 \qquad (3.9)$$

Consequently, all drivers ***with*** the system observe the lead vehicle stopped at the same gap for a specific vehicle speed ***(v_F):***

$$d_o = D_w - v_F * t_o \qquad (3.10)$$

where ts denotes the countermeasure system time delay. At gaps longer than d_o both drivers ***with*** and ***without*** the system are assumed to exhibit the same driving behavior. Therefore, the rear-end crash warning system becomes ineffective at these distances. At gaps shorter than d,, drivers ***without*** the system may "wake up" and observe the stopped vehicle at any instance between the time gap t_o at d_o,($t_o = d_o/v_F$) and the moment of impact. There is a lack of crash information about the distribution of gaps when drivers, who are involved in a rear-end crash, attempt any evasive maneuver prior to impact. This analysis computes the crash probability ***without the*** system by assuming that drivers initiate their reaction at a gap, ***d_o(without),*** with a rectangular distribution between 0 and d_o in an attempt to estimate the effectiveness of the rear-end crash warning system.

The LVNM rear-end precrash scenario was simulated using the Monte Carlo method under dry and wet/ice/snow roadway surface conditions for discrete values of following vehicle speed, v_F ranging between 20 and 60 MPH, in a 5 MPH step. For each vehicle speed, a total of 20,000 Monte Carlo trials were run to estimate a crash probability in which random numbers were picked from statistical distributions of the variables ***aF***, ***do(without),*** and t_D Data distributions of ***aF*** and t_D for the LVNM rear-end precrash scenario are described in the next section.

3.6 DATA DESCRIPTION

The effectiveness of the rear-end crash warning system in both precrash scenarios was estimated based on available experimental data from on-road field tests and driving simulator studies which examined driver performance with and without the use of the countermeasure system. Data were also obtained from other experiments on typical driver behavior and vehicle braking. In addition, expert judgments were used to fill in unavailable data for some of the variables and their interrelationships. This section describes the data for the variables of both tear-end precrash scenarios which are listed in Table 3-4.

Table 3-4. Rear-End Precrash Scenario Variables

LVD Precrash Scenario	LVNM Precrash Scenario
vF: Following vehicle speed before onset of braking	***vF***: Following vehicle speed before onset of braking
aF: Following vehicle deceleration	***aF***: Following vehicle deceleration
tD: Driver reaction time from onset of lead vehicle braking until brake pedal is pressed	***tD:*** Driver reaction time from observing stopped lead vehicle until brake pedal is pressed
ta: Vehicle time delay to reach maximum decleration	***ta:*** Vehicle time delay to reach maximum deceleration
dH(tH): Following (time) gap	***do(To):*** (time) gap when lead vehicle is observed stopped
vL: Lead Vehiile speed before onset of braking	
aL: Lead vehicle deceleration	

In both rear-end precrash scenarios, the driver of the following vehicle is assumed to brake hard at emergency levels in or&r to avoid hitting the lead vehicle. The range limits of maximum vehicle deceleration, aF vary for different roadway surface conditions. The value of aF generally ranges from about 0.5g to 0.75g on dry roads and from 0.25g to 0.5g on wet roads (Wolf and Barrett, 1978; Henderson, 1987; Hitchcock, 1993). On icy or snowy roadway surfaces, track tests have demonstrated that coefficients of friction on such surfaces allow deceleration rates in the wide range of 0. lg to 0.3g (Eddie, 1994). In this analysis, each precrash scenario was simulated under dry and slippery (i.e., wet/icy/snowy) roadway surfaces.

The following vehicle deceleration was a random variable having a rectangular distribution with range limits between 0.5g and 0.75g on dry roads and between 0.2g and 0.5g on slippery roads. It should be noted that a triangular distribution of aF was assumed in a previous study (Hitchcock, 1993). The vehicle time delay to reach maximum deceleration level was considered constant at 0.3 second for both rear-end precrash scenarios. Data elements that are specific to each precrash scenario are described next.

3.6.1 Lead Vehicle Decelerating Rear-End Precrash Scenario

The crash probability in this scenario was estimated at discrete values of following vehicle speed, vF, ranging from 20 MPH to 60 MPH with a 5 MPH increment. The distribution of vF given in Table 3-2 was assumed to be the same on dry and slippery roadway surfaces. A comparison of speed distributions at a sample of eighteen sites collected during daylight hours on wet and dry days showed no significant difference in the speeds drivers select when driving on the same roads under wet or dry conditions (Olson, Cleveland, Fancher, Kostyniuk, and Schneider, 1984). Drivers ***with*** and ***without*** the countermeasure system were also assumed to have a similar speed distribution. The values of the variables ***aL, tH, tD*** and ***vL*** were picked at random from statistical distributions described below.

3.6.1.1 Lead Vehicle Deceleration, a_L: The effectiveness of the rear-end crash warning system was estimated using two normal distributions of lead vehicle deceleration (a,) under routine conditions for dry and slippery roadway surface conditions. On dry roads, this analysis adopted a normal distribution with a mean of 10 ft/sec2 and a standard deviation of 5.7 ft/sec2, which was obtained from 839 observations of drivers stopping under routine conditions at six signalized intersections (Wortman and Matthias, 1983). The approach distances within which these values were measured extended almost 122 m (400 ft) from the intersections. Under these circumstances, many drivers can be expected to brake their vehicles to stop in a leisurely manner. On slippery roads, a normal distribution with a lower mean of 5.44 ft/sec2 and a standard deviation of 3.2 ft/sec2 was used, which was based on data collected for an average of 350 vehicles at each of twelve intersection sites (Farber, Janoff, Cristinzio, Blubaugh, Reisener, and Dunning, 1974).

3.6.1.2 Following time Gap, tH : The statistics on following time gaps with and without using the rear-end crash warning system were obtained from an on-road field study to evaluate four collision warning presentations (Iowa, 1995). Sixteen drivers between 18 and 24 years of age, split by gender, participated in this field test. One collision warning presentation included a combination of visual gap maintenance information and auditory alarms as described in section 3.2 using similar logic. A liquid crystal flat panel display was mounted in the vehicle dashboard over the tachometer which presented the collision warning symbologies. A laser sensor was used to detect the distance of the vehicle's gap and closing velocity with a range over 100 m (328 ft).

Subjects were instructed to follow a confederate vehicle at their normal following distance on a course that consisted of two-lane interstates, two-way state highways, and local residential streets. Each subject was tested under a baseline condition and a collision warning condition. The baseline condition on the outward leg of the data collection run presented a digital speedometer on the display while different braking and constant speed events were initiated by the confederate vehicle. On the return drive, subjects received the collision warning presentation and ran through the same events in a different order. The course covered approximately 25 miles in each direction. The collision waming display showed significantly longer gaps than the baseline as shown in Table 3-5 in non-braking events where the vehicles were in a state of coupled headway, including sets of 55 and 65 MPH measures. It should bc noted that drivers in this study were novices and that an experimenter was present. It is possible that at least some of the increase in following gap would extinguish over time with system use.

The field test results presented in Table 3-5 agree with those of a similar on-road study which was conducted few years earlier with a larger number of subjects (McGehce, 1993). This earlier study employed one hundred and eight paid volunteer drivers from three different age groups (18-25,30-45, and over 65 years of age), split by gender (McGehee, 1993). Three different gap maintenance visual displays without any auditory warnings were evaluated under daylight and dusk lighting conditions. The driving course was 15 mile long on a rural two-lane highway. The results also showed that drivers kept longer gaps with the warning display than in the baseline, especially in the low-level braking events.

Table 3-5. Field Test Results on Following Gaps

Display	Mean (t_H) sec	Stand. Dev. (t_H) sec
Baseline (without)	1.564	0.8239
Warning (with)	2.1372	0.6151

The distribution of the time gap variable was modeled as a lognormal distribution based on an analysis of field measurements on car following (Chcn, 1996). Roughly 5600 data points from 75 video sessions taken on I-93 and I-90 in Massachusetts were analyzed to study the environmental effects on car-following behavior, including effects of weather, illumination, traffic density, and location. Based on the collected data, the average following gap was not significantly greater on rainy days than under clear weather for some of the speed ranges. There were no statistically significant differences between means for different conditions for speed ranges over 25 MPH, while the effect was significant for the ranges from 6 to 25 MPH (Chen, 1996). Based on these results, the values of t_H in Table 3-5 were assumed similar for both dry and slippery roadway surface conditions. In addition, drivers with and without the countermeasure system were assumed to maintain the same time gap at all vehicle speeds, even though the data presented in Table 3-5 were obtained from following vehicle speeds of 55 and 65 MPH.

3.6.1.3 Driver Reaction Time, t_D: Data on driver reaction time to lead vehicle braking were recently gathered from an experiment conducted at the University of Iowa's driving simulator (Camey and Dingus, 1995). Thirty-two subjects between the ages of 18 and 24 were recruited for participation in this study and were split evenly into four groups to simulate four different experimental conditions. For the baseline condition, eight subjects drove through a scenario without the use of a collision warning device. For the other three conditions, three groups drove with a collision warning device that provides either long (400 ft/122 m), moderate (300 ft/91 m), or short (200 ft/61 m) range warning condition. The driver/countermeasure system interface resembled the one described in section 3.2 and provided an auditory warning to brake with an activation criterion for each of the warning conditions. The results of the moderate range warning experimental condition were adopted for this analysis since its warning activation criterion approximated the warning logic provided in Equation (3.1) closer than the other two conditions.

Scenarios used during the experimental drive consisted of seven pie-scripted events spread across a 20 mile long course. Each subject drove through the exact same scenario. The last event of the drive was the most relevant to this analysis, which evaluated driver reaction time and behavior in an extreme lead vehicle braking condition in which maximum braking by the following vehicle was necessary to avoid a rear-end collision. Initially, the following vehicle was coupled with the lead vehicle at 2 second time gap, both traveling at 65 MPH. After being coupled for 5 seconds, the lead vehicle pressed the brakes at a deceleration of 0.85g to a full stop. Driver reaction times to this event were calculated for subjects in each of the conditions. Table 3-6 compares the results between the baseline condition and the moderate range warning condition.

Table 3-6. Driving Simulator Results on Driver Reaction Times

Experimental Condition	Mean $\{t_D\}$ sec	Standard Deviation $\{t_D\}$ sec
Baseline *(without)*	1.46	0.29
Modem&-Range Warning	1.39	0.31

The statistics of Table 3-6 on driver reaction time were used to estimate the effectiveness of the tear-end crash warning system in the LVD rear-end precrash scenario, even though a small number of subjects were employed in each group who represented only the young driving population. It is acknowledged that their results cannot be generalized to the entire population but were adopted in this analysis for the lack of other appropriate data. It should be noted that a past study showed that young and older (60+) drivers exhibited no significant difference in braking reaction time when confronted with an obstacle in their path of travel (Olson, Cleveland,Fancher, Kostyniuk, and Schneider, 1984).

This analysis assumes that drivers have the same reaction time as listed in Table 3-6 for the wide range of a_L, despite the fact that the results of Table 3-6 were based on 0.85g lead vehicle deceleration. On the other hand, driver reaction times were modified for time gaps less than 2 seconds, considering that driver reaction time decreases as coupled vehicles draw closer together. There arc no experimental data to realistically extrapolate the results in Table 3-6 to account for shorter time gaps. However, expert judgments were used to modify the values of driver reaction time as shown in Table 3-7 below (Farber, 1994).

Table 3-7. Driver Reaction Time as a Function of Time Gap

Time Gap, *tH*	*Without* the System	*With* the System
#0 sec	Mean = 0.79 sec St. Dev. = 0.29 sec	Mean = 0.75 sec St. Dev. = 0.31 sec
0.5 < ***tH*** < 2 sec	Mean = 0.447 X ***tH*** + 0.556 St. Dev. = 0.29 sec	Mean = 0.427 X ***tH*** + 0.536 St. Dev. = 0.31 sec
$2 sec	Mean = 1.46 sec St. Dev. = 0.29	Mean = 1.39 sec St. Dev. = 0.31 sec

Driver reaction times were represented by a lognormal distribution since it was surmised that the lognormal distribution for brake reaction tune is more realistic than a standard normal distribution because of the skewness of the lognormal distribution (Taoka, 1989). Most studies have shown that.the distribution mean is greater than the median because there are more large reaction times at the high end of the distribution than the normal distribution would indicate.

3.6.1.4 Lead Vehicle Speed *vL*: The lead vehicle speed was modeled as follows:

$$vL = vF - vc \qquad \textbf{(3.11)}$$

where :

***vc* = closing velocity**

Closing velocity is represented with a rectangular distribution varying from 0 to 10 MPH. This assumption was made since experimental data on distributions of closing velocity were not available from the various events discussed in this section.

3.6.2 Lead Vehicle Not Moving Rear-End Precrash Scenario

The crash probability in this scenario was estimated at discrete values of following vehicle speed, v_F, ranging from 20 MPH to 60 MPH with a 5 MPH increment. The distribution of v_F given in Table 3-2 was assumed to be the same on dry and slippery roadway surfaces. For each vehicle speed, the crash probability without the system was estimated by assuming that drivers observe the stopped vehicle at a random distance, d_o*(without)*, with a rectangular distribution between 0 and d, (3.9). In addition to the random variables aF and d_o *(without)*, driver reaction time is also a random . variable with a lognormal distribution described below.

3.6.2.1 Driver Reaction Time t_D: Experimental data on driver reaction time to a lead vehicle stopped with and without a countermeasure system were not available, especially in scenarios where the lead vehicle was observed stopped at gaps requiring emergency braking to avoid a rear- end crash. The results from the lead vehicle braking event, discussed in section 3.6.1.3, could not be used in the LVNM rear-end precrash scenario because studies have shown that drivers react faster to stationary obstacles than to moving obstacles (Chen, 1996). Consequently, a driver reaction time with a mean of 1.1 seconds and a standard deviation of 0.3 second was adopted for both drivers with and without the countermeasure system, based on a "surprise" driver reaction time obtained from a field study (Olson, Cleveland, Fancher, Kostyniuk, and Schneider, 1984). The purpose of this study was to develop data on "surprise" driver reaction time to a single roadway obstacle under realistic conditions. The obstacle was a piece of light yellow foam rubber 6 inches (15 cm) high and 3 ft (0.91 m) wide which created in combination with the road surface a relatively low-contrast condition. The site test was on a two-lane tangent road in a rural area where the obstacle was placed in the middle of the road at the bottom of a crest Useful data were obtained from 49 young drivers (18 to 40 years of age) and from 15 older drivers (from 60 to 84 years of age). The driver reaction time was measured from the time the obstacle became visible until brake contact was made. This analysis assumes that driver reaction time is independent of vehicle speed and gap at which the stopped vehicle was observed.

3.7 SYSTEM EFFECTIVENESS ESTIMATION

Based on the information presented in section 3.4, the total system effectiveness, SE, of the rear-end crash warning system is calculated from:

$$SE=(p(S11)*E(S11)+p(S12)*E(S12))*F2+(p(S21)*E(S21)+p(S22)*E(S22))*F2 \qquad (3.12)$$

$$SE=(0.714*E(S11)+0.286*E(S12))*0.673+(0.746*E(S11)+0.254*E(S12))*0.259$$

where :

E(S11) **=** Effectiveness of rear-end crash warning system in LVD scenario on dry roadway surface

E(S12) **=** Effectiveness of rear - end crash warning system in LVD scenario on slippery roadway surface

E(S21) **=** Effectiveness of rear -end crash warning system in LVNM scenario on dry roadway surface

E(S22) **=** Effectiveness of rear-end crash warning system in LVNM scenario on slippery roadway surface

F1 **=** Proportion of rear - end crashes occuring in the LVD scenario

F2 **=** Proportion of rear - end crashes occuring in the LVNM scenario

where ***E11*** and ***E12*** are the effectiveness values of the rear-end crash warning system in the LVD precrash acenario on dry and slippery roadway surface conditions, respectively. Similarly, ***E21*** and ***E22*** are the effectiveness values of the rear-end crash warning system in the LVNM precrash scenario on dry and slippery roadway surface conditions, respectively. The individual effectiveness values, ***Eij's***, were determined from the crash probabilities with and without the countermeasure system which were estimated by the Monte Carlo method. Next, the evaluation of Eij's is delineated for the LVD and LVNM rear-end precrash scenarios.

3.7.1 Lead Vehicle Decelerating Rear-End Precrash Scenario

The individual values of crash probabilities, p_w and p_{wo} , on dry and slippery roads and respective effectiveness values are shown in Table 3-8 for each following vehicle speed, vF The values of ***E11*** and ***E12*** at all speeds were computed by a weighted average of the individual values at each vehicle speed, VF using the "posted speed limit" variable distribution of the LVD rear-end crashes listed in Table 3-2. As a result, ***E11*** equals 0.45 and E12 equals 0.34. Therefore, the system effectiveness in reducing all "relevant" LVD rear-end crashes is estimated at about 42.0 percent.

Table 3-8. Crash Probabilities and Effectiveness Values in LVD Precrash Scenario

VF (MPH)	Dry Roads			Wet/Icy/Snowy		
	Pw	*Pwo*	*E*	*Pw*	*Pwo*	*E*
20	0.212	0.365	0.42	0.247	0.373	0.34
25	0.182	0.318	0.43	0.215	0.326	0.34
30	0.156	0.218	0.44	0.189	0.288	0.35
35	0.136	0.250	0.46	0.167	0.259	0.36
40	0.124	0.226	0.45	0.152	0.235	0.35
45	0.112	0.205	0.46	0.144	0.219	0.34
50	0.101	0.187	0.46	0.135	0.202	0.33
55	0.092	0.171	0.46	0.131	0.192	0.32
60	0.086	0.160	0.46	0.124	0.177	0.30
E11 =0.45				E12 = 0.34		

3.7.2 Lead Vehicle Not Moving Rear-End Precrash Scenario

The individual values of ***pw*** and ***pwo,*** on dry and slippery roads and respective values of ***E's*** are shown in Table 3-9 for each following vehicle speed, ***vP*** The values of ***E21*** and ***E22*** at all speeds were computed by a weighted average of the individual values at each vehicle speed, ***vF***, using the "posted speed limit" variable distribution of the LVNM rear-end crashes listed in Table 3-2. As seen in Table 3-9, ***E21***= 0.86 and ***E22***= 0.43. Consequently, the system effectiveness in reducing all "'relevant" LVNM rear-end crashes is estimated at about 75.1 percent.

Table 3-9. Crash Probabilities and Effectiveness Values in LVNM Precrash Scenario

VF (MPH)	Dry Roads			Wet/Icy/Snowy		
	Pw	*Pwo*	*E*	*Pw*	*Pwo*	*E*
20	0.408	0.932	0.56	0.722	0.994	0.27
25	0.318	0.918	0.65	0.692	0.995	0.30
30	0.227	0.897	0.75	0.637	0.995	0.36
35	0.144	0.876	0.84	0.590	0.992	0.41
40	0.093	0.851	0.89	0.560	0.992	0.43
45	0.057	0.829	0.93	0.523	0.989	0.47
50	0.037	0.820	0.95	0.511	0.987	0.48
55	0.024	0.800	0.97	0.479	0.984	0.51
60	0.014	0.874	0.98	0.475	0.982	0.51
E11 =0.86				E12 = 0.43		

3.8 PRELIMINARY SAFETY BENEFITS

Based on the analysis explained above and using 1994 GES statistics, the rear-end crash warning system has the potential to prevent about 791 thousand PR rear-end crashes, or about 47.7 percent of all PR mar-end crashes or about 51 percent of all "relevant" PR rear-end crashes. Of the total number of crashes avoided, there are about 469 thousand PR LVD rear-end crashes and about 322 thousand PR LVNM rear-end crashes. Given the average economic cost per rear-end crash scenario in the U.S. (Section 3.3.1) (Wang, Knipling, and Blincoe, 1996), the rear-end crash warning system would save about 6.5 billion dollars for preventing PR LVD rear-end crashes plus about 4.2 billion dollars for preventing PR LVNM mar-end crashes, annually. In total, the rear-end crash warning system would save about 10.7 billion dollars annually in PR rear-end crash economic costs.

3.9 CONCLUDING REMARKS

A methodology was presented to estimate the safety benefits of a rear-end crash warning system based on experimental data on driver performance with and without the countermeasure system. The results presented in this report reflect a first attempt to date to assess safety benefits of a crash avoidance system using experimental data obtained from on-road field tests or driving simulator studies, and are considered preliminary in nature. The validity of any experimental test results depends on the experimental condition effects that were placed on the drivers. During short-term experiments, it is not possible to completely reduce the demand characteristics of the warning displays which can only occur in long-term demonstrations (McGehee, 1993). Despite the lack of needed and representative data, this chapter outlined a simple process that allows preliminary estimates of system effectiveness to be revised as new data elements become available from future tests. Computer simulations based on the Monte Carlo method were utilized to extrapolate experimental data from very few conditions to all conceivable conditions of the crash experience. This methodology represents a best effort to predict the effectiveness of a countermeasure system that remains in the research and development stage.

Moreover, this chapter revealed data needs and potential research areas which are necessary for a proper estimation of safety benefits. Due to limited data available for this analysis, many assumptions were made to fill in the gaps. In addition, the benefit estimation problem was simplified in order to take advantage of information available about rear-end crashes, rear-end crash warning systems, and driver interaction with these systems. Most important, this analysis did not take into account the effects of nuisance alarms and driver compensation which may degrade the effectiveness of any crash avoidance system. For instance, the results of a driving simulator experiment showed that the use of a forward-looking crash avoidance system increased the overall driving speed, acceleration/ deceleration levels, and the number of passing maneuvers (Janssen and Nilsson, 1993). However, these results were based on the driving behavior of only seven drivers. Finally, a better estimation of the safety benefits of a rear-end crash warning system can be achieved as more relevant test data are gathered especially from long-term, large-fleet field operational tests.

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Chapter 4: Preliminary Effectiveness Estimates for Lane Change Crash Avoidance Systems

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4.1 INTRODUCTION

4.1.1 Purpose of this Chapter

The purpose of this chapter is to develop and apply an approach for estimating the effectiveness of lane change (side) collision avoidance systems (SCAS). Caveats and potential CAS effectiveness attenuation factors are discussed in Section 8 of this report

4.1.2 Organization of this Chapter

This chapter **is** organized into the following sections. First, the lane change crash problem is described (Section 4.2) to show the number and subtypes of such crashes plus some important facts about the collisions which SCAS are designed to prevent. Next, a functional description of the SCAS analyzed is provided (Section 4.3)

Section 4.4 begins the discussion of effectiveness estimation. A list of anticipated SCAS benefits is provided, followed a list of possible negative consequences of lane change warning systems. A general CAS effectiveness estimation formula is provided and its elements are described in terms specific to the SCAS case. Several assertions that are either implicit or explicit to lane change warning system technology are discussed.

Section 4.5 is devoted to estimating the effectiveness of SCAS due to the SCAS increasing driver awareness during the lane change decision phase. An analytical effectiveness estimation formula is developed from principles of reliability theory. A complete list of the assumptions used to develop and apply this formula is provided in Appendix A. Existing experimental data that are needed to calculate SCAS lane change decision phase effectiveness are presented and the resulting effectiveness estimates shown. This section concludes with a discussion of the strengths and weaknesses of the data used to generate each effectiveness estimate and a selection of the effectiveness estimate that is thought to be most plausible.

