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16. Abstract

This report describe an analysis of the application of Intelligent Vehicle Highway System (IVHS) technology to the reduction of rear-end crashes. The principal countermeasure concept examined is a headway detection (HD) system that would detect stopped or slower-moving vehicles in a vehicle's travel path. The report is organized to correspond to the major steps of the project methodology:

1. Quantify baseline target crash problem size and describe target crash characteristics.
2. Describe, analyze, and model target crash scenarios to permit understanding of principal crash causes, time and motion sequences, and potential interventions.
3. Assess countermeasure technology and mechanisms of action to identify candidate solutions.
4. Assess relevant human factors and other (e.g., environmental, vehicle) factors affecting crash scenario and potential countermeasure effectiveness.
5. Model countermeasure action to predict effectiveness and identify critical countermeasure functional requirements.
6. Identify specific priority technological, human factors, and other R&D issues to be resolved. Case reconstructions and modeling indicate that most rear-end crashes are due to driver inattention, and that this inattention can in theory be addressed successfully by the HD countermeasure concept and available radar technologies.

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Intelligent vehicle highway systems (IVHS), crash avoidance countermeasures, rear-end crashes, headway detection systems, collision warning systems, driver inattention, crash reconstruction	This document is available to the public through the National Technical Information Service, Springfield, VA 22161

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EXECUTIVE SUMMARY

This report describes an analysis of the application of Intelligent Vehicle Highway System (IVHS) technology to the prevention and severity-reduction of rear-end crashes. The principal countermeasure concept examined is a headway detection (HD) system that would detect stopped or slower-moving vehicles in a vehicle's forward travel path.

The purpose of this program is to assess the potential for Intelligent Vehicle-Highway System (IVHS) technology to improve the collision avoidance capability of drivers and vehicles. The program uses a six-step process (Figure ES-l) to model target crash scenarios and conceptual (but realistic) IVHS interventions, to provide device effectiveness estimates, and to identify high-priority R&D needs relating to specific IVHS/crash avoidance countermeasure concepts. The current report is based on a collaborative effort involving the staff of the NHTSA Office of Crash Avoidance Research, the Research and Special Programs Administration (RSPA) Volpe National Transportation Systems Center, and the project contractor team (Contract No. DTRS-57-89-D-00086), which includes Battelle Memorial Institute, ARVIN/Calspan, and Castle Rock Consultants.

Figure ES-l: Crash/Countermeasure Assessment Methodology

1. ***Quantify baseline crash problem size and describe crash characteristics.***
2. ***Describe, analyze, and model target crash*** scenarios to permit understanding of principal causes, time and motion sequences, and potential interventions.
3. ***Assess countermeasure mechanisms of action and technology*** status to identify candidate solutions.
4. ***Assess relevant human factors*** and other "real world" (e.g., environmental, vehicle) constraints affecting potential countermeasure effectiveness.
5. ***Model countermeasure action*** to predict effectiveness and identify critical countermeasure functional requirements.
6. ***Identify priority technological, human factors, and other R&D issues.***

The methodology of this program is primarily analytical rather than empirical. That is, the program analyzes existing accident data and reviews available information on technology and driver/vehicle performance. The countermeasure modeling is intended to be heuristic rather than definitive, and is intended to stimulate empirical research on countermeasure characteristics and associated driver and vehicle performance parameters. This follow-up research will provide data needed to validate and refme the countermeasure models presented in this report.

Baseline Problem Size and Characteristics - There were about 1.5 million police-reported rear-end crashes in 1990, including 2,084 fatalities. This represents about 23 percent of all police-reported crashes and about 4.7 percent of all fatalities. Approximately 1.75 million non-police-reported additional rear-end crashes occur annually. In addition to the societal losses associated with injuries and property damage, approximately one-third of all crash-caused delay is caused by rear-end crashes.

The most important classification within the rear-end crash category is whether the lead vehicle is stationary or moving (LVM). In 1990 there were more than twice as many police-reported LVS crashes (1.05 million) as LVM crashes (0.47 million).

A comparison of the rear-end crash involvements of different vehicle types indicates that passenger vehicles (cars, light trucks, vans) constitute the vast majority of the problem and have higher involvement rates per mile traveled than do combination-unit trucks (i.e., tractor-trailers). Combination-unit trucks, on the other hand, have a greater likelihood of involvement during their operational lives due to high exposure (mileage). Moreover, heavy truck crashes are more likely to be severe. For both vehicle types, rear-end crashes are a sizeable and important target problem that deserves early evaluation for IVHS applicability.

Analysis of Crash Scenarios - The assessment of rear-end crash causes was based primarily on clinical analysis of case reports from the National Accident Sampling System (NASS) Crashworthiness Data System (CDS). These cases were used to identify causal factors and also to establish parameters for the modeling of rear-end crashes relative to hypothetical countermeasure design specifications.

Based on a review of 74 CDS cases, the most common causal factor associated with rear-end crashes was identified to be driver inattention to the driving task. A second, and overlapping, major causal factor was following too closely. Together or separately, these two factors were associated with 93 percent (weighted) of the clinical sample (96 percent of LVS crashes and 82 percent of LVM crashes).

Countermeasure Mechanisms of Action and Technology - Based on the causal factor assessment and consideration of candidate countermeasure concepts, the most applicable countermeasure concept was determined to be a headway detection (HD) system. HD systems monitor the dynamic relationship, including relative distance and velocity, between equipped vehicles and vehicles (or other objects) in their forward paths of travel.

Two promising technologies for fulfilling basic HD system requirements are active laser radar and microwave/millimeter wave radar. Such systems include a transmitter on the following vehicle that emits electromagnetic energy in the direction of the lead vehicle. A portion of this energy is reflected from the lead vehicle and intercepted by a receiver on the following vehicle. The receiver measures both the two-way transit time between vehicles to determine the range and the frequency shift (i.e., Doppler shift) in the reflected beam to determine the relative velocity between vehicles.

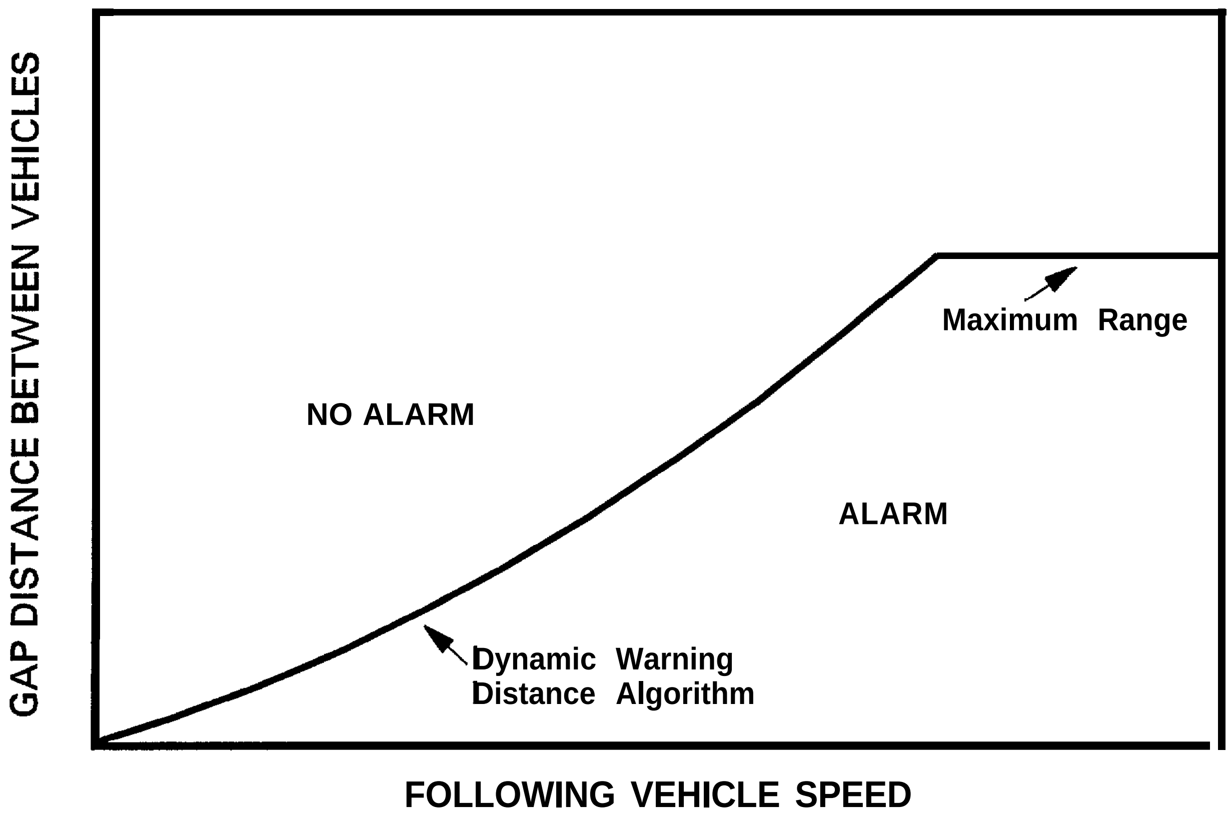
The optimal HD system technology depends on the details of the particular safety application. No specific sensor system is recommended in this report, and the scope of the program does not include engineering trade-off studies. Nevertheless, several examples of laser radar and microwave/millimeter wave prototype systems are presented in light of probable countermeasure system requirements. Current prototype HD system specifications provide part of the basis for the device design parameters used in the effectiveness modeling.

Driver, Vehicle, and Environmental Constraints - A number of complicating factors -- human, environmental, and vehicle -- were identified. These "real world" constraints and problems will need to be overcome or accommodated for HD systems to be viable. Human factors considerations include driver braking reaction time, effect of nuisance alarms (i.e., warning system sounds alarm when detected obstacle poses no real crash threat), compensatory risktaking, and driver errors not addressed by the countermeasure. Practical vehicle considerations include effects of road dirt and poor maintenance, effects of future changes in braking efficiency (e.g., future widespread use of antilock braking systems) on the effectiveness of the HD system, and levels of market penetration. Environmental considerations include potential health risks posed by radar, interference among multiple vehicles and systems, and degrading effects of heavy precipitation on system performance. Probably the most vexing problem is that of irregular roadway geometry (i.e., curves, dips, and hillcrests) over the forward-scanning field.

Countermeasure Effectiveness Modeling - Countermeasure modeling attempts to predict system effectiveness in preventing crashes, to identify principal countermeasure functional requirements, and to identify major factors (e.g., roadway configuration, weather) that are likely to influence countermeasure effectiveness. Countermeasure modeling involves postulating realistic design functional parameters for the system, and then predicting how "real" drivers and vehicles would perform to avoid crashes given the aid of the proposed system. The realism and meaningfulness of modeling results are entirely dependent on the realism of the values used for countermeasure system and driver/vehicle performance parameters. The report provides detailed explanations and rationales for the design and modeling parameters used, and suggests how they may be improved in future research based on new information.

Four possible maximum HD system ranges are addressed (i.e., 300, 250, 200, and 150 feet), although it is clear that a fixed operational range for all travel speeds would lead to excessive nuisance alarms that would be unacceptable to most drivers. Accordingly, HD systems would not automatically issue warnings about obstacles at the maximum system range from the vehicle. Rather, these systems would be designed to reduce their warning distances dynamically when the vehicle is traveling at lower speeds. The term warning distance is used here to specifically mean the critical separation at a given speed in which the HD system would issue a warning alarm signal if a crash threat were detected. Hypothetical kinematically-derived formulas ("HD system algorithms") for this warning distance reduction are postulated, based on design assumptions about drivers' and vehicles' abilities to react and brake to avoid impending crashes given the aid of the system. Figure ES-2 illustrates schematically an HD system warning distance function for the relatively-simple LVS situation.

Figure ES-2
Schematic Representation of HD System Warning Distance Function for LVS Situation

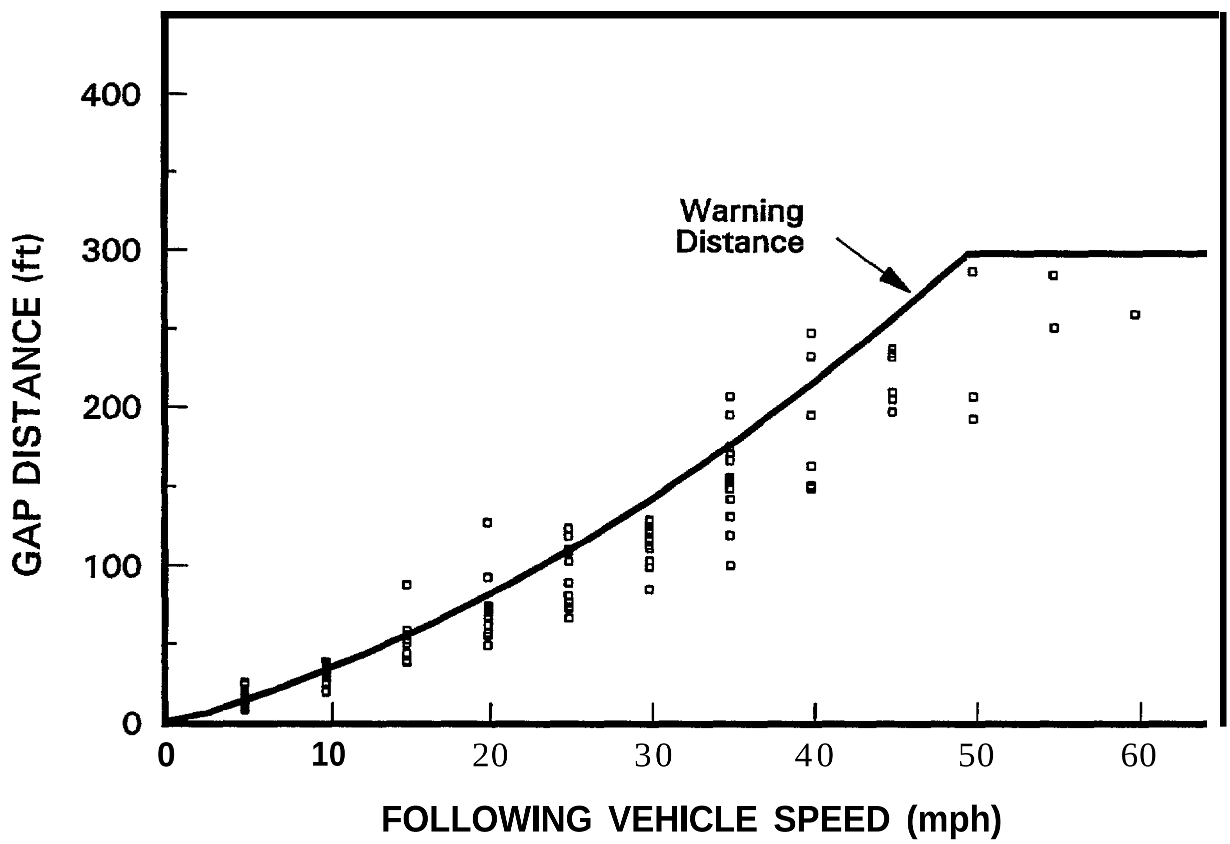


The hypothetical HD system functional parameters and stochastic models of driver/vehicle crash avoidance performance are applied to samples of rear-end crashes to estimate baseline effectiveness rates (i.e., the proportion of crashes avoided). Each effectiveness percentage estimate represents approximately 40,000 hypothetical crash "events" generated via a Monte Carlo computer simulation. The derived baseline effectiveness rates represent theoretical values which are subject to attenuation due to the effects of various factors such as improper driver response, adverse weather, or roadway configuration. The effects of these attenuating factors are not quantified at this time but are noted as topics for future research.

The modeling effort addresses the two major rear-end crash subtypes (LVS and LVM) using two qualitatively different types of modeling samples for each: a small clinical analysis/reconstruction sample (a subsample of the 74 cases used in the causal factor assessments) and a large, nationally-representative General Estimates System (GES) sample. The effectiveness modeling demonstrates that HD systems have the potential to achieve significant reductions in the number of rear-end crashes that occur each year. When various hypothesized HD system countermeasure functional parameters are applied to the modeling samples, a high percentage (generally 40 to 80 percent, depending on specific crash subtypes and modeling parameters) of applicable crashes (i.e., rear-end crashes with driver inattention and/or following too closely as causal factors) were found to be theoretically-preventable.

Figure ES-3 illustrates graphically a small portion of the countermeasure modeling for one crash subtype (LVS), HD system range limit (300 feet), and GES modeling sample. The modeling sample consists of 100 GES LVS cases (1990-91) arrayed by the proportion of coded pre-crash following vehicle speeds. The line in Figure Es-2 represents the design system algorithm for warning distance at different vehicle speeds. Each of the 100 points represents a modeling "event"; i.e., a hypothetical driver/vehicle confronted with the crash situation while aided by the HD system. Each hypothetical driver/vehicle has been randomly assigned a braking reaction time and deceleration rate following braking per the Monte Carlo simulation method. Points below the line represent hypothetical crashes prevented; those above the line represent crashes not prevented by the countermeasure. For the same parameters as shown in Figure ES-2, the full Monte Carlo simulation generated approximately one-half million "events" and yielded an effectiveness estimate of 77 percent.

Figure ES-3:
Illustration of 100 Data Points from the GES LVS Modeling



If 92 percent of police-reported rear-end crashes are HD system-applicable (based on the clinical sample causal factor analysis) and 40 to 80 percent of these are theoretically-preventable (based on modeling results), then HD systems can, theoretically, prevent approximately 37 to 74 percent of all police-reported rear-end crashes.

In addition to the prevention of police-reported rear-end crashes addressed in the modeling, there would likely be other significant categories of HD system benefits, such as prevention of non-police-reported rear-end crashes, prevention of "disguised" rear-end crashes, and severity reduction of target crashes not prevented. An appendix to the report demonstrates analytically the likelihood of significant severity reduction in those rear-end crashes not prevented by the system. When all categories of crash amelioration are considered, it appears that total potential benefits from the application of HD system technologies could be substantial.

On the other hand, there are 'a number of attenuating factors that will reduce the optimistic theoretical effectiveness estimates derived here. Systems operating at the ranges modeled in this report could be prone to unacceptably high nuisance alarm rates. These high rates are typically associated with HD systems responding to roadside appurtenances (i.e., utility poles, guardrail, etc.) at extended ranges or with the misalignment of vehicles which can occur at extended ranges. The driver interface (e.g., warning system design) issue needs to be addressed to ensure that drivers respond reliably and appropriately to the warning signal or other vehicle response to crash threat detection. Extensive research and development will be needed to better assess and to minimize the attenuating effects of these types of problems.

R&D Directions and Needs - An important goal of this project is to identify priority research and development (R&D) requirements related to IVHS crash avoidance countermeasures. Many such R&D issues will be addressed in the next phase of NHTSA's research on IVHS countermeasures to rear-end crashes. This research will focus primarily on transforming the formulations of this project -- i.e., crash reconstructions, functional countermeasure concepts, preliminary technology assessments, and theoretical modeling -- into a set of rear-end crash countermeasure performance speczjications. These performance specifications will be intended to facilitate industry efforts to develop practical, driver-friendly, and commercially-viable countermeasure systems. In this report, the nature of future HD system R&D is addressed through a systematic overview of R&D needs in the areas of countermeasure assessment data collection and modeling, human factors, headway detection technology (e.g., radar), and supporting technologies.

1.0 INTRODUCTION

This report describes a six-step analysis of the application of Intelligent Vehicle Highway System (IVHS) technology to the prevention and severity-reduction of rear-end crashes. The discussion addresses both major classes of rear-end crashes: lead-vehicle stationary (LVS) and lead-vehicle moving (LVM). The principal countermeasure concept examined is a headway detection system that would detect stopped or slower-moving vehicles in a vehicle's forward travel path.

1.1 Program Overview

The National Highway Traffic Safety Administration (NHTSA) Office of Crash Avoidance Research (OCAR), in conjunction with the Volpe National Transportation Systems Center (VNTSC), has initiated a multi-disciplinary project designed to model target crash scenarios and conceptual (but realistic) IVHS interventions, to provide device effectiveness estimates, and to identify high-priority R&D needs relating to specific IVHS/crash avoidance countermeasure concepts. The crash problem studies constitute "front-end analyses" of target crashes and the prospects for preventing them through the application of advanced technology. The project contractor (Contract No. DTRS-57-89-D-00086) is Battelle Memorial Institute, with major involvement of subcontractors ARVIN/Calspan and Castle Rock Consultants. This document is based in large part on contractor analyses of rear-end crashes and applicable countermeasures, in particular rear-end crash causal factor analyses and crash reconstructions performed by Donald L. Hendricks and his colleagues at ARVIN/Calspan (see Chapter 3). This crash data constituted much of the basis for the effectiveness prediction modeling (Chapter 6.0) performed by the two principal authors.

The results of IVHS crash problem analysis, such as this rear-end crash analysis, will form the basis for dedicated NHTSA IVHS countermeasure R&D efforts. These countermeasure R&D efforts will demonstrate whether selected IVHS countermeasure concepts and associated technologies can practicably enhance the crash avoidance performance of motor vehicles and their drivers. A key goal of each countermeasure R&D effort will be the development of performance specifications for IVHS crash avoidance countermeasure concepts. The agency will identify desired safety performance characteristics of the system, and techniques for evaluating system safety. The crash problem analysis project, as exemplified in this report, is of pivotal importance in defining NHTSA's IVHS R&D/performance specification efforts and thus, indirectly, NHTSA's overall IVHS research program. In turn, the ultimate goal of the performance specification efforts and the NHTSA IVHS program is to support the safety-effective development and commercialization of IVHS devices by the automotive industry.

1.2 Methodology

Each crash problem analysis consists of the following six steps or elements, all of which are documented in this report:

1. ***Quantify baseline target crash problem size and describe target crash characteristics.***

2. ***Describe, analyze, and model target crash scenarios*** in sufficient detail to permit understanding of principal crash causes, time and motion sequences, and potential interventions. Model parameters are based on crash data (e.g., GES, FARS) and on intensive "clinical analysis" of individual crash case data.

3. ***Assess countermeasure mechanisms of action and technology status*** to identify candidate solutions (primarily vehicle-based) to these crash problems.

4. ***Assess relevant human factors*** and other (e.g., environmental, vehicle) constraints affecting crash scenario and potential countermeasure effectiveness.

5. ***Model countermeasure action*** to predict effectiveness (in terms of crash avoidance and severity reduction) and identify critical countermeasure functional requirements.

6. ***Identify specific priority technological, human factors, and other R&D issues*** to be resolved to ensure that the countermeasure's potential is reached.

Leasure (1992) describes the rationale for this methodology and how it supports the IVHS initiatives of NHTSA as documented in the ***NHTSA IVHS Plan*** (1992).

Subsequent chapters of this report (i.e., Chapters 2.0 through 7.0) correspond to the above six IVHS crash problem analysis elements.

1.3 Heuristic Nature of the Work

The methodology of this program is analytical, not empirical. It employs existing accident data and available information on technology and driver/vehicle performance. The countermeasure functional models described have been constructed from the best available information. Modeled values of such parameters as countermeasure range, driver reaction time, braking efficiency, and sensor system detection/warning activation decision algorithms have been selected based on the current literature. Researchers with access to better information relating to these parameters or better target crash samples are urged to apply the modeling approaches, or alternative ones, to their data and to share their findings with the agency and the traffic safety research community. Indeed, this presentation of headway detection countermeasure modeling and its parameters is intended to be heuristic, supporting multiple iterations of the modeling using more refined data on system, vehicle, and human parameters.

In addition, the analytical approach is intended to stimulate empirical research, not compete with it. The analytical methodology identifies key parameters and applies nominal values to them. Empirical research, especially that using state-of-the-art research tools such as advanced driving simulation and instrumented vehicles, will provide the critical data needed to validate and refine the countermeasure models.

In this context, the headway detection system effectiveness estimates derived in this report are not intended to assess the merits of immediate countermeasure deployment or regulatory action. Rather, the modeling process and its outputs are intended to stimulate and guide empirical research. Only empirical research will provide essential, verifiable evidence regarding the actual effects, potential benefits, and problems to be overcome in implementing high-technology crash avoidance systems.

2.0 CRASH PROBLEM SIZE AND DESCRIPTION

This chapter presents statistics on the target crash problem size and basic characteristics of rear-end crashes, based primarily on NHTSA accident data systems. The information in this chapter is primarily a summary of that presented in an NHTSA report entitled ***Rear-End Crashes: Problem Size Assessment and Statistical Description*** by Knipling, Wang, and Yin (1993).

2.1 Target Crash Problem Size

Table 2-l displays the problem size estimate for rear-end crashes. This table was compiled based largely on statistics from the NIITSA General Estimates System (GES) and Fatal Accident Reporting System (FARS) Details on the compilation of this table and more statistical information are provided in Knipling, Wang, and Yin (1993). Table 2-l indicates the following regarding the overall rear-end crash problem size:

- In 1990, there were approximately 1.5 million police-reported, rear-end crashes (per GES) on roadways with 2,084 associated fatalities (per FARS).
- There were approximately 844,000 associated injuries, including 68,000 serious (incapacitating) injuries.
- Rear-end crashes constitute about 23 percent of all police-reported crashes, but only about five percent of all fatalities.
- During its operational life, a vehicle can be expected to be involved in 0.226 police-reported (PR) rear-end crashes; one-half (0.113) as the striking vehicle and one-half as the struck vehicle. Note: The term “subject vehicle” refers to the crash-involved vehicle that, if equipped with the countermeasure, could potentially have prevented the crash. Thus, the 0.113 expected involvements for rear-end crashes shown in Table 2-l refers to 0.113 involvements in ***each*** crash role: striking and struck.
- The above statistics relate to police-reported crashes. In addition, there are roughly 1.76 million annual non-police reported (NPR) rear-end crashes.
- Based on the estimation algorithm described in the NHTSA statistical report, rear-end crashes cause approximately 144 million vehicle-hours of delay annually. This is about one-third of ***all*** crash-caused delay.

The most important classification within the rear-end crash category is whether the lead-vehicle is stationary (LVS) or moving (LVM). These two types of rear-end crashes are different in many respects (in particular, pre-crash dynamics; e.g., closing speeds and distances) and are treated separately in the causal factor assessment (Chapter 3.0) and

Table 2-1
Problem Size Estimate: Rear-End Crashes on Roadways
Vehicle Types: All Vehicles

Crash Problem Size Statistics (1990)		All Rear-End	LVS	LVM
Annual #PR Crashes (GES)	Total: Injury: PDO:	1,513,000 535,000 979,000	1,054,000 379,000 674,000	459,000 155,000 304,000
Annual # Fatalities (Note: FARS count is the more accurate statistic; GES estimates provided to show LVS vs. LVM comparison.)	FARS Count: GES Estimate:	2,084 3,000	1,600	1,300
Annual # Non-Fatal Injuries Total: (GES)	A: B: C:	844,000 68,000 150,000 627,000	599,000 40,000 107,000 452,000	245,000 27,000 43,000 174,000
Percentage of All PR Crashes **Percentage of All Fatalities** (Based on FARS)		23.4% 4.7%	16.3%	7.1%
Involvement Rate (as "Subject Vehicle") Per 100 Million VMT		77	54	24
Annual Likelihood (as "Subject Vehicle") Per 1,000 Vehicles		8.6	6.0	2.6
Expected # Involvements (as "Subject Vehicle") During Vehicle Life		0.113	0.079	0.034
Estimated Annual # NPR Crashes	Total: Injury: PDO:	1,764,000 208,000 1,556,000	1,216,000 143,000 1,072,000	549,000 65,000 484,000
Crash-Caused Delay	Veh-Hours:	144 M	92 M	52 M
Percentage of All **Crash-Caused Delay:**		32%	20%	12%

Note: Due to rounding, LVS + LVM totals do not always equal "All Rear-End" values exactly.

Legend:

A	Incapacitating Injuries	LVS	Lead Vehicle Stationary
B	Nonincapacitating Injuries	NPR	Non-Police Reported
C	Possible Injuries	PDO	Property Damage Only
FARS	Fatal Accident Reporting System	PR	Police Reported
GES	General Estimates System	VMT	Vehicle Miles Traveled
LVM	Lead Vehicle Moving		

countermeasure modeling (Chapter 6.0) presented in this report. The second and third columns of Table 2-l present problem size assessment statistics for these two crash subtypes (note: FARS does not provide a LVS vs. LVM breakout). LVS vs. LVM unknowns have been distributed proportionately between the LVS and LVM subtypes.

Comparison of the LVS and LVM columns of Table 2-l shows that there are more than twice as many LVS crashes (e.g., 1.05 million police-reported crashes during 1990) as LVM crashes (0.46 million PR crashes). However, GES statistics on crash injuries and fatalities indicate that LVM crashes, though less frequent, are somewhat more severe on average than are LVS crashes. Still, LVS crashes constitute the larger overall problem in terms of crashes, injuries, and fatalities.

2.2 Passenger Vehicles vs. Combination-Unit Trucks

The above statistics relate to all vehicle types combined. Table 2-2 disaggregates and compares involvements as the striking unit of two vehicle types of particular interest, passenger vehicles (here defmed as cars, light trucks, and vans) and combination-unit trucks (i.e., tractor-trailers). Less than 2 percent of all rear-end crashes involve a combination-unit truck as the striking unit, and combination-unit trucks have a much lower rate of involvement per vehicle mile traveled (VMT) than do passenger vehicles. However, due to their greater exposure (average miles traveled), combination-unit trucks have a much higher expected number of involvements in target crashes during their operational lives than do passenger vehicles; i.e., an average of 0.232 involvements as the striking vehicle in police-reported rear-end crashes versus 0.104 for passenger vehicles. In regard to vehicle-based countermeasure concepts (in particular, devices that last the life of the vehicle), these likelihood statistics (i.e., statistics on expected numbers of involvements) are more relevant to potential payoffs than are statistics on rates of involvement. Likelihood statistics are relevant to the question of how many times an installed countermeasure device will have the opportunity to prevent a crash. Miles traveled (and thus, rate of involvement per VMT) are not as relevant to payoffs as the simple likelihood that the device will be employed to prevent a collision.

Table 2-2
Comparisons Between Passenger Vehicle (PV) and Combination-Unit Truck (CU Trk) Involvements in Police-Reported Rear-End Crashes as the Striking Unit.

Statistic Vehicle Type:	PVS	CU Trks
Annual Crashes (1990 GES)	1,450,000	25,000
Rate of Involvement Per 100 M Veh Miles Traveled (VMT)	73	26
Expected Number of Involvements Over Vehicle Life	0.104	0.232
Fatalities Per Crash (1990 FARS and 1990 GES)	0.0011	0.0133

In addition, Table 2-2 shows that rear-end crashes involving combination-unit trucks as the striking unit are more than ten times more likely to result in a fatality than are those involving passenger vehicles as the striking unit.

In summary, Table 2-2 shows that combination-unit trucks have a greater likelihood of involvement in target crashes (in spite of their low rate of involvement) and that their target crashes are more likely to be severe. These characteristics combine to make combination-unit trucks a potentially-attractive population for early cost-beneficial installation of countermeasures to rear-end crashes.

Two additional characteristics of combination-unit truck rear-end crashes in comparison to passenger vehicle rear-end crashes should be noted. First, for combination-unit trucks (unlike passenger vehicles and "all vehicles"), the majority (58 percent) of rear-end crashes are LVM crashes. Secondly, combination-unit trucks are more likely to be involved as the striking vehicle (62 percent for all rear-end crashes) than as the struck vehicle (3 8 percent).

2.3 Crash Characteristics and Causal Factors

The statistical characteristics of rear-end crashes as evident in GES do not reveal widespread distinctive patterns of occurrence such as roadway or environmental factors. Most crashes (both LVS and LVM) occur during daylight hours on dry, straight roadways. The most common coded pre-crash vehicle maneuver for the striking vehicle is simply "going straight" (89 percent overall). For LVM crashes, accident type data indicate that "lead-vehicle slower" and "lead-vehicle decelerating" subtypes are approximately equal in frequency. Across all rear-end crashes, about 10 percent of lead vehicles are in the process (or have the intent) of making a left turn and about 5 percent a right turn. Obstruction of driver vision is rarely noted.

A few notable differences in the conditions of occurrence of LVS and LVM crashes include the fact that most LVM crashes (54 percent) are non-junction crashes (i.e., not intersection or intersection-related), whereas only 35 percent of LVS crashes are non-junction. In addition, LVM crashes are somewhat more likely to occur on divided highways and other higher-speed roadways than are LVS crashes. Forty-three (43) percent of LVM crashes occur on divided highways, versus 33 percent of LVS crashes. Twenty-nine (29) percent of LVM crashes occur on 55mph+ roadways, versus only 13 percent of LVS crashes. As noted above, Knipling, Wang, and Yin (1993) contains more information on the statistical characteristics of rear-end crashes.

Indiana Tri-Level study (Treat et al, 1979) findings (see Figure 2-1) on the causal factors associated with 45 LVS and 12 LVM crashes (of the 420 total cases in the Tri-Level in-depth sample) were accessed. The analysis of the Tri-Level cases by crash type was possible through the use of an enhanced Tri-Level study data file developed by NHTSA (1990). The Tri-Level statistics portray rear-end crashes as resulting largely from driver inattention and other forms of delayed recognition (i.e., conscious driver does not properly perceive, comprehend, and/or react to vehicle in his or her forward travel path), There is little involvement of vehicle factors, indirect human causes (e.g., alcohol), or environmental factors. This pattern is true for both LVS and LVM crash subtypes -- especially the LVS crashes.

Chapter 3.0 of this report presents a new analysis of rear-end crash scenarios, including identification of causal factors and applicable countermeasure concepts for a clinical sample of 74 rear-end crashes.

Figure 2-l : Tri-Level Study Rear-End Crash Causal Factors

Principal causal factors identified **in** Indians Tri-Level Study (Treat et al, 1979). Indentation reflects Tri-Level taxonomy of crash causes.

Rear-End. Lead Vehicle Stationarv (LVS; 45 cases total):

- Vehicular factors (11 %)
- Human causes (93 %)
  - Direct human causes (93 %)
    - Recognition errors (82%)
      - Recognition delays -- reasons identified (69%)
        - Inattention (42%)
          - Traffic stopped or slowing (33 %)
          - Event in car (e.g., sudden noise) (13%)
        - Internal distraction (4 %)
        - External distraction (11 %)
    - Decision errors (24 %)
  - Indirect human causes (e.g., alcohol, drugs) (9%)
- Environmental causes (e.g., slick roads, view obstructions) (9%)

Rear-End, Lead Vehicle Moving (LVM: 12 cases total):

- Vehicular factors (17 %)
  - Brake system (17%)
- Human causes (92%)
  - Direct human causes (92%)
    - Recognition errors (67%)
      - Recognition delays -- reasons identified (67%)
        - Inattention (25 %)
          - Traffic stopped or slowing (25%)
          - Event in car (e.g., sudden noise) (17%)
        - External distraction (33 %)
    - Decision errors (50%)
      - False assumption (e.g., assumed car was turning, did not) (42%)
- Environmental causes (e.g., slick roads, view obstruct.) (17%).

3.0 ANALYSIS OF REAR-END CRASH SCENARIOS

This chapter presents a detailed analysis of a sample of rear-end crashes. The research approach was based primarily on clinical analysis of case reports from the National Accident Sampling System (NASS) Crashworthiness Data System (CDS). "Clinical analysis" involved intensive review of all case file data by experienced crash reconstructionists. Cases were examined to extract data on primary causal factors and to establish parameters for the modeling of rear-end crashes relative to preliminary IVHS countermeasure specifications. This work was performed by Donald L. Hendricks and his colleagues at ARVIN/Calspan. The rationale, methodology, and results of the analysis are described below.

3.1 Selection of Analysis and Modeling Approaches

To ensure that logical decisions are made in terms of matching IVHS technologies with crash types or subclasses of crash types, it is necessary to determine why specific crashes occur. Thus, a causal factor analysis is a fundamental input to the modeling process. During the early stages of this project, a number of decisions were made which influenced the nature of subsequent causal factor analyses.

A primary issue during the project planning stage was the most appropriate source of causal factor data. The options were to use causal data from available mass databases or to clinically analyze selected case reports to determine the causal factors. After a detailed examination of both potential data sources, the project team selected the clinical analysis approach. A review of causal data elements in existing mass databases revealed that there was insufficient detail in these files to allow a successful match of technologies, causal factors, and crash types.

The next step was to determine the specific hardcopy case files to be examined for the analysis. Here, two issues were of concern. The major issue was to ensure that the data were nationally-representative. This criterion ruled out use of in-depth investigation reports that used geographically-limited samples or were otherwise not representative of the national crash picture. The second issue involved the timely accessibility of report information. Selection of case reports from the NASS CDS program satisfied these criteria. Although the CDS was designed primarily for crashworthiness/occupant protection research, CDS files typically provide sufficient detail to successfully determine causal factors. Thus, they can be used to support crash avoidance research. Moreover, the NASS data set is considered to be nationally representative when weighted with appropriate sampling weights. Since project subcontractor Calspan is a NASS Zone Center, these hard copy files were readily accessible for the current effort.

It was also necessary to specify the sample sizes to be analyzed for each crash type. In an ideal circumstance, fairly large clinical samples would be analyzed to ensure that the full range of causal factors is encountered. In this case, however, there were compelling reasons to limit sample sizes. These reasons included the necessity of reconstructing cases used in the causal factor analysis for subsequent use in the modeling task and the previously noted constraint requiring rapid turn-around times for causal analyses. In view of these constraints, a sample size of approximately 75 cases was designated for the rear-end crash causal factor analysis.

The decision to employ clinical analysis to establish causal factor data also influenced the final form of the modeling effort. Since the project was afforded the opportunity to examine a number of cases in an in-depth fashion, there was an opportunity to extract crash data for use in the modeling process. Specifically, a number of the individual CDS cases used in the causal factor analysis were reconstructed to establish crash/countermeasure modeling parameters such as travel speed, impact speed, and velocity change during the collision impact (ΔV). These parameters were, in turn, used to evaluate the likely performance of the designated countermeasure. Chapter 6.0 presents this countermeasure modeling applied to the clinical sample (and, in addition, applied to a larger crash sample based on General Estimates System data).

3.2 Selection of Modeling Parameters

First, a tentative listing of crash parameters relevant to the modeling process was identified. This effort was completed prior to the causal analysis. The intent here was to have analysts identify and flag cases with sufficient data for subsequent reconstruction as part of the review process conducted for the causal analysis. This step avoided the necessity of having two separate reviews to establish causal factors and to select cases for the modeling effort. The tentative listing included the following parameters:

- Vehicle travel speed (lead and following vehicles)
- Following distance
- Brake inputs
- Closing speeds
- Coefficients of friction
- Impact speed
- ΔV ("Delta V", the change in vehicle velocity during the impact, a primary measure of collision impact severity).

Note the absence of parameters related to steering inputs. For this crash type, steering was not regarded as a reliable crash avoidance maneuver upon which to base a countermeasure concept. For many of the crashes it appeared likely that a steering maneuver to avoid a rear-end crash with a lead vehicle would result in another crash in the adjacent traffic lane or off the roadway. These avoidance maneuver-related impacts would occur if the countermeasure device either recommended an evasive steering maneuver to the driver or initiated an automatic steering maneuver to avoid the lead vehicle. Therefore, only countermeasure concepts involving in-lane velocity reduction (i.e., braking) were considered.

3.3 Clinical Case Sample

The initial case listing developed for this effort identified all rear-end crashes available in the 1991 hard copy NASS CDS file residing at Calspan. These cases were from 13 different NASS Primary Sampling Units located in eight Eastern U.S. states. A sample of 68 cases was then selected from the 137 cases contained in the listing. This sample was selected to reflect as closely as possible the accident severity profiles of the General Estimates System (GES) data file (recall that the GES file was utilized to determine national crash population estimates). Since the NASS CDS oversamples severe cases, the proportion of cases selected for the clinical sample was inversely related to severity. Higher proportions of less severe cases were selected in an attempt to counterbalance the NASS sample and thus make the clinical sample more representative. Within each severity strata, cases were selected based on a simple semi-random rule such as, "For Severity Level 1 (Non-incapacitating injury), select every third case number."

During the course of the causal factor analysis, project analysts identified an additional nine cases from the initial case listing where there was sufficient information to perform complete speed reconstructions and determine values for identified modeling parameters. These cases were added to the clinical case sample to maximize the number of cases available for the subsequent modeling task. The final sample for rear-end crashes, therefore contained 77 cases (case listing provided in Appendix A). A representativeness check performed subsequent to the causal analysis indicated that the accident and injury severity profile of the final sample was more severe than the GES profile. The correction for this bias involved creation of a weighted sample after the fact using case weights equal to the "national inflation factor" assigned to each CDS case at the end of the data collection year. These national inflation factors are based on crash sampling stratification (injury severity and vehicle characteristics) and on location of the investigative unit (primary sampling unit). Case weights (national inflation factors) are provided along with the case list in Appendix A. Note in Appendix A that different cases have vastly different weights based on the CDS sampling scheme. Readers interested in more information on the derivation of CDS case weights are referred to the 1991 NASS Crashworthiness Data System Analytical User's Manual.

3.4 Clinical Analysis Procedure

Experienced accident reconstruction personnel conducted a content analysis of NASS CDS hard copy case reports to determine the major events and causal factors associated with each crash. The case elements most essential to the content analysis procedure were as follows:

- Police reports
- Driver statements
- Witness statements (where available)

- Scaled schematics depicting crash events and physical evidence generated during the crash sequence
- Case slides documenting the physical plant, physical evidence, and damage sustained by case vehicles.

While reviewing the case elements noted above, analysts prepared a written summary of each crash that was examined. The summaries delineated the circumstances surrounding the crash, driver actions, impact events, and causal factors associated with impact events. Part of the intent here was to construct a permanent record of causal factors which could be tabulated and distributed to technology assessment personnel. In addition, however, there was also interest in accumulating crash descriptions for subsequent identification of trends in crash circumstances. For example, review of the summaries would allow analysts to determine if there were crash subtypes within the rear-end crash target category and to determine if there were key/critical relationships within crash subtypes. Results of the latter review are provided in the next subsection.

The clinical analysis conducted for this effort was an independent assessment of available information. Specifically, analysts did not merely accept and record police-reported information and driver statements. These data inputs were evaluated against the physical evidence generated by crash events and in the total context of the crash environment. Thus, in a number of instances, the analyst's interpretation of crash events and contributory causal factors differed from police-reported information. While these clinical assessments were subjective in nature, the degree of subjectivity was probably less than the levels associated with the on-scene observations of investigating officers or the viewpoints expressed by drivers. Unlike police officers at the scene, analysts performing these clinical analyses have an opportunity to weigh all case data dispassionately and are not encumbered by other responsibilities such as assisting the injuried and clearing the crash scene.

3.5 Clinical Analysis Results

In the final sample of 77 cases, 3 cases contained insufficient data to make clinical causal assessments. These 3 cases were eliminated from the study. Therefore, results are based on 74 cases (weighted per the NASS CDS sampling scheme, as discussed above).

3.5.1 Crash Circumstances

Review of the case files provided distinctive insights into the circumstances surrounding rear-end crashes. Major findings may be summarized as follows:

- Two major rear-end crash subtypes were evident:
  - Lead Vehicle Stationary (LVS) (56 of the 74 cases; 74.8% weighted) -- a lead vehicle decelerates to a stop and is then stuck by a following vehicle.

- Lead Vehicle Moving (LVM) (18 of the 74 cases; 25.2% weighted). The lead vehicle is decelerating and is struck in the rear before coming to a stop. Or, the lead vehicle is not decelerating but rather is simply traveling at a lower speed than the following vehicle. For convenience, these subtypes are designated as and , respectively.

- The LVS crash subtype typically does not involve simply a "too-slow" reaction of the following driver to a sudden crash threat. In the most common scenario, the lead vehicle is stopped for an extended interval (i.e., 2-6 seconds) before it is struck by the following vehicle. There is adequate time to provide a warning to the following vehicle's driver and for the driver to avoid the crash. Vehicles involved in this crash subtype should not be viewed as a locked pair where one vehicle is following the other at a specified distance. Instead, the following vehicle is closing on a stationary object. The initial gap distance between the vehicles is often several hundred feet or more. No cases were identified where a lead vehicle decelerated rapidly and then was hit by a closely following vehicle immediately after coming to a stop.

- In contrast, the LVM crash subtype may involve driver reaction time following a sudden crash threat as a critical factor. Vehicles involved in this circumstance are often "locked pairs" with one vehicle following the other. However, gaps or following distances can range from a few car lengths to very substantial distances even in this subtype. Not all LVM crashes are precipitated by rapid deceleration of the lead vehicle. Many involve slow decelerations (e.g., typical slowing before a turn) or simply a speed differential between the lead and following vehicles.

It should be noted that the clinical analysis procedure resulted in some reclassification of cases within the rear-end crash subtype taxonomy. Of 57 cases originally classified as LVS (i.e., per the data file), five were reclassified after in-depth case review as LVM. Of 15 cases originally classified as LVM, two were reclassified LVS. Two unspecified rear-end crash cases were classified LVS after in-depth review. Table 3-l presents the original and fmal rear-end crash case classifications. For each classification, the number and weighted percentage of the total clinical sample are presented.

Table 3-2
Reclassification of CDS Rear-End Crash Cases Based on In-Depth Review

Accident Subtype	Original Classification	Final Classification
Lead-Vehicle Stationary	57177.6%	56/74.8%
Lead-Vehicle Moving	15/19.3%	18125.2%
Unspecified Rear-End	213.2%	------
Total	74/1 00%	74/1 00%

3.5.2 Causal Factors

A summary of causal factors associated with clinical sample rear-end crashes is provided in Table 3-l. Table 3-l shows that the primary causal factor associated with rear-end crashes was driver inattention to the driving task. This causal factor was, of course, attributed to the driver of the following vehicle. The term "driver inattention" was here applied broadly for situations where a conscious, unimpaired driver does not properly perceive, comprehend, and/or react to a crash threat. Thus, "driver inattention" as defined here is similar to "recognition error" as defined in the Indiana Tri-Level Study (Treat et al, 1979). It includes "preoccupation, ", distraction (both from inside and outside the vehicle), and "improper lookout" -- i.e., the driver "looked but did not see" the crash threat.

Driver inattention was cited as the primary cause in 48 of the 74 cases (66.3 percent weighted) of the clinical sample. It was cited as a contributing factor, in combination with following too closely, in 8 additional cases (19.4 percent weighted). In total, driver inattention was a causal factor in 56 of the 74 cases (85.7 percent weighted) in this sample. Note the variety of activities which diverted the driver's attention from the roadway.

A second major causal factor associated with rear-end crashes was following too closely. This factor was cited as the primary cause in 6 of the 74 cases (7.1 percent weighted) and as a contributing factor, with driver inattention, in an additional 8 cases (19.4 percent weighted). Thus, following too closely was a factor in 14 of the 74 cases (26.5 percent weighted) in this sample.

Alcohol involvement was cited as a primary causal factor in 6 of the 74 cases (but only 2.1 percent weighted). A variety of miscellaneous causal factors were associated with the remaining 6 cases (5.1 percent weighted).

Table 3-l
Rear-End Crash Causal Factor Analysis

Causal Factor	Curve	Straight	Total
Driver inattentive to driving task *Subtotal:*	14/21.7%	34/44.6%	48/66.3%
Specific activity unknown	11/17.7%	21/22.9%	32/40.5%
Driver looked left or right for approaching traffic	1/0.7%	3/3.2 %	4/3.9%
Driver looked away from roadway	--	2/2.9%	2/2.9%
Driver watched pedestrian at side of road	1/0.5%	1/1.8%	2/2.3%
Driver looking off-road for a business	—	1/1.3%	1/1.3%
Driver distracted by a parked vehicle on right side of road	1/2.9%	--	1/2.9%
Driver tracking a non-contact vehicle that changed lanes	--	1/0.6%	1/0.6%
Driver attending to a child passenger (feeding baby)	—	1/1.9%	1/1 .9%
Driver sneezed	—	1/7.9%	1/7.9%
Driver illness (light headed due to thumb laceration)	--	1/1 .7%	1/1.7%
Driver turned on wipers/washers	--	1/0.1 %	1/0.1 %
Driver reached to floor to retrieve object	--	110.3%	1/0.3%
Following too closely/Inattentive to driving task (both)	--	8/1 9.4%	8/19.4%
Following too closely	--	6/7.1%	6/7.1%
Alcohol Involvement *Sub total:*	*1/O. 1%*	5/2.0%	6/2.1 %
BAC = .13	—	1/0.1 %	1/0.1 %
BAC = .09 to .14 (3 tests, same driver)	--	1/0.2%	1/0.2%
Unknown BAC	1/0.1 %	3/1 .7%	4 / .8%
Poor judgment	--	1/0.4%	1/0.4%
Encroachment of other vehicle (lead vehicle cut into lane in front of following vehicle)	--	2/1.1%	2/1.1%
Vehicle failure (loss of brakes)	—	1/1.2%	1/1.2%
Driver's vision obscured	--	1/0.1%	1/0.1 %
Icy road (vehicle unable to stop)	--	1/2.3%	1/2.3%
Total	15/21.9%	59/78.1%	74/100%

Note: Italicized values are category subtotals which are not included in the column totals.

Note the relatively low involvement rate for icy/poor road surface conditions (1 case of 74). Tbis same tendency is noted in national accident statistics. In the GES file, for example, 80 percent of rear-end crashes occur in dry weather and 93.8 percent occur on straight roads. The rear-end crash is largely a dry/straight road phenomenon associated with driver inattention. As weather or roadway geometry deteriorated to more difficult conditions, the incidence of driver inattention appeared to decrease within the clinical sample. Apparently, drivers become more attentive to the driving task under demanding driving conditions.

A summary of causal factors for the LVS crash subtype is provided in Table 3-2, and a similar summary for the LVM subtype is provided in Table 3-3. Driver inattention was the predominant causal factor in LVS crashes, and also played a major role in LVM crashes.

Following too closely (usually combined with driver inattention) was also a significant factor, especially in the LVM sample where it was identified in 32.6 percent of the weighted sample. Following too closely was also identified as a factor in 24.3 percent of the weighted LVS sample, raising the question of whether some of these LVS crashes may be “disguised” LVM crashes in which a lead vehicle braked to a stop immediately prior to being struck by a following vehicle (e.g., less than one second before being struck). However, the clinical analysis identified no cases meeting this scenario description. The causal factor “following too closely” when cited on police accident reports of LVS crashes may reflect a “default” traffic violation charge rather than the principal cause of the crash. Driver inattention clearly plays a causal role in many of these crashes.

Combined, driver inattention and/or following too closely were associated with 96.4 percent (weighted) of the LVS clinical sample and 81.8 percent (weighted) of the LVM clinical sample. Other factors besides inattention and following too closely amounted to less than four (4) percent of the LVS sample and less than 20 percent of the LVM sample.

The next chapter will focus on a countermeasure concept that addresses these two predominant causes of rear-end crashes.

Table 3-2
Rem-End, Lead Vehicle Stationary Crashes
Causal Factor Analysis

Causal Factor		Curve	Straight	Total
Driver inattentive to driving task	*Subtotal:*	*1 1/27.1 %*	*28/45.1%*	*39/72.1%*
Specific activity unknown		9/22.2%	16/26.6%	25/48.8%
Driver looked left or right for approaching traffic		1/0.9%	3/4.3%	4/5.2%
Drive looked away from roadway		--	2/3.8%	2/3.8%
Driver watching pedestrian at side of road		—	1/2.5%	1/2.5%
Driver looking off-road for a business		--	1/1.7%	1/1.7%
Driver distracted by a parked vehicle on right side of road		1/3.9%	--	1/3.9%
Driver tracking a non-contact vehicle that changed lanes		--	1/0.8%	1/0.8%
Driver attending to a child passenger (feeding baby)		--	1/2.6%	1/2.6%
Driver sneezed		—	—	—
Driver illness (light headed due to thumb laceration)		--	1/2.3%	1/2.3%
Driver turned on wipers/washers		--	1/0.1%	*1/O.1 %*
Driver reached to floor to retrieve object		—	1/0.4%	1/0.4%
Following too closely/inattentive to driving task		--	6/16.3%	6/16.3%
Following too closely		—	5/8.0%	5/8.0%
Alcohol involvement	*Subtotal:*	*1/0.2%*	*4/1. 7%*	*5/1. 8%*
BAC = .13		--	1/0.1 %	1/0.1 %
BAC = .09 to .14 (3 tests, same driver)		—	1/0.2%	1/0.2%
Unknown BAC		110.2%	2/1 .4%	3/1 .5%
Poor judgment		—	--	
Encroachment of other vehicle		—	—	
Vehicle failure (loss of brakes)		—	111.6%	1/1.6%
Driver's vision obscured		—	—	--
Icy Road (vehicle unable to stop)		--	--	--
	Total	12/27.2%	44/72.8%	56/100%

Note: Italicized values are category subtotals which are not included in the column totals.