Section 4.6 contains the authors' concluding remarks about SCAS effectiveness. The chapter concludes (Section 4.7) with a list of references.

4.2 THE LANE CHANGE ACCIDENT PROBLEM

4.2.1 The Phases of a Lane Change

As indicated in Chovan, Tijerina, Alexander, and Hendricks (1994), "lane change" refers to a family of maneuvers that includes simple lane change, merge, exit, pass, and weave maneuvers. For purposes of this study, a lane change is defined as a deliberate and substantial shii in the lateral position of a vehicle. A "lane change crash" occurs when a driver attempts to change lanes and strikes or is struck by a vehicle in the adjacent lane.

This chapter estimates the effectiveness of SCAS at helping a driver avoid lane change collisions. To develop this estimate, the process undertaken by the driver whenever a lane change is made is divided into two fundamental phases, the decision phase and the maneuver execution phase. Figure 4-l is a timeline of a lane change showing these two phases.

The decision phase is the period of time beginning when the driver desires to perform a lane change. It continues until the driver actually starts to move the steering handwheel to move the SV laterally into the new lane or until the driver decides to postpone the lane change. During this phase, one of the major activities of the driver is to detect either present or upcoming traffic or obstacles in the planned destination lane. Based upon this assessment, the driver either proceeds to the maneuver execution phase or temporarily postpones execution of the lane change.

The maneuver execution phase begins when the driver starts to make the move into the new lane. It continues until the SV has been laterally stabilized in a lane at the conclusion of the maneuver. Note that the driver may decide to abort the lane change during the maneuver execution phase. In this case, the maneuver execution phase would conclude with the vehicle having been laterally stabilized in the original lane and not in the planned destination lane.

SCAS may help prevent lane change crashes during the decision phase by helping the driver make a more accurate assessment of the traffic or obstacles in the planned destination lane. SCAS technology might also help prevent lane change crashes during the maneuver execution phase by warning the driver to abort the lane change if a collision would occur otherwise. The current chapter will only estimate the number of lane change crashes that SCAS may help prevent by providing driver support during the decision phase. Future work may be directed toward estimating expected SCAS benefits gained by warning the driver during the maneuver execution phase.

4.2.2 Number of Lane Change Accidents

According to the National Accident Sampling System (NASS) General Estimates System (GES), there were approximately 244,000 police reported lane change accidents in 1991 (Wang and Knipling, 1994). Thii was 4 percent of all of the 6.11 million police-reported accidents for that year. Additionally, there were an estimated 386,000 non-police reported lane change accidents.

Lane change collisions accounted for 225 fatalities or 0.5% of 1991's 41,508 traffic fatalities. This accident type is estimated to account for roughly 41.2 million hours of crash-caused delay which was approximately 10 percent of 1991's total crash-caused delay.

The number of police reported lane change accidents fluctuates from year-to-year. For 1992 the number of police reported lane change accidents was estimated at 300,000 (Eberhard, Luebkeman, Moffa, Young, Allen, Harwin, Keating, and Mason, 1994). Such year-to-year fluctuations may be due to some assignable (though not necessarily known) cause, statistical variation, or differences between the GES coding schemes used by the various researchers. The importance of GES coding schemes in characterizing crash subtypes is illustrated in a subsequent section of this report.

other facts about lane change accidents of relevance to SCAS are (Wang and Knipling, 1994):

- For passenger vehicles, 77 percent of the accidents occurred on roadways with posted speeds of less than 55 mph (e.g. "city" driving).
- For heavy trucks, 71 percent of the accidents occurred on roadways with posted speeds of 55 mph or more (e.g., "highway" driving).
- 90 percent of the accidents occurred in daylight or on dark-but-lighted roads.

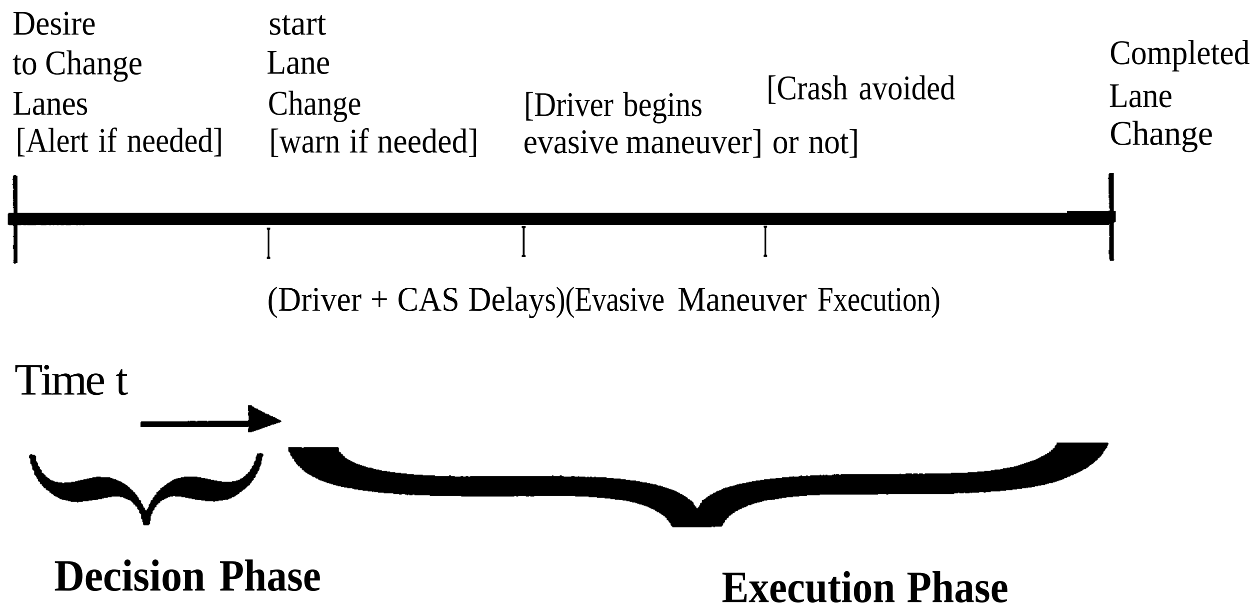


Figure 4-1. Time-Line Showing the Phases of a Lane Change Maneuver

- 8 1 percent of the accidents occurred on dry pavement.
- 68 percent of the accidents were non-junction crashes (i.e., they were simple lane change crashes rather than merge, exit, or weave maneuvers).
- For passenger vehicles, accidents tended to occur about equally for lane changes to the left and to the right
- For heavy trucks, accidents occurred more frequently for lane changes to the right than to the left.

According to Chovan, Tijerina, Alexander, and Hendricks (1994) and Eberhard, Luebkeman, Moffa, Young, Allen, Harwin, Keating, and Mason (1994), available crash records indicate that most drivers were unaware of the imminent crash hazard and took no action to avoid it. Using an SCAS to alert or warn drivers who are unaware of the crash hazard therefore offers potential crash avoidance benefits.

4.2.3 Lane Change Crash Subtypes

Lane change crashes may be divided into the ten subtypes listed below. The first number following each subtype in the list below shows the percentages (rounded) of all lane change crashes in 1992 that are of each subtype as calculated by Eberhard, Luebkeman, Moffa, Young, Allen, Harwin, Keating, and Mason (1994):

Sideswipe Striking	--	26%	(31%)
Sideswipe Struck	--	3%	(4%)
Angle Striking	--	29%	(34%)
Angle Struck	--	8%	(9%)
Drifting Angle	--	9%	(11%)
Drifting Sideswipe	--	8%	(9%)
Both Changing Lanes	--	2%	(2%)
Rear End Struck	--	4%	(0%)
Rear End Striking	--	5%	(0%)
Leaving Parking Space	--	7%	(0%)

The last three lane change crash subtypes in the above list (Rear End Struck, Rear End Striking, and Leaving Parking Space) arc crashes in which one vehicle collides with the rear of another vehicle. In order to provide a clearer definition of the lane change crash problem and distinguish lane change collisions from other crash types (e.g., rear-end crashes), these three subtypes were removed from the search criteria for lane change crashes and the number of police reported lane change crashes for 1994 was determined. This analysis of GES data found that 244,000 police reported, lane change crashes occurred in 1994 that met the revised criteria Redistributing the lane change crash subtype percentages reported by Eberhard et al. (1994) between the remaining seven lane change collision subtypes produces the percentages (rounded) for each subtype that are shown above in parentheses.

The ability of SCAS technology to prevent lane change accidents varies according to both the subtype of the crash and the capabilities of the SCAS. The analysis in this chapter is for SCAS that provide the driver with decision phase support by monitoring the adjacent lanes (on both the left and right) both alongside and to rear of the vehicle. This level of SCAS capability has been chosen because this is what NHTSA expects to be commonly used on vehicles in the future. Both more and less capable SCAS configurations are possible; analyses of these alternative systems may be performed in future research.

The analysis of lane change collisions typically involves two vehicles: the Subject Vehicle (SV) and the Principal Other Vehicle (POV). The SV is the vehicle that actually attempts to change lanes. The POV is generally assumed to have been traveling in the lane adjacent to the SV's lane for some time until it hits the SV or is hit by the SV (except for the Both Changing Lanes accident subtype).

The first four lane change accident subtypes listed above, Sideswipe Striking, Sideswipe Struck, Angle Striking, and Angle Struck, are all situations in which the SV driver initiated a lane change prior to the crash. Furthermore, for these accident subtypes, the POV is alongside the SV when the accident occurs. However, the POV may not have been laterally adjacent to the SV throughout the entire period when the driver was deciding to make, and making, the lane change. By providing coverage of portions of the adjacent lanes behind as well as beside the SV, the SCAS analyzed may assist drivers to avoid lane changes when rapidly overtaking POVs are present.

The accident subtypes Drifting Angle and Drifting Sideswipe are lane change accident subtypes in which the SV is not actually making a lane change but instead drifts out of its current lane due to driver inattention or incapacitation. According to Eberhard et al. (1994), between 85 and 94 percent of such cases that were reviewed indicated no driver impairment for either the SV or POV driver. This suggests that momentary driver inattention is the chief causal or contributing factor. Since the driver does not actually make a decision to change lanes, the start of an inopportune "de facto" lane change may not be prevented by a SCAS with the capability assumed in this analysis. On the other hand, the SCAS may sometimes help the driver stop the drift and bring the vehicle back into the original travel lane. Since this chapter only deals with the estimation of SCAS benefits due to prevention of driver decision errors, it is (conservatively) assumed that the SCAS analyzed will not aid drivers in avoiding lane change accidents of these subtypes.

Aiding drivers in avoiding the Both Changing Lanes accident subtype is considered to be beyond the capabilities of any SCAS currently being developed. SCAS probably will not aid drivers in avoiding lane change accidents of this subtype.

In summary, decision phase support SCAS technology that will provide coverage of the adjacent lanes, both beside and to the rear of the SV, may help prevent driver decision errors for four types of lane change crashes: Sideswipe Striking, Sideswipe Struck, Angle Striking, and Angle Struck. These four lane change crash subtypes account for an estimated 78 percent of all lane change accidents. Therefore, a decision support SCAS of the type analyzed, if it were 100 percent effective at preventing applicable accidents, would prevent approximately three-quarters of all lane change accidents.

4.3 FUNCTIONAL DESCRIPTION OF DECISION SUPPORT SCAS ANALYZED

A driver lane change decision support SCAS consists of sensors, a processing unit, and driver displays whose function is to alert or warn drivers of objects alongside or behind either the left or right side of the subject vehicle (particularly where the driver does not have visibility using mirrors) that might be hit if the driver initiated a lane change. The SCAS is assumed to have the following properties (Eberhard, Moffa, Young, and Allen, 1995):

- Sensors with a field of view that extends approximately 12 feet out from the side of the vehicle over the vehicle's entire length plus 90 feet behind on both the left and right sides. Note that this field of view does not include the area directly behind the SV but only that area behind the vehicle that is outboard of the left and right sides.

- Sensors that measure both the longitudinal position of objects in the detection zone relative to that of the SV and the rate of change of the longitudinal position (longitudinal velocity) of the object in the detection zone relative to that of the SV.

- Sensors that have a measurement latency, for either object detection or object removal, of less than 0.30 seconds (fast enough so that the driver always perceives that the information presented by the SCAS's is up-to-date).

- Sensors that have a detection reliability such that at least 99.95 percent of the time that the SCAS indicates no object is present in either of the left or right side detection zone there is actually no object present in that detection zone.

- Sensors that minimize false positives (alerts or warnings when nothing is present in the detection zones) and nuisance alarms (alerts or warnings due to non-threatening obstacles in the detection zone) such that the driver is willing to have and use the SCAS.

- Include a driver interface that will provide easily detectable visual alerts whenever there is an object in a sensor coverage zone which has a longitudinal position and longitudinal velocity relative to the SV such that if the object's relative longitudinal velocity remained unchanged and the SV driver was to initiate a lane change at that time a crash would result. It will provide more intrusive visual plus either auditory or haptic warnings whenever the SCAS expects the SV driver to initiate a lane change in a direction for which an object is in the sensor coverage zone.

- Use the same algorithm for both the left and right side detection zones. The detection zones function independently (i.e., when the left side detection zone driver display is showing a visual alert, the right side driver display may be showing no alert or warning, a visual alert, or an intrusive visual plus either auditory or haptic warning.

4.4 GENERAL DISCUSSION OF SCAS EFFECTIVENESS ESTIMATION

4.4.1 Benefits Expected From SCAS

The benefits that are expected from an effective lane change collision avoidance system include the avoidance of or reduction in:

- Lane change collisions;
- Related secondary crashes (e.g., chain-reaction crashes);
- Accident related fatalities;
- Accident related injuries;
- Property damage losses;
- Lost work, wages, or productivity due to crash involvement; and
- Accident caused delays.

Additional benefits might also include:

- Increased highway throughput;

- **Reduced** driver stress;
- Increased driver satisfaction;
- Reduced insurance premiums;
- Technology transfer (SCAS technology may have other applications); and
- Increased jobs in the ITS sector.

A truly comprehensive SCAS benefits estimation would consider all of the above expected benefits, each operationally defined and quantified. For the remainder of this chapter, only the estimation of lane change collisions avoided will be considered. This in itself is a difficult task. It should be kept in mind that, if the accident is avoided, the other benefits will ripple down from this benefit. The broad benefits list is provided to indicate the multiple benefits expected from SCAS technology.

4.4.2 Possible SCAS Negative Effects

SCAS technology may also have negative effects. The following is a partial list of possible negative effects (see also Tijerina, 1995):

- Increased crash hazard exposure;
- Secondary crash consequences;
- Decreased safety-relevant driver behavior; and
- Increased risky driver behavior.

Some examples will illustrate these possible negative effects. Increased crash hazard exposure might be manifested in drivers making more lane changes. Secondary crash consequences might arise from an evasive maneuver, prompted by a SCAS alert or warning, itself leading to a crash. Decreased safety-relevant driver behavior, such as reduced mirror sampling, might arise due to reliance on a SCAS. SCAS technology may also encourage increased risky driver behavior, such as making lane changes into smaller traffic gaps or making more aggressive lane changes. If such effects, arise, they might negatively affect the SCAS effectiveness calculated in this chapter.

4.4.3 Benefits as Crashes Avoided: A General Formulation

The estimated benefit of SCAS may be estimated in terms of number of crashes with the collision avoidance system and the number of crashes without the collision avoidance system by means of the relationship given below:

$$N_{WO} - NW = Nwo * MP * A * E \quad \textbf{(4.1)}$$

where

Nwo = Number of lane change crashes that would occur without crash avoidance technology

Nw = Number of lane change crashes that would occur with crash avoidance technology

MP = Proporation of auto fleet equipped lane change collision avoidance technology

A = Proportion of SCAS turned on and available

E = Estimated effectiveness of the SCAS in preventing lane change collisions

The estimated effectiveness can further be defined as

$$E = \sum_i \sum_j p(S_{ij})*p(D_{ij})*p(C_{ij}) \qquad (4.2)$$

where

p(Sij) = Probability of occurrence of a crash hazard scenario i and causal factor j
p(Dij) = Probability that the SCAS will provide a valid warning in scenario i for factor j
p(Cij) = Probability that a driver will comply with a SCAS warning in scenario i for factor j

The estimate of SCAS penetration into the vehicle fleet is assumed, due to a lack of the data needed to make a better estimate, to be 1.0 or 100 percent. Marketing models that estimate penetration based on production costs, retail pricing, driver appeal, advertising, effects, government mandate effects, and so forth are possible but beyond the capability of the authors.

Availability reflects the proportion of SCAS in the fleet that are actually turned on. One concern about having too many false or nuisance alarms generated by SCAS technology is that the frustrated driver might turn the system off. The availability term may capture this effect formally. Another potential effect of false or nuisance alarms is that the driver might keep the system on but take longer to react. This more subtle effect would indirectly be reflected in the possible effect on driver performance of *p(Dij)*. For example, the driver's reaction time would perhaps be longer, necessitating a more aggressive evasive maneuver, increasing the likelihood of a crash resulting from the evasive maneuver itself. Finally, note that availability may vary by crash situation; in this case, subscripts would be needed.

SCAS reliability, *RCAS*, is the probability that the system is operating correctly. This reflects the detection performance and all component performance as well. *RCAS* should be included in all CAS effectiveness estimates. Though not explicitly included in this general formula, *RCAS* plays a key role in the calculation of the SCAS effectiveness, *E*. More will be said about *RCAS* and reliability models later.

Effectiveness has a theoretical range of from -4 to +l.0. If there is no effect of the SCAS at all, then NW = NW,, and *E = 0.0*. If the SCAS improves safety to the extent that NW = 0, then *E* = 1 .0. If CAS were to increase crashes, then the ratio will take on negative values.

Crash scenarios or situations, Sij involve both kinematic and causal or contributing factors. The first subscript refers to kinemauc variations (and may itself stand for a wide array of mote fine-grained kinematic variation). For example, two subtypes for lane change crashes might be the other-vehicle-not-visible-in-mirrors case and the other-vehicle-fast-approaching-from-the-rear case. Each subtype may be further elaborated in modeling to capture travel speeds, lateral accelerations, initial vehicle-to-vehicle separations upon first detection, and so on. Similarly, two causal factors associated with a lane change crash might be driver awareness due to "looked but did not see behavior" or "did not look" behavior. Either causal factor either may apply to each subtype but perhaps with different joint probabilities.

P(Dij) is the probability that the SCAS will provide the driver with an adequate warning to help . avoid a lane change where adequacy is defined in terms of time and distance available, the location of the hazard, and the stability of the recovery maneuver. This may be modeled from simulator studies, from on-the-road testing with prototype units, or from archival human performance and behavior data such as surprise steering reaction time distributions (how long it takes to respond), human error probabilities (whether response was in the right direction), and vehicular control stability during the evasive maneuver.

Driver compliance with a SCAS warning, $p(C_{ij})$, is the probability that the driver responds correctly to a SCAS warning. Driver compliance is difficult to estimate and no archival sources are known to the authors to provide such estimates. For simplicity, a compliance probability of 1.0 is assumed. The actual rate of compliance to a CAS warning may vary due CAS false or nuisance rate, driving conditions, or individual driver preferences. In addition lane changes may be hard to terminate or modify if they are initiated as open-loop maneuvers (Schumann, Godthelp, Farber, and Wontorra, 1993).

4.4.4 Fundamental Assertions

The following four assertions logically underlie the development of lane change (as well as other accident type) countermeasures for the general population. There are, however, some important exceptions that will not be discussed in this paper. The assertions are irrelevant to crashes caused by sudden vehicle defect. These assertions do not necessarily apply to drivers who are suicidal, mentally impaired, or are incapacitated by disease, disorder, or injury while driving (heart attack, seizure, etc.). They do not necessarily apply to drivers are involved in crashes while intoxicated from licit or illicit drugs, including alcohol. These special cases are not considered in this paper.

Assertion 1: Drivers usually act rationally according to their understanding of the driving situation and their current motivations. They are normally alert and attentive to the driving task.

Assertion 2: Drivers usually do not deliberately crash into other vehicles.

Assertion 3: Rational drivers, who wish to avoid crashes, often have crashes because they are unaware of the crash hazard.

Assertion 4: An awareness-inducing technology (such as a SCAS), may be of benefit to drivers otherwise unaware of the crash hazard, as may be a CAS technology that instructs drivers on the appropriate evasive action.

Assertion 1 says that drivers try to make good decisions based on the information available and their mental model of the driving situation developed from such information. Data contrary to this situational understanding (and motivations) may go undetected, ignored, discounted, or otherwise underutilized, even when provided by an electronic collision avoidance system. Rational people do not seek the negative results associated with crashes such as injury, property damage, legal liability, and the like. However, motivations may affect a driver's perception of the likelihood of a crash, the payoffs associated with the risky behavior, or both. Dealing with such motivations may be quite challenging.

Assertion 2 states that rational drivers usually do not deliberately crash into other vehicles. possible exception involves evasive maneuvers. For instance, a driver may steer into an adjacent lane (and vehicle) if the driver believes the ensuing consequence (side-swiping another vehicle) is more acceptable than another imminent threat (e.g., crashing into a stopped tractor-trailer ahead). Except for evasive maneuvers like this, the assertion is tenable.

Assertion 3 states that because drivers usually do not deliberately crash into other vehicles, drivers involved in crashes (save exclusions mentioned above) are often unaware of the crash hazard in sufficient time to avoid the ensuing crash. Unawareness may arise due to the following factors:

"Did not look" problems or inattention to the hazard (i.e., drivers are always attending to something, including other potential crash hazards, but not necessarily the crash hazard that led to a police-reported or target crash);

- "Looked but did not see" problems of human reliability in detection, or identification of thecrashhazard;

- "Looked and misperceived" problems associated with the crash hazard (distance, speed, acceleration, time-to-contact, heading, etc.);

- "Misjudged own capabilities" (e.g., vehicle performance capabilities to accelerate, stop, keep in the lane, own reaction time and control capabilities); and

- Expectancy violations ("I looked, I saw, I perceived, I know myself and my vehicle, but the other guy did something that caught me totally by surprise").

Assertion 4 states that collision avoidance systems may prevent collisions that would otherwise occur when the SCAS warn of an imminent crash hazard or alert the driver of conditions that could potentially lead to a collision presume that inducing awareness.