Table 3-3
Rear-End, Lead Vehicle Moving Crashes
Causal Factor Analysis

Causal Factor	Curve	Straight	Total
Driver inattentive to driving task *Subtotal:*	*3/6.0%*	*6/43.2%*	*9/49.2%*
Specific activity unknown	2/4.1%	5/11.8%	7/15.9%
Driver looked left or right for approaching traffic	--	--	--
Driver looked away from roadway	--	--	--
Driver watching pedestrian at side of road	1/1.9%	--	1/1.9%
Driver looking off-road for a business	--	--	--
Driver distracted by a parked vehicle on right side of road	--	--	--
Driver tracking a non-contact vehicle that changed lanes	--	--	--
Driver attending to a child passenger (feeding baby)	--	--	--
Driver sneezed	--	1/31.4%	1/31.4%
Driver illness (light headed due to thumb laceration)	--	--	--
Driver turned on wipers/washers	--	--	--
Driver reached to floor to retrieve object	--	--	--
Following too closely/inattentive to driving task	--	2/28.4%	2/28.4%
Following too closely	--	1/4.2%	1/4.2%
Alcohol involvement *Subtotal:*	--	*1/2.6%*	*1/2.6%*
BAC = .13	--	--	--
BAC = .09 to .14 (3 tests, same driver)	--	--	--
Unknown BAC	--	1/2.6%	1/2.6%
Poor judgment	--	1/1.6%	1/1.6%
Encroachment of other vehicle	--	2/4.5%	2/4.5%
Vehicle failure (loss of brakes)	--	--	--
Driver's vision obscured	--	1/0.4%	1/0.4%
Icy road (vehicle unable to stop)	--	1/9.1%	1/9.1%
Total	**3/6.0%**	**15/94.0%**	**18/100%**

Note: Italicized values are category subtotals which are not included in the column totals.

4.0 ASSESSMENT OF POTENTIAL IVHS COUNTERMEASURES

This chapter identifies applicable crash avoidance countermeasure concepts based on the causal factor analysis; defines and describes the principal applicable countermeasure concept, headway detection (HD) systems; reviews the concepts of “nuisance” alarms and false alarms and their relevance to HD systems and other crash threat sensors; reviews technology options for HD systems; and presents representative HD system parameters based on an existing device.

4.1 Applicable Countermeasures Based on Causal Factor Analysis

In the clinical analysis of rear-end crashes, nine major causal factors were identified. Of these, two were cited as primary causes or co-contributing factors in more than 90 percent of the crashes. The two primary causal scenarios were instances when the driver was inattentive to the driving task and circumstances when the driver followed the lead vehicle too closely. Note that these two factors/scenarios may overlap and did in fact overlap in the clinical sample. Because of the predominance of these two factors, the assessment of countermeasures is limited to technologies that directly address them.

Driver inattention was identified as the most common cause of the rear-end crashes. This factor was noted as the primary cause in 66.3 percent (weighted) of all rear-end crashes in the clinical sample, and as a contributing factor in another 19.4 percent (weighted). Crashes included in this category represent incidents occurring as a result of the driver’s attention being partially or fully directed away from the vehicle operating task.

Mitigation of this particular crash type is aided by detecting the presence of an obstacle in the vehicle’s path and reporting this presence to the driver. The provision of an effective warning affords the driver the opportunity to take corrective action. Audible warnings may be particularly effective for inattentive drivers (Morgan et al, 1963; McCormick, 1976). To ensure that all relevant observations are made and that minor fluctuations in the traffic status are recorded, any countermeasure needs to constantly monitor the road environment ahead of the vehicle.

The second major factor associated with rear-end crashes is following too closely. This factor was cited as a principal cause in 7.1 percent (weighted) of the crashes in the clinical sample. It was a contributing factor, along with driver inattention, in a further 19.4 percent (weighted). This category of crashes includes incidents which occur when drivers allow insufficient distance between their vehicle and the lead vehicle.

The causal factor analysis indicates that the incidence of rear-end crashes may be reduced by a countermeasure that monitors the distance between a forward obstacle and the vehicle, as well as such factors as closing speed, and alerts the driver to approaching hazards.

4.2 Headway Detection Systems

Table 4-1 displays the nine major causal factors identified for rear-end crashes against some major countermeasure concepts. The table identifies specific technologies that may be suitable for applicable causal factors in the appropriate cells. A Headway Detection (HD) system has the greatest single potential among the technologies to have a significant effect on rear-end crashes. Crashes potentially applicable to the HD countermeasure (i.e., those involving driver inattention and/or following too closely) total 92.8 percent (weighted percentage) of the clinical sample (96.4 percent of the LVS crashes and 81.8 percent of the LVM crashes). Consequently, this report focuses primarily on HD systems.

HD systems monitor the dynamic relationship, including relative distance and velocity, between the following vehicle and an object in the path of travel. These offer the greatest potential for mitigating problems associated with driver inattention.

A safe headway margin can be defined as the distance a driver needs in front of his or her vehicle to react safely to changes in traffic flow and to come to a complete stop without making contact with the object ahead. An HD system must have the capability to measure at least the following characteristics:

- Distance between lead and following vehicles
- Closing speed between vehicles
- Following vehicle's speed
- Following vehicle's current operating status.

The following vehicle's current status is assessed by monitoring the vehicle control operations undertaken by the driver. This information, together with an assessment of the following vehicle's speed, is fed into an onboard microprocessor. Using preprogrammed headway control algorithms, the microprocessor can relate the vehicle's status and dynamic parameters to those of the object ahead and determine a safe driving margin. If this margin is compromised, the microprocessor can initiate a warning to the driver. The establishment of a safe driving margin depends on these factors being accurately assessed, as well as judicious selection of alarm thresholds, i.e., sensitivity and alarm criterion. Accurate parameter measurement is dependent on the accuracy of the sensors and the sampling rate at which the data are recorded and transmitted.

Such a system could be enhanced by the installation of vehicle-identifying reflectors/ transponders on the rear surfaces of vehicles. Regardless of the sensor technology used, these reflectors/transponders would function to provide a more salient vehicle-identifying signal to the following vehicle, and thus would help to improve signal-to-noise ratios and reduce the probability of alarm activations resulting from signals reflected from non-vehicular objects.

Table 4-1
Applicable Countermeasure Concepts for Rear-End Collisions

	Causal Factor and Weighted Percentage of Sample								
Countermeasure concepts	**Driver inattention** 66.3%	**Inattention *and* following too closely** 19.4%	**Following too closely** 7.1%	Alcohol 2.1%	Poor Judgment 0.4%	Encroachment of other vehicle 1.1%	Vehicle Failure 1.2%	Vision obscured 0.1%	Icy roads 2.3%
Forward obstacle detection	Headway detection systems	Headway detection systems	Headway detection systems						
Monitor driver status				Driver impairment detection systems					
Control vehicle position in lane						Lateral control systems			
Monitor brake status							Brake monitoring system		
Enhance driver vision								Vision enhancement systems	
Prevent loss-of-control									Antilock brakes/ traction control
Monitor pavement condition									Pavement condition monitoring systems

4.3 Headway Sensor Requirements; "Nuisance" and "False" Alarms

HD systems will generally include one or more sensors that provide a simultaneous measurement of range and of relative velocity between the lead and following vehicles. The sensor transmits an electromagnetic pulse toward the lead vehicle. The lead vehicle reflects a portion of this energy, perhaps aided by a specialized reflector or transponder as described above. The reflected energy is intercepted by a receiver on the following vehicle.

The receiver measures the two-way transit time of a transmitted pulse to determine the range between vehicles. The receiver may also determine the relative velocity due to the frequency (Doppler) shift in the reflected electromagnetic energy.

In considering electronic sensor systems in general and HD systems in particular, it is important to establish the distinction between ***nuisance alarms*** and ***false alarms*** ***The*** terms are defined as follows for the purposes of this report and related assessments of countermeasure technologies:

- **Nuisance alarms** -- Alarm activations occurring when a system functions as designed but when the situation does not constitute a true crash threat for the driver in question. For example, an HD system operating at a functional range of 300 feet might sound numerous alarms based on correct detections of vehicles in the forward travel path, but in which there is little or no actual crash threat. Obviously, drivers will come to regard such activations as a "nuisance" and will not tolerate excessive incidents of nuisance alarm activation.

- **False alarms** -- Alarm activations in which a device does not function as designed; e.g., an electronic sensor interprets ambient noise as a signal and activates the alarm. The system is not functioning according to its intended functional specifications and there is no true signal (e.g., radar pulses reflected from a vehicle in the forward travel path) causing the system to activate the alarm. Drivers will perceive these as system malfunctions and will also consider them objectionable if they are excessive.

Sound engineering practice dictates that the distinction between nuisance and false alarms be made, particularly during the final testing phases of a developing system. False alarms occur when a device has an insufficient threshold signal-to-noise ratio, and thus not all noise voltages are blocked. Nuisance alarms occur when real but "undesirable" energy is received; they are indicative of poor discrimination between signals having similar characteristics or signatures, but distinctly different levels of significance as crash threats. From an R&D perspective, nuisance alarms are more difficult to eliminate than false alarms since a tradeoff typically exists between maximizing detection of crash threats and minimizing "detection" of non-threats. A prudent approach to nuisance alarm problems is to operate sensors with the lowest sensitivity consistent with an acceptable probability of detection of the desired target, and to use signal processing logic to further filter out non-threats. Of course, establishing these detection parameters and signal processing routines are complex research problems. This is complicated by the fact that driver capabilities such as reaction time vary greatly (see Chapter 5.0). An alarm activation constituting a nuisance for one driver may constitute a real crash threat for another driver.

The remainder of this chapter discusses some important general features of active HD systems that require specification for particular IVHS applications.

4.4 Technology Options for Headway Detection Sensors

Two sensor options for active HD systems are laser radar and ***microwave/ millimeter wave radar.*** HD systems that employ laser radar transmit energy in the THz range (1 THz = 10^{12} Hz). Normally, laser radar is more conventionally specified in terms of its wavelength in the micron range (1 micron = 10^{-6} meters). For reference purposes, the human eye responds to electromagnetic energy in the range of approximately 0.4 to 0.7 microns. The infrared (IR) region of the spectrum extends from about 0.75 to 1,000 microns. HD systems that employ microwave/millimeter wave technology operate in the lower frequency regime of tens of GHz (1 GHz = 10^9 Hz) and have corresponding wavelengths from 1 to 15 millimeters.

The potential utility of an active system for IVHS countermeasures is partially based on its atmospheric transmission properties and its spatial resolution ability to locate the position of the lead vehicle. In the case of millimeter wave radar, there are frequency bands centered at 34, 95, 140, and 220 GHZ where transmission is less atmospherically attenuated. It is noteworthy, however, that high attenuation might be a desirable attribute for the automotive short-range microwave/millimeter wave radar which is required to avoid mutual interference with distant radars. There are several atmospheric transmission bands for laser radar propagation, namely bands centered at 1.25, 1.65, 2.20, 2.75, 4.75, and 10 microns. Microwave/millimeter wave radar provides better adverse weather penetration than active laser systems, although operation in adverse weather for rear-end crashes may not be absolutely essential, since the causal analysis shows that these incidents usually occur on dry roads under clear atmospheric conditions. On the other hand, a relatively small number of disasterious fog-related rear-end crashes occur each year involving large numbers of vehicles and multiple injuries. Thus, the importance of weather penetration ability is still an open question for further research.

The angular resolution of an active system is determined by many considerations, including the ratio of its wavelength to the transmitter aperture diameter. Active systems with smaller wavelengths and larger transmitter diameters possess better angular resolution. Therefore, laser radar offers far better spatial resolution quality than millimeter wave for the detection and identification of lead vehicles.

In general, the optimum utilization of a particular sensor is highly dependent on the details of a specific application. Therefore, the specification and design of a HD sensor should be the subject of an engineering trade-off study. Although this report does not recommend a particular sensor, active laser radar and millimeter wave radar technology issues are briefly reviewed in this section. Several examples of active systems are also provided. These examples are not endorsements of a particular products, but are presented to illustrate the availability of current HD technology. Chapter 7.0 discusses sensor parameters which are important for a future engineering trade-off assessment to formulate performance specifications for IVHS applications.

4.4.1 Active Laser Systems

Near/Far IR Bands: In the near-IR band (0.75 to 3 micron) band, active systems include incoherent Gallinum Arsenide (GaAs) diodes (0.9 microns), incoherent Neodymium:YAG (Nd:YAG) (1.06 microns) and coherent GaAs-pumped Nd:YAG lasers. The coherence property of a laser source refers to its monochromaticity and directionality; i.e., a "coherent" laser source is one that has a highly monochromatic output radiation and a very directional light beam. High coherence is essential for accurate measurement of relative vehicle velocities; beams with low coherence are "blurred" when received by the sensor and, thus, would yield unacceptably high velocity measurement error margins. GaAs lasers are coherent, reliable, efficient and rugged, and have been utilized as pulsed illuminators for range-gated arrays (detectors). Range-gating refers to the measurement of a laser radar return at preselected times to reduce background clutter from rain or snow.

Used as range finders for military applications, Nd:YAG lasers are activated by flash pumping and usually have short pulses for accurate range measurement. However, in the near-IR band, the performance of these laser sources is highly limited due to atmospheric effects, such as fog and rain.

The dominant system in the far-IR band (6-15 microns) is the CO_2 laser. CO_2 systems tend to be complex because they use coherent chirp signal processing and are unlikely to perform well with respect to wet objects or targets whose surface roughness is the order of the laser wavelength (10.6 microns).

Practical Considerations and Examples: Some laser radar systems employ common aperture optics. Common aperture means that both the transmitter and receiver use the same optics. A mixer is also used in the case of coherent laser sources. The mixer combines the reflected optical wave from the lead vehicle and the wave from the system's local oscillator to measure the relative vehicular velocity in the return beam. The local oscillator may consist of a separate laser or may be provided to the laser transmitter by means of a beam splitter. Cost, power and the added complexity of frequency-stabilizing two separate lasers usually dictate the use of a single source for both transmitter and local oscillator.

An example of an active laser system is the collision warning product for trucks called "Traffic Eye" produced by Nissan (Hosaka and Taniguchi, 1992). It employs two laser diodes which transmit 50 nanosecond pulses (1 nanosecond = 10^{-9} seconds) at a repetition rate of 6 KHz Using two photodiodes, the sensor field of regard is 3.4 (Vertical) x 5.7 (Horizontal) degrees. Range resolution is reported to be about 9 centimeters.

A competing active laser system is the "Multisegment Car Distancer," developed by Wild Leitz Ltd. (Arndt, 1990). It is equipped with five 1.5" segments which span the range of 50 to 150 meters, as well as one 4^0 segment which monitors the range of 5 to 50 meters to provide distance and relative speed of the lead vehicle. Additional systems have been tested by Renault and Peugeot/Citroen.

4.4.2 Microwave/Millimeter Wave Systems

Practical Considerations: A microwave/millimeter wave transmitter consists of an antenna which is fed by an oscillator whose modulation is controlled according to the dictates of a particular IVHS application. For example, transmitted wave forms could include individual pulses (e.g., in the range of tens of nanoseconds), as well as frequency or amplitude modulated continuous waves (CW).

Pulse wave forms can be used when the range between lead and trailing vehicles is desired. A timing circuit measures the two-way transit time between vehicles to determine the range. The range resolution is given in terms of the effective pulse width.

Frequency modulation (FM) can be employed when relative velocity is desired. As an example of the use of FM-CW, reflected waves from the lead vehicle are intercepted by the antenna, amplified, and mixed with the transmitter oscillator to generate a difference (beat) frequency which is proportional to the lead vehicle's relative velocity. The resultant beat signal is applied to a square law detector, such as a diode, and a signal amplitude threshold circuit to reduce false alarms.

Examples: A microwave HD system available from Vehicle Radar Safety Systems, Inc. (Vehicle Safety Radar Systems, 1983) continuously measures the distance and closing rate between the host vehicle and an obstacle in the travel lane. Both visual and audible warnings are provided. The system issues a signal when the difference in speed is between 0.1 and 30 mph. If the closing speed is greater than 30 mph, the warning is eliminated to reduce the possibility of nuisance alarms from oncoming traffic. A dashboard monitor produces a visual alarm when a slower traveling vehicle is detected.

VORAD Safety Systems, Inc. manufactures an HD system which tracks the movement and position of targets. The system operates at 24.125 GHz and has a detection range of 300 feet. The warning system issues a yellow light when a target is detected, a red light when the closing speed or traveling distance is unsafe and an audible tone when there is danger of a collision. Salient features of this system based on the VORAD brochure (undated) are given in Table 4-2. Some of these functional parameters are employed in the countermeasure modeling presented in Chapter 6.0.

Table 4-2
VORAD HD System Parameters

VORAD HD system parameters employing 24.125 GHz k-band microwave scanning technology:	
Maximum Functional Range	300 feet
Maximum Vehicle Closing Rate Accurately Monitored	200 mph
Maximum Absolute Speed Which Can Be Monitored	200 mph
Maximum Time From Verified Detection of Obstacle to Assessment of Driving Status	0.1 seconds
Maximum Time to From Detection to Initiation of Warning to Driver	0.1 seconds
Maximum Time for Verification Cycle	0.05 seconds

5.0 DRIVER, VEHICLE, AND ENVIRONMENTAL CONSTRAINTS

Based on the project causal factor analysis and technology assessment, Headway Detection (HD) has been identified as the key countermeasure concept addressing rear-end collisions. This chapter examines the I-ID countermeasure concept from the perspective of "real world" driver, vehicle and environmental constraints and problems. These constraints and problems would need to be overcome or accommodated in order for an HD system to be fully effective. To the extent that these problems are not solved, they will generally tend to act as attenuating factors that will reduce HD system effectiveness to some degree.

The research literature relating to these factors was reviewed to assess their likely relevance and impact on driver/vehicle performance and whether they need be incorporated in countermeasure effectiveness modeling and/or assessment of countermeasure benefits.

5.1 Driver/Human Factors Considerations

51.1 Driver Reaction Time (RT)

Driver braking reaction time (RT) following the activation of a headway detection warning will have a major effect on crash avoidance probability. In one major study, Olson et al found that driver "surprise RTs" had a mean equal to 1.1 seconds, with a range (2 to 98 percentile) of 0.81 to 1.76 seconds. Brake RTs vary widely, in part because they include the component times of driver perception, decision, and response initiation. Furthermore, detection times can vary depending on whether the signal is visual or auditory. In the Olson study, the signal was an obstacle in the road, and was visually perceived.

Taoka (1989) has suggested that the distribution of brake RTs of unalerted drivers can be represented by a lognormal distribution. The lognormal distribution characterizes driver braking RT better than a standard normal distribution primarily because of the skewness of the lognormal distribution. Most studies of RT have shown the distribution to be positively skewed; that is, the distribution mean is greater than the median because there are more extreme RTs at the high end of the distribution than at the low end. At the low end, RT approaches a physiological limit which makes extreme deviations from the median relatively rare. However, extreme deviations are more common at the high end because RT can be degraded by problems of health/fitness, disability, age, impairment, or inattention.

Taoka presents several different possible parameter values of the lognormal distribution based on RT research by different investigators. In this report, the lognormal distribution suggested by Taoka based on RT data collected by Sivak et al (1982) has been used to model driver responses. Sivak et al's data are based on reactions of drivers approaching signalized intersections where a green light turns amber. More definitive RT values -- ideally an empirically-derived distribution function of RT values more representative of the traffic situation under consideration here -- would refine the current modeling results.

Section 6.4.1 addresses the parameters of Taoka's suggested RT distribution in greater detail. Of course, it may be possible for other researchers to refine Taoka's statistical model, either by collecting data of greater direct relevance to the rear-end crash/headway detection situation or by developing better statistical characterizations of existing data.

5.1.2 Nuisance Alarms and Driver Acceptance

The nuisance alarm (see definition, Section 4.3) issue is relevant to HD systems (and to similar collision-threat-detection countermeasures). As illustrated by the Figure 5-l schematic, a short warning distance implies the admonition, "don't engage system warning/control (at a given speed) until the object is very close." A long detection range implies "pick up more objects earlier at farther distances."

The dilemma depicted in Figure 5-l is that the warning distance must be sufficient to allow time for the driver to respond to avoid a collision. However, if the warning distance is too great, nuisance alarm rates will be high. Frequent nuisance alarms may prompt the driver to ignore system alarms (the "cry wolf" effect) or to defeat the system altogether. The apparent trade-off between nuisance alarm rate and crash avoidance performance is not well understood at present and merits research. Moreover, the tolerance of drivers to nuisance alarms (i.e., the number/percentage of such alarms they will accept before ignoring or disabling the system) is not known.

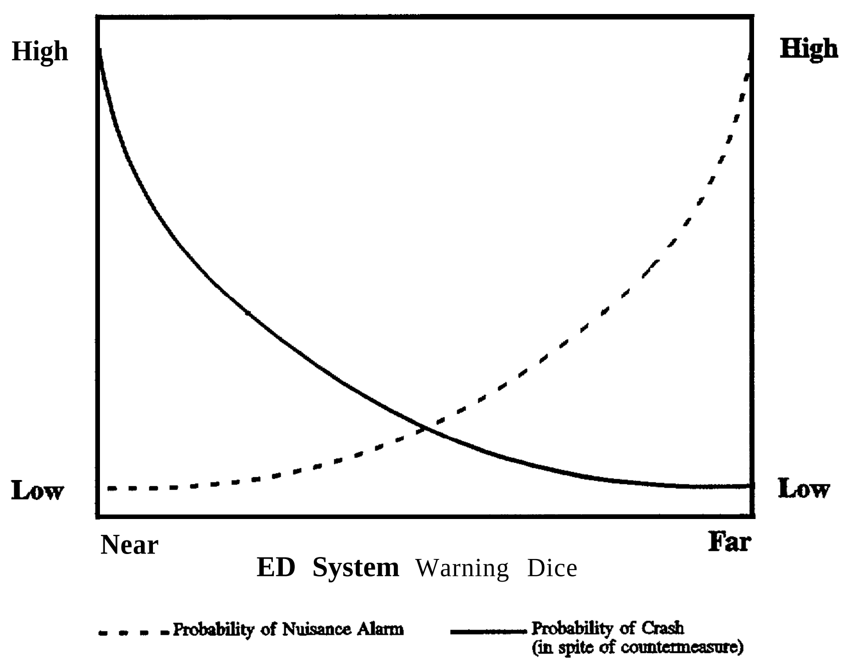


Figure 5-1:
Schematic Depiction of Warning Distance/Nuisance Alarm Problem

5.1.3 Pedal Error

Degraded HD system effectiveness might occur if the driver commits a pedal error -- e.g., his or her foot slips from the brake pedal onto the accelerator pedal. Perel (1976) reviewed 114,986 accident reports (of all crash types) from 1974 and 1975 in North Carolina. He found 62 accident reports which contained key words related to problems of foot placement. From this result, an estimate of the proportion of crashes involving pedal error is 62/114,986 or 0.054%

Supporting evidence for a minuscule incidence of pedal error can be found in the human reliability literature (Topmiller, 1982). Specifically, the Bunker-Ramo human reliability probabilities for "discrete control activation" (assumed to be indicative of applying maximum braking pressure for a stop) range between 0.9996 and 0.9993 or with corresponding error probabilities from 0.0004 to 0.0007 under conditions similar to braking.

These data imply that operator pedal error is not likely to be a significant factor in crash causation or in driver response to a crash threat.

5.1.4 Compensatory Risktaking

One factor influencing "real world" countermeasure success is the risk-taking behavior of drivers. Several researchers have hypothesized that the increased level of safety provided by some countermeasures will be negated by drivers who adapt to the vehicle design change by modifying their behavior to maintain a safety margin that is similar to that which existed without the device (Naatanen and Summala, 1976; Wilde, 1982). One implication of this concept is that countermeasures are likely to be more effective if they can reduce the actual risk relatively greater than they reduce the perceived risk.

Little empirical data is available relating to the size and scope of the compensatory risktaking phenomenon. Farber (1991) analyzed data on the reliability of drivers as "longitudinal controllers" to show that the driver aided by an HD system will almost certainly be even more reliable than will a driver alone, even if some degree of risk compensation occurs. However, compensatory risk-taking still needs to be better understood both as an underlying general mechanism in driver behavior and also as a specific consideration relating to HD countermeasures.

5.1.5 Driver Errors Not Addressed by the HD Countermeasure Concept

The HD system primarily addresses rear-end crashes that are inattention-related and/or following-too-closely related. Other causal factors (e.g., unsafe driving acts, "poor judgment," false assumptions about other vehicle's path of travel, slippery roads, vehicle component failure, driver impairment) would not be addressed as effectively. Recall that the project clinical sample causal factor assessment indicated that 12 of 74 cases (7.2 percent weighted) were not related to inattention or following too closely but rather were related to the kinds of "other" factors listed above. In the Indiana Tri-Level Study (Treat et al, 1979), recognition errors were ***not*** cited in 12 of 57 rear-end crash cases (21 percent); many of these non-recognition-error cases would likely not be applicable to HD countermeasure concepts.

5.2 Vehicle Considerations

5.2.1 Incomplete Market Penetration

Over the next 5-20 years, IVHS technologies will be available to some, but not all, drivers and vehicles. Market penetration levels will gradually increase over these years. During the period of incomplete market penetration, the maximum crash avoidance capabilities of the device will apply only to those collision situations involving equipped vehicles. If the overall system requires transponders on lead vehicles to reflect the radar signal back to the device-equipped vehicle, then HD systems will not accurately and reliably detect vehicles that are not equipped with these transponders.

To illustrate the sort of problems that may arise, assume two passenger vehicles are equipped with detection systems. The following vehicle has microwave/millimeter wave radar and the lead vehicle has a headway detection transponder (reflector). The technology has the potential to help the drivers maintain a safe distance between their vehicles, perhaps through warning, automatic braking, or speed control. If a motorcycle without a reflector enters between the two vehicles, the possibility of a crash increases because the system is operating based on the signal from the transponder-equipped passenger vehicle, not based on the motorcycle.

5.2.2 Device Self-Test and Calibration

In general, preventive maintenance, self-test, and calibration of IVHS technologies will be required to maintain detection performance. For example, on-vehicle sensors that use lenses and antennas may degrade due to road dirt and general inattention to maintenance. Degradation in capabilities will go unnoticed by the driver unless special care is taken in the design with some form of calibration provided by the system. Such calibration must be achieved with minimal inconvenience to the driver.

5.2.3 Variations in Braking Efficiency

Another vehicle consideration is the braking efficiency, assumed to range from 0.5g to 0.85g (see Section 6.4.2). Increased deployment of antilock brakes could have a substantial impact on the effectiveness of this MIS countermeasure. Furthermore, if the setting of the detection system is to be tailored, the braking efficiency must be known, That is, decreased braking efficiency might be compensated by earlier warning within the range limitations of the device.

5.3 Environmental Considerations

5.3.1 Roadway Geometry

Perhaps the most vexing environmental constraint on HD systems is roadway geometry. In general, HD systems are line-of-sight. Therefore, roadway geometries such as curves and hillcrests may diminish system performance. If the curve is sharp or partially obscured by terrain or man-made features, the detection system will not discern an obstacle around the other side of the curve. Similarly, if a hillcrest blocks an obstacle, the detection system may not warn the driver in time. Conversely, roadway curves and dips would likely be a source of nuisance alarms (e.g., vehicles or objects just off the road but in a direct line-of-sight with the subject vehicle). This issue is addressed in more detail in Section 6.6.1.

A similar problem relates to roadway surface roughness and its effect on vehicle bounce and sway. Such bounce and sway could have the effect of greatly altering the trajectory of the HD radar beam.

Research will be required to determine the actual effect of variations in roadway geometry on HD system performance. The degree of effectiveness attenuation is likely to vary greatly with terrain and man-made features. Advanced HD systems may use wider beams that can selectively detect targets in the travel lane and/or beams that adjust their directionality in accordance with the steering direction of the vehicle.

5.3.2 Effect of Precipitation

Degradation of sensor performance due to precipitation has not been addressed in this report. There could be some small attenuation of HD system effectiveness due to precipitation, although this attenuation would likely be limited since most target crashes occur under clear environmental conditions.

5.3.3 Interference Among Multiple Systems

Another potential concern is that HD-equipped vehicles may pick up spurious signals from other HD-quipped vehicles operating nearby. Such mutual interference may arise among radar systems operating at the same time in a small area.

At least two forms of inter-vehicle interference have been described (Shefer and Klensch, 1973). Blinding occurs when sufficient power is exchanged between two radars onboard vehicles traveling in opposite directions to cause one or both to be blinded and thus fail to detect a valid obstacle. Circular polarization has been used in millimeter/microwave radar systems to suppress intersystem blinding. The direction of polarization is defined as the direction of the electric field vector. A circularly-polarized wave is one in which the electric field vector rotates with constant amplitude about the axis of propagation at the radar frequency. The circularly-polarized wave transmitted by one radar system impinges on the other in the opposite direction and is rejected by the latter.

A second form of intersystem interference is crosstalk. Suppose that two vehicles are traveling in the same direction in adjacent lanes on a freeway or other roadway with two or more adjacent travel lanes in the same direction. As the right lane vehicle approaches a slow-moving target vehicle in the lane ahead, both adjacent vehicles may pick up the return HD radar signal. For the left lane vehicle, this would be a false alarm. Crosstalk interference can be minimized through the use of a transponder on the target vehicle which reflects a narrow, well-defined return beam covering the width of one lane only.

5.3.4 Health Concerns

Use of radar or other sensing technologies may cause concerns related to real or imagined health risks. Estimates of the health impact of composite or cumulative radiated energies under specified levels of vehicle compliance and driving conditions (e.g., urban freeways at rush hour) would be helpful in this regard.

6.0 COUNTERMEASURE EFFECTIVENESS MODELING

6.1 Introduction

6.1.1 Purpose

This chapter presents models of Headway Detection (HD) system intervention in rear-end crashes. The purposes of this modeling are to predict the likely effectiveness of HD systems, to identify principal countermeasure functional requirements, and to identify major factors (e.g., roadway configuration, weather) that are likely to influence countermeasure effectiveness. In the modeling, hypothetical HD system functional parameters (i.e., algorithms and stochastic models of driver/vehicle crash avoidance performance) were applied to samples of rear-end crashes to estimate baseline effectiveness rates (i.e., the proportion of crashes avoided). The derived baseline effectiveness rates represent theoretical values which are subject to attenuation due to the effects of various factors such as improper driver response, adverse weather, or roadway configuration. The effects of these attenuating factors cannot be accurately quantified at this time but have been noted in this chapter as topics for future research.

6.1.2 Design vs. Modeling Driver/Vehicle Performance Parameters

In performing its crash prevention function, an HD system would become part of the total driver/vehicle performance system. Specifically, the HD system would be designed to respond to crash threats according to particular parameters (i.e., distance/time of threat from vehicle) and would "assume" a certain level of subsequent driver performance (i.e., reaction time to warning) and vehicle performance (i.e., braking deceleration magnitudes) to avoid the crash. The "design assumptions" that an HD system makes about driver/vehicle performance need to be conservative enough to allow even relatively slow-reacting drivers and relatively slow-braking vehicles to avoid the crash, but not so conservative that drivers are inundated with unnecessary warnings (i.e., nuisance alarms). So, the benchmark design assumptions about driver/vehicle performance programmed into the hypothetical system are somewhat below the average values actually found in the population of drivers and vehicles. Specifically, the benchmark driver reaction time assumed by the system design is somewhat higher (i.e., slower) than the population average and the hard braking deceleration values assumed by the system are somewhat lower (i.e., slower) than the likely average.

In contrast, the driver/vehicle performance distributions used in the modeling to predict crash avoidance performance are intended to approximate the actual parameter distributions. This is consistent with the objective of the modeling; i.e., to obtain theoretically-accurate predictions of system effectiveness based on hypothetical, but realistic, system functional parameters and driver/vehicle performance parameters.

Later sections of this chapter address the specific system design parameter values used and the fixed and variable driver/vehicle performance parameter values used for modeling.

6.2 Case Samples Used for Countermeasure Modeling

The countermeasure modeling was applied separately to Lead-Vehicle Stationary (LVS) and Lead-Vehicle Moving (LVM) rear-end crashes, and was applied to two fundamentally-different rear-end crash data sets:

- Small samples of reconstructed cases from the LVS and LVM Crashworthiness Data System (CDS) clinical samples used for causal factor analysis (see Chapter 3.0), and

- General Estimates System (GES) samples of LVS and LVM cases with varying crash parameters (i.e., pre-crash travel speeds) based on information coded on Police Accident Reports (PARs).

Each of these two samples is discussed in greater detail below:

6.2.1 Clinical Analysis/Reconstruction Samples

As discussed in Chapter 3.0, a clinical approach (i.e., intensive review of individual crash case files) was used for the causal factor identification and countermeasure assessment. The use of "real world" accident data offered three key advantages:

- First, review of clinical accident data allowed a more precise delineation of causal factors associated with specific crash types than would be possible through examination of mass databases. With a clear understanding of crash causation factors, the selection of appropriate countermeasure concepts (and then technologies) became a more straightforward process.

- Secondly, reconstruction of "real world" crashes provided "hard" parameters (i.e., travel speeds, gap distances for LVM crashes, impact speeds, ΔVs, etc.) for use in the modeling process to determine the potential performance levels of recommended technologies.

- Third, since the causal factors for specific sample cases were identified, the modeling could be applied to cases known to be applicable to the countermeasure concept -- i.e., known to be associated with driver inattention and/or following too closely and thus applicable to the HD system countermeasure.

Consistent with the last item above, the clinical analysis/reconstruction sample used for the modeling was restricted to cases with applicable causal factors (i.e., driver inattention and/or following too closely). Recall from Section 3.5.2 that 56 of the 74 rear-end clinical sample cases had driver inattention and/or following too closely as causal factors. Of these 56 HD system-applicable cases, 18 (13 LVS and 5 LVM) contained sufficient data to allow complete reconstruction.

The low percentage of cases reconstructible does not reflect CDS case quality or completeness but rather reflects the fact that the CDS was designed to collect detailed information on *crashworthiness*-related safety issues. The current modeling was not a "design application" of the CDS data but rather was a fortuitous use of information available in raw CDS case files.

Appropriate sampling weights were assigned to the 13 LVS and 5 LVM cases to make statistics based on the sample more nationally representative. These sampling weights were used to tabulate modeling results. However, it is recognized that the reconstruction samples size were small (especially the LVM sample) and thus that the quantitative results are subject to significant sampling error. On the other hand, the values derived for the various modeling parameters (e.g., closing speeds, separation distances) were based on skilled case reconstruction and thus were considered to be more accurate than similar information available from PAR-based data systems such as GES (discussed below). And, as noted, all 18 cases are HD system-applicable in their causal factors. **Tables 6-1** and **6-2** present the reconstruction data from the 13 LVS and 5 LVM clinical sample cases. In Table 6-1, the impact speeds and Delta V (ΔV) statistics shown are not directly relevant to crash *avoidance* modeling but are used in Appendix B to demonstrate crash severity reduction modeling.

Table 6-1
Lead Vehicle Stationary Clinical Sample (13 Cases)

LVS Case #	Case Weight (LVS Sample %/Cum %)	Travel Speed (mph)	Impact Speed (mph)	Impact ΔV (mph)[1]
#1	4.0% / 4.0%	26.4	26.4	11.5
#2	1.3% / 5.3%	27.2	24.9	13.6
#3	0.8% / 6.1%	30.7	26.6	14.1
#4	10.4% / 16.4%	31.0	19.5	10.1
#5	3.3% / 19.7%	31.9	31.9	13.0
#6	12.1% / 31.8%	32.6	32.6	14.5
#7	5.7% / 37.5%	34.3	34.3	21.9
#8	4.5% / 42.1%	35.2	29.8	15.7
#9	15.7% / 57.8%	37.4	23.2	9.6
#10	2.3% / 60.1%	38.8	29.2	11.7
#11	2.8% / 62.9%	39.7	22.5	10.6
#12	9.5% / 72.4%	39.8	22.2	9.4
#13	27.6% / 100.0%	48.7	36.3	17.4

1. ΔV = Velocity change occurring during the impact (a principal measure of collision impact severity and injury-producing potential). ΔV is derived using energy absorption calculations based on vehicle damage crush measurements.

Table 6-2
Lead Vehicle Moving Clinical Sample (5 Cases)

LVM Case #	Case Weight (LVM Sample %/Cum %)	Following Vehicle T. Spd. (mph)	Following Vehicle Imp. Spd. (mph)	Following Vehicle ΔV (mph)[1]	Gap (Ft.)[2]	Lead Vehicle T. Spd. (mph)	Lead Vehicle Imp. Spd. (mph)
#1	4.5% / 4.5%	37.9	37.9	11.9	91.2	37.9	12.0
#2	41.3% / 45.8%	40.6	34.7	10.0	105.7	40.6	12.5
#3	5.2% / 50.9%	51.7	30.4	11.8	197.2	40.0	10.0
#4	2.0% / 52.9%	41.8	35.8	9.4	115.2	30.0	10.0
#5	47.1% / 100.0%	72.4	59.1	24.4	335.2	45.0	15.0

1. ΔV = Velocity change occurring during the impact (a principal measure of collision impact severity and injury-producing potential).
2. Gap = Gap interval when lead vehicle began braking.

Note in Tables 6-1 and 6-2 that there are no low-speed crashes in either the LVS or LVM clinical samples. The lowest pre-crash travel speed in the LVS clinical sample was 26 mph; the lowest in the LVM sample was 38 mph. This bias toward higher speed crashes is reflective of the by-design CDS sampling bias toward more severe crashes, and is one reason that the clinical sample was supplemented by use of GES LVS and LVM samples as described below.

6.2.2 General Estimates System (GES) Samples

GES data offer the advantages of much greater sample sizes and better national representativeness. In particular, lower-severity crashes are better represented in GES data as compared to CDS data. GES contains the data variable "Travel Speed" (i.e., pre-crash speed), which is the most important parameter for HD system countermeasure modeling. However, there are several disadvantages of GES data for this application:

- Travel speed data are based on the estimates of the investigating police officer, as entered on the PAR. No post hoc reconstruction is possible.

- The unknown rates for the travel speed variable are high: 67 percent of 1990-91 GES LVS crash travel speeds (of the following vehicle) were unknown. For LVM crashes, the travel speeds of one or both vehicles were unknown in 70 percent of cases.

- The GES sample is not "causally pure;" an identification of HD system-applicable cases is not possible based on coded GES variables. However, an effort was made to eliminate, where possible, GES rear-end crashes not likely to be HD system-applicable. Excluded from the GES sample were crashes where the striking vehicle was likely to not be under driver control, including those involving:

Snowy/icy roadway conditions
Gross intoxication of the driver of the following vehicle (i.e., alcohol/drug violation charged)
A brake defect in the following vehicle
Gross physical impairment of the driver of the following vehicle (e.g., blackout); and
Following vehicles making an avoidance maneuver (i.e., avoiding an animal, pedestrian, object, or vehicle in the roadway).

The remaining rear-end crashes are here termed "under control" (UC) crashes.

The specific LVS and LVM modeling samples obtained from GES (1990-91 combined) are shown in Tables 6-3 and 6-4 and are described as follows:

- LVS-UC ("under control") crashes where the following vehicle travel speed was coded as a speed divisible by 5 mph (i.e., 5, 10 15, 20 . . . 70 mph). There was an unweighted total of 2,966 such cases representing a weighted estimate of 478,000 crashes. By comparison, there was a weighted total of 571,000 1990-91 GES LVS-UC cases where the following vehicle travel speed was known (i.e., all values, including values not divisible by 5) out of 1,689,000 total LVS-UC crashes for 1990-91. These statistics show that following vehicle travel speed is generally not known (i.e., not coded) but when it is, it is generally coded in 5 mph increments.

- LVM-UC crashes (not involving snowy/icy roadway, gross intoxication of following vehicle driver, or brake defect in the following vehicle) where the lead and following vehicle travel speeds were coded in 10 mph increments, where the lead vehicle speed was 10 to 60 mph, where the following vehicle speed was not more than 30 mph greater than the lead vehicle speed, and where the maximum following vehicle speed was 80 mph. There was an unweighted total of 264 such cases representing a weighted estimate of 41,000 crashes. By comparison, there was a weighted total of 238,000 1990-91 GES LVM-UC cases where the following vehicle travel speed was known (i.e., all values, including other combinations of travel speeds) out of 791,000 total LVM-UC crashes for 1990-91.

Note that the GES LVM-UC modeling sample represents a much smaller unweighted number of cases and a much smaller proportion of LVM-UC crashes with known travel speeds than does the LVS-UC modeling sample. The small proportion is due to the many possible combinations of two travel speeds. However, the subsample percentages shown in Table 6-4 show that the modeling sample used is generally representative of the range of LVM-UC cases. For example, the number of crashes with 30 mph discrepancies between the lead and following vehicles is small, indicating that including crashes with even greater discrepancies would not add appreciatively to the sample.

Table 6-3
Distribution of Following Vehicle Travel Speeds
1990-91 GES "Under Control" Lead Vehicle Stationary Rear-End Crashes

Speed	Number of Crashes (Weighted)'	Percent'	Cumulative Percent'
5	65,000	13.5%	13.5%
10	53,000	11.0%	24.6%
15	45,000	9.5%	34.1%
20	53,000	11.2%	45.2%
25	51,000	10.6%	55.8%
30	53,000	11.2%	67.0%
35	71,000	14.8%	81.8%
40	33,000	6.8%	88.6%
45	27,000	5.7%	94.3%
50	13,000	2.7%	97.0%
55	11,000	2.3%	99.4%
60	2,000	0.5%	99.8%
65	1,000	0.1%	100.0%
70	0	0.0%	100.0%
Total	478,000	100.0%	100.0%

1. Rounded to nearest 1,000 crashes
2. Percentages calculated before rounding of crash estimates.

In summary, the two modeling samples described here complement each other; the clinical analysis/reconstruction sample was small but more accurate and entirely "causally-applicable." The GES sample was much larger and nationally-representative and, in particular, contained many more low-speed, low-severity crashes. However, GES data is based on PAR speed estimates only and contains an unknown proportion of cases with causal factors not applicable to the HD system countermeasure concept.

Table 6-4
Distribution of Following and Lead Vehicle Travel Speeds
1990-91 GES "Under Control" Lead Vehicle Moving Rear-End Crashes

Lead Vehicle Speed	Following Vehicle Speed	Number of Crashes (Weighted)'	Percent'
10	10	2,400	5.9%
10	20	5,600	13.8%
10	30	3,000	7.4%
10	40	4,000	9.7%
20	20	2,200	5.4%
20	30	2,700	6.7%
20	40	1,200	3.0%
20	50	400	1 .O%
30	30	5,200	12.8%
30	40	1,500	3.8%
30	50	500	1.1%
30	60	400	1 .O%
40	40	5,400	13.2%
40	50	1,700	4.2%
40	60	200	0.5%
40	70	0	0.1%
50	50	2,600	6.3%
50	60	800	1.8%
50	70	100	0.3%
50	80	0	0.0%
60	60	500	1.1%
60	70	200	0.6%
60	80	100	0.3%
Total		41,000	100.0%

1. Rounded to nearest 100 crashes
2. Percentages calculated before rounding of crash estimates.

6.3 HD System Design Parameters

The most important design parameters of an HD system relate to the gap distance (i.e., between the equipped vehicle and obstacles in its forward path) at which the system could potentially sound an alarm. This section addresses these gap distance-related design parameters. First, it defines and explains the two major components of the operational detection range function of the device: the maximum range and the dynamic warning distance algorithm. Secondly, it presents benchmark assumptions about driver/vehicle performance used to define the warning distance algorithm. Thirdly, it presents specific formulas for the warning distance algorithm under LVS and LVM crash-threat situations.

6.3.1 Factors Detemining the HD System Range Function: Maximum Range and Dynamic Warning Distance Algorithm

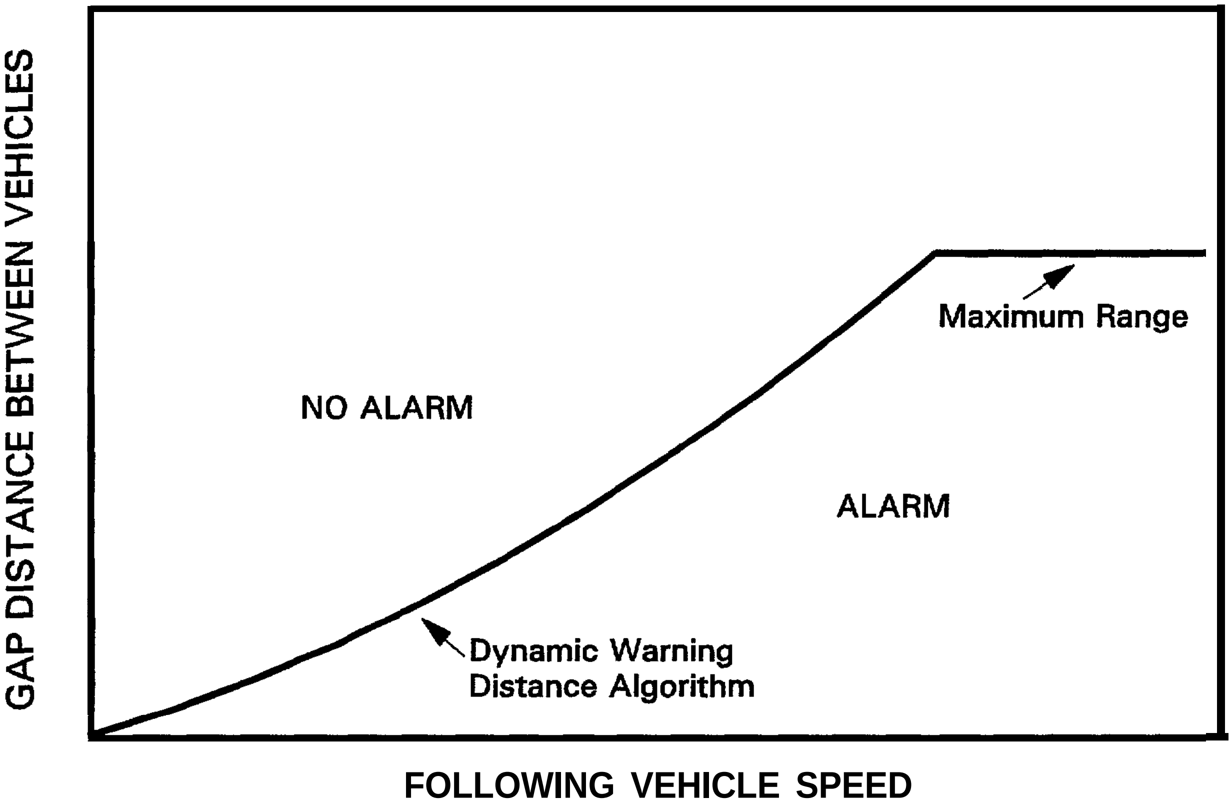
For the purpose of countermeasure modeling, the most critical characteristic of an HD system is the gap distance at which it could detect targets and potentially sound an alarm. Two major elements define the gap distance: the maximum range of the system and the dynamic reduction of warning distance that would be required at lower speeds to reduce nuisance alarms.

Table 4-2 presented the principal functional specifications of one existing HD system. The maximum detection range of this system is 300 feet. Although a 300-foot range capability is available, shorter system ranges may prove advantageous from the perspectives of cost, technical performance, and/or nuisance alarm rate. Therefore, three shorter HD system maximum ranges are modeled here in addition to the 300-foot range: 250, 200, and 150 feet.

Regardless of the maximum range of the system, it is clear that a fixed warning distance would be too simplistic and would lead to excessive nuisance alarms that would likely be unacceptable to drivers. At low to moderate speeds, an HD system that always activated an alarm for objected detected at maximum range (e.g., 150, 200, 250, or 300 feet) would likely inundate the driver with nuisance alarms. For example, a driver/vehicle traveling in traffic at 25 mph (37 feet/second) requires only about 80 to 120 feet to brake to a stop following the appearance of a stationary object in its forward path (this distance includes distance traveled during the driver reaction time plus the distance traveled after braking). At 25 mph, an object 150 to 300 feet ahead would normally constitute no immediate threat and therefore should not evoke an alarm.

Accordingly, HD systems would be designed to reduce warning distance dynamically when the vehicle is traveling at lower speeds. The term warning distance **is used here specifically to** mean the critical separation at a given speed at which the HD system would be fully activated and would issue a warning if a crash threat were detected. The term dynamic warning distance algorithm (or simply the "algorithm") refers to mathematical equation for warning distance as a function of vehicle speed. The system would be capable of monitoring objects at distances between the criterion and maximum ranges, but would not issue an alarm. And, of course, the system would never respond to targets beyond its maximum range. Figure 6-l illustrates this conceptually for the relatively-simple situation involving a stationary target (e.g., the LVS situation).

Figure 6-l
Schematic Representation of HD System Warning Distance Function for LVS Situation



A reasonable approach to formulating a specific algorithm for warning distance is to base it primarily on driver/vehicles' abilities to react and brake to avoid impending crashes. Accordingly, a number of current HD system prototypes incorporate kinematically-derived algorithms into their logic sequences. These algorithms specify safe following distances for the following vehicle in response to varying velocities of both the lead and following vehicles. The systems issue a warning to the driver of the following vehicle whenever the gap interval between the vehicles is less than the interval specified by the algorithm.

6.3.2 Benchmark Design Assumptions About Driver/Vehicle Performance

As noted previously, the "design assumptions" that an HD system makes about driver/vehicle performance need to be conservative enough to allow most drivers/vehicles to avoid the crash, but not so conservative that drivers are inundated with unnecessary warnings (i.e., nuisance alarms). Accordingly, the hypothetical HD system algorithms used for the current modeling assumed a benchmark driver braking reaction time of 1.5 seconds, corresponding approximately to the 75%ile reaction time in the actual driver population (e.g., Sivak et al, 1982; Taoka, 1989).

The total time delay for the driver of the following vehicle is equal to the sum of the time interval required by the HD system to process information and issue a warning (assumed to be 0.25 seconds), the driver reaction time following the warning (1.5 seconds), and the delay to maximum braking efficiency following initiation of braking (assumed to be 0.30 seconds for an braking efficiency of 0.6gs) Therefore, the design assumption is that total delay time is 0.25 + 1.50 + 0.30 = 2.05 seconds,

In addition, the HD system algorithms assumed a benchmark hard braking for the following vehicle of 0.6g (19.3 feet/sec^2) for both LVS and LVM situations. No reliable data were available regarding the actual distribution of hard braking in the driver/vehicle population; the 0.6g value is regarded as conservative. Specifically, 0.6g braking is likely to be in the 20 to 40%ile range for actual hard braking in response to a crash threat (under normal road surface conditions), based on the crash reconstruction experience of the project team. In the LVM situation, it is assumed that the lead vehicle brakes at 0.35gs (i.e., 11.3 feet/sec^2). The rationale for the smaller value is that lead vehicle may or may not be responding to a specific crash threat, whereas the following vehicle is always responding to a specific threat.

6.3.3 HD System Warning Distance Algorithm

The modeling approach employed a dynamic warning distance algorithm that is typical of current HD system prototypes. The algorithm equations of motion establish HD system warning distances (for detection of a stationary or decelerating lead vehicle and activation of a warning signal) as a function of lead and following vehicle velocities. Two versions of the algorithm are presented:

- The LVS version, actually a simplified special case of the full expression where lead-vehicle speed equals zero (i.e., $V_L = 0$). Thus, the key determinant of warning distance is following vehicle speed.

- The LVM version, utilizing the full expression of the algorithm and including a consideration of the measured speeds of both vehicles.