4.5 SCAS EFFECTIVENESS ESTIMATION DURING THE DECISION PHASE

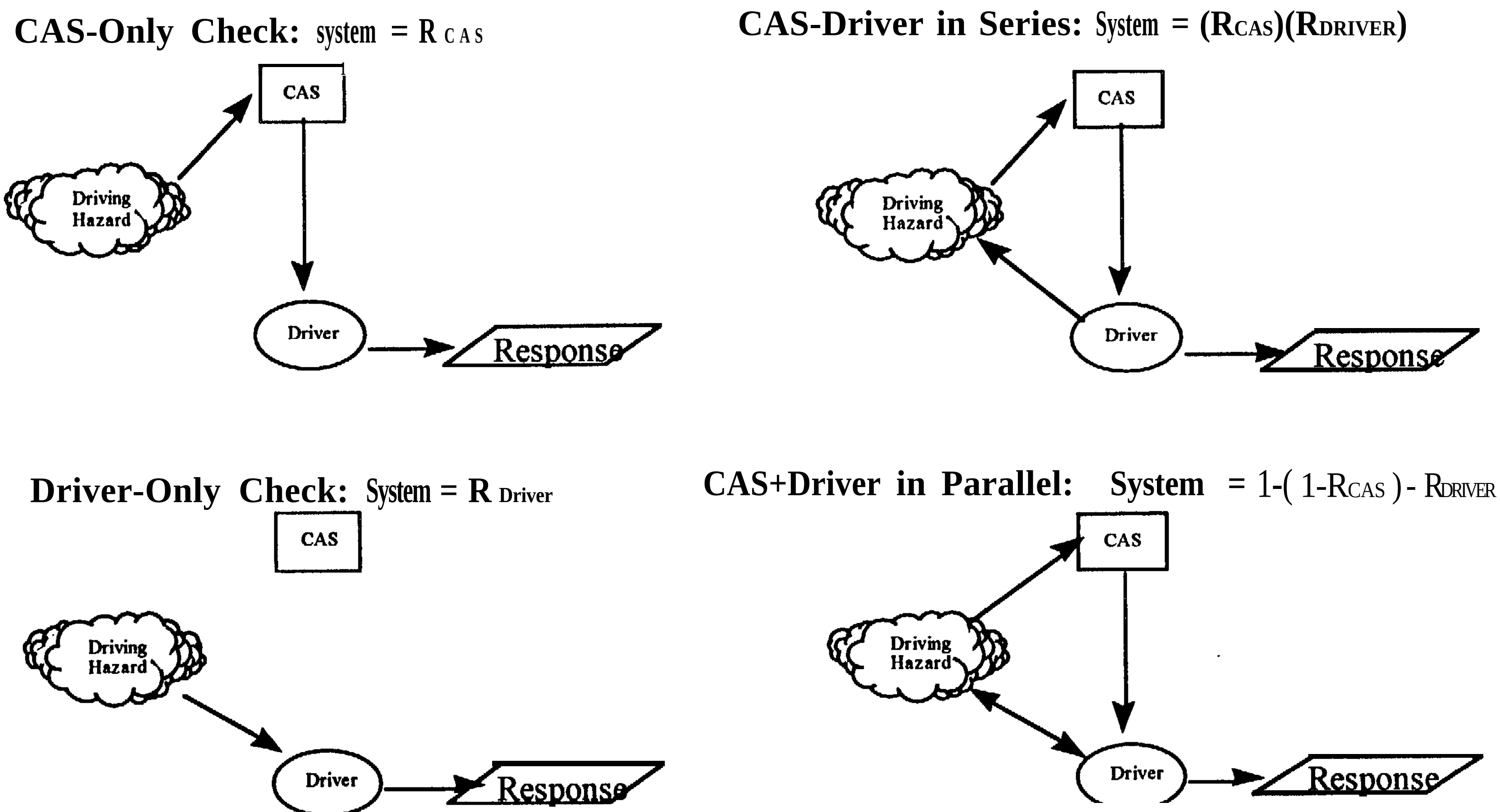
4.5.1 Problem Formulation

During the decision phase, the driver decides whether or not to make a desired lane change. The assumption made in this chapter is that this decision is based solely upon the driver's perception of the traffic or other obstacles in the destination lane (i.e., since the driver has already decided that he/she wants to change lanes, a lane change will be made unless the driver decides that there is too high a probability that doing so would result in a mishap). 'The function of the SCAS during the decision phase is to support the driver by improving their awareness of traffic or other obstacles in the destination lane before the maneuver begins. SCAS effectiveness during the decision phase may be modeled in terms of system reliability, i.e., the likelihood that the driver-vehicle-roadway-SCAS system will perform satisfactorily versus the likelihood that the driver-vehicle-roadway-SCAS system will not perform satisfactorily. During the decision phase, satisfactory performance is defined as postponing a lane change when making a lane change would result in a collision.

Figure 4-2 shows four possible driver-SCAS interaction modes, and their corresponding system reliability formulations (Hillier and Lieberman, 1986), that may arise in the lane change decision phase. A fifth possible driver-SCAS interaction mode, which is not shown in Figure 4-2, is for the driver not to make any checks for traffic or obstacles in the planned destination lane prior to proceeding to the maneuver execution phase. For this interaction mode, drivers are deciding whether to change lanes upon their assumptions about or expectations of the traffic in the planned destination lane. No data is available as to driver reliability when in this interaction mode. However, the method used in this chapter (see 4.5.2) to determine the reliability of the driver when the driver does not use a SCAS includes all lane change crashes including those in which the driver did not perform any checks. Therefore, this case is lumped with the Driver Only Check interaction mode in Figure 4-2.

In Figure 4-2, R_{system} is the probability of satisfactory performance by the combined driver-vehicle-SCAS system utilized as specified for the particular case. R_{CAS} is the probability of satisfactory performance if the driver only utilizes the SCAS when deciding whether or not to change lanes and R_{Driver} is the probability of satisfactory performance if the driver does not utilize the SCAS at all.

CAS-Driver System Interaction Modes



Note: Single-head arrows pointed toward a component signify detection of a stimulus by a component.
Single-head arrows pointed toward a hazard signify verification of the activity by the driver.
Double-head arrows signify concurrent monitoring or verification activity by a driver.

Figure 4-2. Possible SCAS-Driver System Interaction Modes

For the CAS-Only Check interaction mode, the driver polls only the SCAS to decide whether or not to proceed with the lane change. If the SCAS presents an alert or alarm, the driver waits. Otherwise, the driver will proceed with the lane change. A driver may behave like this if he/she has great faith in SCAS technology and perceives this mode of interaction to be labor-saving as well as acceptable, given the current driving context. Because the lane change decision depends solely on the reliability of the SCAS, the reliability of the overall system is equal to the reliability of the SCAS alone.

The SCAS and driver operating in series (upper right quadrant of Figure 4-2) is an example of an alerted-monitor system (Pollack and Madans, 1964; Sorkin and Woods, 1985). In this interaction mode, the driver first checks the SCAS. If, and only if, the SCAS provides an alert or warning, the driver follows up by mirror checks or direct glances to confii the presence of an obstacle. If the driver detects an obstacle, the driver postpones the lane change. Otherwise, the lane change is started with the driver assuming that the SCAS is generating a false or nuisance alarm. If the SCAS does not provide a warning, the driver starts to change lanes. In this interaction mode, if either the SCAS or the driver fail to detect an obstacle, a detection phase failure ensues and an inopportune lane change is started. This type of driver behavior might be exhibited with a sensitive SCAS that appears to always provide warnings when obstacles are present but also generates a large number of false or nuisance alarms. Since SCAS sensors that miss very few obstacles in an adjacent lane also tend to have high false alarm rates (Kantowitz and Sorkin, 1983), series system behavior is a distinct possibility

The question of SCAS-only or Series behavior looms large in any consideration of SCAS effectiveness and benefits. Both of these reliability structures decrease effectiveness and safety when compared for either the driver alone or parallel behavior. That series or SCAS-only behavior will occur is beyond doubt. Consider the case of driver behavior at railroad grade crossings. The at-grade crossing warning lights (and gates) constitute a crash avoidance or warning system. Prototypical driver behaviors are provided below,

- Upon approaching the crossing, a motorist stops if the crossing lights are flashing and waits until the crossing lights stop, or otherwise proceeds without visually checking for a train. This is prototypical CAS-only behavior;

- Upon approaching the crossing, a motorist proceeds without visually checking for a train if the crossing lights are off. Otherwise, the motorist slows or stops if the crossing lights are flashing and checks for a train. If a train is visually detected, the driver waits until the train has passed and the crossing lights are off. If no train is visually detected, the motorist proceeds through the crossing even if the lights are flashing. This is prototypical series behavior.

Driver behavior at railroad grade crossings provide real-world evidence that Series or SCAS-only behavior occurs with at least some crash avoidance systems. What is unknown is with what frequency such behaviors will arise in the lane change setting and what factors will influence this behavior. No sound data is available on this topic at this time but is a part of planned NHTSA research into the human factors of crash avoidance systems.

In the Driver-Only Check interaction mode (lower left quadrant of Figure 4-2), the driver uses assumptions about traffic and obstacles in the planned destination lane, mirror checks and/or diit glances to determine whether or not to change lanes. The SCAS, if present, is not used at all. This interaction mode reflects the unsupported driver (a baseline situation) and system reliability reduces to the reliability of the driver alone. This interaction mode might occur for a very skeptical driver who does not trust the SCAS and does not use it even though it is available.

The SCAS and driver may also operate as a parallel system (lower right quadrant of Figure 4-2). For this interaction mode, the driver looks at the SCAS, looks in the mirrors, and/or makes direct glances at the situation in the adjacent lane. Both the driver and the SCAS are redundantly monitoring for traffic or obstacles in the adjacent lane. If the driver detects the presence of another vehicle either through direct observation or through a message from the CAS, the lane change is postponed; otherwise it is not, This behavior is the best from a safety standpoint because if either the SCAS or the driver detect an obstacle, the lane change maneuver is postponed. Put another way, both the SCAS and the driver, operating as redundant or concurrent detectors, have to fail for a system failure to occur.

In the actual SCAS-equipped driving population, a mixture of all four of these interaction modes will probably be present, either across drivers or within a single driver over time. To model this, more complex system reliability models may be built up from the basic elements presented above. Consider the case where the SCAS is in all vehicles (i.e., 100 percent fleet penetration). Furthermore, assume that in the fleet, the proportions, U_{CAS}, U_{Driver} U_{Series}, and $U_{parallel}$ of lane change instances of each of the above driver-SCAS interacuon modes, where each U is a proportion between 0.0 and 1.0 and all are mutually exclusive, may be estimated. Since one of the above four driver-SCAS interaction modes is assumed to be used by the driver during every attempted lane change, the U's must meet the following constraint:

$$U_{CAS} + U_{Driver} + U_{Serices} + U_{Parallel} = 1.0 \qquad (4.3)$$

where

U_{CAS} = Proportion of drivers using CAS- Only Check interaction mode

U_{Driver} = Proportion of drivers using Driver - Only Check interaction mode

U_{Series} = Proportion of drivers using CAS and driver in series

$U_{Parallel}$ = Proportion of drivers using CAS and driver in parallel

Based on these expressions, an overall reliability model may be constructed:

$$R_{DWC} = U_{Driver} * R_{Driver} + U_{CAS} * R_{CAS} + U_{series} * R_{CAS} * R_{Driver} + U_{Parallel} * (1- (1-R_{CAS} * (I- R_{Driver})) \qquad (4.4)$$

where

R_{DWC} = Probability of satisfactory performance of a driver with a SCAS available

R_{Driver} = Probability of satisfactory perfornance of a driver not using a SCAS

R_{CAS} = Probability of satisfactory performance of a driver using only the SCAS

The resulting value of *RDWC* is a value between 0.0 and 1.0 that represents the probability (or, equivalently, the proportion) of satisfactory traffic or obstacle detection performance by the driver plus SCAS together during the decision phase of a lane change maneuver. Note that for the crashes targeted by the SCAS, failure to detect an obstacle may result in a crash. This is the form that will be used to estimate SCAS effectiveness during the decision phase by helping improve driver awareness of traffic or obstacles in the adjacent lane. What is needed to calculate *RDWC* for SCAS are data with which to estimate each of the terms in the model.

4.5.2 Developing Estimates for Driver Decision Phase Reliability Without a SCAS

An estimate of lane change crash probability, for the relevant lane change crash subtypes, may be determined by taking the number, in a given year, of lane change crashes of the relevant subtypes that occurred divided by the number of lane changes attempted. General Estimates Systems (GES) statistics indicate that in 1994 there were 244,000 (after excluding lane changes that resulted in rear-end collisions) police-repotted lane change crashes. As was discussed earlier, 78 percent (190,320) of these accidents are of a subtype that may be prevented by a decision support SCAS of the type analyzed. The accidents occurred over the 2,392,706 millions of vehicle miles that were traveled during 1994 by all types of vehicles (Wang, personal communication, 1996). Assume that there is an average of one lane change per vehicle mile traveled. Further assume that lane change crashes are randomly distributed among these lane change attempts. Subtract 2 percent of the attempted lane changes as those involved with the "Both Changing Lanes" crash subtype. This leaves 2,344,852 millions of lane changes annually from which the target lane change crashes arise. The probability of a lane change crash may then be estimated as:

$$P_{LCCWO} = \frac{\text{number of target lane change crashes}}{\text{number of associated lane change attempts}} \qquad (4.5)$$

where

P_{LCCWO} = Probility of a crash during a single lane change attempt without SCAS

This probability can bc estimated as

$$P_{LCCWO} = \frac{190320}{2.34485\ 2 * 10^{12}} = 8\ 116.50 * 10^{-8} = 0.000000081165 \qquad (4.6)$$

This high reliability reflects the influence of several factors. First, humans are generally very reliable performers (Swam and Guttmann, 1983). Second, the highway is generally a forgiving system (Rockwell, 1972); drivers frequently make mistakes that do not lead to crashes. Third, a lane change crash is actually the product of both subject vehicle (SV) and principal other vehicle (POV) driver failures. The lane change crash may be avoided if either the POV driver or the SV driver is alert and takes appropriate action. For example, the POV driver might sound the vehicle horn to alert the SV driver or might steer away or brake to compensate for the encroaching SV. Thus, the reliability of the driver-vehicle-highway system without CAS appears to be that of the SV driver and POV driver operating as a parallel "driving hazard" monitoring system.

$$P_{LCCWO} = 1-[1-(Psv)*(Ppov)] = (Psv)*(Ppov) \qquad (4.7)$$

where

P_{SV} = Probability of a driver failure in the subject vehicle

Ppov = Probability of a driver failure in the P principal other vehicle

Assuming that the reliability of the SV driver is the same as the reliability of the POV driver (i.e. $P_{SV} = Ppov$) and that these reliabilities are independent, driver reliability for lane changes without assistance from an SCAS may be estimated by use of the parallel system reliability model:

$$P_{LCCWO} = (psv)*(Ppov) = P2DFWO = 0.0000000811650 \qquad \textbf{(4.8)}$$

$P_{DFWO} = \overline{\$0.0000000811650}$

$P_{DFWO} = 0.00028495$

where

P_{DFWO} = Probability of a driver failure without **SCAS** available

Individual driver reliability, without **SCAS,** may now be estimated by taking 1 minus the probability of driver failure:

$$R_{Driver} = 1-P_{DFWO} = 1.0 - 0.000284895 = 0.999715105 \quad (4.9)$$

A lane change collision avoidance system would be effective to the extent that it enhances driver reliability above this number.

4.5.3 Developing Estimates for SCAS Decision Phase Reliability

The reliability of the hypothetical SCAS was assumed to be 0.9995 in situ. Although the overall effectiveness of the SCAS am relatively insensitive to small variation in reliability, some explanation of the rationale behind this assumption is in order. *RCAS* in situ is a phrase coined to capture the fact that there can be no failure of obstacle detection when there is no obstacle to detect, as will usually be the case for lane change maneuvers. For example, consider an SCAS that detects 99 percent of targets present. Thus, *RCAS* = 0.99 for detection. Assume that 5 percent of all lane changes desired in driving involve another vehicle in a conflict position (i.e., in the CAS sensor field of view). Thus, for 10,000 desired lane changes (say, over a year's worth of driving given 10,000 miles traveled and one lane change per mile, on average), 500 of those instances will involve a vehicle in a potential conflict zone. If the SCAS is always available and used, it will teoretically miss (1 .00 - 0.99)(500) = 5 of those potential conflict obstacles and properly detect 495 of those conflict obstacles. (Usually, the 5 instances where there is no detection should by and large be uneventful because the **SV** and **POV** drivers am looking out for hazards too). In the driving context or in situ, reliability of the CAS is not 0.99 but rather is much higher because there is no opportunity for a detection failure when there is no target to begin with. Thus, the SCAS reliability in situ, is

$$R_{CAS} = \frac{9{,}500 + (500-5)}{10{,}000} = 0.9995 \quad (4.10)$$

The probability of SCAS failure to detect an obstacle in the sensor field of view is one minus the assumed reliability. That is:

$$P_{CF} = 1-R_{CAS} = 1-0.9995 = 0.0005 \quad (4.11)$$

where

P_{CF} **= Probability of a SCAS failure**

The assumed reliability value is an attempt, albeit arbitrary, by the authors to factor in the consideration that many lane change attempts are made when there is no vehicle in the adjacent lane. Thus, there oftentimes is no obstacle to detect and hence no possibility of a missed detection or SCAS detection failure. No information is currently available on how often this situation arises. Given the use of the SCAS reliability values in subsequent calculations, an adjusted figure was nonetheless needed. Planned research by NHTSA will attempt to gather data with which to estimate the proportion of lane change attempts that do and do not involve a POV in the adjacent lane.

The probability of R_{Series} and $R_{Parallel}$ can be calculated from the preceding estimates, given the assumptions of independence between driver and SCAS and the assumption that such values am stationary or stable over some reasonable period of time. From Figure 4-2, The series system reliability calculations are given below:

$$R_{Series} = R_{Driver} * R_{CAS} = (0.99971505) * (0.9995) = 0.99921525 \tag{4.12}$$

where

R_{Series} = Probability of satisfactory performance of a driver using SC AS in series

$$P_{SF} = 1 - R_{Series} = 1 - 0.99921525 = 0.00078475 \tag{4.13}$$

where

P_{SF} = Probability of failure of a driver using SCAS in series

Figure 4-2 also provides the formula for parallel system reliability:

$$\begin{aligned} R_{Parallel} &= 1 - [(1 - R_{CAS} * (1 - R_{Driver})] \\ &= 1 - [(1 - 0.9995)*(1 - 0.99971505)] \\ &= 0.99999986 \end{aligned} \tag{4.14}$$

where

$R_{parallel}$ = Probability of satifactory performance of a driver using SC AS in parallel

$$P_{PF} = 1 - R_{parallel} = 1 - 0.99999986 = 0.00000014 \tag{4.15}$$

where

P_{PF} = Probability of failure of a driver using SCAS in parallel

4.5.4 Derivation of Effectiveness Formula

The SCAS being considered in this analysis has a sensor field of view that extends laterally 12 feet for the full length of the SV and looks backward up to 90 feet in both left or right adjacent lanes. Data provided from the GES in Wang and Knipling (1994) indicate that approximately 63.2 percent of lane change crashes involve relative velocities of 5 mph or less. This implies that the SV and POV were laterally overlapping for some period of time prior to the crash. If there is 100 percent penetration of SCAS technology into the fleet of vehicles, both the SV driver and POV driver would be alerted of a crash hazard by their respective SCAS in the cases when they laterally overlap. To estimate the probability of a target lane change crash with SCAS, it has been assumed that SV driver and POV driver reliabilities with SCAS are equal for this percentage of target crash subtypes.

The remaining 36.8 percent of lane change crashes involved relative velocities greater than 5 mph. For the target crash subtypes, such relative velocities would involve a PGV approaching from the rear (among other possible scenarios). Given that the SV's SCAS would be looking backward, the SV driver would receive an SCAS alert early on (if the system operates as intended). On the other hand, since the POV's SCAS does not look forward, there would be no SCAS alert to the POV until later on when the vehicles are laterally overlapping. For these cases, the POV driver reliability is assumed to be that of the baseline unsupported driver without SCAS, as derived from the GES data, while the SV driver reliability is the calculated driver reliability with a SCAS.

Given an estimate of the reliability of the driver with SCAS, the following terms can be defined:

$$P_{POVFW} = P_{SVFW} = 1 - R_{DWC} \qquad (4.16)$$

where

P_{POVFW} = Probability of failure of principal other vehicle driver with SCAS available

P_{SVFW} = Probability of failure of subject vehicle driver with SCAS available

and

$$P_{POVFWO} = P_{DFWO} \qquad (4.17)$$

where

P_{POVFWO} = Probability of failure of principal other vehicle driver without SCAS available

Note that the P_{DFWO} is the value derived in equation 4.8 from GES data.

Assume that all vehicles are equipped with SCAS. Also, there is a need to consider separately the 63.2 percent of crashes that occur with a relative velocity of 5 mph or less between SV and POV and the 36.8 percent of crashes that occur with a relative velocity of greater than 5 mph between SV and POV. By the logic presented earlier on how lane change crashes occur by the joint occurrence of SV and POV driver failures, the probability of a target lane change crash with SCAS technology in the fleet may be estimated as:

$$P_{LCCW} = (0.632) * (P_{SVFW})(P_{POVW}) + (0.368)(P_{SVFWS})(P_{POVFWO}) \qquad (4.18)$$

where

P_{LCCW} = Probability of a target lane change crash with both cars equipped with SCAS

The effectiveness estimate for the SCAS analyzed, with respect to the target lane change crash subtypes, is given as:

$$E_T = \frac{N_{WOT} - N_{WT}}{N_{WOT}} = \frac{N_{WOT} - (P_{LCCW}) * (N_{LC})}{N_{WOT}} \qquad (4.19)$$

where

E_T = Effectiveness of SCAS with respect to target crashes

N_{WOT} = Number of target lane change crashes without SCAS

N_{WT} = Number of target lane change crashes that would occur with SCAS

N_{LC} = Number of target lane changes attempted

The number of lane change crashes addressed by the SCAS is estimated as 78 percent of the 244,000 police reported crashes or 190,320 crashes annually. The number of lane change attempts associated with targeted lane change crash subtypes is estimated to be 2.344852 x 10 attempted lane changes annually.

The above effectiveness estimate is with reference to target lane change crash subtypes only. An effectiveness estimate that addresses the lane change crash problem as a whole is provided below:

$$E_{LC} = \frac{N_{WO} - N_W}{N_{WO}} \tag{4.20}$$

$$= \frac{N_{WO} - (P_{LCCW}) * (N_{LC})}{N_{WO}}$$

where

E_{LC} = Effectiveness of SCAS with respect to entire lane change problem

N_{WO} = Number of lane change crashes occurring without SCAS

N_W = Number of lane change crashes that would occur with SCAS

N_{LC} = Number of target lane changes attempted

4.5.5 Developing Usage Estimates for the Four Driver-SCAS Interaction Modes

Only limited experimental data is available on the usage patterns of SCAS by drivers. The main existing source of data is a study of SCAS for heavy, commercial, vehicles by Mazzae and Gatrott (1995). Driver behavior data obtained during this study of lane change collision avoidance system effectiveness comes from testing two SCAS devices and two mirror systems. This testing was conducted on public roads by eight professional truck drivers, each driving an instrumented heavy tractor-semitrailer with a gross weight of approximately 80,000 pounds and an in-vehicle experiment. Each driver drove for four sessions on different days with one day devoted to each of the SCAS or mirror systems. (Note that even when a SCAS was present, the baseline plane and convex sideview mirrors were also present). During each day of testing, the data collection route was driven once. The route driven covered two road types (arterial and highway).

According to a predefined schedule, each driver was repeatedly asked the question "Is the right clear?", to which the driver had to respond "yes" or "no." "Right clear" questions were asked approximately the same number of times for each of the eight drivers, four SCAS/mirror systems, and three different traffic conditions (traffic next to the tractor, thaffic next to the semitrailer, or no object next to the tractor-semitrailer). Each "right clear" response was scored as either correct or incorrect. Data as to the driver mode of interaction with the SCAS was also recorded for each "right clear" question.

In addition to the "right clear" questions, the drivers were observed making natural lane changes to the right (natural lane changes are ones that were not requested by the in-vehicle experimenter but were performed at the driver's own volition) during the data collection sessions with each of the four SCAS/mirror systems. Data as to the driver mode of interaction with the SCAS was also recorded for each natural lane change.

The four different SCAS/mirror system configurations tested consisted of :

- System 1 -- west coast planar plus shallow convex sideview mirrors mounted just forward of the doors (baseline configuration);
- System 2 -- the baseline mirrors plus a shallow convex sideview mirror mounted on the right front fender;
- System 3 -- the baseline mirrors plus a radar-based SCAS; and

- System 4 -- the baseline mirrors plus an ultrasonic-based SCAS.

System 3, a radar-based SCAS, was a prototype unit which was obtained for this testing. The system had three radar sensors which were mounted along the right side of the tractor-semitrailer. The system's visual display consisted of separate red tractor and trailer warning LEDs with different flash rates mounted on the center of the dashboard. This system's auditory warning (a beep) operated only when the tum signal was activated. Therefore, the auditory warning was not available during the "right clear" questions since the turn signal was not on because the driver did not intend to change lanes.

System 4, an ultrasonic-based system, was a commercially available SCAS which was obtained for this testing. The system had a single ultrasonic sensor which was mounted on the right side of the tractor. The system's visual display consisted of a plan view of an outline of a tractor-semitrailer surrounded by warning LEDs positioned to correspond to sensor locations (only the right side LED was active in the configuration used for this testing). These visual warning LEDs turned orange when a vehicle was within 3 m of the sensor and red when an object was within 1.5 m of the sensor. System 4 also had a red numerical LED display that indicated the distance, in feet, to a vehicle present in a detection zone. System 4 had an auditory warning that produced two short beeps when a vehicle was within 1.5 m of a sensor. (Unlike System 3, this auditory display could sound during "right clear" questions).

Due to the nature of field research, the number of "right clear" questions asked differed slightly across drivers and conditions but numbered approximately 8 questions for each condition per driver for each combination of system, road type, and traffic condition. A total of 1473 responses were collected to the "right clear" question. Data was also analyzed for 132 natural right lane changes.

During the "right clear" questions, no lane change was actually made. The response to this question was purely verbal. There was no safety consequence associated with a wrong answer. The "right clear" results might, therefore, be treated as a surrogate for a lane change maneuver under conditions where the possibility of a crash is perceived by the driver to be quite low. Under such circumstances, the driver might be more lax in data gathering during the decision phase and prior to lane change start. Table 4-l presents the results from the "right clear" questions.

Table 4-2 presents additional data on driver behavior gathered during the natural right lane changes. Several points are worth notice. First, no driver ever used only the SCAS device prior to starting the lane change. This might be interpreted as a healthy dose of skepticism about such devices providing alerts or warnings under all circumstances. Second, the proportions of lane change instances where the driver checked both the mirrors and the SCAS went up substantially relative to those observed during "right clear" questions. This is interpreted to indicate that the drivers, though reluctant to rely solely on the SCAS to make the lane change, nonetheless thought it useful to see the current SCAS status. Third, mom than half of the drivers with System 3 still did not visually sample the driver interface during the lane change maneuver. (If the driver activated the turn signal prior to performing the lane change then System 3's audio display was also active during the natural lane changes. During "right clear" questions, drivers never activated the turn signal and so System 3's audio display was never presented.). For System 4 less than one quarter of the lane changes involved drivers who elected not to look to the SCAS during the lane change. (System 4's audio display was always active during the natural lane changes and "right clear" questions.) The interpretation of this behavior is unclear. Perhaps the design of System 3's auditory display prompted drivers to rely less on its visual display and more on its auditory warnings.

Table 4-1. Reliability and Usage Results from "Right Clear" Questions
by Device and Error Type

Metrics	DEVICE TYPE			
	System 1 – Standard Sideview Mirror System	System 2 -- Mirror Plus Baseline Mirrors	System 3 -- Radar-Based SCAS Plus Baseline Mirrors	System 4 -- Ultrasonic-Based SCAS Plus Baseline Mirrors
Total "Right Clear" Questions	332	398	386	357
Number Incorrect	7	1	8	12
Proportion Correct	0.979	0.997	0.979	0.966
Proportion Incorrect	0.021	0.003	0.021	0.034
Number of Missed Vehicles	2 of 7 errors	0 of 1 errors	4 of 8 errors	4 of 12 errors
Proportion of Missed Vehicles	0.006	0.000	0.011	0.011
Number of False Detections	5 of 7 errors	1 of 1 errors	4 of 8 errors	8 of 8 errors
Proportion of False Detections	0.015	0.003	0.011	0.023
Proportion of Visual Sampling to Both SCAS and Mirrors During Question	Not Applicable		0.135	0.076
Proportion of Visual Sampling to SCAS Only During Question	Not Applicable		0.036	0.011
Proportion of Visual Sampling to Mirrors Only During Question	1.0		0.829	0.913

Notes:

- The total number of "right clear" questions asked was 1473 (Mazzae and Garrott, 1995).
- The overall proportion of correct responses to the "right clear?" questions was 0.981 or 98.1%.
- The proportion of visual sampling is drawn from eye glance video taken while the driver answered the "right clear" question.

Table 4-2. SCAS Reliability and Driver Visual Sampling Behavior Observed during Lane Changes

Measures	CAS Devices	
	System 3 - Radar-Based SCAS Plus Baseline Mirrors	System 4 – Ultrasonic-Based SCAS Plus Baseline Mirrors
Overall Proportion of Vehicles in Adjacent Right Lane Missed	0.032	0.063
Proportion of Visual Sampling to Both SCAS and Mirrors During Lane Change	0.412	0.758
Proportion of Visual Sampling to SCAS Only During Lane Change	0.000	0.000
Proportion of Visual Sampling to Mirrors Only During Lane Change	0.588	0.242

Note that there is no distinction in Tables 4-l and 4-2 between parallel and series ‘behavior. At the time this study was performed the importance of looking for series versus parallel behavior had not yet been realized As a result, no experimental methods were in place to distinguish between the two alternatives. Therefore, the assumption will be made that only parallel behavior was seen during this testing based on experimenter impressions of truck driver attitudes towards safety during the study.

4.5.6 Driver-SCAS System Reliability and Effectiveness Calculations

Table 4-3 presents the calculated SCAS effectiveness estimates for System 3 and System 4 for both “right clear” questions **and** natural lane changes based on data from Mazzae and Garrott (1995). The second and third columns of Table 4-3 represent, respectively, data for System 3 and System 4 from the “right clear” trials of Mazzae and Garrott. It should be noted that the drivers did not actually make a lane change during these trials and so there was no penalty for not determining that a POV was present alongside the SV. This apparently influenced driver behavior such that the drivers occasionally used the SCAS alone when answering the question. As a result, the effectiveness values of 13 and 8 percent, for System 3 and System 4, respectively, that were calculated from this data are probably unduly pessimistic.

The third and fourth columns of Table 4-3 represent data from the “natural lane change” cases of Mazzae and Garrott for System 3 and System 4, respectively. In these cases, there was a real penalty for missing an obstacle and drivers were much more cautious, never relying on the SCAS only prior to making the lane change. As indicated in the bottom of each column, the pattern of observed driver behavior with the SCAS was such that effectiveness estimates of 44 to 68 percent crashes avoided were calculated for System 3 and System 4, respectively.

The “natural lane change” effectiveness estimates appear overly optimistic. The Mazzae and Garrott (1995) study involved professional truck drivers, pre-selected to have good driving records, operating a government-marked instrumented vehicle with a ride-along observer, on non-revenue runs, using relatively unreliable SCAS devices for the first (and only) time. It is reasonable to assume that the observed driver behavior was highly conservative in terms of risk taking. It is unreasonable to assume that drivers at large, in their own vehicles, perhaps after developing some false sense of security with the technology, would behave in a similar risk-averse manner.

With the wide variation in the calculated effectiveness in the estimates presented and a sparsity of data to determine the accuracy of the estimates, the insight of experts can be used to develop an expected effectiveness. Given that the effectiveness calculated from the “right cleat” questions is believed to be overly pessimistic and that the effectiveness calculated from the “natural lane changes” is believed to be overly optimistic, the authors generated a fmal column by averaging the driver usage data contained in the preceding four columns. This column indicates that an estimated 37 percent of all lane change crashes (not just lane change crashes of the targeted subtypes) might be avoided if all assumptions and data used in the analysis were valid. Section 8 discusses some of the key caveats and research needs associated with developing effectiveness estimates.

It is important to remember that the Mazzae and Garrott (1995) study methodology could not distinguish between parallel and series behavior. However, as previous discussion has pointed out, series or system only behavior occurs for at least one other crash avoidance system, i.e., at-grade railroad crossing signals. Unfortunately, no data is available with which to estimate the proportion of SCAS usage that might reflect series behavior. This value is almost certainly not going to be the zero value used in the current analysis.

Table 4-3. Calculated SCAS Reliability and Effectiveness Based on the Mazzae and Garrott Study

Basis for Effectiveness Estimate	Based on Data from the "Right Clear" Questions		Based on Data from the Natural Right Lane Changes		Based on Averaged Driver Usage Data.
Equipment on Vehicle	System 3 -- Radar Based SCAS Plus Baseline Mirrors	System 4 -- Ultrasonic Based SCAS Plus Baseline Mirrors	System 3 -- Radar Based SCAS Plus Baseline Mirrors	System 4 -- Ultrasonic Based SCAS Plus Baseline Mirrors	Systems 3 & 4 -- "Right Clear" Questions and Lane Changes
R_{CAS} (assumed)	0.9995	0.9995	0.9995	0.9995	0.9995
R_{Driver} (calculated from accident data), See Section 4.5.2.	0.999715	0.999715	0.999715	0.999715	0.999715
U_{CAS} (from test data)	0.036	0.011	0.000	0.000	0.01175
U_{Driver} (from test data)	0.829	0.913	0.588	0.242	0.64300
$U_{Parallel}$ (from test data)	0.135	0.076	0.412	0.758	0.34525
U_{Series} (assumed)	0.000	0.000	0.000	0.000	0.00000
R_{DWC} (calculated), See Section 4.5.1.	0.999746	0.999734	0.999832	0.99993095	0.999811
P_{LCCW} (calculated), See Section 4.5.4.	6.749×10^{-8}	7.244×10^{-8}	3.532×10^{-8}	1.025×10^{-8}	4.243×10^{-8}
Number Crashes Avoided	32071	20464	107507	166278	90830
E (calculated), See Section 4.5.4.	+13 %	+8 %	+44 %	+68 %	+37%

4.6 CONCLUDING REMARKS

For lane change and merge collision avoidance, a highly reliable system was analyzed that will provide an unobtrusive alert when an object is in the coverage zone and a more intrusive warning when the operator indicates intention to change lanes by using a turn signal. Although both decision and execution phases of the lane change/merge maneuver are discussed, the effectiveness of the system was predicted only for driver support during the decision phase. Four different interaction modes were described for ways in which operators may use the side collision avoidance system based on combinations of visual attentiveness and device usage. Based on data from different studies, estimates of effectiveness of the system consisting of the driver plus the CAS were compared to the current effectiveness of the driver alone. Estimates in the decrease, for all lane change collisions, range from 8% to 68%. The authors' best estimate of the effectiveness is a reduction of relevant collisions by 47%. This translates into a decrease for all lane change collisions of 37% or about 90,000 crashes annually Caveats and limitations associated with this estimate are discussed in Section 8 of this report

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Chapter 5: Preliminary Safety Benefits for Road Departure Crash Avoidance Systems

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This chapter presents preliminary effectiveness estimates of a Road Departure Countermeasure System and its potential crash reduction benefits. Although many different measures can be used to estimate benefits, this analysis focuses on target crashes prevented by the conceptualized countermeasure.

This chapter is organized as follows:

Section 5.1 defines the road departure crash problem size and the economic costs
Section 5.2 describes the countermeasure system
Section 5.3 presents the approaches and methods to calculate the effectiveness rate and estimate the benefits.

5.1 SINGLE VEHICLE ROAD DEPARTURE CRASHES

Based on 1994 data from the GES, there were approximately 1.238 million police-reported road departure crashes which constituted 19 percent of all police-reported crashes. These crashes were associated with 540,000 non-fatal injuries and 13,330 fatalities. In addition, there are numerous "nonpolice-reported" road departure crashes. Based on the algorithm presented in Wang and Knipling (1994), a conservative estimate of 1.437 million non-police-reported roadway crashes has been made.

Road departure crashes have a huge economic impact. Wang, Knipling, and Blincoe (1996) estimate the annual monetary costs associated with these crashes to be $31.3 Billion, about 20 percent of all crash-related monetary costs. Each police-reported road departure crash has an average monetary cost (including all damage, injuries, and related economic loss; but not "societal value" above actual economic loss) of $17,500. On average, each motor vehicle produced will be associated with $1,800 in economic loss due to road departure crashes alone. For combination-unit trucks, this value skyrockets to $4,100, primarily due to the high mileage exposure of these trucks over their operational lives. From a monetary cost-benefit perspective, these average per-vehicle-produced monetary values may be regarded as a "budget" for a hypothetical countermeasure which would prevent all of these crashes.

5.2 DESCRIPTION OF THE COUNTERMEASURE SYSTEM

Two countermeasure systems have been proposed under the NHTSA ITS crash avoidance countermeasure performance specification program: a lateral system and a longitudinal system.

Both systems would be equipped with a pavement condition detection sensor which would support and enhance the performance of the two major systems.

5.2.1 Lateral System

The lateral countermeasure is designed to detect when the vehicle begins to depart the road. It utilizes data about the dynamic state of the vehicle, in combination with information about the geometry of the road ahead to determine if the vehicle's current position and orientation will likely lead to a road departure. If the likelihood of departure exceeds a threshold, a sequence of driver interface functions is triggered to alert the driver of the danger and avoid a crash. The lateral functional sequence is designed to prevent those road departure crashes caused primarily by driver inattention and driver relinquishing steering control (e.g., associated with alcohol intoxication or other impairment).

In the lateral systems tested, data about the vehicle's current position on the roadway and the geometry of the road ahead is obtained from a forward or side looking vision system that tracks lane markings or other features delineating the roadway.

5.2.2 Longitudinal System

ln the longitudinal countermeasure, the goal is to detect when the vehicle is traveling too fast for the upcoming roadway segment. The longitudinal countermeasure utilizes vehicle dynamic state and performance data in combination with information about the current pavement conditions and upcoming roadway geometry to determine the maximum safe speed for the vehicle. If the vehicle's current velocity exceeds the safe speed, a sequence of driver interface functions is triggered to alert the driver of the danger and avoid a crash. The longitudinal countermeasure is designed to prevent those road departure crashes caused by excessive speed and loss of directional control.

Vehicle dynamic state information is provided by on-board sensors, and includes vehicle velocity, acceleration, heading, and position on roadway (relative to the upcoming curve). The vehicle performance data includes vehicle braking efficiency, center of gravity, cornering characteristics, etc.

5.2.3 Pavement Monitoring Function

An approximate estimate of current pavement conditions (more specifically, the current coefficient of friction) can be inferred by monitoring the state of the windshield wipers (active windshield wipers indicate wet pavement, and therefore reduced coefficient of friction). More accurate estimates may be obtained by sensing the slip of the individual wheels. The information about the geometry of the road ahead includes such data as the approximate curvature and superelevation, and can be encoded in a digital map.

5.3 APPROACH/METHODS

ITS countermeasures are designed to prevent specific types of crash scenario. Since these crash scenarios and countermeasure interventions vary, overall system effectiveness is the sum of specific effectiveness values of the component interventions into the various dynamic crash scenarios. Based on this concept, the four steps listed below are used to analyze the crash reduction problem and estimate benefits:

(1) Build a mathematical model to best describe the overall crash problem.
(2) Analyze road departure crash scenarios and assess the likelihood of occurrence of each scenario.
(3) Derive an effectiveness rate for each specific crash scenario.
(4) Apply information and data in (2) and (3) to fit the mathematical model and calculate the weighted crash reduction rate (or weighted effectiveness rate).

5.3.1 Mathematical Model

The total weighted crash reduction rate can be derived using the following mathematical model.

$$\mathbf{SE = MP*U*}\left(\sum_i \left(\sum_j \mathbf{P(S}_{ij}\mathbf{)E(S}_{ij}\mathbf{)}\right)\right)\mathbf{*F}_i \qquad \mathbf{(5.1)}$$

Where

SE = Total weighted crash reduction rate
MP = Proportion of roadway departure countermeasure market penetration
U = Proportion of equipped vehicles that have a fully functioning countermeasure system
P(Sij) = Probability of a crash occurring under circumstance j given precrash scenario i
E(Sij) = Effectiveness of countermeasure in preventing crashes occurring under scenario j within causal factor i
Fi = Fraction of a relevant precrash scenario i to the road departure crash size

The details of scenarios and causal factors significant to road departures will be described in the following sections.

5.3.2 Crash Scenarios

Crash scenarios were adapted from the situation trees contained in the Performance Specification Contract report by the Robotics Institute of the Carnegie Mellon University [Carnegie, 19941. The Carnegie report did a thorough analysis of data using a clinical sample from the National Accident Sampling System (NASS) Crashworthiness Data System (CDS). The Carnegie report analyzed why road departure crashes occurred. The six mutually-exclusive road departure crash causal factors identified were excessive speed, loss of directional control (generally on slippery road surfaces), driver relinquished steering control (i.e., loss-of-control due to driver condition), driver inattention, evasive maneuver, and vehicle component failure. Two of these-evasive maneuver and vehicle component failure-are not addressed further in this analysis, Evasive maneuver-related crashes are addressed in the tear-end countermeasure benefits analysis, and vehicle component failures are not addressed at all in the current project due to their relative infrequency and the difficulty of assessing countermeasure effectiveness.

The Carnegie report applied engineering analysis of dynamic scenarios (driver state, vehicle state, and environmental conditions) of each crash type. Based on these analyses, situation trees were developed for each causal factor. In the report, a probability (i.e., the likelihood of occurrence of the scenario), was derived for each scenario by using these situation trees.

A total of 24 crash scenarios were identified to be potentially preventable by deployment of the countermeasures. These 24 scenarios and their brief descriptions are listed below by causal factors (Also see Figure 5-4, which illustrates the crash scenario trees, each branch of which corresponds to a specific causal factor.) Countermeasures having no effect on those scenarios were excluded, and will be discussed in the effectiveness section.

As stated before, the lateral functional sequence is designed to prevent those road departure crashes caused primarily by driver inattention and driver relinquishing steering control. The longitudinal countermeasure is designed to prevent those road departure crashes caused by excessive speed and loss of directional control (first two causal factors listed above).

5.3.3 Scenario Probability

The crash scenario probability, i.e., p(Sij), is defined as the possibility of the occurrence of a particular combination of crash principal causal factors (e.g., excessive speed, driver inattention), roadway alignment (straight or curved), roadway surface condition (wet or dry), and shoulder presence. Within a particular scenario category, there may be different possible driver conditions (e.g., alert, fatigued, intoxicated). Numerical values for crash scenario probabilities are taken from Figures 5-l through 5-4.

5.3.4 Effectiveness Rate

The effectiveness rate for any safety device is defmed as [Burgett, 1995]:

$$E = \frac{NWO - NW}{NWO} \tag{5.2}$$

where

E = Estimated effectiveness of a countermeasure system

NWO = Number of collisions that occurred when no vehicles were equipped

NW = Number of collisions that would occur if all vehicles were equipped

Currently, the proposed countermeasure systems have not reached the operational stage, implying that the system effectiveness measure cannot be directly derived. Hence, measurement from simulation experiment was adapted. The baseline lateral system effectiveness rate of 0.8 for inattentive drivers (0.8) was used for both the lateral and the longitudinal system. The 0.8 value for lateral system was obtained from road departure crash studies performed using the Iowa Driving Simulator [Carnegie, Task 3, V(II) 19951. The Iowa simulation studies did not produce a large enough sample of crashes at curved roadways to derive a statistically-reliable system effectiveness rate. The value 0.8 was adopted for the longitudinal system because the longitudinal system uses a more advanced technology such as digital map, and the system has a much longer preview or anticipation time than the lateral system. From the technology perspective, the longitudinal system should be more effective than the lateral system. Effectiveness rates for other crash scenarios were then derived from this baseline value and various assumptions (stated below)

Scenarios (S_{1j}) for Causal Factor 1 - Excessive Speed

S11 ***Alert drivers,*** crashes occurred on curved and ***dry*** roadways.

S12 Alert drivers, crashes occurred on curved and wet roadways.

S13 Alert drivers, crashes occurred on curved and ***icy/snowy*** roadways.

S14 ***Driver*** had ***been drinking*** (BAC <= 0.09), crashes occurred on curved and ***dry*** roadways.

S15 Driver had been drinking, crashes occurred on curved and wet roadways

S16 Driver had been drinking, crashes occurred on curved and ***icy/snowy*** roadways.

S17 ***Inattentive drivers,*** crashes occurred on curved and dry roadways.

S18 Inattentive drivers, crashes occurred on curved and wet roadways.

S19 Inattentive drivers, crashes occurred on curved and ***icy/snowy*** roadways.

Crash Scenarios

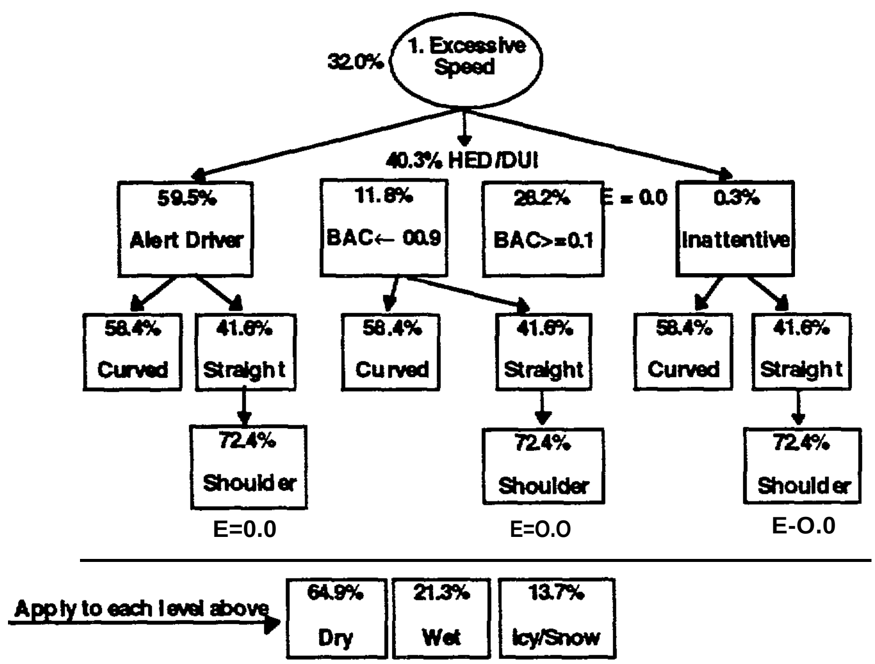

Figure 5-l. Crash Scenarios for Excessive Speed Causal Factor

Scenarios (S2i for Causal Factor 2- Lost Direction Control

S21 Alert drivers, crashes occurred on ***curved*** and ***dry*** roadways.