Lead-Vehicle Stationary. For the circumstance where the lead vehicle is stationary (i.e., $V_L = 0$), the expression may be stated simply as:

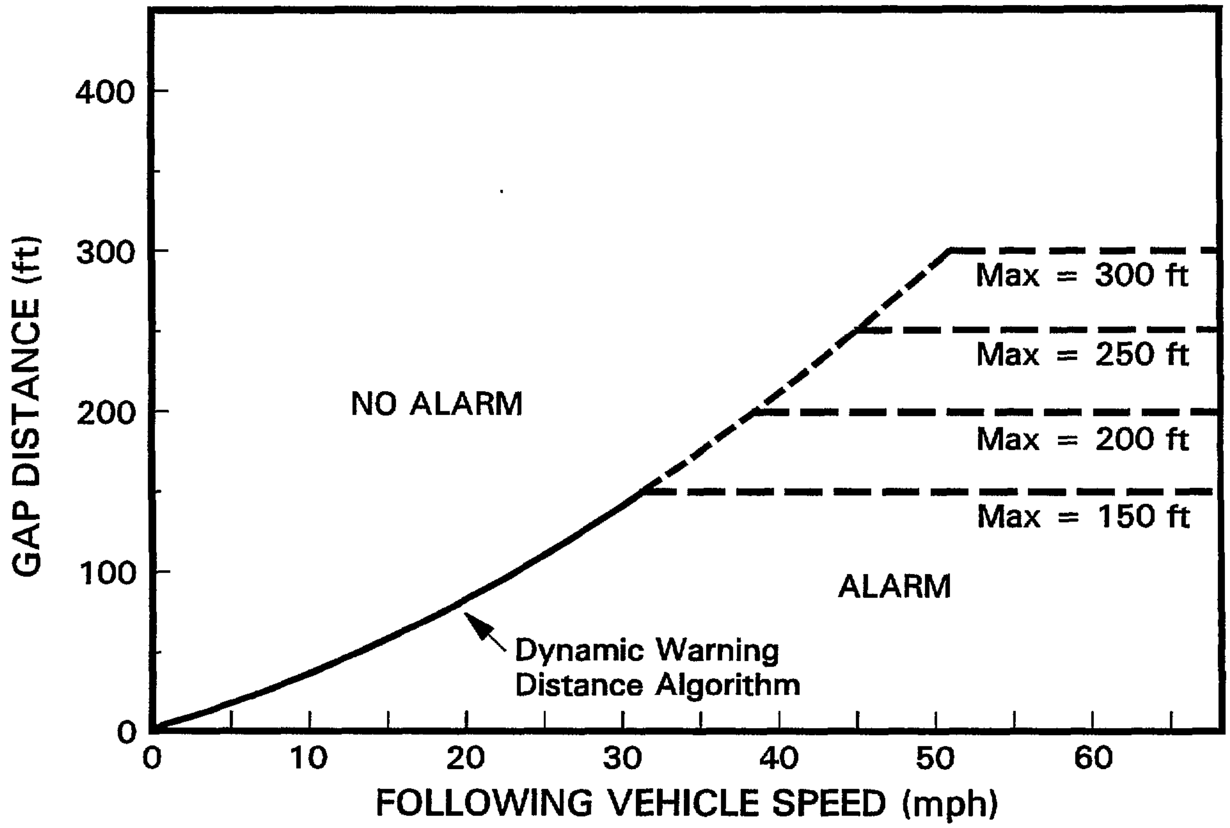
$$D_W = \frac{T_f^2}{2a} + TDV_f$$

Where:

D_W	=	HD system warning distance (distance in feet)
V_f	=	Velocity of following vehicle
a	=	Deceleration rate of following vehicle (0.6gs or 19.3 ft/sec^2)
T_D	=	Total time delay before the driver of the following vehicle initiates a full response (2.05 seconds).

In this circumstance the warning distance, D_W, is simply the required separation distance that allows the benchmark following vehicle (and driver) to react (T_D V_f) and then decelerate to a stop uniformly ($V_f^2/2a$) just behind the stationary lead vehicle. **Figure 6-2** illustrates this algorithm along with the four modeled maximum ranges.

Figure 6-2
Warning Distance Function (with Four Possible Maximum Ranges) for LVS Situation



Lead-Vehicle Decelerating. For the lead vehicle decelerating condition, the HD system warning distance is determined by the equation:

$$D_W = \frac{V_f^2}{2a_f} + T_D V_f - \frac{V_L^2}{2a_L}$$

Where:

D_W	=	HD system warning distance (distance in feet)
V_f	=	Measured velocity of following vehicle
a_f	=	Assumed deceleration rate of following vehicle (0.6gs or 19.3 feet/sec^2)
V_L	=	Measured velocity of lead vehicle
a_L	=	Assumed deceleration rate of lead vehicle (0.35gs or 11.3 feet/sec^2)

T_D = Assumed total time delay before the driver of the following vehicle initiates a full response (2.05 seconds).

The warning distance, D_W, represents the required separation distance such that, after both vehicles have decelerated to a stop, the benchmark following vehicle ends up immediately behind the lead vehicle. The algorithm is an expeditious method of providing insight into the factors that affect hazardous conditions, namely:

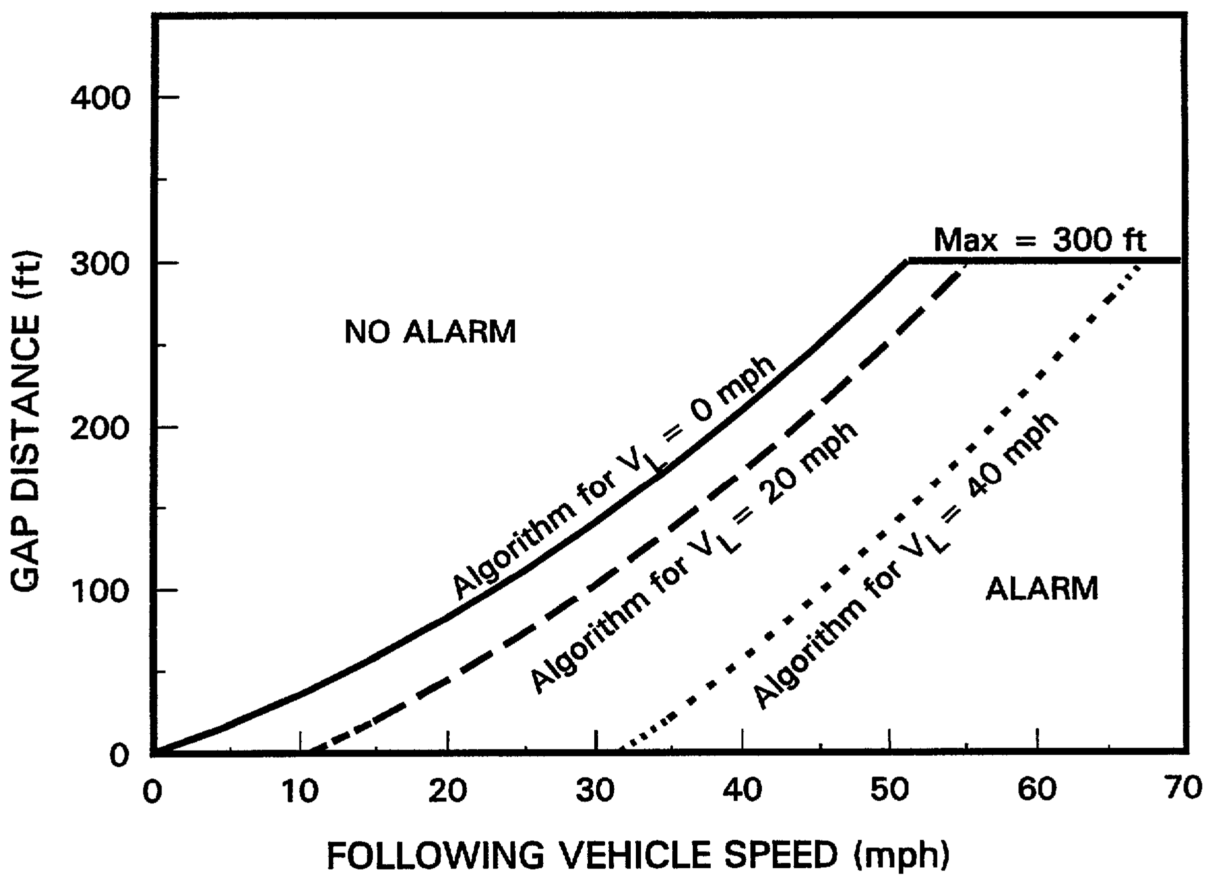
$V_L^2/2a_L$ represents the distance the lead vehicle moves during a uniform deceleration to a stop.

$V_f^2/2a_f$ represents the distance the following vehicle moves during a uniform deceleration to a stop.

$T_D\ V_f$ represents the distance the following vehicle moves during the vehicle/driver response period.

Figure 6-3 illustrates this algorithm for the 300-foot maximum range and three hypothetical lead-vehicle speeds: 0 (i.e., the LVS version of the algorithm), 20mph, and 40mph.

Figure 6-3
Warning Distance Functions for Three Lead-Vehicle Speeds
(All With Maximum Range = 300 Feet)



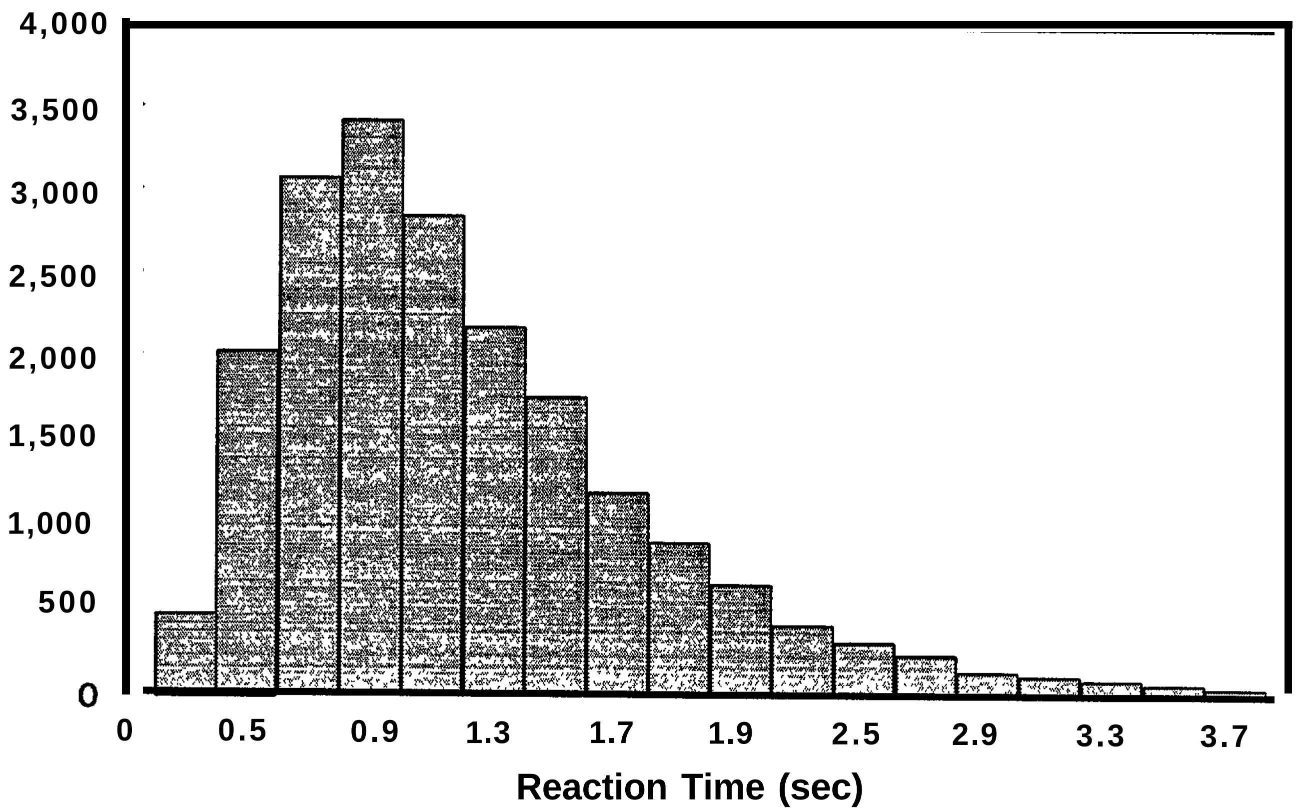
6.4 Modeling Parameters and Approach

Section 4.3 above presented the HD system design parameters and assumed driver/vehicle performance parameters established for the modeling. This section describes the two major parameters used in modeling driver/vehicle performance and describes the modeling simulations used to calculate the estimated effectiveness rates. The conceptual distinction between design parameters (e.g., the "algorithm") and modeling parameters is again emphasized: Design parameters are the benchmark assumptions (usually conservative) about driver/vehicle performance that are programmed into the hypothetical system, whereas modeling parameters are intended to capture *actual* driver-vehicle performance parameter distributions. The purpose is, of course, to predict the performance of actual drivers/vehicles while using the hypothetical system design.

6.4.1 Driver Reaction Tie (RT)

As discussed in Section 5.1.1, Taoka (1989) has suggested that the distribution of brake reaction times of unalerted drivers can be represented by a lognormal distribution (see Figure 6-4). The lognormal distribution characterizes driver braking RT better than the standard normal distribution primarily because of its skewness. Most studies of RT have shown the distribution to be positively skewed; i.e., having more extreme RTs at the high end of the distribution than at the low end. Taoka presents different possible parameter values of the lognormal distribution based on RT research by different investigators. Much of this research is based on reactions of drivers approaching signalized intersections where a green light turns amber. Figure 6-4 presents a

Figure 6-4
Lognormal Distribution of Driver Braking RTs (Histogram at 0.2 Second Intervals)



lognormal distribution of driver RTs at 0.2 second intervals based on Taoka's statistical characterization and RT data collected by Sivak et al (1982). This RT distribution is used in the current modeling. Taoka characterizes the distribution by the following population statistics:

- Median = 1.07 seconds
- Mean = 1.21 seconds
- Standard Deviation = 0.63 seconds
- Dispersion Parameter = 0.49.

(Note: the dispersion parameter is a measure of relative variability around the distribution mean.)

6.4.2 Vehicle Braking Deceleration Rate

No definite data were available to characterize the distribution of hard braking decelerations of vehicles. Based on the traffic crash investigation and reconstruction experience of the project team, the distribution of ***following*** vehicle braking for both LVS and LVM crashes is modeled as a uniform distribution ranging from 0.5g to 0.85g This is intended to approximate hard crash avoidance braking under "normal" conditions. It does not address highly degraded driver states and conditions such as extreme intoxication and snowy/icy road surface conditions. These are addressed as "attenuating factors" in Section 6.7.

The braking deceleration rate for lead vehicles in LVM crashes is presumed to be less severe than the braking of following vehicles. Unlike following vehicles, lead vehicles may not be responding to an imminent crash threat. Their braking decelerations may be moderate or may be closer to "normal" braking (e.g., typical of a vehicle slowing to make a turn; see Section 3.5.1). Accordingly, three lead vehicle braking deceleration rates are modeled for LVM crashes: 0.25g, 0.35g and 0.5g.

6.4.3 Modeling Approach: Lead Vehicle Stationary

As noted, HD system countermeasure modeling was performed using two contrasting rear-end crash data sets, a small sample of clinical analysis/reconstruction cases and a large sample of GES cases with travel speed estimations. In each case, determination of baseline HD system effectiveness rates (i.e., the proportion of crashes avoided) was completed by comparing the hypothesized design performance of the HD system to hypothesized expected performance of the driver/vehicle population based on the modeling parameters described in the previous sections.

Expected driver/vehicle performance was modeled using a Monte Carlo simulation of driver RTs (see Section 6.4.1 above) and vehicle braking deceleration rates (see Section 6.4.2). The Monte Carlo technique is a method of estimating the probable outcome of an event that is dependent on one or more random factors. In this case it was assumed that driver RT follows a lognormal distribution, and that following vehicle braking level is rectangularly distributed. A computer was used to randomly generate values conforming to these distributions. The program determined the results for each case; i.e., "crash" or "no crash." This determination was made for 40,000 combinations of parameter values (i.e., RT + braking deceleration) for each following vehicle velocity. From these 40,000 outcomes the percentage of crashes avoided for that velocity was determined.

For this effort, the simplifying assumption was made that driver RT and vehicle braking deceleration are *independent* (non-correlated) variables -- that is, the value of one variable has no effect on the value of the other variable. Actually, in the real world, these two variables are *not* likely to be independent; e.g., younger and more aggressive drivers generally react faster and brake harder. However, the simplifying assumption of independence was made for the present first-order modeling of countermeasure effectiveness.

For each simulation data point, the warning distance provided by the HD system at the travel speed under consideration was compared to the "actual" distance needed to avoid the crash for particular combination of driver performance (i.e., RT) and vehicle performance (i.e., braking deceleration) being modeled. In other words, the following two values were compared:

D_W = Warning distance of HD system at the travel speed under consideration (i.e., the critical separation at which the HD system would be fully activated and would sound an alarm if an obstacle were detected). For any given speed, this value is fixed by the design parameters (e.g., maximum range and dynamic warning distance algorithm) assumed.

D_B = Distance required for following vehicle to brake to a complete stop

$$D_B = \frac{V_f^2}{2a} + T_D V_f$$

Where:

V_f = Velocity of following vehicle

a = Deceleration rate of following vehicle

T_D = Total time delay before the driver of the following vehicle initiates a full response (system delay time + driver RT).

If $D_W \geq D_B$, then the crash was avoided. $D_B > D_W$, then the crash was *not* avoided. The percentage of crashes avoided (per the Monte Carlo simulation) was determined for each crash sample travel speed (whether of the clinical reconstruction sample or GES sample). Then the weighted total percentage of crashes avoided for each maximum range value was tabulated.

6.4.4 Modeling Approach: Lead Vehicle Moving

As previously for LVS crashes, HD system countermeasure modeling was performed using two contrasting rear-end crash data sets, a small sample of clinical analysis/reconstruction cases and a large sample of GES cases with travel speed estimations. In each case, determination of baseline HD system effectiveness rates (i.e., the proportion of crashes avoided) was completed by comparing the hypothesized design performance of the HD system (i.e., the detection range function at various travel speeds) to hypothesized expected performance of the driver/vehicle population.

Thus, as previously, the modeling parameters included HD system maximum range (300ft., 250ft., 200ft., 150ft.), following driver RT (lognormal distribution; see Section 6.4.1), and following vehicle hard braking deceleration rate (uniform distribution ranging from 0.5gs to 0.85gs; see Section 6.4.2). However, an additional modeling variable was required: the separation distance between vehicles at the time of lead vehicle braking. No data were available to select representative distances except for the gaps determined for the five cases in the LVM reconstruction sample (see Table 6-2). These five values were: 91.2', 105.7', 115.9', 197.2', and 335.2'. For the GES sample modeling, four nominal separation distance values corresponding to the maximum range values were used; i.e., 300ft., 250ft., 200ft., and 150ft.

For each data point, the effectiveness of the HD system was determined by examining the trajectories of the two vehicles as a function of time. At each time step of 0.05 seconds, the positions and velocities of each vehicle were determined and compared to determine if a collision had occurred (i.e., to determine if the separation between the vehicles was reduced to zero). The equations for calculating the instantaneous gap between the vehicles were:

Prior to braking by following vehicle (i.e., $t \leq t_D + t_{WARN}$):

$$S=S_0+(V_{L_0}-V_{f_0})\,t-\frac{1}{2}a_L t^2$$

After onset of braking by following vehicle (i.e., $t > t_D + t_{WARN}$):

$$S=S_0-\frac{1}{2}a_L t^2+V_{L_0}t-V_{f_0}t+\frac{1}{2}a_f(t-t_D-t_{WARN})^2$$

Where:

S	=	Instantaneous separation (gap) between vehicles
S_0	=	Separation at time = 0
a_L	=	Assumed lead vehicle deceleration level (i.e., 0.25g, 0.35g, or 0.5g)
t	=	Elapsed time since lead vehicle began braking
V_{L0}	=	Initial travel velocity of the lead vehicle
V_{F0}	=	Initial travel velocity of the following vehicle
a_F	=	Randomly determined following car deceleration
t_{WARN}	=	Time when the warning distance is reached
t_D	=	Randomly determined total time delay for the following vehicle to initiate braking.

Relevant to the range of a_L values used, recall from the causal factor assessment (Section 3.5.1) that LVM crashes seem to involve a wide range of lead vehicle decelerations. Many cases involve hard braking by the lead vehicle (e.g., braking response to a crash threat), but many others involve "normal" deceleration (e.g., prior to a turning maneuver). Not modeled here is the case where the lead vehicle is simply traveling at a lower speed than the following vehicle and is not decelerating at all. Of course, in these cases the probability of crash avoidance would be greater, other factors being equal. In this respect, the present LVM modeling is conservative.

The above equation assumes constant lead vehicle deceleration. Thus, the lead vehicle would begin travelling *backwards* if given enough time. To prevent consideration of this during the modeling, the above equation was slightly modified by setting $a_L = 0$ after $V_L = 0$.

6.4.5 Summary of Design and Modeling Parameters

Table 6-5 summarizes assumptions made regarding the various parameters applied in the HD system countermeasure modeling. Two categories of parameters are listed: *design* parameters used to specify the hypothetical HD system, and *modeling* parameters used to characterize likely driver/vehicle performance using the system.

Table 6-5
Summary of Assumed Design and Modeling Parameters for HD System Effectiveness Modeling

Parameter	Design Parameter Values/Assumptions	Modeling Parameter Values/Assumptions
Principal Causal Factor	Driver inattention and/or following too closely; see Section 4.2.	*Same*
HD System Maximum Range	150ft., 200ft., 250ft., and 300ft.; see Section 6.3.1.	*Same*
HD System Dynamic Warning Distance Algorithm	LVS (see Section 6.3.3): $D_W = \frac{V_f^2}{2a} + T_D V_f$ LVM (see Section 6.3.3): $D_W = \frac{V_f^2}{2a_f} + T_D V_f - \frac{V_L^2}{2a_L}$	*Same*
Assumed Driver Response	Braking only (e.g., no steering); see Section 3.2.	*Same*
Assumed Driver Compliance	Full	*Same*
Assumed Driver Response Error Rate	Zero (i.e., no pedal errors); see Section 5.1.3.	*Same*
System Delay Time (to issue warning)	0.25 seconds; see Sectin 6.3.2.	*Same*
Driver Reaction Time	1.50 seconds; see Section 6.3.2.	Lognormal distribution with median = 1.07 seconds; mean = 1.21 seconds; standard deviation = 0.63 seconds; dispersion parameter = 0.49 seconds; see Section 6.4.1
Delay to Maximum Braking	0.30 seconds; see Section 6.3.2.	*Same*
Total Delay Time	Sum of the above three values; i.e., 2.05 seconds; see Section 6.3.2.	Sum of the above three values; i.e., lognormally-distributed RT values + 0.55 seconds.

[Table continued, next page]

Table 6-5 (Continued)
Summary of Assumed Design and Modeling Parameters for HD System Effectiveness Modeling

Parameter	Design Parameter Values/Assumptions	Modeling Parameter Values/Assumptions
Lead Vehicle Velocity	LVS: zero LVM: no assumption made	LVS: zero LVM (see Section 6.2): Clinical Sample: Values obtained from case reconstruction. GES Sample: Values coded on PAR (selected increments)
Following Vehicle Velocity	LVS: no assumption made LVM: no assumption made	LVS and LVM (see Section 6.2): Clinical Sample: Values obtained from case reconstruction. GES Sample: Values coded on PAR (selected increments)
Lead Vehicle Braking Deceleration	LVS: not applicable LVM: 0.35**g** (11.3 feet/sec^2); see Section 6.3.3.	LVS: not applicable LVM: 0.25**g** (8.0 feet/sec^2), 0.35**g** (11.3 feet/sec^2), and 0.5**g** (16.1 feet/sec^2); see Section 6.4.2.
Separation Distance at Time of Lead Vehicle Braking	LVS: not applicable LVM: no assumption made	LVS: not applicable LVM (see Section 6.6): Clinical Sample: Values obtained from case reconstruction. In addition, two alternative assumptions (both modeled) were: A. Lead vehicle detected at "real world" gap. B. System maintains safe headways (usually greater than "real world" gap). GES Sample: 150ft., 200ft., 250ft., and 300ft..
Following Vehicle Braking Deceleration	0.6**g** (16.1 feet/sec^2); see Section 6.3.2.	Uniform (rectangular) distribution ranging from 0.5**g** to 0.85**g**; see Section 6.4.2.
Stopping Distance Required Following Warning (LVS)	Implicitly equal to system warning distance	$D_S=\frac{V_f^2}{2a}+T_D V_f$ (see Section 6.4.3)
Distance Required for Crash Avoidance (LVM)	Not applicable	$S=S_0-\frac{1}{2}a_L t^2+V_{L_0}t-V_{f_0}t$ (see section 6.4.4)

6.5 Modeling Results: Lead Vehicle Stationary (LVS)

6.5.1 Clinical Analysis/Reconstruction LVS Sample

Table 6-6 provides the results of the HD system modeling applied to the 13 cases of the LVS clinical analysis/reconstruction cases (as presented earlier in Table 6-3). Each clinical sample case-by-HD system range percentage presented in Table 6-6 is the result of a Monte Carlo simulation of driver RTs and vehicle braking deceleration values against a prototype system detection algorithm based on benchmark assumptions about driver and vehicle performance.

Table 6-6
Modeling Results -- Lead Vehicle Stationary Clinical Sample (13 Cases)

LVS Case #	Travel Speed (mph)	Case Weight (LVS Sample %)	Theoretical Percent Effectiveness			
			150ft. Range	200ft. Range	250ft. Range	300ft. Range
#1	26.4	4.0%	77.8%	78.1%	78.2%	78.1%
#2	27.2	1.3%	78.0%	78.5%	78.3%	78.2%
#3	30.7	0.8%	78.5%	78.7%	78.5%	78.7%
#4	31.0	10.4%	78.4%	78.8%	78.5%	78.5%
#5	31.9	3.3%	76.0%	78.5%	78.8%	78.6%
#6	32.6	12.1%	72.5%	79.0%	78.8%	78.8%
#7	34.3	5.7%	60.2%	79.0%	78.6%	79.3%
#8	35.2	4.5%	53.5%	78.7%	79.0%	78.9%
#9	37.4	15.7%	35.4%	79.1%	79.1%	78.8%
#10	38.8	2.3%	24.7%	78.5%	79.3%	79.2%
#11	39.7	2.8%	18.9%	74.2%	79.3%	79.1%
#12	39.8	9.5%	17.7%	73.7%	79.0%	79.4%
#13	48.7	27.6%	0.0%	15.2%	60.7%	79.8%
Weighted Mean Percentage:			**38%**	**61%**	**74%**	**79%**

Percentage estimates in Table 6-6 (and subsequent tables of modeling results) are provided to the first decimal place for individual cases, and to the nearest whole percentage for the weighted means. It is recognized that this convention may imply a finer level of precision than is actually warranted given the simplifying assumptions made for modeling and the many real-world "attenuating factors" that will affect actual system affectiveness. Nevertheless, this rounding convention has been adopted here to help show trends in the data across multiple variables. The reader is cautioned that the results are theoretical approximations based on various simplifying assumptions and imperfect case samples, and that the results do not incorporate a consideration of attenuating factors (which are addressed post hoc in Section 6.7).

The percentages at the bottom of each column in Table 6-6 represent the weighted means of the columns. Note that HD system effectiveness asymptotes at approximately 79 percent and never exceeds 80 percent. This asymptotic limit is, in effect, “by design.” That is, recall that the benchmark design parameters of the modeled HD systems (e.g., the dynamic warning distance algorithms) were selected to be conservative enough to allow most drivers/vehicles to avoid the crash, but not so conservative that drivers are inundated with unnecessary warnings (i.e., nuisance alarms). Such a system would never be 100 percent effective; its maximum “asymptotic” effectiveness level would be a function of the actual benchmark design assumptions made in formulating the system algorithm. In other words, the modeled HD system was designed to limit nuisance alarms. If the system were to warn the slowest-reacting and/or weakest-braking drivers, the number of warning alarms would be intolerable to average and “high-performance” drivers.

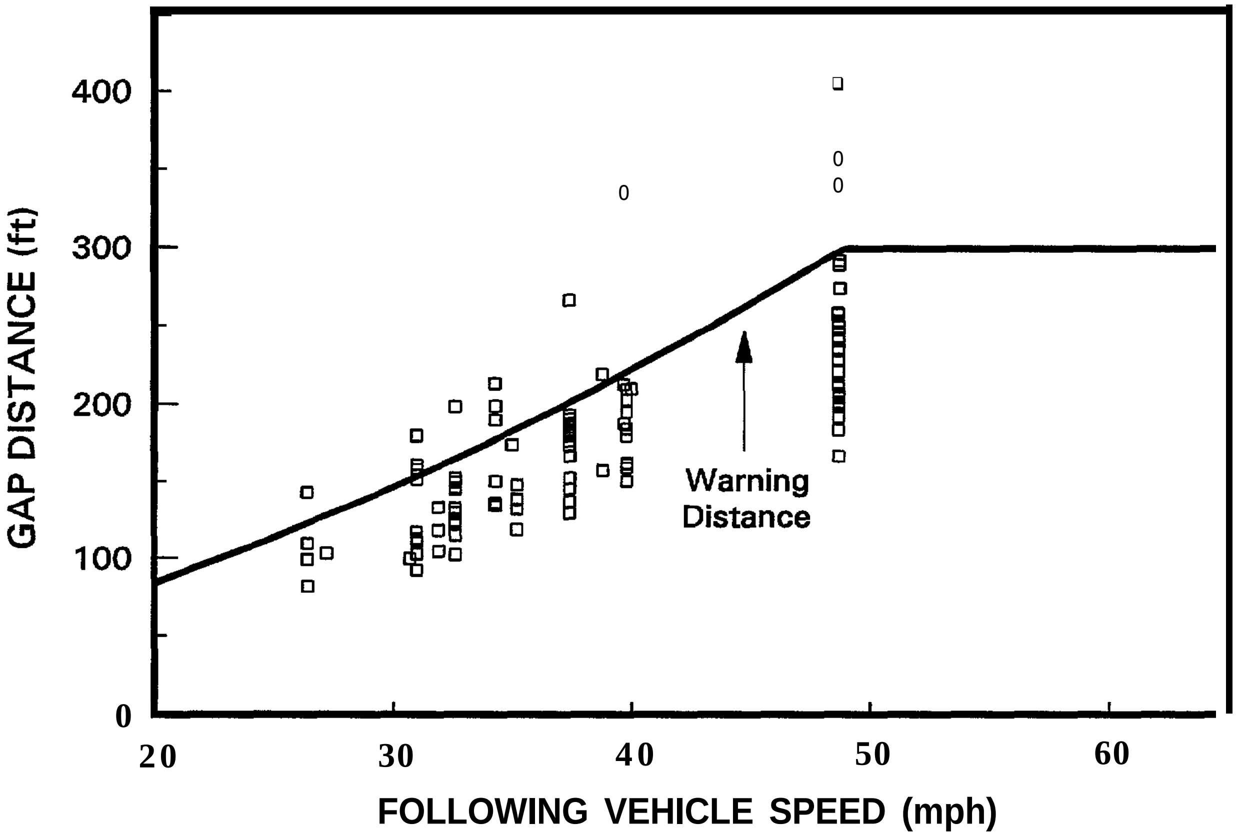
Some of the slight variations in percent effectiveness at asymptotic levels of effectiveness in Table 6-6 are simply random variations resulting from the Monte Carlo methodology. Although a very large number of RT/braking deceleration combinations were modeled, these were randomly generated. Thus, some slight random variations in percent effectiveness are seen. Examples include cases were, at asymptotic levels of effectiveness, the 250ft. range system is slightly more effective than the 300ft. system. These slight anomalies are artifacts of the Monte Carlo simulation methodology.

The weighted mean percentage effectiveness values in Table 6-6 range from about 38 percent for an HD system with 150ft. maximum range to 79 percent for an HD system with 300ft. maximum range.

Also note in Table 6-6 that effectiveness actually increases slightly with increasing speed until it suddenly decreases. The slight increases in countermeasure effectiveness with increasing speed across much of the sample range may appear counterintuitive. The reason for slightly lower levels of effectiveness at lower speeds is that the system as modeled assumes a relatively more conservative value for braking (in relation to the modeled distribution) than for RT. Since braking distance is related to the square of velocity (while distance traveled during the driver braking reaction is directly proportional to velocity), the relative “under-estimating” of braking deceleration by the design system has more effect on the outcome at higher speeds, resulting in a slightly higher effectiveness rates. Of course, selection of slightly different design parameter might eliminate or reverse this trend within the asymptotic portion of effectiveness tables.

Figure 6-5 illustrates graphically a small portion of the LVS clinical sample countermeasure modeling for an HD system with a 300ft. maximum range. To illustrate the modeling, 100 simulation data points were generated based on a stratified random sampling routine. The number of data points for each clinical sample case was determined based on the sample weight of that case (from Table 6-6) rounded to the nearest whole number. For example, Case #l represented four percent of the weighted clinical sample; thus, four randomly-generated modeling points are shown for the Case #l travel speed of 26.4 mph. The solid line in Figure 6-5 represents the HD system algorithm for a system with a 300ft. maximum range. The y-value of each simulation data point is the stopping (reaction plus braking) distance required to avoid the crash (see Section 6.4.3). Points below the line represent crashes avoided. Of the 100 simulation data points shown in this illustration, 77 represent crashes prevented by the countermeasure. This proportion deviates only slightly from the 79 percent effectiveness estimate obtained for the 300ft.-system using a much larger modeling sample as shown in Table 6-6.

Figure 6-5
Illustration of 100 Simulation Data Points from the LVS Clinical Sample Modeling



6.5.2 GES LVS Sample

Table 6-7 provides the result of the HD system modeling applied to the GES LVS "under control" sample (as presented earlier in Table 6-4). Each travel speed-by-HD system range percentage presented in Table 6-7 is the result of a Monte Carlo simulation of driver RTs and vehicle braking deceleration values. The percentages at the bottom of each column represent the weighted means of the columns. The percentage rounding convention discussed above in Section 6.5.1 has been applied; i.e., percentage estimates for individual travel speeds are rounded to one decimal place whereas the weighted means are rounded to the nearest whole percentage. As seen previously in the clinical sample, estimated HD system effectiveness asymptotes at approximately 79 percent and never exceeds 80 percent.

Table 6-7
Modeling Results -- Lead Vehicle Stationary GES Sample

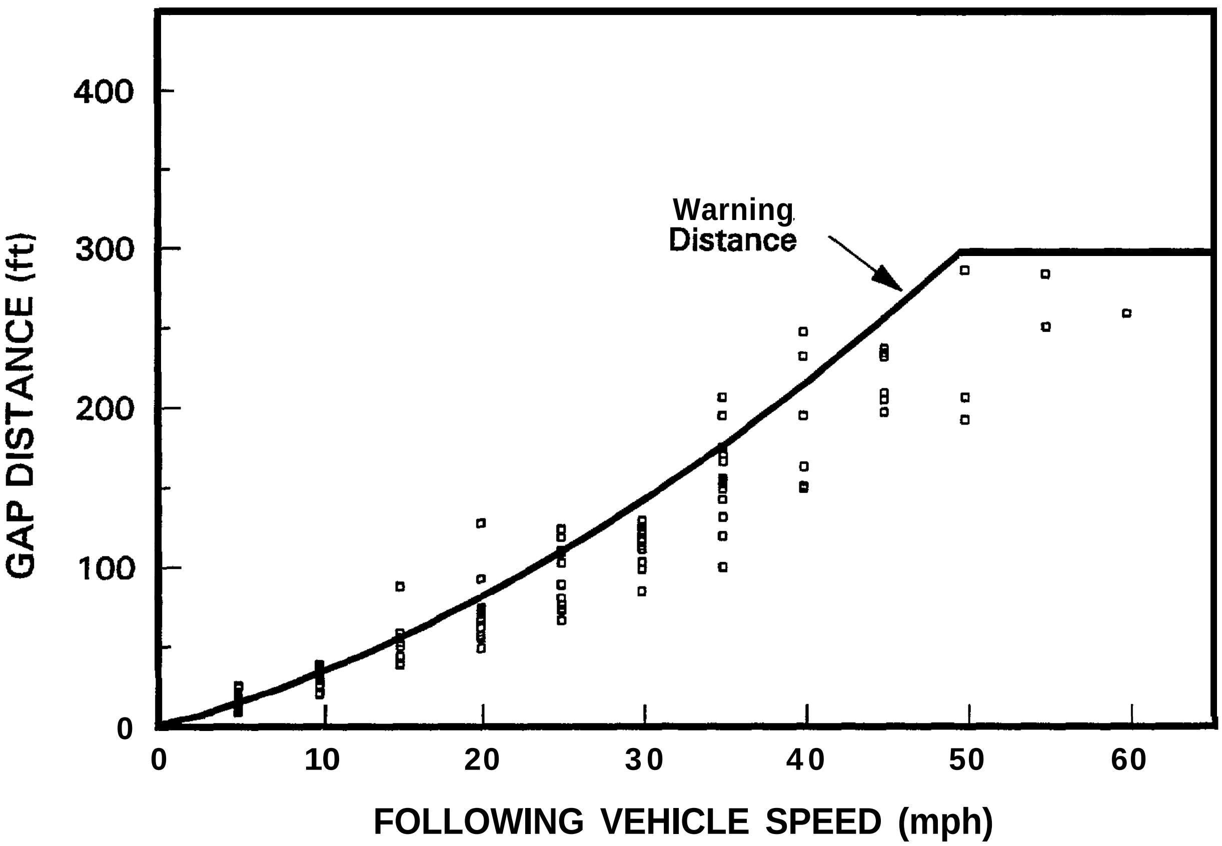
Travel Speed (mph)	Weight (GES LVS Sample %)	Theoretical Percent Effectiveness			
		150ft. Range	200ft. Range	250ft. Range	300ft. Range
5	13.5%	75.7%	76.1%	76.1%	76.0%
10	11.0%	76.5%	76.4%	76.2%	76.3%
15	9.5%	77.2%	77.1%	77.1%	77.5%
20	11.2%	77.4%	77.5%	78.0%	77.6%
25	10.6%	77.7%	78.3%	78.0%	78.0%
30	11.2%	78.6%	78.7%	78.3%	78.7%
35	14.8%	55.5%	79.3%	78.8%	78.8%
40	6.8%	16.8%	72.9%	78.9%	79.0%
45	5.7%	1.1%	38.0%	79.6%	79.7%
50	2.7%	0.0%	9.5%	51.9%	79.3%
55	2.3%	0.0%	0.5%	20.9%	60.3%
60	0.5%	0.0%	0.0%	3.5%	29.5%
65	0.1%	0.0%	0.0%	0.1%	8.3%
70	0.0%	0.0%	0.0%	0.0%	0.6%
Weighted Mean Percentage:		**61%**	**71%**	**75%**	**77%**

The weighted mean percentage effectiveness values in Table 6-7 range from about 61 percent for an HD system with 150ft. maximum range to 77 percent for an HD system with 300ft. maximum range.

Again note that effectiveness actually increases slightly with increasing speed until it suddenly decreases. This occurs for the reasons explained in Section 6.5.1 above.

Figure 6-6 illustrates graphically 100 data points from the GES LVS sample countermeasure modeling for an HD system with a 300ft. maximum range. This figure is analogous to Figure 6-5, except that it uses the GES LVS modeling sample. Here, the number of data points for each following vehicle travel speed along the abscissa was determined based on the sample weight of that speed (from Table 6-7) rounded to the nearest whole number. Of the 100 simulation data points shown in this illustration, 81 represent crashes prevented by the countermeasure. This proportion deviates only slightly from the 77 percent effectiveness estimate obtained for the 300ft.-system using a much larger modeling sample as shown in Table 6-7.

Figure 6-6
Illustration of 100 Simulation Data Points from the GES LVS Modeling



6.5.3 Comparison of LVS Clinical Sample and GES Sample Results

As noted previously in this chapter, the two modeling samples complemented each other; the clinical analysis/reconstruction sample was small but more accurate and entirely "causally-applicable." The GES "under control" sample was much larger and more nationally-representative, but was based on PAR speed estimates only and contained an unknown proportion of cases with causal factors not applicable to the HD system countermeasure concept.

Application of the prototype HD system algorithm to these two contrasting LVS modeling samples yielded similar results. The theoretical performance of the 300ft. range HD system approached its asymptotic limit for both modeling samples. As expected, the 25Oft., 2OOft., and 15Oft. yielded lower levels of theoretical effectiveness for both samples. Only the derived effectiveness values for the 15Oft. system differed substantially between the samples (i.e., 38.4 percent for the clinical sample versus 60.8 percent for the GES sample). This difference may be partly explained by Case #13 in the clinical sample which was never prevented by the 15Oft. system and which had a large weighted value equal to 27.6 percent of the clinical sample.

6.6 Modeling Results: Lead Vehicle Moving (LVM)

6.6.1 Clinical Analysis/Reconstruction LVM Sample

Five cases were available to the modeling effort in the LVM clinical analysis/reconstruction sample. Table 6-2 in Section 6.2.1 provided kinematic data (e.g., velocity and gap) and case weights for the five cases. Two of these cases (#l and #2) involved the circumstance where the lead and following vehicles are traveling at the same approximate travel velocity. The lead vehicle driver then initiated braking action. In the remaining three cases (#3, #4, and #5), the following vehicle was beginning to pass the lead vehicle. Before the initial lane change of the passing maneuver, however, the lead vehicle braked, leading to a collision.

Tables 6-8A and 6-8B provide summary results of the HD system modeling applied to the five cases of the LVM clinical analysis/reconstruction sample. Parts A and B represent two different sets of assumptions about the gap between the vehicles at time of lead vehicle braking and potential initiation of the warning signal. The percentages shown are weighted mean effectiveness values for each of the four system ranges and three lead vehicle braking decelerations. Most estimates range between 25 and 50 percent. Within each set of assumptions, effectiveness increases with longer system ranges and decreases with greater A_L rates.

Table 6-8
Countermeasure Modeling Results: HD Systems Applied to Clinical Sample LVM Crashes

Assumption A: Lead Vehicle First Detected at "Real World" Gap

A_L	HD System Range Limit			
	150ft.	200ft.	250ft.	300ft.
A_L = 0.25g	48%	50%	64%	88%
A_L = 0.35g	39%	42%	44%	64%
A_L = 0.50g	23%	26%	26%	34%

Assumption B: System Activates Warning at Prescribed Headway (Generally Greater Than "Real World" Gap)

A_L	HD System Range Limit			
	150ft.	200ft.	250ft.	300ft.
A_L = 0.25g	50%	51%	73%	93%
A_L = 0.35g	39%	40%	46%	73%
A_L = 0.50g	14%	15%	15%	33%

As noted, the difference between Tables 6-8A and 6-8B lies in the assumptions made regarding the "real world" gap derived from the clinical sample reconstructions. As explained previously in Section 6.4.4, two alternative assumptions were made, resulting in two sets of effectiveness predictions. The two alternative assumptions were:

A. The lead vehicle is first detected at the "real world" gap, as might occur if the lead vehicle quickly cut in front of the following vehicle or if the lead vehicle were first detected as the following vehicle went over a hillcrest. This gap would also be the warning distance, unless it was greater than the maximum system range; in that case, the maximum system range would be the warning distance.

B. The HD system activates the warning at the prescribed gap specified by the system algorithm. Thus, in most cases, short "real world" gaps would be prevented by a prior warning signal issued at a longer separation distance (derived from the HD system detection algorithm).

For three of the five clinical modeling sample cases, Assumption **B** results in longer gaps, earlier braking and higher effectiveness. For two cases (#3 and #5), however, Assumption **B** results in shorter gaps for some or all maximum system ranges. Because of these reversals, neither Assumption **A** nor Assumption **B** leads to consistently higher theoretical effectiveness estimates across the modeling parameters shown in Table 6-8.

6.6.2 GES LVM Sample

Table 6-9 provides the results of the HD system modeling applied to the GES LVM sample (as described earlier; see Section 6.2.2 and Table 6-4). The percentages shown are mean percentage effectiveness values for each of the four system ranges and three lead vehicle braking decelerations. Each percentage vlue represents the mean percentage effectiveness for four hypothetical gaps; i.e., 150, 200, 250, and 300 feet. The percentages for each gap (not shown in the figure) were *weighted means* of the Monte Carlo simulation results for each lead and following vehicle travel speed combination presented in Table 6-4.

Table 6-9
Countermeasure Modeling Results: HD Systems Applied to GES Sample LVM Crashes

	HD System Range Limit			
A_L	150ft.	200ft.	250ft.	300ft.
A_L = 0.25g	61%	79%	82%	82%
A_L = 0.35g	54%	72%	77%	78%
A_L = 0.50g	50%	66%	72%	72%

Assumption **B** as described above for the clinical case sample was used for the LVM GES

Assumption B as described above for the clinical case sample was used for the LVM GES modeling. That is, it was assumed that the system would be activated to prevent gaps less than the system warning distance for a given closing speed between vehicles.

As with the clinical sample, theoretical effectiveness increases with longer system ranges and decreases with higher lead vehicle deceleration rates.

6.6.3 Comparison of LVM Clinical Sample and GES Sample Results

As noted previously in this chapter, the two modeling samples complemented each other; the clinical analysis/reconstruction sample was small but more accurate and entirely "causally-applicable" to the HD countermeasure concept. The GES sample was much larger and more nationally-representative, but was based on PAR speed estimates only and contained an unknown proportion of cases with causal factors not applicable to the conceived countermeasure concept.

Recall that for the LVM clinical sample modeling, two different assumptions were made about the gap between the vehicles at braking. Assumption A was that the lead vehicle was first detected at the "real world" gap distance obtained from the crash reconstruction. Assumption B was that the system would act to maintain safe headways and thus would sound a warning when short "tailgating" gaps first occurred. In the GES sample modeling, only Assumption B was used; i.e., that the system would be activated to prevent gaps less than the system warning distance for a given closing speed between vehicles. Thus, the most valid comparison between the two sample modeling results is between the clinical sample Assumption B results and the GES sample results.

Comparison of the results in Table 6-8B and Table 6-9 reveals that the GES sample yielded somewhat higher percentage effectiveness estimates with just one exception -- the 300-foot range/0.5g combination. But, for both samples, effectiveness estimates generally ranged from 40 to 80 percent, depending on the system parameters and other assumptions applied in the modeling.

6.7 Factors Likely to Attenuate Actual Effectiveness Rates

Baseline "theoretical" effectiveness rates of the modeled HD system were established in the clinical modeling effort and reported in previous sections of this chapter. Other factors, not incorporated into the baseline countermeasure modeling, would negatively affect countermeasure functioning or driver/vehicle response, and thus would tend to reduce the actual effectiveness of fielded systems. These confounding influences are here termed attenuating factors. To account for these factors, statistics are provided below on the nature of the factor and incidence within the rear-end crash population. This is intended to provide an "order of magnitude" assessment of the likely influence of the factor. Future research will assess and quantify the likely attenuating effects of these factors in greater detail.

6.7.1 Specific Attenuating Factors

The baseline "theoretical" effectiveness rates presented thus far are pertinent only to those rear-end crashes where the HD countermeasure concept was applicable. Recall from the rear-end crash causal factor assessment (Chapter 3.0) that 96 percent of LVS crashes and 82 percent of LVM crashes in the clinical sample (93 percent of the total weighted sample) involved driver inattention and/or following too closely. For these crashes, headway detection was considered to be a principal applicable countermeasure. The remaining clinical sample crashes were associated with non-applicable causes such as alcohol, vehicle failure, or icy roads. These crashes would presumably not be preventable through the use of HD systems.

Similarly, 92 percent of 1990-91 GES LVS crashes and 91 percent of LVM crashes were "under control" -- that is, not involving snowy/icy roads, gross intoxication or physical impairment of the striking vehicle driver, brake defect in the striking vehicle, or an avoidance maneuver by the striking vehicle. These "not under control" crashes would not generally be applicable to the HD system countermeasure concept. Non-HD-system-applicable rear-end crashes may be considered an attenuating factor if one attempts to assess the likely effect of the HD system countermeasure on the overall rear-end crash problem.

A fundamental assumption made in modeling the countermeasure is that the driver would respond appropriately to the warning signal; i.e., that he or she would not disable, ignore, or be confused by the system, and would respond with hard braking immediately after the onset of the warning signal. This issue was addressed under human factors considerations in Section 5.1 and is addressed further as a research and development need in Section 7.2. No statistics are currently available to estimate accurately the level of compliance and degree of appropriate response that might be expected from drivers.

Examples of specific attenuating factors, including some already noted above, include the following:

- Curvy/hilly roads. The HD system would operate at full effectiveness only on roadways that are sufficiently straight and level for the system to utilize its full detection range function.

- Snow/ice-covered roads. Similarly, the system would operate at full effectiveness only on roads with sufficient friction to permit normal braking decelerations. Countermeasure effectiveness would be greatly lessened on snow and ice-covered roads.

- Heavy truck crashes. The modeling assumptions are not relevant to the circumstance where the striking vehicle is a heavy truck since heavy truck braking efficiencies are typically lower than the modeled 0.7g benchmark value.

- Brake defect in the striking vehicle. HD countermeasures would not prevent crashes resulting from brake failure or other defect in the striking vehicle.

- Grossly-intoxicated drivers. The modeling results do not reflect the circumstance where the driver of the following vehicle is grossly intoxicated.

Estimates of the approximate magnitudes of these factors are provided in Table 6-10. For all five factors, it may be assumed that the modeled countermeasure would have greatly decreased effectiveness if the factor is present in the crash scenario. However, since the degree of decreased countermeasure effectiveness is not known (and likely depends on unique combination of factors associated with each target crash), the attenuation of countermeasure effectiveness as modeled in this chapter cannot be quantified definitively at this time.

Table 6-10
Specific Attenuating Factors and Their Incidence in the Rear-End Crash Population

Factor	Information Source	% Incidence: LVS Crashes	% Incidence LVM Crashes
Curve/Hillcrest	1990 GES	8.2%	8.2%
Snow/Ice	1990 GES	3.4%	3.3%
Striking Vehicle is Heavy Truck	1990 GES	1.9%	2.0%
Striking Vehicle has Brake Defect	1990 GES	1.0%	0.7%
Striking Vehicle has Grossly Intoxicated Driver	Calspan, 1992 1990 GES	2.9%[1] 2.9%[2]	3.3%[2] 2.9%[2]

1. Driver (of striking vehicle) has blood alcohol content level greater than 0.15.
2. Driver of striking vehicle charged with driving while intoxicated (alcohol and/or drugs).

Table 6-10 shows roadway alignment to be the most significant of the factors listed, and it may be even more significant than indicated by these statistics. A portion of the roadway segments coded as "straight and level" in the GES file (91.8 percent) may in fact be slightly "misaligned." For example, the roadway may be slightly curved (e.g., l-2 degrees), which would result in misalignment of vehicles at extended range limits. GES data are based on police accident reports which, in turn, are based on visual inspection of the crash scene by traffic officers They are not based on precise measurements of alignment over extended segments of the roadway. Further research will be required to determine the portion of roadway segments that are sufficiently straight and level for the HD system to function normally and/or to develop scanning beam technologies to accommodate curved roadway segments (note: see Chapter 7.0).

6.7.2 Likely System Adjustments To Reduce Nuisance Alarms

Field evaluations of HD system prototypes have documented system tendencies to produce excessive nuisance alarm rates (e.g., Stein, Ziedman, and Parseghian, 1989). One category of nuisance alarms can be traced to operational characteristics of the radar unit portion of the system. As a result of these characteristics, units tend to respond to extraneous targets such as parked vehicles and roadside appurtenances, including guardrails, utility poles, and signs.

A variety of methods have been used to reduce the incidence of nuisance alarms. Examples include use of narrow-beam antennas, reduction of system range limits, suspension of system operation during steering and braking maneuvers, and the introduction of time delays before alarms are issued. Evaluation of these methods is beyond the scope of the current effort. Successful problem resolution, however, is likely to result in selective reduction in system warning distance or restrictions in criterion target signatures. These restrictions will likely result in reduction of system effectiveness rates since they would likely cause some "real" crash threats to be missed.

A second category of nuisance alarms can be traced to the kinematically-derived algorithms used in the prototypes and in this modeling effort. These algorithms tend to require substantial gap distances which are difficult to maintain in urban driving environments. This category of nuisance alarms has also been addressed with a variety of methods including the introduction of time delays before alarms are issued and the suspension of alarms in specific conditions. Again, complete evaluation of these measures is beyond the scope of the current effort; however, it is informative to examine a limited number of potential corrective actions.

Many nuisance alarms stem from the assumption that the lead vehicle is going to brake heavily. This assumption must be made since it is not possible for the HD system to determine the deceleration rate of the lead vehicle using currently-available radar technology. If a more sophisticated system were used which communicated the lead vehicle's deceleration to the following vehicle, the nuisance alarms could be greatly reduced. The technology for such an enhancement may involve sensors in the following vehicle to monitor the lead vehicle stop lamp (modified to transmit additional information), or radio-based communication devices. However, all of these system enhancements require additional research.

One type of corrective action to reduce nuisance alarms involves use of less conservative input parameters in the system design stage. For example, for the design algorithm used in the present modeling, a 1.5-second benchmark value was assumed for driver RT. In addition, the design algorithm assumed lead vehicle braking at 0.5gs (i.e., 16.1 feet/sec^2) and following vehicle braking at 0.6gs (19.3 feet/sec^2) Substitution of a faster driver RT and differing deceleration rates for the two vehicles (e.g., 0.45gs for the lead vehicle and 0.65gs for the following vehicle) would result in a substantial reduction of algorithm-specified warning distances. An engineering trade-off evaluation would be required before this correction is initiated since the suggested changes are likely to influence effectiveness rates.