S22 Alert drivers, crashes occurred on curved and wet roadways.

S23 Alert drivers, crashes occurred on curved and ***icy/snowy*** roadways.

S24 Alert drivers, crashes occurred on ***straight*** and dry roadways ***with shoulder.***

S25 Alert drivers, crashes occurred on straight and wet roadways with shoulder.

S26 Alert drivers, crashes occurred on straight and ***icy/snowy*** roadways with shoulder.

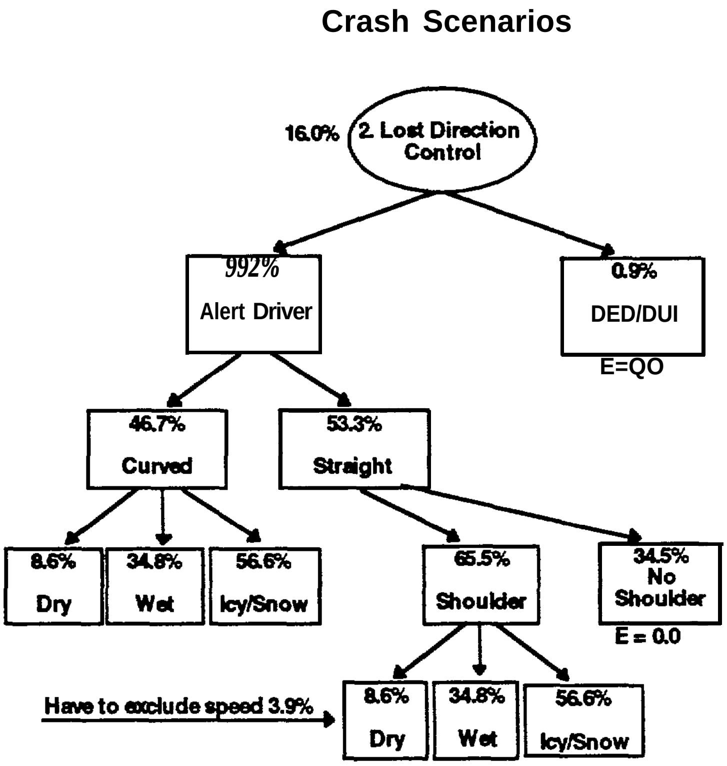

Figure 5-2. Crash Scenario for Lost Direction Control Causal Factor

Scenarios (S_{3j}) for Causal Factor 3- Driver Relinquished Steering Control

S_{31} Drowsy Drivers, crashes occurred on *curved* and *dry* roadways.

S_{32} Drowsy drivers, crashes occurred on curved and *wet* roadways.

S_{33} Drowsy drivers, crashes occurred on curved and *icy/snowy* roadways.

S_{34} Drowsy drivers, crashes occurred on *straight* and *dry* roadways *with shoulder.*

S_{35} Drowsy drivers, crashes occurred on straight and *wet* roadways with shoulder.

S_{36} Drowsy drivers, crashes occurred on straight and *icy/snowy* roadways with shoulder.

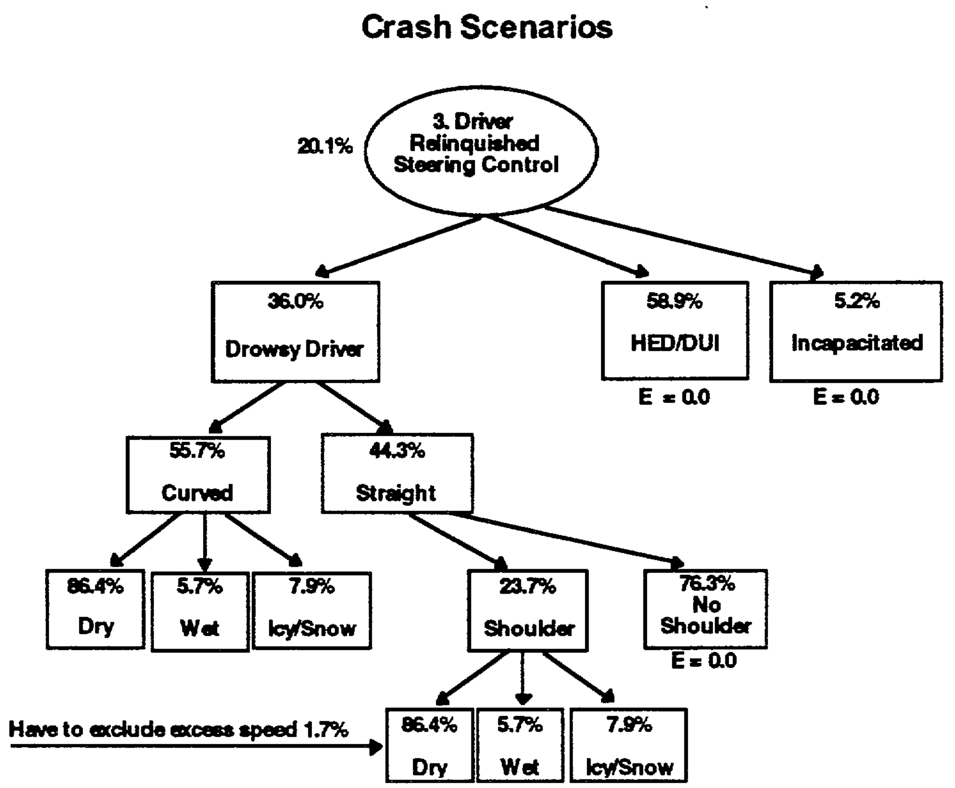

Figure 5-3. Crash Scenario for Driver Relinquished Steering Control Causal Factor

Scenarios (Sij) for Causal Factor 4-Driver Inattention

S41 Crashes Occurred on ***curved*** and ***dry*** roadways.
S42 Drowsy Drivers crashes occurred on ***straight*** and ***dry*** roadways ***with shoulder***
(Note: The analysis of statistical characteristics indicated that almost all road departure crashes of this type occurred on dry roadways).

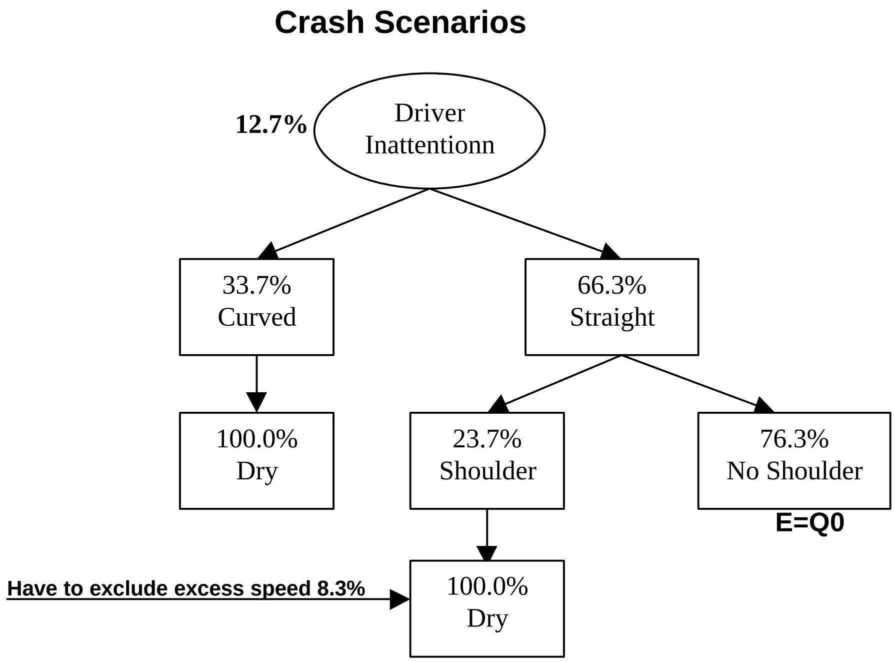

Figure 5-4. Crash Scenario for Driver Inattention Causal Factor

about the relative performance of inattentive drivers versus other drivers, and assumptions about roadway conditions.

Inattentive Drivers

As stated above, the crash reduction effectiveness rate (0.8) for inattentive drivers was derived from Iowa Driving Simulator studies. This serves as the basis for estimating crash reduction effectiveness for other crash scenarios.

Alert Drivers

The simplistic and conservative assumption is made that the countermeasure would be at least as effective for alert drivers as for inattentive drivers. Driven

Alcohol Impaired Drivers

In this section, the effectiveness was examined separately for two sub-groups: “grossly-intoxicated” (BACs >= 0.1) and “had been drinking” (HBD; 0 <BACs <= 0.09). The effectiveness rate for grossly-intoxicated drivers was assumed to be 0 based onMoskowitz’s study of the effects of alcohol on driving skills and behavior woskowitz et al, 1988] The authors reviewed 177 citations and concluded that even very low BACs were sufficient to affect skills relevant to driving. Driving performance measures, including reaction time, tracking and visual search, recognition, etc., might be impaired at BAC level as low as 0.05%. So far, the only countermeasure concept for intoxicated drivers is to monitor the driver and prevent vehicle operation upon detection of driver intoxication. However, at the current stage, this function is beyond the conceived goals of the road departure countermeasure. Therefore, the currently proposed road departure countermeasure is assumed to have no effect on grossly-intoxicated drivers, but some effect on HBD drivers.

For HBD drivers, the degradation by 8.4% of the mean control-response time for braking and steering was taken from the Driver Performance Data Book, 1987. Therefore, a simplistic assumption was made that countermeasure effectiveness for this type of driver could be derived by adjusting the baseline effectiveness rate for inattentive drivers (0.8) by 9 1.6%; i.e., 0.8*0.916 = 0.7.

Drowsy Driver

The assumption is made here that drowsiness is equivalent to HBD and thus that the same effectiveness rate would apply; i.e., 0.7.

Straight Roadway without Shoulder

Present road departure technology is severely challenged to warn the driver of an impending road departure condition before the vehicle actually leaves the side of the road. This is particularly true on straight roads because the road departure angle is usually very small and it is difficult to determine if the vehicle is actually going to leave the road until the vehicle actually leaves the road. If the road does not have a shoulder, the vehicle will be in very serious dynamic instability just as the warning system tells the driver that the vehicle is off the road. This situation allows the warning system to provide only a very small safety benefit at this time. Therefore, for this analysis, the effectiveness rate of present systems is estimated as 0.0. Future road departure warning systems using improved technology are expected to provide a much earlier warning and thus generate greater safety benefits.

Slippery Roadway

Analysis of crash statistical characteristics indicates that 65 percent of slippery roadway-related road departure crashes also involve adverse weather (e.g., raining). Assuming that information on windshield wiper functioning would be used to modify system assumptions about roadway coefficient of friction (i.e., the forward pavement detection function), one may assume the effectiveness rate to be O-8*0.65 = 0.5. With limited capability to sense pavement conditions, the system algorithm could be adjusted to account for wetness in 65% of the cases where there is a reduced coefficient of friction. With this adjustment, the effectiveness would be 80%. For the other 35% of the cases, the effectiveness should be zero.

5.3.5 Fitting Data To Model

Table 5- 1 summarizes the calculation of crashes reduction rate and effectiveness rate for each applicable scenario. A total weighted crash reduction rate of 24.0 percent was derived. If market

Table 5-l. Summary of Crash Scenarios and Corresponding Effective Rate

Causal Factor	Scenario S_{ij}	Effective Rate $E(S_{ij})$	Crash Scenario Probability $p(S_{ij})*F_i$	Crash Reduction Rate $p(S_{ij})*F_i*E(S_{ij})$
1. Excessive Speed	S_{11}	0.8	0.072	0.058
	S_{12}	0.5	0.024	0.012
	S_{13}	0.5	0.015	0.008
	S_{14}	0.7	0.014	0.010
	S_{15}	0.4	0.005	0.002
	S_{16}	0.4	0.003	0.001
	S_{17}	0.8	0.000	0.000
	S_{18}	0.5	0.000	0.000
	S_{19}	0.5	0.000	0.000
2. Lost Directional Control	S_{21}	0.8	0.006	0.005
	S_{22}	0.5	0.026	0.013
	S_{23}	0.5	0.042	0.021
	S_{24}	0.8	0.005	0.004
	S_{25}	0.5	0.019	0.010
	S_{26}	0.5	0.031	0.016
3. Driver Relinquished Steering Control	S_{31}	0.7	0.035	0.024
	S_{32}	0.4	0.002	0.001
	S_{33}	0.4	0.003	0.001
	S_{34}	0.7	0.006	0.005
	S_{35}	0.4	0.000	0.000
	S36	0.4	0.0001	0.000
4. Driver Inattention	S41	0.8	0.043	0.034
	S_{42}	0.8	0.018	0.015
Total				0.240

penetration rate and system maintenance rate are assumed to be 100 percent, the countermeasure systems could prevent 24.0 percent of 1.238 million road departure crashes, i.e., 297,000 crashes.

For simplicity, the weighted crash reduction rate of 24.0 percent was applied to fatalities and non-police-reported road departure crashes. Hence, the countermeasures will eliminate about 3,200 (0.240*13,300) fatalities associated with road departure and 345,000 (0.240*1,437,000) non-police-reported crashes, using previously published equations (Wang and Knipling 1994).

However, to derive a mote realistic estimate, market penetration rates of 5 percent to 20 percent were assumed. System maintenance rate is assumed to be 1. The total weighted crash reduction rate is estimated to range from 1.2 percent to 4.8 percent. Table 5-2 lists the possible reduction figures based on 5 percent and 20 percent of market penetration rates. Table 5-2 shows that the countermeasure systems are estimated to prevent 32,000 to 128,000 (police-reported and non-police-reported) crashes and 160 to 640 fatalities.

Table 5-2. Number of Crashes and Fatalities Reduced

	Number	Market Penetration Rate	
		At 5% Level	At 20% Level
Police-Reported Crashes*	1,238,000	15,000	59,000
Non-Police-Reported Crashes	1,437,000	17,000	69,000
Total Crashes	2,675,000	32,000	128,000
Fatalities**	13,330	160	640

* Rounded to nearest 1,000

** Rounded to nearest 10

5.4 REFERENCES

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Chapter 6 : Effectiveness Summary

The preceding sections covered in detail current knowledge and theory surrounding effectiveness of Collision Avoidance Systems (CAS) for tear-end, road departure, and lane change/merge crash types. To estimate potential benefits, the susceptibility of each crash type was analyzed by considering individual situations based on causal factors, crash scenario, and crash circumstance. The level of detail considered was such that valid estimates of effectiveness of crash avoidance systems could be made for that situation. The overall system effectiveness for each crash type was then calculated by summing the estimate of effectiveness of individual crash situations weighted by the relative size of each crash situation.

For rear-end collision avoidance, a system was analyzed that produces continuously more insistent driver warnings as the time gap between cars decreases from a safe gap to marginal to unsafe. The situations considered in the analysis include two precrash scenarios (lead vehicle decelerating and lead vehicle not moving) and two circumstances (dry pavement and slippery pavement}. Causal factor analysis was used to determine the portion of rear-end crashes that are able to be addressed using the rear-end crash warning system. Using results from driver behavior studies under highway conditions and in driving simulators to set parameters in a kinematic model, Monte Carlo simulation was used to determine the probability of a crash occurring in each combination of precrash scenario and circumstance both with and without the crash warning system. The simulation indicated a reduction of 42% of relevant crashes, or a total of 469,000 crashes annually, with the lead vehicle decelerating and 75.1% of relevant crashes, or a total of 322,000 crashes annually, with the lead vehicle not moving. The overall system effectiveness for relevant rear-end collisions is 51% representing a total of 791,000 annual crashes. No estimates are made regarding reductions in severity of crash in the 49% of crashes that do occur, or reduction in injuries and fatalities due to avoided crashes:

For lane change and merge collision avoidance, a highly reliable system was analyzed that will provide covert alert when an object is in the coverage zone and a more intrusive warning when the operator indicates intention to change lanes by using a turn signal. Although both decision and execution phases of the lane change/merge maneuver are discussed, the effectiveness of the system was predicted only for driver support during the decision phase. Four different interaction modes were described for ways in which operators may use the side collision avoidance system based on combinations of visual attentiveness and device usage. Based on data from different studies, estimates of effectiveness of the system consisting of the driver and the collision avoidance system were compared to the current effectiveness of the driver alone. Estimates of the decrease in collisions range from 8% to 68%. The authors' best estimate of the effectiveness is a reduction of 37% or about 90,000 crashes annually.

For the single vehicle road departure collision avoidance, the analysis considers one type of system that detects drift of the vehicle as it begins to depart the roadway and another that detects when the vehicle is predicted to be unable to safely negotiate the upcoming roadway segment. The situations considered in the analysis were categorized by causal factors and dynamic scenario. The causal factors included excessive speed, loss of directional control, relinquishing of steering control, inattention, evasive maneuver, and vehicle component failure, of which the last two were not considered relevant to the analysis. Dynamic scenarios consisted of a combination of alert, drinking, drowsy, or inattentive drivers; curved or straight roadway; roadways with or without shoulders; and dry, wet, or icy/snowy roadway surface. Using data from studies of driver performance, estimates of the effectiveness of the devices in each crash situation, and statistics on probability of causal factor combination resulting in an accident, the system effectiveness was estimated at 24% of road departure crashes or about 297,000 road departure crashes annually.

Since avoidance of a road departure accident can be assumed proportional to the number of serious or fatal crashes, approximately 3,200 fatalities and 130,000 non-fatal injuries can be expected to be avoided annually.

To develop an estimate of the potential for CAS technology to reduce crash experience on the highway network of the United States, the results from each type of CAS can be tabulated. Totals produced by a simple summation of these estimates yield a first estimate of the magnitude of the total number of crashes that could be avoided annually. It should be noted that the estimates only reflect police-reported crashes.

Crash Condition	Total Number of Crashes	Relevant Crashes Addressed by Countermeasures	Effectiveness Estimates for Relevant Crashes	Number of Crashes Reduced
Rear-End Crashes	1.66M	1,547,000	51%	791,000
Lane Change/Merge	0.24M	190,000	47%	90,000
Road Departure	1.24M	458,000	65%	297,000
Totals	3.14M	2,195,000		1,178,000

Chapter 7: Monetary Benefits of Collision Avoidance Systems (CAS)

Jing-Shiarn Wang
Rob Sherrer
Larry Blincoe

7.1 INTRODUCTION

This section describes the methods used to derive estimates of the monetary benefits of three collision avoidance systems (CASs) currently under research and development by the National Highway Traffic Safety Administration (NHTSA). It also takes a preliminary look at the cost-effectiveness of CASs, presenting benefit-cost ratios for estimated monetary benefits and a range of CAS costs.

7.2 MONETARY BENEFIT ESTIMATES

NHTSA has estimated the 1994 economic costs of motor vehicle crashes to be $150.5 billion (Blincoe, 1996). This cost represents the lifetime costs of 40,676 fatalities, 5.2 million people with non-fatal injuries, 3.8 million uninjured occupants, and 27 million damaged vehicles. These estimates are based on both police-reported and unreported crashes. Included in the economic costs are the direct value of goods and services which must be purchased as a result of motor vehicle crashes. They include medical care, legal services, workplace costs, vocational rehabilitation, emergency services, vehicle repair services, and insurance administration costs. In addition, economic costs include the value of both workplace and household productivity lost due to death or injury, and the value of travel delays to non-involved motorists. However, the economic values do not include those less tangible values such as a valuation for "pain and suffering" and loss of life. These intangible values can be derived from "willingness-to-pay" studies which examine marketplace behavior to determine the value that people place on reducing risk. There is far more uncertainty involved with these estimates than those based on direct economic costs. Thus, this analysis addresses direct economic costs only.

The monetary benefit of any CAS can be represented by the costs of crashes prevented by that system. Therefore, one measure of benefits of a CAS is the total cost savings of motor vehicle crashes which can be estimated as the sum of the cost of all crashes prevented. In this manner, crash reduction benefits provided by ITS CAS can be translated into monetary values. The analysis of benefits is done for a hypothetical future year when all vehicles in the fleet are equipped with CASs, but in terms of 1994 dollar value.

The three ITS CASs discussed in this document have different estimated effectiveness rates for reduction of relevant crashes. According to these estimates, the rear-end countermeasure system could prevent 47.7 percent of rear-end crashes, the lane change/merge countermeasure could prevent 37.0 percent of Jane change/merge crashes, and the road departure countermeasure system could prevent 24.0 percent of road departure crashes. Overall, these three countermeasure systems could provide an estimated effectiveness, or crash reduction, of 18 percent of aLl crashes. The economic benefits of these systems would be roughly $25.6 billion in 1994 dollars (NHTSA had previously provided an estimated of $23.4 billion in benefits based on 1990 dollars, ITS America

6th Annual Meeting, Houston, Texas, April 14-16, 1996). As noted above, these potential economic benefits include only cost savings from crashes that would be prevented by the three selected ITS countermeasure systems. They do not include estimates of the savings due to reduction of injury severity in non-preventable crashes that could result from some of these CASs. Analytical studies (e.g. Knipling et al., 1993) have indicated that for some countermeasures, the benefits from these injury reductions could be significant.

In addition, this document presents preliminary cost saving estimate for each individual ITS CAS. Unit costs provided by Blincoe (1996) were used to estimate the CAS economic benefits. Like previous NHTSA monetary estimates, the Blincoe (1996) estimates utilized here include police-reported, non-police-reported, and under counted crashes. The General Estimates System (GES) and Fatal Accident Reporting System (FARS) were the major sources for police-reported non-fatal injuries and fatalities respectively. Insurance claims were used to assess the number of property-damage-only vehicles. The fundamental steps involved and the methodology are described as follows:

Police-reported KABCO severity were converted to Maximum Abbreviated Injury Scale (MAIS) values using conversion matrices generated for injuries based on 1982- 1986 National Accident Sampling System data

Non-fatal injuries (by MAlS scale), and property-damage only (PDO) vehicles were then adjusted to account for under counting in police reported and non-police-reported crashes.

Fatalities were adjusted by redistributing the total number of fatalities from 1994 FARS to each crash type based on the fatality ratios in GES.

Costs for component categories (the five MAIS scale values, fatalities, and PDO vehicles) were then calculated by multiplying the corresponding unit costs and the number of incidents.

CAS benefits are estimated by applying the effectiveness rate of the CAS to the sum of costs for all cost components. It is noted that there was no detailed effectiveness analysis of the CAS for each cost component available; therefore, the same effectiveness rate for the CAS was applied across all components.

Table 7-1 summarizes the crash costs by each cost component for rear-end, lane change merge and single vehicle road departure crashes. Non-fatal injuries and property damaged vehicles were rounded to nearest 1,000. The U.S. total monetary costs for the above three crash types are: $35.4 billion, $3.5 billion, and $30.7 billion respectively.

Table 7-2 shows the economic benefits of each CAS type by applying the effectiveness rate to the total costs. Annual monetary benefits are estimated to be $16.9 billion for rear-end, $1.3 billion for lane change/merge, and $7.4 billion for single vehicle road departure CAS. The total savings estimate for these three CAS of $25.6 billion assumes that there would be no other disbenefits when these three CAS are integrated into vehicles.