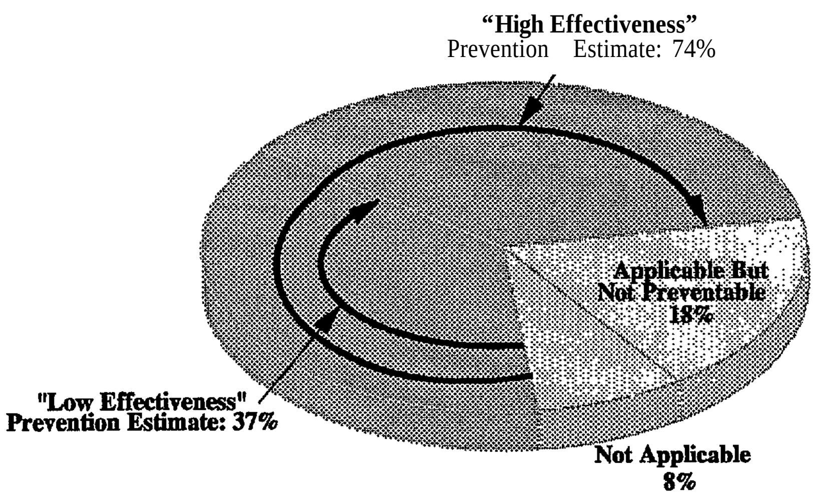
A related type of corrective action would be to allow the driver to set the system for his or her specific RT via a switch or knob control. Slower-reacting drivers could set the system to a more conservative setting, whereas drivers with quicker RTs could utilize a more aggressive setting. Cautious consideration of this approach is needed since providing such an option affords drivers the opportunity to utilize settings which are not appropriate for their actual RTs This in turn introduces new safety and product liability concerns.

As indicated above, another approach to this problem involves suspension of the alarm mechanism in specific conditions. For example, algorithms modeled here would tend to result in a high incidence of alarms when a traffic stream is either decelerating to stop for a traffic signal or accelerating away from a traffic signal. One possible solution would be to suspend the alarm below a preselected travel velocity. This action would, however, impinge on effectiveness rates. Travel velocity distributions drawn from the 1990 GES indicate that suspension of the alarm at travel velocities below 10 mph would render approximately 18.5 percent of LVS crashes and 11.8 percent of LVM crashes non-applicable (i.e., not preventable by the countermeasure). Obviously, these changes to system operational characteristics should not be made prior to in-depth engineering trade-off evaluations.

6.8 Benefits

The countermeasure modeling presented in this report indicates that the potential exists for prevention of a significant portion of the 1.5 million annual police-reported rear-end crashes through the application of HD system technology. The causal factor analysis indicated that approximately 92 percent of rear-end crashes were potentially applicable to the HD countermeasure (i.e., involved driver inattention and/or following too closely). When various hypothesized HD system design parameters were applied to the modeling samples, large percentages were found to be theoretically-preventable through the application of the HD countermeasure system. For HD system applicable crashes, most theoretical effectiveness estimates ranged between 40 and 80 percent (depending on crash subtype, modeling sample, HD system parameters, and other modeling assumptions). Multiplying these two sets of percentages (i.e., applicable X theoretically-preventable), one finds that roughly 37 to 74 percent of rear-end crashes are theoretically preventable by the use of HD systems. Figure 6-7 shows this schematically. ***It is emphasized that these derived percentages are both approximate and theoretical.***

Figure 6-7
Approximate Theoretical HD System Effectiveness in Preventing Rear-End Crashes



AU Rear-End Crashes
1,513,000 in 1990

Moreover, prevention of police-reported rear-end crashes is just one category of prospective benefits. In addition, there would be several other important categories of crash reduction:

- Prevention of many of the roughly 1.75 million annual non-police-reported rear-end crashes. Countermeasure effectiveness for these crashes may even be greater than for police-reported crashes due to their generally lower severities and associated closing speeds.

- Prevention of "disguised" rear-end crashes -- i.e., crash scenarios that begin as rear-end crash threats but end up as some other crash type (e.g., single vehicle roadway departure, head-on). In the typical "disguised" rear-end crash, a following vehicle initiates panic braking or steering to avoid a rear-end collision, but loses control or steers out of the traffic lane, resulting in a non-rear-end crash. Such crashes are common. For example, the clinical assessment of 100 single vehicle roadway departure (SVRD) crashes performed as part of this research program found that 14 of 100 SVRD crashes were actually "disguised" rear-end crashes.

- Severity reduction of applicable target crashes (including both LVS and LVM, police-reported and non-police-reported, and "disguised" and true rear-end crashes) that are not prevented by the system. Benefits from such severity reduction may be significant; for example, Appendix B presents an experimental analysis, performed as part of this effort, showing that the 150-foot range HD system would reduce the injury severity of crashes not prevented by 40 to 50 percent.

- Reductions in crash-caused delay associated with target crashes. This reduction would generally be proportionate to the reduction in crashes.

Thus, the prospective benefits of the HD countermeasure extend well beyond the simple prevention of some portion of police-reported rear-end crashes. However, the "bonus" benefits described above are tempered by the fact that the modeled effectiveness estimates would be attenuated by factors such as those listed in Table 6-10.

6.9 Conclusion

This modeling effort has addressed the two major rear-end crash subtypes (LVS and LVM) using two qualitatively different types of modeling samples for each: a small clinical analysis/ reconstruction sample and a large, nationally-representative GES sample. The effectiveness modeling has demonstrated that HD systems have the potential to achieve significant reductions in the number of rear-end crashes that occur each year. When various hypothesized HD system countermeasure design parameters were applied to the modeling samples, a high percentage (generally 40 to 80 percent, depending on specific crash subtypes and modeling parameters) were found to be theoretic&y-preventable.

In addition to the prevention of police-reported rear-end crashes, there would likely be other significant categories of HD system benefits, such as prevention of non-police-reported rear-end crashes, prevention of “disguised” rear-end crashes, and severity reduction of target crashes not prevented. Thus, it appears that the total potential crash reduction benefits from the application of HD system technologies could be substantial.

On the other hand, there are a number of attenuating factors that will reduce the optimistic theoretical effectiveness estimates derived here. Systems operating at the extended ranges modeled in this report could be prone to unacceptably high nuisance alarm rates. These high rates are typically associated with HD systems responding to roadside appurtenances (i.e., utility poles, guardrail, etc.) at extended ranges or with the misalignment of vehicles which can occur at extended ranges. The driver interface (e.g., warning system design) issue would need to be addressed to ensure that drivers respond reliably and appropriately to the warning signal or other vehicle response to crash threat detection. Extensive research and development will be needed to better assess and to minimize the attenuating effects of these types of problems.

7.0 COUNTERMEASURE RESEARCH & DEVELOPMENT NEEDS

An important goal of this project has been to identify priority research and development (R&D) requirements related to the collision avoidance potential of IVHS rear-end crash countermeasures. Many of these R&D issues will be addressed in the next phase of NHTSA's research on IVHS countermeasures to rear-end crashes. This research will focus primarily on transforming the formulations of this project -- i.e., crash reconstructions, functional countermeasure concepts, preliminary technology assessments, and theoretical modeling -- into a set of rear-end crash countermeasure performance specifications. These performance specifications will be intended to facilitate industry efforts to develop practical and commercially-viable countermeasure systems. Some specific R&D needs relating to headway detection (HD) countermeasure assessment data collection and modeling, human factors, HD system technologies, and supporting technologies are discussed below.

7.1 Data Collection and Modeling Needs

A variety of data collection and modeling needs have been uncovered in the process of preparing this report. Key R&D needs are: more refined modeling based on improved algorithms and/or parameter values, an archival knowledge base for collision avoidance, technology infusion model development, and further data collection.

7.1.1 More Refined Modeling

In this program, preliminary countermeasure functional models have been constructed from the best available information. Modeled values of such parameters as countermeasure range, driver reaction time, braking efficiency, and sensor system detection/warning activation decision algorithms have been selected based on the current literature. As better data relating to these parameters becomes available, they may be applied to the models contained in this report for more refined modeling results. Moreover, the detection algorithms themselves may be refined in ways that yield better detection probabilities and/or lower probabilities of nuisance alarms or other problems. As noted in the introduction to the report, this program is intended to be heuristic, supporting multiple future iterations of the modeling.

One simplistic way that the current modeling results could be improved would be to apply the current models to larger clinical samples. The clinical data samples for the current countermeasure effectiveness modeling were small -- 13 Lead Vehicle Stationary cases and five Lead Vehicle Moving cases. It would be helpful to include additional clinical cases to verify the assumptions and the validity of the current effectiveness estimates.

7.1.2 Archival Knowledge Base on Vehicle Location and Motion

Police accident reports and similar crash data generally provide little data on precise vehicle locations and motions. And, of course, they provide no data on non-crash-related vehicle motions. Such data would greatly strengthen the basis for countermeasure modeling since it would provide empirical data on driver behavior and vehicle motion. An archival knowledge base of vehicle location and motion would provide empirical data relating to such rear-end crash-related issues as vehicle time and motion sequences (e.g., LVS versus LVM), intervehicle gaps, and deceleration rates. Data on “normal driving” and “near miss” situations could be used to model crash situations. NHTSA has addressed this research need by initiating a program to develop a specialized measurement system to quantify the “vehicle motion environment”. At a given road site, the program will use roadside imaging devices to capture passing vehicle motion variables and provide discrete data and statistical distributions of these variables. Vehicle speed and headway data obtainable by such a system will enable significant refinements to the current rear-end countermeasure assessment.

7.1.3 Documentation of Roadway Geometry

The range of an HD system is limited by the straight-line distance available in the forward path of the vehicle. As noted in Section 6.7.1, more than 90 percent of rear-end crashes occur on roadways coded as “straight and level” on police accident reports. However, it is not known what proportion of roadways would be “straight and level” from the perspective of HD system functioning. Slight curves, dips, and hillcrests not noted by police officers may cause significant misalignment of the HD system beam. The extent of this misalignment would depend on roadway geometry as well as the nature of the HD system and its features (e.g., beam steering). An empirical or analytical assessment of the actual straight-line distance available for system functioning on various roadways, consistent with the operational capabilities of current/near-future I-ID systems, will likely be required.

7.1.4 Projections of HD System Market Penetration

An implicit assumption in effectiveness modeling is that all involved vehicles are equipped with the proposed IVHS crash avoidance technology. Of course, in reality such technology will be gradually introduced into the vehicle population. Therefore, the proportion of device-equipped vehicles will be substantially less in the early years just after technology introduction than it will be in later years. It would be useful to model this market penetration over a planning horizon and incorporate the results into effectiveness estimates. This would require parameter estimates for vehicle replacement rates, initial device penetration (i.e., numbers and types of vehicles appropriately equipped), and projections regarding expected market penetrations.

7.1.5 Effects of HD System on Vehicle Spacing on Highways

By design, I-ID systems would be intended to reduce “tailgating.” For example, if lead and following vehicle speeds were both 40 mph, the hypothetical HD system algorithm illustrated in Figure 6-3 would sound an alarm for headways of less than 56 feet. To the extent that drivers compiled with system warnings, such “tailgating” would be reduced in frequency, thereby increasing safety margins. However, such tailgating warnings may be perceived as a nuisance by drivers, and any significant reduction in the number of short headways on crowded roadways may significantly reduce roadway throughput. These factors may undermine public acceptance of the device.

Representative data on vehicle speeds and headways on crowded roadways would permit estimation of the proportion of headways at the low end of distribution that would be affected. This in turn would permit an assessment of the percent of headways affected by the system and thus the "trade-offs" between increased safety on the one hand and the "nuisance factor" and decreased throughput on the other.

Detailed analysis of short headway and throughput effects is beyond the scope of the present work. However, a small supplemental analysis performed under the current project applied the lead vehicle decelerating HD system algorithm (see Section 6.3.3) to a limited sample of urban freeway speed and headway data. This analysis approach, demonstrated by Farber and Paley (1993), was applied to vehicle speed and headway data (approximately 36,000 vehicle pairs) recorded on Interstate 40 near Albuquerque, NM. Assuming full penetration and full compliance by drivers, the current lead vehicle decelerating algorithm would have eliminated the shortest 25 percent of the headways in the Albuquerque sample.

This calculation was based on a limited sample and involved important unverified assumptions. However, such analyses, including a consideration of expected rates of driver compliance, are required to assess the likely operational effects of HD systems on traffic spacing and flow. A trade-off may exist between the degree of curtailment of "tailgating" and driver acceptance/compliance; overly ambitious algorithms may in theory curtail tailgating but in practice be rejected by drivers. Further research may identify an optimal system algorithm that curtails tailgating significantly but which is generally accepted by drivers and is not viewed as a nuisance alarm.

7.2 Human Factors

7.2.1 Warning System Design

Attendant to all IVHS crash avoidance countermeasures which warn the driver is the need to ergonomically design the warning system. This type of research would address such issues as levels of warning (e.g., danger possible, danger probable, danger imminent), information content of the warning (e.g., alert vs. directives), modality of warning (e.g., visual, auditory, tactile), and coding of warnings (e.g., frequencies, durations of sounds, location, shape and size of visuals). More subtle issues in warning design should also be addressed. These factors might include the noxiousness/acceptability of a warning and the distinctiveness of one warning from another warning in an integrated IVHS system.

7.2.2 Nuisance and False Alarms

The issue of nuisance alarm and false alarm rates and human performance is not well understood at present (see Section 4.3 for the definitions of these terms). One might expect that the driver's reaction to nuisance and false alarms will vary as a function of the following variables:

- **Payoff.** The driver will accept nuisance and false alarms to the extent that the cost of a miss (an unnoticed obstacle in front of the car) is high.

- **Frequency.** If nuisance/false alarms occur infrequently, they may be tolerated more than if they repeat several times a mile. The relative frequency of nuisance/false alarms to "hits" (i.e, correct detections) may influence driver response as well.

- **Time scale.** Nuisance/false alarm rate is likely to be very important. One may tolerate 5 false alarms within one hour much more readily than one will tolerate 5 false alarms within one minute.

- **Locus of control.** The driver may accept the system more readily if he or she has some control over alarm thresholds, presence or absence of positive speed control or braking control, alarm loudness, and so on.

7.2.3 Driver Acceptance/Compliance

Many factors will influence whether the broad population of drivers will accept the HD system concept and comply with HD system warnings -- i.e., immediately brake to avoid the collision upon onset of the warning signal. The two factors discussed above (warning system design and nuisance/false alarms) will be critical. Other factors may include drivers' basic understanding of the countermeasure concept and their feelings of "locus of control" while driving a vehicle equipped with the device. That is, some drivers may feel that use of collision warning systems or other high-technology driving aids lessens their sense of being "in-control" and thus lessens the gratification and enjoyment of driving.

Another consideration relating to public acceptance of headway detection systems is their effect on prevailing vehicle headways and highway throughput (see Section 7.1.5 above). Reducing "tailgating" is likely to be viewed favorably by many drivers, while reductions in urban highway throughput would likely be viewed unfavorably. Extensive human factors, public opinion, and marketing research will be required to address the many factors likely to influence driver acceptance/compliance and to design and implement systems that will be welcomed by the driving public.

7.2.4 Model of Driver Reaction Times and Other Performance/Behavior Parameters

In the course of carrying out effectiveness modeling, there will be a need for more refined driver reaction time and other performance/behavior estimates. A useful research reference would be a catalog of driver reaction times (RTs) indexed by factors such as driver state, traffic situation/crash threat, driver expectancy of threat, modality of warning, number of response alternatives the driver must consider, and need for verification of threat.

The lognormal RT distribution suggested by Taoka (1989) and used in the present driver performance modeling captures the positive skewness of the RT distribution but is based largely on direct observations of drivers responding to traffic signal changes (green to yellow). Determination of more precise and valid reaction time and other related distribution functions will require a combination of archival, field, laboratory, and statistical research. This research would also correlate driver reaction time with driver behavior measures such as travel speed. Chang et al (1985) has reported that drivers who travel at higher speeds tend to have faster-than average reaction times. Here, the simplifying assumption has been made that driver RT and braking deceleration rate are independent variables, even though it is recognized that the two factors are almost certainly correlated to some unknown degree in the "real world."

7.2.5 Human Factors of Automatic Vehicle Control (i.e., Braking)

The modeling effort described in this report has assumed that an HD system would provide a warning to the following driver as he or she encroaches upon another vehicle. However, a more effective system may be one that initiates automatic braking (most likely "soft" braking) immediately upon detection of a crash threat in the forward path of the vehicle. Such systems offer clear advantages in terms of probability of crash avoidance (e.g., Farber, 1991). However, very little is known about driver reactions to automatic vehicle control, including such basic questions as whether drivers would accept an automatic vehicle control feature such as soft braking and, if so, what degree of braking would be safe (i.e., non-disruptive of performance) and acceptable to drivers.

7.2.6 Elderly Drivers and IVHS

There is concern that the elderly will have difficulty in interacting with IVHS technology. Elderly drivers generally take longer to respond to various events, are more sensitive to automation-driven timing constraints, and are less flexible in using different device interaction techniques. A large percentage of elderly drivers may refuse to use IVHS technology. Thus, IVHS use by elderly drivers merits research investigation. A major goal would be to derive a set of IVHS design guidelines for incorporating age-related limitations in cognitive functioning, perceptual abilities, body size and strength, as well as memory and learning styles.

7.2.7 Systems Integration of IVHS Countermeasures

Since the proposed countermeasure concept for rear-end crashes assumes only a single response (e.g., braking), the integration of systems must be addressed at some point. Individual IVHS technologies, when brought together, might overwhelm the driver with warnings or information, or compete with each other in unexpected ways (e.g., through crosstalking). For example, the driver's workload might increase with multiple warning systems because the driver must determine the kind of warning and then the appropriate response. These problems can be alleviated through systems integration research.

7.3 HD System Technologies

Several contributory causes for rear-end collisions were cited in Chapter 3.0. Causal factors such as driver inattention and following too closely imply that an effective IVHS solution might be an HD system which measures range, lateral position (i.e., perpendicular to the range) and speed of the lead vehicle. Microwave/millimeter wave radar has been discussed in this report as a candidate technology for HD systems (see Section 4.4), and has been used as the basis for hypothetical system functional parameters. Microwave/millimeter wave sensors may satisfy all the above requirements, especially the need for lateral position information concerning the lead vehicle if beam steering is used. Another candidate technology for HD systems is laser radar (see Section 4.4).

At present, an optimal technology for the HD system cannot be recommended, since at least two competing technologies exist, each with its own set of advantages and disadvantages. The sensor specification process should include experiments or analytical studies to determine appropriate sensor technologies and their implementation for HD systems. The following subsections briefly explain some of the possible studies. Essentially, these studies comprise major two tasks, an overall technology review to compare competing sensors (Section 7.3.1) and a detailed engineering trade-off analysis (Section 7.3.2) to determine the optimum sensor type for rear-end collision avoidance. Important parts of this analysis are highlighted in Sections 7.3.3 and 7.3.4.

7.3.1 Technology Review

There is a need for an extensive review of available sensor types to determine their technical maturity, cost, and ability to satisfy IVHS countermeasure requirements. For example, microwave/millimeter wave (i.e., an active system) radar has been the focus of considerable military development, especially at the frequencies of 35 and 95 GHz, which correspond to atmospheric transmission "windows." At 35 GHz, phased array and conformal microstrips may provide electronic beam steering for future applications, while at 95 GHz only mechanical beam control is currently feasible. Phase or frequency control of the radiating elements is the means by which electronic beam steering is achieved. In addition to being less cumbersome than mechanical scanning, electronic control permits beam pattern modification and selection of side lobe nulls to minimize interference.

Laser radar (an active system) is a potential alternative to microwave/millimeter wave radar due to its superior angular resolution. With a stable output and narrow bandwidth, CO_2 lasers (10.6 microns) represent a mature technology for applications which require range and velocity measurements, such as military fire control and navigation systems. A potential alternative to CO_2 lasers are Nd:YAG lasers (1.06 microns) which are used extensively as military range finders. At 1.06 microns, these lasers may be used with fiber optic beam combiners to avoid alignment problems which are prevalent in CO, lasers.

Both microwave/millimeter wave and laser radar systems could be used functionally as gated imaging systems which accept return signals from predefmed ranges to reduce signals from undesired objects. As an alternative to active radar, passive sensors could be configured as a stereo pair to measure range between following and lead vehicles. Sensor pairs may be either electro-optical (i.e., visible imaging due to target reflection) or infrared (i.e., imagery due to radiant self-emission from targets and backgrounds). Modulated reflectors could function in conjunction with active sensors to provide information about lead vehicle speed.

7.3.2 Sensor System Engineering Tradeoff Analysis

After the completion of an overall technology review, some sensors will likely be eliminated from consideration for reasons relating to cost, technical maturity, etc. Surviving sensor candidates will be subjected to a detailed engineering tradeoff analysis to determine optimum system parameters. For example, there are advantages and disadvantages to both microwave/millimeter wave radar and laser radar which should be systematically evaluated. For a particular sensor technology, *bandwidth, spatial resolution, and signal encoding are among the sensor system parameters which could be optimized through such an analysis. These parameters are considered below.

7.3.3 Range/Velocity Measurement Errors

As a minimum, an HD system needs to provide simultaneous range and velocity measurements. Errors in either of these quantities will cause substandard performance from the HD system on board the following vehicle. For example, the required range measurement accuracy translates into a bandwidth requirement of the sensor transmitter/receiver. If the required range measurement accuracy is equal to one car length (e.g., 12 ft for a small vehicle), then the bandwidth of the system must be 38 MHz. In the case of velocity measurements, the Doppler shift is 5 MHz for a CO, laser and only 4 KHz for a 24 GHz millimeter wave radar when the relative speed is 60 mph between the lead and following vehicles. Therefore, receiver electronics are impacted by the type of transmitter employed (especially its wavelength) as well as target parameters such as reflectivity and speed.

Transmitter characteristics also play a role in range/velocity measurement errors of HD systems. For example, in the case of a laser radar with a spectral stability of 100 KHz, the velocity accuracy of the initial velocity measurement is +1 mph, which results in a stopping distance uncertainty of approximately 10 feet at 60 mph.

7.3.4 Spatial Resolution Capability

There is a need to assess sensor resolution capability, particularly at maximum ranges, for situations in which the roadway is obscured by geometry, and under adverse weather conditions. This study could also assess the ability of sensors to minimize nuisance alarms. The examination of roadway geometries may require documentation of the straight-line distances that are actually available on roadways (as previously discussed in Section 7.1.3).

Location of the lead vehicle's position within the following vehicle's sensor field of view is an important factor when determining whether or not the driver alert feature should be activated. This requirement depends on sensor angle resolution, the distance between the lead **and** following vehicles, and the size of the lead vehicle.

For a CO_2 laser and a separation of 300 feet between 6-foot-wide vehicles, there would be 48 pixels across the lead vehicle. This is more than enough to differentiate between the lead vehicle and roadside objects. However, for a 24 GHz millimeter wave sensor with the same range and vehicle width, there are approximately 0.4 pixels across the lead vehicle, a number which is insufficient for object identification. This may lead to false alarms.

These difficulties associated with microwave/millimeter wave radar may be rectified by a transponder whose encoded signal provides lane position information derived from a separate lane-following sensor. A lane-encoded signal may be necessary because the lead vehicle transponder does not provide accurate positional information capacity if the transponder is a relatively low frequency instrument.

7.4 Supporting Technologies

7.4.1 Development of Optimum Forms of Logic Sequences for HD Systems

The modeling conducted in Chapter 6.0 was based on an existing HD system and its incorporated logic. Obviously, the parameters used for vehicle gap monitoring and closing velocity monitoring are crucial to the effectiveness of driver warnings and driver compliance. More sophisticated logic routines should result in fewer nuisance alarms and thus better driver acceptance and performance. More research needs to be conducted on the optimum forms of logic sequences relative to rear-end collision subtypes.

7.4.2 Detection of Lead Vehicle State

Another method of reducing the nuisance alarms generated by the HD system would be to replace the assumed lead-vehicle deceleration (0.5gs and 0.25gs were used in the present modeling) with a measured value. Current digital signal processing techniques are too slow to determine deceleration based on radar data, but processing time could be reduced in the future. Also, the lead vehicle could communicate its deceleration rate to the following vehicle using radio, infrared or a modified stop lamp, for example. Further research is necessary to determine which of these, or other, systems could most effectively lead to an accurate measure of lead-vehicle deceleration.

7.4.3 Automatic Braking

As noted earlier in Section 7.2.5, an important system option to be considered is that of automatic vehicle control (i.e., automatic braking) in response to crash threat detection. In addition to the human factors issues addressed in Section 7.2.5, there are technological

R&D issues associated with the implementation of automatic braking. Most importantly, nuisance/false alarms (i.e., initiation of automatic braking when the crash threat is minimal or non-existent) would need to be miuimized through the use of signal processing logic or other means.

7.4.4 Advanced HD System with Automatic Steering Capability

In the future, additional IVHS technology development might be pursued. In particular, a vision or other sensing system might be coupled with an HD system and also with automatic steering capabilities which guide a vehicle around an obstacle. Significant technical challenges include development of "intelligent sensing" to ascertain if the maneuver can be performed safely (e.g., berm is clear, no collision possibilities in adjacent lane, etc.). Since steering is a high-risk avoidance maneuver (whether performed manually or automatically), safety would be a major concern associated with the development of this capability.

Table 7-l is a summary of R&D requirements addressed in this chapter. This list includes several recommended tasks for data collection and modeling, human factors, HD sensors, and supporting IVHS technologies.

Table 7-l
R&D Needs for Use of
Headway Detection Technology in Preventing Rear-End Collisions

R&D Needs	Key Issue(s) To Be Addressed
Data Collection and Modeling:	
1. More Refined Modeling	Sample Sizes, Modeling Parameter Values, HD System Algorithms
2. Vehicle Motion Environment	Vehicle Speeds and Positions
3. Roadway Geometry Documentation	Straight Line Distances Available
4. Market Penetration Projections	Device Sales, Associated Benefits
5. Vehicle Spacing on Highways	Short Headways and Roadway Throughput
Human Factors:	
1. Warning System Design	Ergonomics of Warning; Optimal Design
2. Nuisance/False Alarms	Prospects for Minimizing Negative Effects
3. Driver Acceptance/Compliance	Predicting and Maximizing Acceptance/Compliance
4. Model of Driver/Vehicle	Reaction Times/Other Driver/Vehicle Performance
5. Driver Reaction to Automatic Braking	Acceptance, Performance Disruption
6. Elderly Drivers	Reaction Times/Driver Errors
7. Systems Integration/Multiple Alarms	Driver Response Disruption/Negative Transfer
Sensor Svstems:	
1. Technology Review	Technology Maturity, Cost, Availability
2. Sensor System Engineering Tradeoff Analysis	Optimum Sensor Type; Design Parameters for HD Applications
3. Range/Velocity Measurement Errors	Relation of Velocity and Range Errors to Sensor Types and Parameters
4. Spatial Resolution Capability	Location of Lead Vehicle/Nuisance Alarm Reduction
Supporting Technologies:	
1. Logic Sequence for HD System	Improved Performance, Reduced Nuisance Alarms
2. Detection of Lead-Vehicle Deceleration	More Accurate Sensing or Intervehicle Communication Technology
3. Automatic Braking	Reliability and Nuisance/False Alarm Control
4. Advanced HD with Automatic Steering	Feasibility, Safety

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APPENDIX A
CLINICAL SAMPLE CASE LISTING
(1991 NASS Crashworthiness Data System)

Case #	National Inflation Factor
02-015H	49.78
02-023E	260.46
02-024G	911.62
02-04OH	166.00
02-069E	25.13
02-088G	123.09
04-016H	372.86
04-025C	15.87
04-028G	357.00
04-036G	209.47
04-046E[1]	43.51
04-05OF	45.60
04-060G[1]	71.14
04-064G	285.52
04-075G	119.01
05-007E	530.56
05-008F	928.47
05-012H[1]	680.64
05-017C	71.61
05-04OH	1044.39
05-056G	966.94
05-063G	650.25
05-076H	987.14
06-016G[3]	274.01
06-062E	53.61
06-088H[1]	225.46
08-OOlE[1]	129.45
08-OllG	309.92
08-015F	430.37
08-016G	860.74
08-041 G[1]	534.12
OS-059G	204.24
08-065G	583.61
08-066G[1]	583.61
08-074E	90.69
08-078H	634.84
08-090G	649.63
08-093E	55.49
08-096G	192.39
08-107G[1]	254.36
08-l 17G[1]	185.11
08-124G	378.48
08-135E	92.51
09-018F	736.50
09-024G	520.39
09-098E[2]	403.87
09-l 1OE[2]	465.97
1 l-028F	1324.92
l l -092E	1035.27
12-OllG	614.87
12-012H	1229.74
12-029G	675.49
12-069C	25.65
12-097E	91.74
12-144G	436.32
12-159F	285.54
13-042H	561.31
13-048G[3]	2340.12
1 3-064G[2]	177.96
1 3-076F[3]	185.23
13-108H	418.29
13-113F[1]	319.95
41-030G	674.16
41-033E	351.60
41-04OH	1642.60
43-002F	1086.93
43-008H	5641.94
43-04OD[1]	156.12
43-046G[1]	1551.02
45-016G	2047.59
45-028H[2]	4246.54
45-047F[1]	885.05
45-048H	3540.19
45-054D	109.60
45-060H[2]	3725.19
45-092H	1278.17
45-106G	1904.64

1 **Also included in LVS reconstruction sample**
2 **Also included in LVM reconstruction sample**
3 **Insufficient information for causal factor assessment**

APPENDIX B
ESTIMATION OF INJURY SEVERITY REDUCTION FOR CRASHES NOT PREVENTED

Crash *avoidance* countermeasures that improve the driver-vehicle response to crash threats are likely to affect *both* the occurrence and the severity (e.g., impact speeds and resulting injuries) of crashes. Earlier driver awareness, faster braking, improved vehicle control, and other such measures enable drivers to avoid crashes and tend also to decrease the severity of crashes that do occur. **Figure B-1** shows a conceptual model of crash avoidance countermeasure effects.

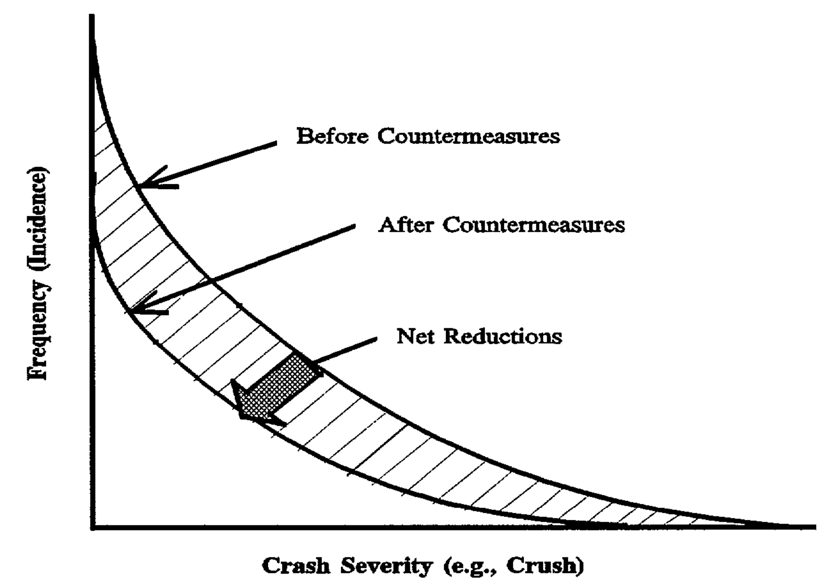

Figure B-1: Conceptual Model of Countermeasure Payoffs; Decreases in Both Crash Frequency and Severity.

Figure B-1 is a conceptual representation. The rear-end crash countermeasure effectiveness modeling performed under this program addressed primarily crash prevention (see Chapter 6.0) but also included a preliminary examination of the level of crash severity reduction that might be expected in rear-end crashes *not prevented* by the headway detection (HD) system countermeasure concept. This appendix presents a series of statistical formulations designed to demonstrate that some degree of occupant injury reduction that could be expected due to reductions in crash (i.e., impact) severity and to provide a rough estimate of the degree of such reduction. "Impact severity" is measured in terms of Delta V (ΔV), the change in vehicle velocity that occurs during a collision. Injury severity is measured in terms of Maximum Abbreviated Injury Severity (MAIS) Scale value. Reductions in ΔV are reflected in reductions in occupant injury profiles per the MAIS measure.

Two different analyses are presented, both based on the same clinical sample cases and countermeasure modeling parameters. In the most simplistic analysis, reductions in ΔV are associated with reductions in the *probability* of a moderate (or greater) severity injury. This analysis is presented in Section B.1. Then, to extend this analysis, the same "before and after" injury data are used to estimate *percentage* reductions in injury severity (Section B.2). This latter analysis converts MAIS values to "fatal equivalent" values so that injuries of different severities can be measured on a single ratio scale. In such a ratio scale, a hypothetical reduction in injury severity (e.g., from MAIS 4 [severe] to MAIS 2 [moderate]), can be converted to a *percentage* reduction in injury severity (e.g., 0.3882 to 0.0411 "fatal equivalents", or an 89 percent reduction).

B.1 Reduction in Probability of MAIS 2+ Injury

The four-step procedure outlined below was used to demonstrate analytically the potential for significant reduction in *injury* severity (i.e., probability of a MAIS 2+ injury) resulting from the application of a HD countermeasure which reduces the *crash* severity (i.e., ΔV) of rear-end lead vehicle stationary (LVS) crashes:

1. **Determine the probability of an MAIS 2+ injury as a function of ΔV for occupants involved in baseline target crashes.**

   This was determined for the LVS crash type using unweighted statistics from the 1982-1986 NASS data file. For consistency (and to avoid "double counting"), the ΔV of only the *striking* vehicle was considered. However, the injury severities of *all* involved occupants (i.e., both the striking and the struck vehicle) were included in the analysis.

   The specifications for the retrieval were as follows:

   For two-vehicle LVS crashes occurring on dry or wet (but not icy/snowy) with known ΔV and not involving a medium/heavy truck as the striking vehicle, defined as follows (1984 Variable Codes Used):
   - Number of Vehicle Forms Submitted (vehicles in crash) (VEHFORMS) = 2
   - Manner of Collision (MANCOLL) = 1 (Rear-End)
   - Relation to Roadway (RELROAD) = 1 (On-Roadway).
   - Roadway Surface Condition (SURCOND) = 1 (Dry) or 2 (Wet)
   - Travel speed (TRAVELSP) of struck vehicle {Vehicle with Vehicle Role (VEHROLE) = 2 (Struck Unit)} = 0
   - Vehicle type (VEHTYPE) of striking vehicle {Vehicle with Vehicle Role (VEHROLE) = 1 (Striking Unit)} **not** = 70-79

   The following unweighted bivariate distribution was constructed:
   - Total Delta V (DVTOTAL) of the striking vehicle (in 5 kph intervals: 0 - 5, 5.01 - 10, 10.01 - 15, etc.) by
   - Most severe injury (in AIS) for each occupant (in both vehicles) (MAIS)

Table B-1 (next page) presents data relating to the probability of a MAIS 2+ injury as a function of LVS rear-end crash ΔV. The statistics are presented for 5 kilometer per hour (kph) intervals through 50.01-55 kph. Above 55 kph, there were insufficient data for meaningful analysis.

Table B-1
Probability of MAIS 2+ Injury as a Function of LVS Crash ΔV

ΔV Interval (kph)	MAIS 2+ Occupants	Total Occupants	Probability of MAIS 2+ Injury	ΔV Interval (kph)	MAIS 2+ Occupants	Total Occupants	Probability of MAIS 2+ Injury
0.01 - 5	1	57	0.018	30.01 - 35	22	187	0.118
5.01 - 10	16	901	0.018	35.01 - 40	17	141	0.121
10.01 - 15	43	1542	0.029	40.01 - 45	9	50	0.180
15.01 - 20	66	1327	0.050	45.01 - 50	5	53	0.094
20.01 - 25	44	755	0.058	50.01 - 55	2	23	0.087
25.01 - 30	41	506	0.081	55.01+	Insufficient Data		

2. **Determine, through accident reconstruction of the clinical analysis sample and countermeasure modeling, baseline ΔVs and predicted ΔVs of sample crashes *not prevented* by the countermeasure.**

This was performed using a slightly different and less complex modeling approach than that described in Chapter 6.0. Instead of using a Monte Carlo-generated population of driver reaction time (RT) and braking deceleration values, single benchmark values for RT and braking deceleration were used. Then, the maximum travel velocity at which crashes could be avoided for a given system range limit was established by comparing the braking distance provided by the HD system with the distance required by the following vehicle to decelerate to zero. For those crashes *not* prevented, impact travel speeds and estimated ΔVs were derived. Estimation of HD System ΔVs required consideration of vehicle size and weight and estimation of kinetic energy absorption and, therefore, ΔV, likely to occur during the collision impact. The simplified approach to designating modeling parameters was necessary to reduce the number of ΔV derivations required for the analysis.

In addition, slightly different detection algorithm and stopping distance equations were used. Specifically, the modeling equation used here includes a correction factor to account for the fact that some braking occurs between the onset of braking and full activation of braking. This second change is minor and has no significant impact on results.

Table B-2 shows those parameters of the severity reduction modeling that *differ* from the LVS modeling of HD system effectiveness described in Chapter 6.0. The reader is referred to Chapter 6.0 for a more detailed discussion of the use of design and modeling parameters in the countermeasure modeling.

Table B-2
Assumed Design and Modeling Parameters
for HD System Crash Severity Reduction Modeling
(Differences From Crash Avoidance Modeling Presented in Chapter 6.0)

Parameter	Design Parameter Values/Assumptions	Modeling Parameter Values/Assumptions
Driver Reaction Time	1.5 seconds	1 .1 seconds
"System" Delay Time	0.55 seconds: 0.25 system processing + 0.3 sec to achieve braking efficiency of 0.5g	0.65 seconds: 0.25 system processing + 0.4 sec to achieve braking efficiency of 0.7g
Total Delay Time	2.05 seconds	1.75 seconds
Following Vehicle Braking Deceleration	0.5g (16.1 feet/sec^2)	0.7g (22.5 feet/sec^2)
HD Warning Distance Function	$D_W = V_f^2/2a + T_D V$, where: D_W = Warning distance (in feet) V_f = Velocity of following vehicle a = Deceleration rate of following vehicle (0.5g) To = Total time delay before the driver of the following vehicle initiates a full response (2.05 seconds).	*Same* as design parameter
Stopping Distance	Implicitly equal to warning distance	$D_S = V_f^2/2a + T_D V_f - C$ where: D_S = Stopping distance. a = Deceleration rate of the following vehicle (0.7g) T_D = Total time delay before the driver initiates a full response (1.75 seconds). C = Correction factor. Accounts for deceleration occurring between initial and maximum braking. Value utilized: 0.13 V_f.

The results of this reconstruction of LVS crashes and modeling of interventions are presented in Table B-3. These are crashes that would not be prevented by the modeled countermeasure, but which could potentialy be reduced in severity.

The "crash circumstance" column in Table B-3 refers to two different assumptions that were made regarding the pre-crash movement of the lead vehicle. One assumption was that the lead-vehicle was stationary for the entire period of following vehicle braking (lead-vehicle stopped, entire period; LVSEP). The alternative assumption was that the lead vehicle had just come to a stop at the point of impact (lead vehicle stationary at point of impact; LVSPOI).

Table B-3
Estimated Crash Severity Reduction in Delta V for Clinical Sample for Different HD Ranges and Hypothesized Crash Circumstances

			Real World Values			Values with HD System	
HD System Range Limit (FT)	Crash Circum-stance	Sample Ref #	Travel Velocity (mph)	Impact Speed (mph)	ΔV (mph)	Impact Speed (mph)	ΔV (mph)
250	LVSEP	13	48.7	36.3	17.4	13.7	6.6
200	LVSEP	13	48.7	36.3	17.4	27.9	13.2
	LVSPOI	13	48.7	36.3	17.4	21.0	10.0
150	LVSEP	13	48.7	36.3	17.4	36.9	17.7
		12	39.8	22.2	9.4	24.0	10.1
		11	39.7	22.5	10.6	23.8	10.6
		10	38.8	29.2	11.7	22.3	8.9
		9	37.4	23.2	9.6	19.8	9.8
		8	35.2	29.8	15.7	15.2	8.0
		7	34.3	34.3	21.9	14.2	9.1
		6	32.6	32.6	14.5	7.4	3.3
	LVSPOI	13	48.7	36.3	17.4	28.9	13.8
		12	39.8	22.2	9.4	7.1	3.0
		11	39.7	22.5	10.6	6.6	3.1
		10	38.8	29.2	11.7	0.5	0.2

LVSEP = Lead vehicle stopped for the entire period (of vehicle braking).
LVSPOI = Lead vehicle stopped at the point of impact (immediately following period of deceleration)

Note that Table B-3 shows some cases where the ΔV *increases* with use of the countermeasure. In these cases, the sample crash driver "outperformed" the hypothetical system as specified. Although the increased ΔVs are shown in the table, it was assumed here that, were an HD system implemented, drivers would continue to "outperform the system" in such cases and thus the actual ΔVs and injury severities would be unchanged.

3. **Determine reduction in probability of MAIS 2+ injury.**

Based on predicted ΔV changes (baseline vs. with countermeasure), the predicted probability of an MAIS 2+ occupant injury was determined for each case shown in **Table B-4**. The LVSEP and LVSPOI crash circumstances *were treated as two different possible crashes*. As noted above, in some cases the countermeasure would have no predicted effect on crash severity. In other cases, the countermeasure would enable a faster collision avoidance response and would result in reduction of crash and injury severity. **Table B-4** shows the modeled results for three HD ranges and the two crash subtypes (LVSEP and LVSPOI). For all three ranges, the HD system markedly reduces the mean probability of an MAIS 2+ injury. Mean probability reductions range from 33 to 64 percent.

Table B–4: HD Systems Applied to Rear–End LVS Crashes: Est. Reduction in Probability of MAIS 2+ Injury (for Occupants in Crashes Not Prevented)

HD Range	CrshType	Ref #	Real World Values DltaV(MPH)	Real World Values DltaV(KPH)	Probability of MAIS 2+ Injury	Values With HD System DltaV(MPH)	Values With HD System DltaV(KPH)	Probability of MAIS 2+ Injury	Est. Reduct. Probability MAIS 2+ Inj.
250	LVSEP	13	17.4	28.0	0.081	6.6	10.6	0.029	64.2%
				Mean:	0.081			0.029	64.2%
200	LVSEP	13	17.4	28.0	0.081	13.4	21.6	0.058	28.4%
	LVSPOI	13	17.4	28.0	0.081	10.0	16.1	0.050	38.3%
				Mean:	0.081			0.054	33.3%
150	LVSEP	13	17.4	28.0	0.081	17.7	28.5	0.081 *	0.0% *
		12	9.4	15.1	0.050	10.1	16.3	0.050 *	0.0% *
		11	10.6	17.1	0.050	10.6	17.1	0.050 *	0.0% *
		10	11.7	18.8	0.050	8.9	14.3	0.029	42.0%
		9	9.6	15.4	0.050	9.8	15.8	0.050 *	0.0% *
		8	15.7	25.3	0.081	8.0	12.9	0.029	64.2%
		7	21.9	35.2	0.121	9.1	14.6	0.029	76.0%
		6	14.5	23.3	0.058	3.3	5.3	0.018	69.0%
	LVSPOI	13	17.4	28.0	0.081	13.8	22.2	0.058	28.4%
		12	9.4	15.1	0.050	3.0	4.8	0.018	64.0%
		11	10.6	17.1	0.050	3.1	5.0	0.018	64.0%
		10	11.7	18.8	0.050	0.2	0.3	0.018	64.0%
				Mean:	0.064			0.037	42.0%

*Note: In cases where the Delta V (and expected injury severity) "increases" with the with the system operative, it is assumed that the driver will perform as previously. For these cases, it is assumed that there is no change in probability of MAIS 2+ injury.

The NASS CDS (the source of the clinical analysis sample) oversamples more severe crashes. Recall from Chapter 6.0 that the LVS clinical sample contained crashes with relatively high pre-crash travel speeds compared to the broader range of pre-crash travel speeds seen in the GES sample. The bias in the clinical sample toward more severe crashes means that these crashes probably have less potential for amelioration. However, since the entire analysis is directed toward crashes *not prevented* (i.e., the most severe crashes), the extent of this bias in the clinical analysis sample is not likely to be great.

B.2 Percentage Reduction in Injury Severity ("Fatal Equivalents")

An analytical extension of the above analysis is to estimate *percentage* reductions in injury severity that would occur in crashes not prevented through use of the countermeasure. In this analysis, MAIS values are converted to "fatal equivalent" values so that injuries of different severities can be measured on a single ratio scale. In such a ratio scale, a hypothetical reduction in injury severity (e.g., from MAIS 4 [severe] to MAIS 2 [moderate]), can be converted to a *percentage* reduction in injury severity (e.g., 0.3882 to 0.0411 "fatal equivalents", or an 89 percent reduction). **Table B-5**, derived by NHTSA Plans and Policy from Blincoe and Fagin (1992) provides "fatal equivalents" for crash occupant MAIS values.

Table B-5
Conversion Table for Deriving "Fatal Equivalents" from MAIS
(derived from Blincoe and Fagin, 1992)

"FATAL EQUIVALENTS" INJURY SEVERITY SCALE		
Injury Severity (MAIS)	**"Willingness to Pay" $ Value Per Injury**	**"Fatal Equivalents"**
Fatality (K)	$2,620,516	1.0000
Critical (5)	$2,122,642	0.8100
Severe (4)	$1,017,331	0.3882
Serious (3)	$400,310	0.1528
Moderate (2)	$107,638	0.0411
Minor (1)	$6,180	0.0024
Not injured (0)	-----	0.0000

Note in Table B-5 that the use of "fatal equivalents" cancels out the dollar values so that only *relative* values assigned to fatalities and injuries of various severities are factored into the severity reduction calculations. Note also the sharply increasing "Willingness to Pay" value of injuries with increasing MAIS, and thus the sharply increasing "fatal equivalent" value. For example, in the analysis, one MAIS 4 injury carried the same weight as approximately nine MAIS 2 injuries. Thus, the more severe injuries (and fatalities) will tend to "drive" the average "fatal equivalent" injury severity values.

Given the above scale, the remaining steps for determining percentage reduction in crash severity correspond to Steps 1 and 3 of Section B.1. **Table B-6** (next page) provides the aggregate "fatal equivalents" for each MAIS level for each ΔV interval, along with the average occupant "fatal equivalent" value. For the intervals up to 40 kph, "fatal equivalent" injury severity shows a roughly linear increase. Above 40 kph, the function becomes irregular as the number of subjects in each cell decreases. Fortunately, the LVS clinical sample contained no cases ΔVs greater than 40 kph. A general guideline for future analyses might be to use the smallest ΔV interval that can provide an increasing linear relationship between ΔV and average "fatal equivalent" injury severity across the ΔV range of the sample of interest.

Table B-7 (following page) shows the modeled results for three HD ranges and two possible crash subtypes (LVSEP and LVSPOI). This table is identical to Table B-4 except that average fatal equivalent values are substituted for the probabilities of MAIS 2+ injury. In other respects, this Table B-7 is identical to Table B-4; i.e.,:

- It is based on the ΔV severity reduction estimates shown in Table B-3.
- The LVSEP and LVSPOI crash circumstances *were treated as two different possible crashes.*
- There are some cases where the countermeasure would have no predicted effect on crash severity.

The results shown in Table B-7 are also similar to those seen earlier. In the modeling sample, HD systems provide a 45 to 65 percent decrease in average "fatal equivalent" injury severity for occupants involved in crashes that are not prevented by the countermeasure.

This analysis of crash/injury severity reduction for crashes not prevented has been based on a small number of LVS clinical sample cases that have been reconstructed as they actually occurred and given a hypothetical HD system intervention in the crash scenario. The severity reduction statistics derived here should be regarded as preliminary. The principal value of the analysis is that it demonstrates, using two metrics, that the application of HD systems will likely yield significant crash severity reduction benefits in addition to crash prevention benefits.

Table B-6: NASS 1982-86 Occupant Injury Severity Distribution and Average "Fatal Equivalents" for Rear-End LVS Crashes

Delta V lntervals(kph)

	0.01-5		5.01-10		10.01-15		15.01-20	
MAIS	Freq	Fatal Eqv	Freq	Fatal Eqv	Freq	Fatal Eqv	Freq	Fatal Eqv
0	44	0	584	0	888	0	675	0
1	12	0.0288	301	0.7224	611	1.4664	586	1.4064
2	1	0.0411	14	0.5754	29	1.1919	54	2.2194
3	0	0	2	0.3056	11	1.6808	9	1.3752
4	0	0	0	0	2	0.7764	1	0.3882
5	0	0	0	0	1	0.8100	1	0.8100
6	0	0	0	0	0	0	1	1.0000
Total	57	0.0699	901	1.6034	1542	5.9255	1327	7.1992
Average		0.0012		0.0018		0.0038		0.0054

	20.01-25		25.01-30		30.01-35		35.01 -40	
MAIS	Freq	Fatal Eqv	Freq	Fatal Eav	Freq	Fatal Eqv	Freq	Fatal Eqv
0	336	0	238	0	65	0	41	0
1	375	0.9000	227	0.5448	100	0.2400	83	0.1992
2	30	1.2330	30	1.2330	16	0.6576	IO	0.4110
3	12	1.8336	8	1.2224	5	0.7640	4	0.6112
4	2	0.7764	0	0	0	0	0	0
5	0	0	3	2.4300	1	0.8100	2	1.6200
6	0	0	0	0	0	0	1	1.0000
Total	755	4.7430	506	5.4302	187	2.4716	141	3.8414
Average		0.0063		0.0107		0.0132		0.0272

	40.01-45		45.01-50		50.01-55	
MAIS	Freq	Fatal Eqv	Freq	Fatal Eav	Freq	Fatal Eqv
0	21	0	17	0	7	0
1	20	0.0480	31	0.0744	14	0.0336
2	7	0.2877	3	0.1233	2	0.0822
3	1	0.1528	2	0.3056	0	0.0000
4	1	0.3882	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
Total	50	0.8767	53	0.5033	23	0.1158
Average		0.0175		0.0095		0.0050

Table B-7: HD Systems Applied to Rear-End LVS Crashes: Estimated Percentage Injury Severity Reduction (for Occupants in Crashes Not Prevented)

HD Range	CrshType	Ref #	Real World Values DltaV(MPH)	Real World Values DltaV(KPH)	Expected AvgOccInj FatlEquiv	Values With HD System DltaV(MPH)	Values With HD System DltaV(KPH)	AvgOccInj FatlEquiv	Expected % Reduction FatlEquiv
250	LVSEP	13	17.4	28.0	0.0107	6.6	10.6	0.0038	64.5%
				Mean:	**0.0107**			**0.0038**	**64.5%**
200	LVSEP	13	17.4	28.0	0.0107	13.4	21.6	0.0063	41.1%
	LVSPOI	13	17.4	28.0	0.0107	10.0	16.1	0.0054	49.5%
				Mean:	**0.0107**			**0.0059**	**45.3%**
150	LVSEP	13	17.4	28.0	0.0107	17.7	28.5	0.0107 *	0.0% *
		12	9.4	15.1	0.0054	10.1	16.3	0.0054 *	0.0% *
		11	10.6	17.1	0.0054	10.6	17.1	0.0054 *	0.0% *
		10	11.7	18.8	0.0054	8.9	14.3	0.0038	29.6%
		9	9.6	15.4	0.0054	9.8	15.8	0.0054 *	0.0% *
		8	15.7	25.3	0.0107	8.0	12.9	0.0038	64.5%
		7	21.9	35.2	0.0272	9.1	14.6	0.0038	86.0%
		6	14.5	23.3	0.0063	3.3	5.3	0.0018	71.4%
	LVSPOI	13	17.4	28.0	0.0107	13.8	22.2	0.0063	41.1%
		12	9.4	15.1	0.0054	3.0	4.8	0.0012	77.8%
		11	10.6	17.1	0.0054	3.1	5.0	0.0012	77.8%
		10	11.7	18.8	0.0054	0.2	0.3	0.0012	77.8%
				Mean:	**0.0086**			**0.0042**	**51.6%**

*Note: In cases where the Delta V (and expected injury severity) "increases" with the with the system operative, it is assumed that the driver will perform as previously. Thus, it is assumed that there is no actual change (i.e., a 0.0% reduction) in injury severity.