7.3 COST-BENEFIT ANALYSIS

The extent to which CASs would be economically cost-effective can be assessed by comparing the above-estimated dollar value of safety benefits to the cost of CASs. The annual cost to consumers is the total cost of installing a CAS in all new model vehicles. For the purpose of this analysis, it its assumed that 14.5 million new vehicles (passenger cars, light trucks, and medium/heavy trucks) are sold each year. (Note that for the last 9 years, based on the DRI/McGraw-Hill; Review of US. Economic, April 1996, the average number of new vehicles sold in the United States was 14.5

Table 7-1. Economic Cost for Three Crash Types by Cost Components

Cost Components	Unit Costs* (1994 $)	Crash Types: Rear-End # of Units	Rear-End Total $ in Billions	Lane Change/ Merge # of Units	Lane Change/ Merge Total $ in Billions	Single Vehicle Road Departure # of Units	Single Vehicle Road Departure Total $ in Billion
Property Damaged Only Vehicles	$1,663	7,551,000	$12.6	1,171,000	$1.9	1,827,000	$3.0
MAIS 0, Not Injured	$1,129	879,000	$1.0	65,000	$0.1	439,000	$0.5
MAIS 1, Minor	$7,243	1,354,000	$9.8	112,000	$0.8	655,000	$4.7
MAIS 2, Moderate	$34,723	122,000	$4.2	8,000	$0.3	99,000	$3.4
MAIS 3, Serious	$103,985	32,000	$3.3	2,000	$0.2	35,000	$3.6
MAIS 4, Severe	$230,042	3,000	$0.7	200	$0.0	5,000	$1.2
MAIS 5, Critical	$706,754	2,000	$1.4	100	$0.1	3,000	$2.1
Fatalities	$831,919	2,881	$2.4	78	$0.1	14,702	$12.2
Total			$35.4		$3.5		$30.7

* Unit costs were adapted from Blincoe 19%.

Table 7-2. Annual Economic Benefits of CAS

Collision Avoidance Systems	Effective Rate %	Economic Cost-Savings (1994 $ in Billions): Crash Cost	Saving
Rear-End	47.7	35.4	16.9
Lane Change/Merge	37.0	3.5	1.3
Single Vehicle Road Departure	24.0	30.9	7.4
Total			25.6

million including 9.2 million passenger cars, 5.0 million light trucks, and 0.3 million medium/heavy trucks annually). The cost of CASs is not yet known, and therefore, for the purpose of this analysis a range of potential costs is used. The consumer cost is assumed to be in the range of $100 to $2,000 per car. The value of $100 represents an optimistic view of the potential lower limit on cost to consumers while $2,000 represents a subjective view of the upper limit on what consumers would be willing to pay. Based on this range, the total costs of ITS countermeasures for equipping these 14.5 million vehicles therefore would range from $1.4 billion to $29.0 billion, annually.

The cost of CASs would be incurred by consumers at the tune of new vehicle purchase in the form of higher sales prices, while the crash-prevention (and crash-severity-mitigation) benefits of CASs would accrue over the operating lives of the vehicles purchased.' For cost vs. benefit comparison, therefore, the cost of equipping a given model year fleet with CASs would have to be compared to crash-prevention benefits that would be realized in future years. For a valid comparison of benefits and costs, the present value of these future benefits must be estimated by discounting them back to the time of vehicle purchase on an annualized basis. For this estimation, it is assumed that benefits will accrue year-by-year in proportion to the annual mileage accumulated each year by a given model year light-vehicle fleet as it ages. (Estimates of annual year-by-year fleet mileage takes into account vehicle scrappage rates and the fact that vehicles are driven somewhat less each succeeding year as they age.) The derivation of the discount factors for passenger cars and light trucks is shown in tables contained in Appendix B. For determining benefit-cost ratios, a discount rate of 4 percent (the rate applied in estimating the economic cost of accidents by Blincoe, 1996) is applied to the above estimated monetary benefits to derive their discounted present value. As shown, the respective passenger-car and light-truck discount factors for the 4 percent discount rate are 0.8327 and 0.8018, respectively. The weighted average discount factor for the two vehicle types combined is 0.8218 (assuming annual sales of 9.2 million passenger cars, 5.0 million light trucks, and 0.3 million medium/heavy trucks). This factor is used to adjust the aboveestimated monetary benefits to derive the present discounted value of benefits which are then compared to the costs on an annualized basis. The present total discounted value of benefits is thus estimated to be $21.0 billion ($25.6 billion * 0.8218):

A direct comparison between the estimated present discounted benefit value of $21.0 billion and potential costs is shown in Figure 7-1. As shown in this figure, the net annual monetary benefits would be the difference between the present value of potential benefits of crashes prevented and the total CAS costs. Net annual monetary benefits would range from -$8.0 billion ($21.0 billion - $29.0 billion) to $19.6 billion ($21.0 billion - $ 1.4 billion), depending on whether the CAS cost would be $2,000 or $100 per vehicle.

Another common cost-effectiveness comparison is to calculate benefit-cost ratios. Table 7-3 shows the cost effectiveness of an integrated CAS in terms of benefit-cost ratios for the present discounted value of benefits and the range of CAS cost estimates. The benefit-cost ratio is the ratio of present discounted benefits ($21.0 billion) to total CAS costs for 14.5 million passenger vehicles. For example, total CAS costs would be $1.4 billion if CAS cost $100 per vehicle; thus, the benefit-cost ratio would be $21.0/$1.4= 15.0.

As indicated, the economic benefits of the conceived CAS could be 15 times higher than the cost if its cost is $100, about three times higher if the cost is $500, and 1.5 times higher if the cost of the CAS is around $1,000. There would be no net economic benefit if CAS costs were $1,500 or greater.

Based on the above estimates, it would appear that our efforts in developing CAS should strive to keep the consumer cost of these systems per vehicle to below $1,500. This derived dollar value is based on the assumption of a 4 percent discount rate. Different assumptions regarding the discount rate yield different benefit-cost ratios, as shown in the Table 7-4.

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1 As discussed above, annual benefits arc estimated for a hypothetical future year when all vehicles would be equipped with CASs for cost effectiveness analysis, it is assumed that lifetime benefits accruing to a given model year fleet that is fully equipped with CASs would be equal to this estimate of annual benefits. This would be the case assuming constant annual vehicle sales volumes and constant vehicle travel and scrappage rates.

2 Note: The estimates provided by NHTSA at the ITS America 6th annual meeting was based on undiscounted economic benefits using 1990 dollars.

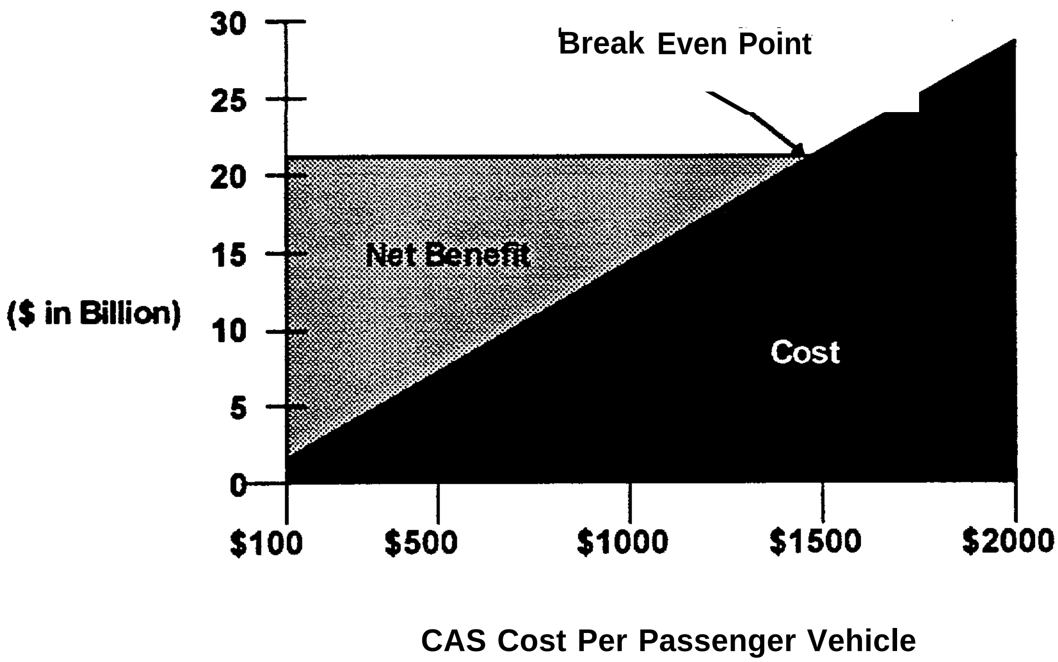

Figure 7-1. Benefits and Cost of an Integrated ITS Crash Countermeasure

Table 7-3. Cost Effectiveness:
Benefit-Cost Ratio for a Range of CAS Costs

	CAS Costs				
	$100	$500	$1,000	$1,500	$2,000
Benefit-Cost Ratio	15.0	2.9	1.4	1.0	0.7

Table 7-4. Benefit-Cost Ratios at different discount rates for a Range of CAS costs

Discount Rate	Discount Factor	Present Value of Benefits ($ in Billion)	Benefit-Cost Ratio by CAS Costs				
			$100	$500	$1,000	$1,500	$2,000
2%	0.9029	$23.1	16.4	3.2	1.6	1.1	0.8
4%	0.8218	$21.0	15.0	2.9	1.4	1.0	0.7
7%	0.7230	$18.5	13.1	2.6	1.3	0.8	0.6

Table 7-4 indicates that benefit-cost break even points differ depending on the discount rate applied. The economic benefit-cost break even point would be $1,586 at a 2 percent discount rate, $1,500 at a 4 percent discount rate, and $1,269 at a 7 percent discount rate.

Moreover, it is important to recognize that the previous analysis is expressed in terms of "economic benefits". It measures savings in the flow of goods and services and productivity that could result from deployment of CAS. It does not reflect the less tangible, but often more important benefits such as prevention of pain, suffering and death. These "humane" benefits increase the quality of life for potential crash victims and their families. They represent additional benefits which accrue beyond the economic impacts. Therefore, a break even point derived from economic benefits defines the point at which society begins to pay some level of cost for the improved quality of life that results from the specific countermeasure. At cost levels below the break even point, these "humane" benefits are free because the costs of the countermeasure arc offset by economic benefits.

The issue of how high costs could rise above the break even point and still be acceptable to society is largely a matter of judgment. When laws or regulations requiring safety countermeasures are contemplated, policy makers must make these judgments. If CASs are voluntarily offered by industry, either as standard equipment or as options, consumers will judge the worth of the systems in light of their own perceptions of the level of personal risk that they are wiling to accept.

Economists have attempted to measure the implied value that consumers place on life through market behavior. These "willingness-to-pay" studies examine, for example, the relative wage rates for risky and safe jobs, or the prices that consumers voluntarily pay for safety products. There is wide variation in the results of these studies, but most economists agree that the value of fatal risk reduction lies in the $2-$5 million range.

It is also important to understand that cost-benefits would bc different depending on the involved vehicle types. Earlier studies (e.g., Wang, et al., 1996) have indicated that combination-unit trucks (CUTs) have high mileage exposures, long operational lives and high crash severities; and thus have much higher per-vehicle life cycle monetary crash costs. These high crash costs imply that a CAS for a CUT can generally afford to be considerably more expensive than that installed on a passenger car and still achieve positive net benefits. However, the total annual national benefits from CUT CAS deployment would be limited, since they represent a small percentage of the vehicle population.

In summary, these three countermeasures could achieve significant monetary benefits. The economic benefit estimates provided here illustrate that, if all vehicles were equipped, these three countermeasures have the potential to save a total of $25.5 billion annually. The benefits do not include other potential benefits such as injury severity reduction which could result from a CAS. Also, the estimates were based on current ITS technologies that have been developed under NHTSA ITS research programs. Effectiveness rates of CASs will improve as new technologies are developed and arc introduced into vehicles. In addition, trends in safety countermeasures and advanced electronics in general indicate that the price of hardware would decline. Therefore, benefits-per-unit-cost of CASs would likely bc greater in the future.

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Chapter 8: Discussion

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Predicting the future is a difficult task It depends on data that ate largely unavailable, requires assumptions that often cannot be verified (else they would not be assumptions), and generally presumes a rather simplistic view of the world. Predictions of systems with human components are even more challenging because humans are very context-dependent creatures who exhibit creativity and change over time. Rational and informed citizens will best view predictions with skepticism and caution, as hints into possible futures rather than as ground truth. Predictions provide insights into fruitful areas of research and development and indicate what factors in CAS development and deployment might be significant Some key limitations and caveats associated with the preliminary benefit estimates contained in this document are provided below. Though organized by section, many caveats apply to the benefits estimation effort in general.

8.1 LIMITATIONS OF REAR-END CRASH AVOIDANCE RESULTS

The rear-end crash avoidance system effectiveness estimates presented in this report offer a preliminary assessment of the potential offered by rear-end CAS technology like that described in this report The modeling and simulation were carefully carried out to make use of existing data that attempts to compare the effects of CAS support with no CAS support. The current state of knowledge in this area is such that many assumptions were made and many extrapolations were required. In addition, it is extremely difficulty to conduct human factors research in the crash avoidance arena that is fully realistic and yet safe to all involved. These considerations necessitate caution in interpreting the results reported here. Future research into critical areas of rear-end crash avoidance will lead to a better understanding of these issues and their informed resolution.

Monte Carlo simulations of simple kinematic representations were used to model the effectiveness of a hypothetical rear-end crash avoidance system. This work involved modeling substantial amounts of empirical data in a well-known modeling scheme. However, a range of caveats must accompany the results. These caveats arise from the preliminary nature of the work and the absence of sound empirical data with which to model all relevant aspects of the CAS effectiveness problem. Key caveats arc presented below.

8.1.1 General Simplifying Assumptions

The analysis assumed full fleet penetration, full CAS usage, 100 percent CAS reliability, perfect driver compliance via execution of fully controlled braking maneuvers, and no change in driver data gathering behaviors or risk compensation. These arc simplifications and the true state of affairs will undoubtedly differ in at least some respects.

8.1.2 Assumed Independence Among Modeling Parameters

The Monte Carlo simulation conducted assessments based on combinations of parameters that were assumed to be independent of one another (with the exceptions of driver reaction time and initial time headway or gap between lead and subject vehicle). There may be correlations among parameters in crash events that will lead to different outcomes than those predicted.

8.1.3 The Relationship Between Driver Reaction Time and Time Headway

The assumption that driver brake reaction times will be shorter given shorter time gaps assumes that the subject vehicle driver is, in fact, aware of the gap. The target population of drivers are, however, by definition inattentive to the rear-end crash hazard, at least momentarily. Thus, such crash-involved drivers may be unaware of the gap (which may change suddenly) and therefore may not respond earlier or more quickly.

8.1.4 Driver Reaction Time (RT) Budgets

The use of Equation 3.9 for the LVNM case assumed that all drivers brake at the same time, i.e., within $V_F{*}t_B$ feet of CAS warning onset. This implies a fixed driver reaction time "budget" of 0.9 seconds. This time budget is shorter than the median or mean surprise brake reaction times of several published studies (Taoka, 1987). Therefore, there may be a sizable percentage of the driver population who will not respond that quickly, thereby reducing effectiveness.

8.1.5 Multiple CAS Presentations and the Psychological Refractory Period (PRP) Effect

A related concern is the possibly rapid succession of 'Look Ahead" and "Brake" auditory warnings. Horowitz (1994) also raised a concern that the rapid succession of CAS signals could induce the psychological refractory period (PRP) effect in which reaction to a second stimulus is delayed by the presentation of an earlier stimulus. This effect has been demonstrated in the laboratory and diminishes steadily until there is generally no effect at stimulus onsets separated by 0.5 seconds or longer. Whether the PRP effect is a legitimate concern for ITS crash avoidance systems is an empirical question that may merit further investigation.

8.1.6 Point at Which SV Driver Becomes Aware of the Crash Hazard

The assumption that drivers without the system may become aware of the lead vehicle anywhere during the approach to that vehicle makes it plausible to use a rectangular distribution. However, the assumption that neither CAS-supported drivers nor drivers without CAS support will ever respond at greater than d_0 feet is a simplification that will likely differ in real-world settings. The simplification is made in light of the fact that no empirical information was available on this issue.

8.1.7 Feasibility of Assumed Evasive Braking Maneuvers and Secondary Crash Consequences

The assumed distributions of following-vehicle braking levels used in the evaluations may differ from those undertaken in actual rear-end crash circumstances. Perhaps of even greater concern is the instability (uncontrolled skid) that may accompany the more aggressive braking levels or combined braking and steering when performed by average automobile drivers. Secondary crash consequences (e.g., chain reaction crashes) are also not addressed in this (or any other) effectiveness estimation.

8.1.8 Lead Vehicle Deceleration Distributions

The lead vehicle decelerations for rear-end crashes were assumed to follow distributions like those observed at intersections on dry and wet pavements. However, rear-end crashes occur at locations other than intersections and may involve mote extreme lead vehicle braking by the lead vehicle, e.g., emergency braking. An increase in lead vehicle decelerations would decrease CAS effectiveness, all else being equal.

8.1.9 Time Gap Distribution

The time gap data in Table 3-5 was taken from an on-road study in which the test participants followed a confederate vehicle they knew was part of the study. They car-followed first without driver support and then with rear-end CAS driver support. The results showed that without CAS support, drivers adopted shorter time gaps for car following than with CAS support However, these results may reflect the influence of experimental procedures as much or more than CAS effects alone. For example, unsupported driving always preceded driving with CAS support Thus, unsupported driving gave the drivers the opportunity to realize that the confederate vehicle was driving erratically. This experience alone might have prompted maintenance of greater car following time gaps when the CAS was introduced, independent of the CAS effects. In addition, the test participants drove an instrumented vehicle and knew they were in a study. This, plus the obvious introduction of the CAS interface, may have prompted the test participants to try to please the experimenters or work with the CAS in a manner they thought was expected of them. Thus, the observed behavior with the CAS may not bc similar to behavior that would occur when the driver is alone, in his or her own vehicle, driving under time pressure, etc.

8.1.10 Time Gap Distributions and Crash-Involved Drivers

The time gap distributions of Table 3-5 may not necessarily reflect those of crash-involved drivers. In a study examining the distributions of car following time gaps as a function of driver traffic violations (no violations versus one or more violations in a seven-year period), Evans and Wasielewski (1982) found 27.5 percent of drivers with violations were observed following at gaps of less than 1 second compared to 21.6 percent for the violation-free drivers. This suggests that crash-involved drivers may adopt more risky driving strategies. This effect may hold even in the face of CAS technology.

8.1.11 Assumed Driver Brake Reaction Times for Rear-End LVD Scenarios

The driver brake reaction time (RT) distribution used in the rear-end LVD scenarios was taken from a simulator study in which two vehicles were locked as a pair traveling with a 2 second time gap at 65 mph for 5 seconds, followed by sudden 0.85 g braking of the lead vehicle. While this data has some relevance to the rear-end LVD case, it may not extrapolate fully to cases involving travel speeds of 20 to 60 mph and much more mild lead vehicle decelerations. Also, to the extent that test participants in the simulator study were looking for or expecting sudden changes in the lead vehicle, this data may differ from momentarily inattentive drivers in the real world who look up to fmd the vehicle ahead has suddenly slowed down.

8.1.12 Extrapolations of Driver Brake Reaction Time Distributions in Rear-End LVD Scenarios

The extrapolations of driver brake reaction times in Table 3-7 are based on the assumption that shorter time gaps are accompanied by faster reaction times. The validity of this assumption for momentarily inattentive drivers (the target population for the CAS concept evaluated) has already been discussed. In addition, the modifications for time gaps of less than 2 seconds are assumed for convenience The superiority of CAS warning may not always hold in the real world, especially if non-auditory CAS warnings are considered. Also, there are normally correlations between brake RT and the subsequent maximum deceleration applied yet this was not explicitly considered. Longer reaction times can be compensated for by greater decelerations, up to a point and less aggressive braking will require earlier brake applications, all else being equal.

8.2 LIMITATIONS OF LANE CHANGE/MERGE CRASH AVOIDANCE RESULTS

In this section, several caveats associated with SCAS effectiveness estimation and interaction modes are brought out. (See also comments in Appendix A). Effectiveness attenuation factors and research needs arc also discussed.

8.2.1 Limitations of the Decision-Execution Phase Concept

The characterization of a driving maneuver into decision and execution phases is an obvious over-simplification. Decision making continues throughout the execution phase as maneuver execution is carried out. There is not a sharp demarcation between the decision phase and the execution phase. For certain crash scenarios there may be no "decision" at all.. For example, road departure is a crash type but is not a maneuver, per se While there may be a decision to drive at excessive speed into a curve, more than likely it is the execution of the route-following task during which speed is adjusted as new information is obtained. Similarly, a lane drift due to inattention or incapacitation is not a maneuver and therefore does not have an associated decision phase

8.2.2 The Importance of Specific SCAS Features

The effectiveness of a SCAS will depend on the specifics of its implementation. There will be a variety of SCAS products, for example. These will differ, in their Sensor performance, their warning or control algorithms, their driver interface, and so on. Any or all of these factors will likely affect the overall performance of the driver-plus-SCAS system. Thus, it is not possible to accurately estimate the effectiveness of a SCAS without fairly in-depth information or assumptions about design characteristics.

8.2.3 The Importance of Crash Circumstances

The effectiveness of a SCAS will depend on the specifics of the crash circumstances to which it is targeted. Factors such as initial lateral gap between SV and POV, lane change aggressiveness, and lateral acceleration levels are important characteristics of hazard conditions. However, they are probably not sufficient to predict crash avoidance effectiveness. Effectiveness estimation with center high-mounted stop lights (CHMSLs) provide an illustration of this fact.

A large scale field study was conducted in the early 1970s using taxi-cabs in a city setting to assess the impact of CHMSLs on rear-end crash incidence. The results were impressive. The prediction was that tear-end crashes should be reduced an estimated 50% to 60% with the broad-scale introduction of CHMSLs into the fleet. Almost 20 years later, the crash record indicates that the effectiveness of such technology is closer to 8% to 12% (Goodman, personal communication, 1995). The reasons for this attenuation arc unclear. However, a "theory" of why CHMSLs should work might have led to insights into the attenuation. For example, one theory might be that CHMSLs work by providing the subject vehicle (SV) driver with additional information about the actions of one or more vehicles in front of the lead vehicle. If so, then attenuation might be predicted by the representativeness of such crashes in the original fleet study, by the attenuation that might result from changes in the tinting of windshields, by variations in the &sign of CHMSLs that are inferior in detectability to those tested in the original fleet study, by the increasing numbers of vans (that do not allow for viewing of the CHMSLs of the vehicles in front of the lead vehicle), and so on.

8.2.4 The Potential Non-Representativeness of Archival Driver Performance Data

Even simple modeling efforts of effectiveness make use of human performance data that may differ from the performances of crash-involved drivers. Insurance underwriters subscribe to a belief in error-prone drivers. If there really are a sub-set of error-prone drivers, they may perform or behave differently than the drivers represented in the data used for modeling purposes. Elderly drivers may be another example of drivers who are over-involved in certain types of crashes, yet are under represented in the archival data set used for modeling SCAS effectiveness.

8.2.5 The Similarity in Response of Modeled Versus Actual Performance

The paradigm used in collecting data for effectiveness or benefits estimation must be carefully considered. Surprise braking in response to a rapidly decelerating lead vehicle may be different than the braking observed in response to, say, a block of Styrofoam beiig launched off the back of a lead vehicle in a human factors study of surprise brake reaction time. The decelerations observed at a signalized intersection may not reflect the braking behavior observed on the highway in a terminus crash circumstance. Finally, simulator data may not reflect real-world driving behavior because of effects due to the visual scene generator, hrnitations of the motion base to provide realistic motion cues, and demand characteristics of the simulator setting on the driver.

8.2.6 Modes of Driver-SCAS Interaction

There is, with the exception of Mazzae and Garrott (1995), virtually no published information known to the authors on the relative frequency of each of the driver-SCAS interaction modes. Thus, the necessary information to make a sound preliminary estimate of SCAS effectiveness or benefits is not available. New research techniques are needed to discriminate between series and parallel system behavior. Research is needed to examine how and why such interaction modes vary across drivers and within the same driver over time.

8.2.7 SCAS Driver Interface Design

The diagrams of driver and CAS interaction presumed a fully reliable link between the SCAS and the driver. In application, there are many challenges to conveying necessary and sufficient information reliably to the driver. The design of the driver interface will therefore be crucial to the effectiveness of the SCAS as a whole. The design of such an interface is challenging given the range of driving situations (lighting, noise levels), driver in-vehicle behaviors (visual allocation, head movements, and so on), and driver distractions that the driver interface must accommodate.

8.2.8 Driver Workload or Distraction

The performance of a SCAS may be degraded by distractions both in the outside the vehicle around the time of a lane change. Driving scene distractions and attcntional demands may take the driver's attention away from the SCAS display and thus decrease its effectiveness. In-vehicle distractions such as cellular phone use, car radio use, other ITS devices, or other passengers may similarly compromise the performance of a SCAS that, when evaluated without such real-world distractions, appears more promising.

8.2.9 Open-loop Behavior

Many human behaviors are performed automatically and without much conscious attention. Such behaviors include habits or over learned behavior patterns that, once the performer's intent is set, are performed in an open-loop fashion, i.e., without attentional checks or control during their execution. There is evidence that lane changes may be open-loop in at least some instances

(McRuer, Wier, Allen, & Klein, 1977). Recent research has demonstrated that a SCAS may break or interrupt the open-loop nature of the lane change maneuver (Schumann, Godthelp, Farber, and Wontorra, 1993) but more research is needed into this important phenomenon.

8.2.10 Perceptual Filtering of SCAS Alerts

The SCAS description given earlier assumes that the SCAS will provide a covert alert to the driver whenever an object is detected in the hazard zone. Alerts will be a common occurrence under normal driving conditions due to other traffic overtaking the subject vehicle. One problem that may arise is that such alerts will become largely extraneous to normal driving. People routinely filter out extraneous (situationally defined) sensory inputs to avoid being overwhelmed by what otherwise would be ". . ..one great blooming, buzzing confusion" (James, 1890). SCAS alerts in the decision phase of a lane change will be compromised if their presentation during non-lane change driving periods renders them extraneous.

8.2.11 False or Nuisance Alarms

There has been much concern raised over the impact of false or nuisance alarms on driver compliance with a SCAS alert or alarm. Tijerina (1995) outlines some of the negative consequences that may arise: the SCAS is turned off, the SCAS display is turned down, the driver takes longer to react, or the driver does not comply at all. Very little empirical research in the driving environment has been reported to shed light on the real magnitude and nature of this problem area but it merits further research and may considerably affect the effectiveness of SCAS technology.

8.2.12 Indicators of Driver Intent

Chovan, Tijerina, Alexander, and Hendricks (1994) pointed out the difficulty in discriminating a lane change start from normal lane keeping variation based on the vehicle trajectory alone. It appears that if SCAS technology is to be truly intelligent, more research is needed to detect and make use of indicators of driver intent to change lanes. Such a vector of indicators, if available and processed in real time, might selectively alter the driver alerts or warnings (e.g., presentation, stimulus magnitude, etc.). Artificial intelligence tools such as neural networks might be trained to discriminate instances where the driver will change lanes in the next few seconds from instances where the driver will not. Hypothetical examples of indicators of intent to change lanes might include a following distance of less than x feet and a closing rate of greater than y feet per second to the vehicle ahead, an upcoming exit given the chosen route in an Automated Traveler lnformation System (ATIS), an obstacle detected in the roadway ahead, etc.

8.2.13 Driver Individual Differences

Age, perceptual-motor skills differences, risk-taking differences may all affect the drivers response to lane change CAS technology. If the drivers most likely to be involved in a lane change crash are those who find dangerous driving thrilling, the effectiveness of SCAS technology in reducing lane change crashes is probably going to be low. More research is needed to understand the characteristics of the crash-involved driving population. Similarly, the SCAS algorithm (especially for SCAS warning after lane change has begun) must be sensitive to both the time and distance budgets available for crash avoidance and to vehicle control stability. A SCAS will not be effective if its warnings startle the driver or otherwise prompt unsafe evasive maneuvers.

8.3 LIMITATIONS OF ROAD DEPARTURE CRASH AVOIDANCE RESULTS

There is no operational system to measure against. The computer simulation data sample was relatively small and the criteria imposed on the simulated crash countermeasure system were loose.

The small sample could cause the whole experiment to be statistically insignificant. The loose criteria would cause the system to have an unacceptable nuisance alarm rate. In either way, the accuracy of the effectiveness rate would be questionable.

Scenarios were adapted from the Task 1 of the performance specification report [Carnegie, 1994]. That analysis might be sufficient to provide sufficient insight to design the countermeasure systems. However, more detailed crash statistical characteristics (e.g., causal factors) and crash dynamic analyses are needed to refine the study. For example, fatal and non-fatal crashes have to be analyzed separately. Furthermore, non-fatal crashes, property damage and other non-fatal injury crash data could be analyzed separately. Scenario modeling for different levels of crash severity would allow much more accurate estimates of overall benefits. It is expected that there would be different effectiveness levels for the different crash severity levels which range from police-reported, fatal down to non-police-reported, no-injury.

Effectiveness rates will be affected by design factors such as the driver-system interface, false alarm rate. nuisance alarm rate, etc. And these design factors will eventually affect other factors **such** as customer acceptance rate, and hence influence the market penetration rate. Due to the lack of both operational data and simulation data, the team is unable to develop a mathematical model that explicitly addresses the complexity of the problem.

The eventual system design would need to consider many different human factors issues including those discussed above. The quality of the design will in turn have an effect on driver performance, driver acceptance, and, therefore, overall system effectiveness.

The benefit estimates were calculated under the assumption that the effectiveness rates of two proposed systems are additive. However, the combined system could have some disbenefits. The combined system might increase driver workload and induce some crashes. Lack of an operational system and limited information make it difficult to estimated disbenefits as well as benefits.

8.4 LIMITATIONS OF MONETARY BENEFIT RESULTS

In business and government, benefits estimates, like costs, are often expressed in dollar amounts. This assumes a great deal of information is available with which to make such fiscal statements. It also by-passes intangible benefits such as pain and suffering or quality of life. Therefore, the monetary benefits estimates provided in this report characterize the "value" of a set of CAS technologies in a somewhat restricted sense. Additional caveats associated with the monetary benefits estimates are provided below.

8.4.1 Carry Over of Limitations on Individual CAS Effectiveness Estimates

The limitations and caveats associated with CAS-specific effectiveness estimates will affect the quality of the monetary benefits estimates in which they are used.

8.4.2 Full Market Penetration Assumption

Full market penetration of CAS technologies may be very difficult to achieve. Even if it is achievable, this will take several years, during which time the benefits will likely be less than predicted.

8.4.3 Self-Selected "Safe" Drivers as CAS Consumers

There remains a concern that the types of drivers most willing and able to purchase CAS technologies will represent a portion of the driving population that is relatively uninvolved in crashes. If this arises, it will diminish the benefits realized accordingly because the CAS technologies are not in the hands of the drivers most in need of them.

8.4.4 Crash Cost Estimate Uncertainties

Many extrapolations underlie the crash cost estimates for each crash type. These include crash severity conversions, redistribution of fatalities based on fatality ratios in mass crash databases, adjustments for under counting of crashes, and so on. Since each of these extrapolations introduces some error of estimation, the actual versus predicted crash costs are likely to vary somewhat.

8.4.5 Differential CAS Effectiveness

It was assumed in lieu of data that the CAS effectiveness rate is constant across all crash severity categories. If, CAS technologies are especially good at eliminating the more severe crashes, monetary benefits would presumably be greater than if CAS technologies are only able to relieve the lowest-severity crashes of a particular crash type.

8.4.6 Discounting Percentage Assumed

A discounted rate of 4% per annum was assumed for the monetary benefits estimations. In light of the numerous uncertainties involved, this figure appeared reasonable. However, it is subject to substantial shifts based on the economy.

There is an implicit assumption in the work reported here that CAS technologies will be purchased as stand-alone items, unrelated to other aspects of vehicles. This need not be the case. The sensors and information processing needed for crash avoidance systems may be the same as those needed for other user services to be provided by the Intelligent Transportation System. For example, if a Global Positioning System (GPS) is used in a route guidance system or for emergency collision notification, its availability for roadway departure crash avoidance applications to warn of curves ahead need not necessarily involve added costs. If a unified driver interface can be developed and deployed for multiple crash countermeasures, then multiple driver interfaces need not be bought and paid for. lf the Automated Highway System (AHS) requires lane tracking sensors, in principle these same sensors could be applied for lane change and roadway departure crash avoidance. A unified architecture could make it possible for a single CPU to manage the entire vehicle's subsystems. The final point, then, is that the economic costs of CAS technologies may be marginal given the other technological capabilities that will already be present in the road vehicles of the future.

8.5 CONCLUDING REMARKS

This chapter has attempted to point out some of the important limitations associated with the methods and data used to develop crash avoidance system benefits predictions or estimates reported here. The authors of this report are acutely aware of the tenuous nature of the these results. This uncertainty is the price one pays for attempting to forecast a future that may be very different from the past, with little directly applicable data, using simplified models and a great many assumptions. Thus, this discussion chapter is not a defense or justification of the results as "truth", but rather a general ***caveat emptor*** for the reader.

Evans (1991) has written a thoughtful review of driver responses to interventions that might influence traffic safety. The literature review covered such varied systems as crash worthiness enhancements, studded tires, changes in speed limits, anti-lock brakes, and so forth. The review indicated that safety may increase, remain unchanged, or decrease in sometimes perverse ways. Evans concludes that human behavior feedback or reaction to safety systems may greatly alter safety outcomes from what is expected. A general pattern that appears is that safety change effects that noticeably improve vehicle performance will probably increase mobility by way of increased speeds, closer car following, and faster cornering. Safety may also increase, Evans points out, but by less than if there had been no behavioral response lTS crash countermeasures may be perceived or even marketed as mobility enhancements or may induce a sense of security that is not justified relative to compensatory changes in driving behavior. Thus, there is a legitimate concern that safety benefits from CAS technologies will be less than expected. If ITS is deployed as a truly integrated "system", then perhaps safety will be maintained along with mobility enhancements. This benefits estimation effort may ultimately have its greatest utility in helping to direct systems development in directions that arc fruitful and to avoid unexpected and detrimental "surprises" in ITS deployment.

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Appendices

Appendix A: Data and Assumptions Used in Lane Change or Side Crash Avoidance System (SCAS) Benefits Estimation.

Parameter or Property	Value or Form Taken in Modeling	Source	Caveat
Reliability Formulas for R_{Series} and $R_{Parallel}$	Reliability formulas assume driver and SCAS reliabilities individually remain stationary (i.e., constant over time) and are statistically independent of one another.	Basic reliability formulas provided in Hillier and Lieberman (1986). Independence assumption and stationarity assumption each made for simplicity.	It is possible that driver reliability will change with the presence of an SCAS. This interactive effect might also vary over time within a driver or across drivers.
SCAS Reliability, R_{CAS}, *in situ*	0.9995 probability of obstacle detection, *in situ*	Arbitrary Assumption of R_{CAS} = 0.99 for detection. Further assumed that, on the average, 5% of all lane changes are initiated when there is a POV in a conflict position	R_{CAS} *in situ* is a phrase coined to capture the fact that there can be no failure of obstacle detection when there is no obstacle to detect, as will usually be the case for lane change maneuvers. Consider a SCAS that detects 99% of targets present. Thus, R_{CAS} = 0.99 for detection. Assume that 5 percent of all lane changes desired in driving involve another vehicle in a conflict position (i.e., in the CAS sensor field of view). Thus, for 10,000 desired lane changes (say, over a year's worth of driving given 10,000 miles traveled and one lane change per mile, on average), 500 of those instances will involve a vehicle in a potential conflict zone. If the SCAS is always available and used, it will theoretically miss (1.00 - 0.99)(500) = 5 of those potential conflict obstacles and properly detect 495 of those conflict obstacles. (Usually, in these 5 instances where there is no detection should by and large be uneventful because the SV and POV drivers are looking out for hazards too). In the driving context or ***in situ,*** reliability of the CAS is not

Parameter or Property	Value or Form Taken in Modeling	Source	Caveat
			0.99 but rather is much higher because there is no opportunity for a detection failure when there is no target to begin with. Thus, the SCAS reliability ***in situ,*** is ***RCAS,= (9500 + (500 - 5)}/ 1000 = 0.9995***
Driver Realibility without SCAS, R_{driver}	0.999715105	GES Police-Report Crash Data, plus assumption that there is, on average, 1 attempted lane change per vehicle mile traveled (VMT), using VMT values as reported in the GES. Furthermore, there is an assumed joint failure to detect the hazard on the part of both subject vehicle (SV) driver and Principal Other Vehicle (POV) driver. In a target lane change crash, both SV and POV driver reliablities are assumed to be equal in the baseline or No-SCAS case. See Section 4.5.2.	This assumption about the reliability of the driver population to detect obstacles in the adjacent lane while considering a lane change may vary depending on the accuracy of the GES data base, the validity of the assumed incidence of lane change attempts, and the validity of the assumed etiology of lane change crashes as it pertains to SV and POV driver reliabilities
Fleet Penetration, ***MP***	1.0 (proportion or 100 percent)	Simplifying assumption, a standard reference point	The infusion of SCAS technology into the fleet of vehicles may never reach 100 percent. Furthermore, any infusion that takes place will occur over a period of years.
Availability, ***A***	1.0 (proportion or 100 percent)	Simplifying assumption, a standard reference point	Even if all vehicles are equipped with SCAS, some may not be available because they ate being repaired or maintained, or because the driver does not have the system turned on or the driver

Parameter or Property	Value or Form Taken in Modeling	Source	Caveat
			interface turned up sufficient for driver alerting or warning.
Driver Compliance, p(C)	1.0 (proportion or 100 percent)	Simplifying assumption, a standard reference point	This assumption will be violated to the extent that drivers do not heed the SCAS alerts (or warnings) due to false alarm effects, open-loop behavior, confusion, inability to verify the threat, etc.
Target lane change crash subtype incidence or probability, ***P(S)***	0.78 (proportion or 78 percent of all GES police-report lane change crashes)	GES; Chovan, et al. (1994); Eberhard, et al. (1994)	There may be other lane change crash subtypes that the proposed SCAS could address.
Usage Proportion, u_{Driver}	See Table 4.3. Average of Table 4.3 values used in final estimate	Mazzae and Garrott (1995)	This proportion varied with experimental task and prototype system evaluated in the Mazzae and Garrott (1995) study. Validity of such data to the hypothetical SCAS under analysis is unknown. See also discussion of this study in the narrative.
Usage Proportion, U_{CAS}	**See Table 4.3. Average of values in Table 4.3 used in final estimate**	**Mazzae and Garrott (1995)**	**This proportion varied with experimental task and prototype system evaluated in the Mazzae and Garrott (1995) study. Validity of such data to the hypothetical SCAS under analysis is unknown. See also discussion of this study in the narrative.**
Usage Proportion, U_{Series}	**0.0**	**Assumed.**	**No data was available from the Mazzae and Garrott (1995) study with which to assess this. It is likely to be greater than zero in SCAS applications. However, in light of the lack of data, this was reluctantly left alone.**

Parameter or Property	**Value or Form Taken in Modeling**	**Source**	**Caveat**
Usage Proportion, $u_{parallel}$	See Table 4.3. Average of values in Table 4.3 used in final estimate	Mazzae and Garrett (1995), plus assumption that all observed driver-and-CAS interactions were of parallel type*	The Mazzae and Garrott (1995) study methods could not distinguish between series and parallel behavior with the SCAS. This was assumed to be parallel behavior based on experimenter impressions of driver attitudes toward safety during the study. It probably involves at least some fraction of series behavior.
SV and POV Driver Reliability with SCAS, R_{DWC} and application to SV and POV driver reliability with SCAS, R_{SVDWC} R_{POVDWC},	See calculated values Table 4.3 and formulas in Section 4.5.1 and 4.5.3	Derived from formulas developed in this chapter.	The validity of these values depends on the validity of the assumptions and data that went into their calculation.
Effectiveness estimate, E	See calculated values in Table **4.3.**	General form for the Effectiveness equation presented in Burgett (1995). Refinements for this estimation are presented in Section 4.5.4.	The validity of these values depends on the validity of the assumptions and data that went into their calculation.
Probability of Target Lane Change	Random occurrence with probability as indicated in Section 4.5.2 and Section	Simplifying Assumption. The logic of the weighting scheme used in Section 4.5.4 is	Insurance companies and others consider that the Occurence of crashes is not random but is greater for some (error-prone) drivers, vehicles, driving

Parameter or Property	Value or Form Taken in Modeling	Source	Caveat
Crashes among associated attempted lane changes, *PLCCWO* *PLCCW*	4.5.4	described there.	circumstances, and the like. If so, the concentration of lane changes crash incidence may not be reflected in the calculated values presented here.

APPENDIX B

This appendix presents tabulated data used to estimate CAS costs and benefits.

Table B-l
Mid-Year Discount Factors
Passenger Cars

					Weighted PDV Factors*			
Vehicle Age (Years)	VMT	Survival Prob.	Weighted VMT	Percent Total VMT	2%	4%	7%	10%
1	14,535	1.000	14,535	0.1359	0.1346	0.1333	0.1314	0.1296
2	13,924	0.993	13,827	0.1293	0.1255	0.1219	0.1168	0.1121
3	12,846	0.982	12,615	0.1179	0.1122	0.1069	0.0996	0.0929
4	11,378	0.964	10,968	0.1026	0.0957	0.0894	0.0809	0.0735
5	10,749	0.935	10,050	0.0940	0.0860	0.0788	0.0693	0.0612
6	10,119	0.892	9,026	0.0844	0.0757	0.0680	0.0582	0.0500
7	9,490	0.831	7,886	0.0737	0.0648	0.0571	0.0475	0.0397
8	8,860	0.753	6,672	0.0624	0.0538	0.0465	0.0376	0.0305
9	8,231	0.662	5,449	0.0509	0.0431	0.0365	0.0287	0.0227
10	7,601	0.568	4,317	0.0404	0.0334	0.0278	0.0212	0.0163
11	6,972	0.476	3,319	0.0310	0.0252	0.0206	0.0152	0.0114
12	6,343	0.394	2,499	0.0234	0.0186	0.0149	0.0107	0.0078
13	5,713	0.323	1,845	0.0173	0.0135	0.0106	0.0074	0.0052
14	5,084	0.263	1,337	0.0125	0.0096	0.0074	0.0050	0.0035
15	4,454	0.213	949	0.0089	0.0067	0.0050	0.0033	0.0022
16	3,825	0.172	658	0.0062	0.0045	0.0033	0.0022	0.0014
17	3,195	0.139	444	0.0042	0.0030	0.0022	0.0014	0.0009
18	2,566	0.112	287	0.0027	0.0019	0.0014	0.0008	0.0005
19	1,937	0.090	174	0.0016	0.0011	0.0008	0.0005	0.0003
20	1,307	0.073	95	0.0009	0.0006	0.0004	0.0002	0.0001
Total			106,953	1.0000	0.9094	0.8327	0.7379	0.6617

*** Calculated by multiplying "Percent Total VMT" by the respective discount rate factor for each year as reported in Table B-3.**

Table B-2
Mid-Year Discount Factors
Light Trucks

					Weighted PDV Factors*			
Vehicle Age (Years)	VMT	Survival Prob.	Weighted VMT	Percent Total VMT	2%	4%	7%	10%
1	14,200	1.000	14,200	0.1108	0.1097	0.1086	0.1071	0.1056
2	14,800	0.999	14,785	0.1153	0.1120	0.1087	0.1042	0.1000
3	13,900	0.988	13,733	0.1071	0.1020	0.0971	0.0905	0.0844
4	12,200	0.966	11,785	0.0919	0.0858	0.0801	0.0725	0.0659
5	11,100	0.946	10,501	0.0819	0.0749	0.0687	0.0604	0.0533
6	9,900	0.925	9,158	0.0714	0.0641	0.0576	0.0492	0.0423
7	9,300	0.897	8,342	0.0651	0.0572	0.0504	0.0419	0.0350
8	8,800	0.862	7,586	0.0592	0.0510	0.0441	0.0356	0.0290
9	8,000	0.825	6,600	0.0515	0.0435	0.0369	0.0290	0.0229
10	7,600	0.771	5,860	0.0457	0.0379	0.0315	0.0240	0.0185
11	7,300	0.710	5,183	0.0404	0.0328	0.0268	0.0199	0.0149
12	6,900	0.645	4,451	0.0347	0.0276	0.0221	0.0159	0.0116
13	6,000	0.573	3,438	0.0268	0.0209	0.0164	0.0115	0.0081
14	6,000	0.502	3,012	0.0235	0.0180	0.0138	0.0094	0.0065
15	5,300	0.441	2,337	0.0182	0.0137	0.0103	0.0068	0.0046
16	5,000	0.380	1,900	0.0148	0.0109	0.0081	0.0052	0.0034
17	5,700	0.320	1,824	0.0142	0.0103	0.0074	0.0047	0.0030
18	5,100	0.260	1,326	0.0103	0.0073	0.0052	0.0032	0.0020
19	4,600	0.200	920	0.0072	0.0050	0.0035	0.0021	0.0012
20	4,200	0.140	588	0.0046	0.0031	0.0021	0.0012	0.0007
21	4,000	0.080	320	0.0025	0.0017	0.0011	0.0006	0.0004
22	3,700	0.050	185	0.0014	0.0009	0.0006	0.0003	0.0002
23	3,200	0.030	96	0.0007	0.0005	0.0003	0.0002	0.0001
24	2,500	0.020	50	0.0004	0.0002	0.0002	0.0001	0.0000
25	2,000	0.010	20	0.0002	0.0001	0.0001	0.0000	0.0000
Total			128,199	1.0000	0.8910	0.8018	0.6956	0.6134

*** Calculated by multiplying "Percent Total VMT" by the respective discount rate factor for each year as reported in Table B-3.**

Table B-3
Discount Rate Factors

(Mid-year Discount Factors)

Year	2%	4%	7%	10%
1	0.9901	0.9806	0.9667	0.9535
2	0.9707	0.9429	0.9035	0.8668
3	0.9517	0.9066	0.8444	0.7880
4	0.9330	0.8717	0.7891	0.7164
5	0.9147	0.8382	0.7375	0.6512
6	0.8968	0.8060	0.6893	0.5920
7	0.8792	0.7750	0.6442	0.5382
8	0.8620	0.7452	0.6020	0.4893
9	0.8451	0.7165	0.5626	0.4448
10	0.8285	0.6889	0.5258	0.4044
11	0.8123	0.6624	0.4914	0.3676
12	0.7963	0.6370	0.4593	0.3342
13	0.7807	0.6125	0.4292	0.3038
14	0.7654	0.5889	0.4012	0.2762
15	0.7504	0.5663	0.3749	0.2511
16	0.7357	0.5445	0.3504	0.2283
17	0.7213	0.5235	0.3275	0.2075
18	0.7071	0.5034	0.3060	0.1886
19	0.6933	0.4840	0.2860	0.1715
20	0.6797	0.4654	0.2673	0.1559
21	0.6663	0.4475	0.2498	0.1417
22	0.6533	0.4303	0.2335	0.1288
23	0.6405	0.4138	0.2182	0.1171
24	0.6279	0.3978	0.2039	0.1065
25	0.6156	0.3825	0.1906	0.0968

Appendix C: Preliminary Safety Benefits of an Intelligent Cruise Control System

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C.l INTRODUCTION

The preliminary safety benefits of the intelligent cruise control (ICC) system are estimated using experimental data obtained from a road test on driver performance with and without the use of a testbed ICC system. The analysis in this appendix follows the same approach that was utilized to predict the preliminary safety benefits of the rear-end crash warning system (refer to Chapter 3 for details). The effectiveness of the ICC system in reducing the probability of a rear-end crash is evaluated at different vehicle speeds using the Monte Carlo method. In addition, the number of rear-end crashes that might be avoided with the ICC system and concomitant savings in economic monetary costs are predicted based on assumptions about market penetration and system usage at various speeds.

This appendix consists of six major sections that succeed this introduction in the following order: description of the experimental ICC system being investigated for the safety benefits estimation, formulation of estimating the system effectiveness, description of the data elements used as input data to computer simulations, system effectiveness results at different vehicle speeds, preliminary safety benefits, and concluding remarks.

C.2 SYSTEM DESCRIPTION

The intelligent cruise control system under study is an experimental (testbed) system which performs an automatic longitudinal control function of both speed and headway by throttle manipulation. The system was developed by the University of Michigan Transportation Research Institute (UMTRI) in conjunction with Leica as part of a three-year program to foster the development, evaluation, and deployment of forward crash avoidance systems [1]. Next, the driver/system interface, control algorithm, and forward-looking sensor are briefly described.

C.2.1 Driver/System Interface

The driver/system interface consists of conventional cruise control switches, a headway controller switch, and an informative display. The driver sets the desired cruising speed by pushing a "SET' button when the vehicle is traveling at that speed. If the system is disconnected by depressing the brake pedal, the driver can reengage the system with a "RES" button. Both "SET' and "RES" buttons are also used to incrementally increase or decrease the value of the set cruising speed. The headway controller is activated by an "ON" button in the ICC control unit. The system display shows the set cruising speed and includes a green light emitting diode (LED) indicating when the system is engaged and a red LED that illuminates when the system detects a valid target. The system does not provide any active warning signal to the driver; however, a haptic cue is generated by throttling "down" when a slower lead vehicle is encountered.

C.2.2 Control Algorithm

The input data for the control algorithm consist of lead vehicle data (range, range rate, and tracking), driver's set speed, and host vehicle speed. The output is a velocity command fed to the cruise control unit. The system performs headway control by maintaining a desired distance headway which is the product of the lead vehicle speed and the desired time headway. In this system, the desired time headway was preset at 1.4 seconds. The system autonomously chooses a valid target to follow. Stationary objects or traffic in the opposite direction are classified by the algorithm as non-valid targets. If a valid target is detected by the forward-looking sensor, the controller evaluates the driving situation, calculates the appropriate distance headway and corresponding speed, and then sends a speed command so that the distance headway is achieved. If no valid target is detected, or when the lead vehicle either disappears or accelerates above the desired speed, the ICC operates as a normal cruise control according to the speed set by the driver. The longitudinal control authority given to the ICC system was limited to throttle manipulation. The maximum available deceleration rate was the prevailing deceleration during zero-throttle coastdown (approximately 0.05g) [l][2].

C.2.3 Forward-Looking Sensor

A near-infrared monobeam sensor was utilized to measure the distance (range) and relative velocity (range rate) between the ICC-equipped vehicle and the vehicle in front. The sensor is capable of measuring distances from 2 m (6.6 ft) up to 160 m (525 ft), and relative velocity between -248 MPH and 124 MPH. The sensor updates its data at a frequency of 100 Hz for targets up to 120 m (394 ft) and at 10 Hz for targets farther than 120 m. Finally, the sensor only tracks targets that remain longer than 0.3 second in its field of view.

C.3. SYSTEM EFFECTIVENESS ESTIMATION

The rear-end crash type emerges as the primary target for the ICC system. The major rear-end precrash scenarios, statistical characteristics, causal factors, and relevant crash sizes were delineated in Section 3.3 of Chapter 3. Based on the configuration of this ICC system, stationary vehicles are classified as non-valid targets in order to eliminate false alarms. Thus, this ICC system does not respond to vehicles stopped in the host vehicle's traffic lane. As a result, this system only applies to the "lead vehicle decelerating" (LVD) rear-end precrash scenario. Using relevant rear-end crash sires in Section 3.3.3 of Chapter 3, this ICC system applies to 93.5 percent or about 1.12 million police-reported (RR) LVD rear-end crashes.

The number of motor vehicle rear-end crashes that might be avoided with the ICC system, N_a, can be estimated as follows:

$$N_a = N_{wo} - N_w = N_{wo} \times SE \qquad \textbf{(C.1)}$$

where

N_a = Number of rear - end crashes that can be avoided using an ICC system

N_{wo} = Number of rear - end crashes that occur without using an ICC system

N_w = Number of rear - end crashes that occur with ICC system intervention

SE = Total system effectiveness

where N_{wo} and N_w denote the number of tear-end crashes that occurred in a given time period ***without*** and ***with the use*** of the ICC system, respectively. The term SE refers to the total system effectiveness and is estimated as follows:

$$SE = MP \times U \times \left(\sum_{j=1}^{2} p(S_j) \times E(S_j) \right) \times F \qquad (C.2)$$

Where

MP	=	Proportion of ICC system market penetration
U	=	Proportion of ICC system usage during crash hazard
p(Sj)	=	Probability of circumstance j in LVD rear- endprecrash scenario
E(Sj)	=	Estimate of system effectiveness in LVD rear - endprecrash scenario under circumstance j
F	=	Fraction of relevant LVD precrash scenario relative to the rear- end crash size

Based on the statistics presented in Section 3.3 of Chapter 3 about the relative size of the relevant LVD mar-end precrash scenario and its distribution on roadway surface conditions, Equation (C-2) becomes:

$$SE = \left(0.714 \times E(S1) + 0.286 \times E(S2) \right) \times 0.673 \qquad \text{(C-3)}$$

Where

E(S1) = Effectiveness of ICC system in LVD scenario on dry roadway surface
E(S2) = Effectiveness of ICC system in LVD scenario on slippery roadway surface

The values of E(S)'s were determined from the crash probabilities with and without the use of the ICC system, which were estimated by the Monte Carlo Method as explained in Chapter 3. The following section describes the various data elements used as input to the computer simulations.

C.4 DATA DESCRIPTION

Table C-l lists the main variables of the LVD rear-endprecrash scenario which were derived from kinematic modeling in Section 3.5.1 of Chapter 3. The variables **/ /** and **a1** are random numbers that were picked from statistical distributions described in Section 3.6 of Chapter 3. In this analysis, the vehicle time delay to teach maximum deceleration level **tb**, was considered constant at 0.3 second. The values of the remaining variables **vF, vL, d,** and **tD,** are described below as obtained from on-road tests.

Table C-1. LVD Rear-End Precrash Scenario Variables

Variables	Definition
vF	Following vehicle speed vehicle onset of braking
aF	Following vehicle deceleration
tD	Driver reaction time from onset of lead vehicle braking til braking pedal is pressed
tB	Vehicle time is delay to reach maximum deceleration
dH (tH)	Following (time) gap
vL	Lead vehicle speed before onset of braking
aL	Lead vehicle deceleration

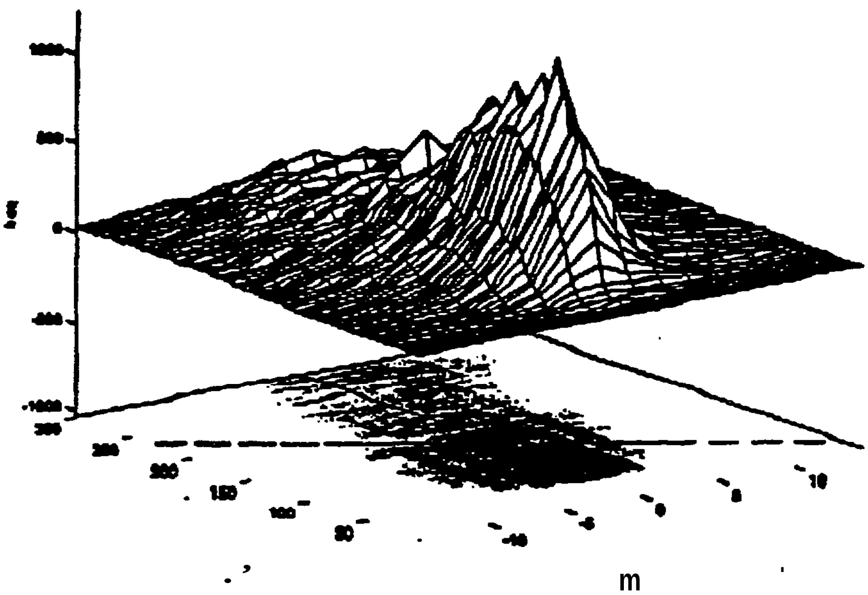
C.4.1 Vehicle Speed, Relative Speed, and Following Gap

Data on vehicle speed, relative speed, and following gap were gathered from an on-road test conducted by UMTRI to investigate human factors issues and safety-related performance as derived from operating a passenger car equipped with an ICC system [1][2]. Thirty-six licensed drivers, balanced for gender, age, and experience in the use of conventional cruise control, were recruited to participate in three experimental trials. On each trial, a different mode of speed assistance was evaluated: no cruise control, conventional cruise control, and ICC. Three age groups were examined: 20 to 30, 40 to 50, and 60 to 70 years of age. Each participant drove a predetermined route on local highways. The same route was followed for testing each of the control modes. The orders in which participants experienced cruise control modes were counter-balanced to eliminate order effects. The length of the route was 55 miles and took approximately 50-60 minutes per trial to complete. The roadway was fairly straight and drivers did not need to make many sharp turns. Participants drove only when weather and road conditions permitted. An experimenter was present at all times to aid participants in route guidance. Test drives only took place during off-rush-hour time, to avoid large fluctuations in traffic density.

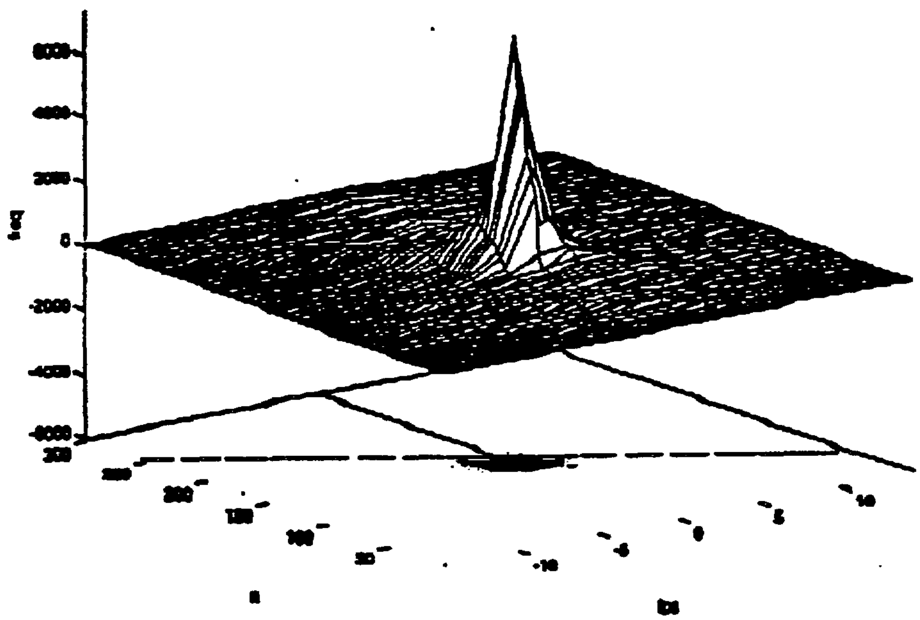
Histograms for variables such as vehicle speed, relative speed (v_L - v_F), and distance between following and lead vehicles (d_H) were generated from raw data representing a 5 Hz time-history of each of the variables. Test data from the normal driving trial (without ICC) and from the ICC system trial (with ICC) were used to estimate the safety benefits of the ICC system. The mean values of the following vehicle speed, v_F, were 65.4 MPH (96.2 ft/sec) and 64 MPH (94.1 ft/sec) without and with ICC, respectively. Figure C-1 compares the histograms of joint variables [d_H, (v_L - v_F)] pertaining to driver performance with and without the ICC system. The results show that the ICC system controlled range and range rate as devised in its control algorithm by maintaining time headway close to the design value of 1.4 seconds and keeping the range rate at approximately zero ft/sec. In manual driving without the ICC system, drivers widely varied their time headways and kept in many instances shorter time headways than those encountered with ICC driving [1]. Consequently, drivers with the ICC system allowed themselves longer available time to react than drivers without the system in case the lead vehicle braked unexpectedly in traffic. Based on the results of this road test, the ICC system could reduce the probability of a rear-end crash in the LVD scenario if drivers with the ICC system remained attentive to the driving task as those without.

C.4.2 Driver Brake Reaction Time

This analysis assumes that drivers with and without the ICC system have similar brake reaction times to lead vehicle braking because the ICC system under study did not include any active warning or significant automatic deceleration levels. The brake light of the decelerating lead vehicle is assumed to stimulate the braking maneuver of the following vehicle driver. A lognormal distribution of brake reaction times by unalerted drivers with a mean value of 1.21 sec and a standard deviation of 0.63 sec is adopted for time gaps greater than or equal to 1.5 seconds. This particular distribution was considered to more closely estimate the true brake reaction time distribution of drivers than other available distributions [3]. The values of this distribution were recorded from a road test of unalerted drivers who were following a test car, while being followed by a monitoring vehicle [4]. The intervehicular spacings were between one and two car lengths at speeds between 32 and 40 Km/h (≅ 20 and 25 MPH) and between three and five car lengths at speeds between 56 and 72 Km/h (≅ 35 and 45 MPH). A total of 1,184 data points representing only brake reaction times of less than 3 seconds were recorded.



(a) *Without ICC*



(b) *With ICC*

Figure C-1, Joint Gap and Relative Speed Histograms

The mean and standard deviation of driver brake reaction time described above were modified for time gaps less than 1.5 seconds, taking into account that reaction time decreases as coupled vehicles draw closer together [5]. The values were adjusted based on assumptions made by a previous study that linked the mean and standard deviation of brake reaction times to time gaps between coupled vehicles [6]. Table A-2 shows the relationship between driver reaction time and time gap as used in this analysis for both with and without the ICC system conditions. It should be noted that the ICC system is assumed to have no impact on driver's attention to the driving task. A recent driving simulator study investigated the effects of an ICC system on driver behavior in safety-critical traffic situations, employing twenty subjects split evenly into two groups to drive with and without the ICC system [7]. The simulated system had an automatic braking capability of up to 0.3g and presented an audible warning to the driver when the braking capability of the ICC system was insufficient to avoid a crash. The results showed that drivers with the ICC system remained vigilant especially in the traffic situation where a lead vehicle in an adjacent lane pulled out in front of the subject drivers. Drivers with and without the ICC system had identical and immediate reactions to this critical event and all ICC drivers reacted by braking before warnings were presented.

Table C-2. Driver Reaction Time as a Function of Time Gap

Time Gap, t_H (sec)	Mean (sec)	Standard Deviation (sec)
<=0.5	0.75	0.49
0.5 < ty < 1.5	0.46 x ty+ 0.52	0.14 x ty + 0.42
>=1.5	1.21	0.63

C.5 SYSTEM EFFECTIVENESS RESULTS

The LVD rear-end precrash scenario was simulated using the Monte Carlo method under dry and slippery (e.g., wet/ice/snow) roadway surface conditions for discrete values of following vehicle speed, vF, ranging between 30 and 60 MPH, in a 5 MPH step. For each value of vF a total of 100,000 Monte Carlo trials were run to estimate the probability of a rear-end crash with and without the ICC system. The experimental results of the following gap and relative speed were extrapolated using their joint distributions in Figure C-l to accommodate following vehicle speeds, vF below 55 MPH. Table C-3 shows the individual values of crash probabilities with and without the ICC system, Pw and Pwo on dry and slippery roads and respective effectiveness values (E= 1 - Pw/Pwo for each following vehicle speed.

Table C-3. Crash Probabilities and Effectiveness Values of the ICC System

v_F (MPH)	Dry Roads			Slippery Roads		
	P_w	P_{wo}	E_1	P_w	P_{wo}	E_2
30	0.096	0.157	0.39	0.091	0.136	0.33
35	0.089	0.143	0.38	0.091	0.127	0.29
40	0.082	0.130	0.37	0.087	0.122	0.29
45	0.077	0.122	0.37	0.088	0.118	0.26
50	0.071	0.112	0.37	0.085	0.114	0.25
55	0.067	0.105	0.36	0.086	0.111	0.22
60	0.064	0.099	0.36	0.085	0.109	0.22

The ICC system augments the function of conventional cruise control and is likely to be installed on passenger cars and light trucks. Based on 1990 statistics [8] there were about 143.6 million passenger cars and 37.4 million light trucks registered in the United States which correspond respectively to about 76 percent and 20 percent of all motor vehicle registrations. Assuming that all passenger cars and light trucks are equipped with an ICC system, market penetration will be about 96 percent (MP= O.%) by excluding buses and heavy trucks. According to Ward's 1992 automotive yearbook, conventional cruise control was installed in about 65 percent of passenger cars and 60 percent of light trucks in the 1991 model year. Assuming that the ICC system will penetrate the passenger car and light truck fleet at these installation levels, an estimate of ICC system market penetration will be about 61 percent of the whole motor vehicle fleet (MP= 0.61).

CurrentIy, conventional cruise control is mostly engaged at highway speeds of 55 MPH and over. Since the ICC system maintains both speed and headway control, drivers are expected to engage the system at vehicle speeds below 55 MPH. Table A-4 illustrates the cumulative effect of system use at various speeds on the effectiveness of the ICC system for two market penetration ratios. The cumulative system effectiveness values were computed by a weighted average of the individual effectiveness values in Table C-3 at each vehicle speed, v_F, using the "posted speed limit" variable distribution of the LVD rear-end crashes listed in Table 3-2 of Chapter 3. As seen in Table A-4, the ICC system has the potential to alleviate about 19.5 percent of all rear-end crashes or about 29 percent of all "relevant" rear-end crashes, if installed on 96 percent of all motor vehicles. If only engaged at highway speeds greater than or equal to 55 MPH, the ICC system may reduce about 3.5 percent of all rear-end crashes or about 5.2 percent of all "relevant" rear-end crashes for a 96 percent market penetration.

Table C-4. Percent Cumulative Effectiveness of the ICC System

v_F (MPH)	MP= 0.96	MP= 0.61
55+	3.5	2.2
50+	4.8	3.0
45+	8.7	5.5
40+	11.1	7.1
35+	17.2	10.9
30+	19.5	12.4

C.6 PRELIMINARY SAFETY BENEFITS

The number of PR rear-end crashes that might be avoided with the ICC system may approximate a high of about 324 thousand crashes using 1994 GES statistics. This number is based on a 96 percent market penetration and system usage at vehicle speeds of 30 MPH and over. If market penetration reached 61 percent of the motor vehicle fleet and drivers engaged the system only at and above 55 MPH, the ICC system could mitigate a total of about 37 thousand PR rear-end crashes. Table A-5 lists the number of PR rear-end crashes that might be avoided with the ICC system for market penetration ratios of 0.96 and 0.61 and usage from 55+ to 30+ MPH.

The average economic cost per PR LVD tear-end crash was appraised at 13,960 dollars in the United States [9]. Thus, the ICC system could provide savings as high as 4.5 billion dollars annually in PR rear-end crash economic costs. In conditions where the ICC system is least effective (v_F 2 55 MPH and MP= 0.61) as listed in Table C-4, the savings in PR LVD rear-end crash economic costs could still amount to about 5 17 million dollars in the U.S. annually.

Table C-5. Number of PR Rear-End Crashes (K) Avoided with ICC System

v_F (MPH)	MP= 0.96	MP= 0.61
55+	58	37
50+	80	50
45+	144	91
40+	184	118
35+	286	181
30+	324	206

C.7 CONCLUDING REMARKS

Preliminary safety benefits of an experimental ICC system were estimated in terms of the number of rear-end crashes that might be avoided with such a system, based on very limited data about driver performance with and without the system obtained from a single on-road test. Computer simulations based on the Monte Carlo method were utilized to exercise a lead vehicle decelerating rear-end precrash scenario and to extrapolate test data from very few driving conditions to all conceivable conditions of the tear-end crash experience. Various assumptions were made to predict the effectiveness of the ICC system. Most notable, drivers with the ICC system kept their vigilance and remained as attentive to the driving task as drivers in the manual driving mode. In addition, risk compensation by drivers with the ICC system was not taken into account. A recent road test sought to empirically quantify the influence of an ICC system on driver comfort and situation awareness to highway driving [IO]. Fifteen subjects participated in two half-hour driving sessions with and without the ICC system in traffic on a major highway. Drivers with the ICC system had the option of selecting set cruising speed and set time headway. The results showed that poor attention to lane positioning and failure to yield to other traffic were more frequent with the ICC system and that faster speeds and shorter time headways were selected with the ICC system than without. On the other hand, the ICC system helped drivers reduce speed and time headway variations.

The validity of any experimental test results depends on the experimental condition effects that were placed on the drivers. During short-term experiments, it is not possible to completely reduce the demand characteristics of the system which can only occur in long-term demonstrations. Moreover, the results of limited road tests are generally based on the driving behavior of few drivers who tested a system with an experimenter present in their vehicle. Finally, a better estimation of the safety benefits of an intelligent cruise control system can be achieved as more relevant test data are gathered especially from long-term, large-fleet field operational tests.

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