Examination of Lane Change Crashes and Potential IVHS Countermeasures

U.S. Department
of Transportation

National Highway
Traffic Safety
Administration

DOT HS 808 071
DOT-VNTSC-NHTSA-93-2

Final Report
March 1994

U. S. Department of Transportation
Research and Special Programs Administration
John A. Volpe National Transportation Systems Center
Cambridge. MA 02142

This document is available to the public through the National Technical Information Service. Springfield. VA 22161

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1994	Final Report February 1993 - October 1993

4. TITLE AND SUBTITLE
Examination of Lane Change Crashes and Potential IVHS Countermeasures

5. FUNDING NUMBERS
HS421/S4007

6. AUTHOR(S)
John D. Chovan, Louis Tijerina, Graham Alexander (Battelle), and Donald L. Hendricks (Arvin/Calspan Corp.)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S Department of Transportation
Research and Special Programs Administration
John A. Volpe National Transportation Systems Center
Cambridge, MA 02142

8. PERFORMING ORGANIZATION REPORT NUMBER
DOT-VNTSC-NHTSA-93-2

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
National Highway Traffic Safety Administration
Nassif Building
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT HS 808 071

11. SUPPLEMENTARY NOTES

Firms contracting to RSPA/VNTSC:	Battelle 505 King Avenue Columbus, OH 43201-2693	Arvin/Calspan Corp. P.O. Box 400 Buffalo, NY 14225

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the National Technical Information Service, Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report provides an analysis of lane change crashes to guide the development of Intelligent Vehicle Highway System (IVHS) crash avoidance systems. It introduces the problem of lane change crashes: A lane change crash occurs when a driver attempts to change Lanes and strikes or is struck by a vehicle in the adjacent Lane. Two crash subtypes are identified and causal factors that contribute to lane change crashes are assessed clinically from a sample of Lane change crash cases. From these data, functional goals for IVHS lane change crash avoidance systems are described. A simple kinematic model of normal lane change and evasive steering maneuvers introduces key pre-crash variables and outlines the space of time and distance available for crash avoidance from a kinematic perspective, concluding with a discussion of key research needed to extend the analysis presented. (Included with the report is a diskette of the Kinematic models developed for this crash type and files for data tables used in generating data plots contained in the report. The file README.TXT is an ASCII file that describes the program and data files on this diskette.)

14. SUBJECT TERMS
Lane change crashes, crash avoidance, countermeasures, Intelligent Vehicle Highway System (IVHS)

15. NUMBER OF PAGES
60

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

7540-01-280-5500

Standard Form 298 (Rev. 2-89
by ANSI Std. 8

PREFACE

The National Highway Traffic Safety Administration (NHTSA) Office of Crash Avoidance Research (OCAR), in conjunction with the Research and Special Programs Administration (RSPA) Volpe National Transportation Systems Center (VNTSC), has a multidisciplinary program underway to identify crash causal factors and applicable Intelligent Vehicle Highway System (IVHS) countermeasure concepts; model crash scenarios and avoidance maneuvers; provide preliminary estimates of countermeasure effectiveness when appropriate; and identify research data needs.

Under this program major target crash types will be examined including the following:

- Rear-End
- Backing
- Single Vehicle Roadway Departure
- Lane Change/Merge
- Intersection/Crossing Path
- Reduced Visibility (Night/Inclement Weather)
- Head-On

This report presents the results of the lane change/merge study. The results are based on 16 hard copy reports and 144 PARs, which were selected from the 1992 Crashworthiness Data System (CDS), and from the 1991 General Estimates System (GES) within the National Accident Sampling System (NASS). The selected cases involve two vehicles. Thus, single vehicle crashes that were coded as lane change maneuvers were excluded from the analysis. The crashes used in the clinical analysis were weighted for severity so that they might more closely approximate the national profile.

The authors of this report are John D. Chovan, Louis Tijerina, and Graham Alexander of Battelle; and Donald L. Hendricks of Calspan.

Wassim Najm of VNTSC served as the technical monitor for this report. Joseph S. Koziol, Jr. and Mark Mironer of VNTSC; William A. Leasure, Jr., Ronald R. Knipling, Robert M. Clarke, and August L. Burgett of NHTSA OCAR; and John Pierowicz of Calspan provided technical guidance and reviewed the report.

The contributions of Battelle staff are also acknowledged: John C. Allen, Jeff Everson, and Nathan Browning for their technical assistance and review; Laura K. Brendon for serving as technical writer and editor; Mary Widner for serving as copy editor, and Viki L. Breckenridge for providing secretarial services. Their support is much appreciated.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd ❑ 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2 = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2 = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (Lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp ❑ 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] ^{o}F ❑ y ^{o}C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

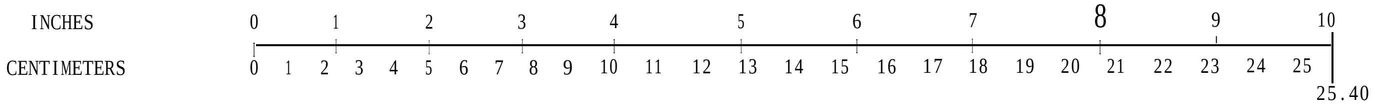
VOLUME (APPROXIMATE)

1 milliliters (ml) ❑ 0.03 fluid ounce (fl oz)
1 liter (1) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] ^{o}C ❑ x ^{o}F

QUICK INCH-CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

^{o}F	-40°	-22^{0}	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

TABLE OF CONTENTS

Section Page

1. BACKGROUND 1

1.1 Introduction 1
1.2 Definition of Lane Change Maneuvers and Crashes 1

2. CRASHPROBLEMSIZE ....\.............. 5

2.1 Problem Overview 5
2.2 Discussion 7

3. ANALYSIS OF LANE CHANGE CRASH CIRCUMSTANCES 9

3.1 Introduction 9
3.2 Clinical Data Sets and Analysis Method 9
3.3 Clinical Analysis Results: Crash Subtypes 12
3.4 Clinical Analysis Results: Causal Factor Overview 13
3.5 Discussion 16

4. IVHS CRASH AVOIDANCE CONCEPTS FOR LANE CHANGE CRASHES . . 17

4.1 Presence Indication and Driver Situation Display 18
4.2 Driver Warning Systems 19
4.3 Control-Intervention System 20
4.4 FACS for Lane Change Crash Avoidance 21

5. MODELING REPRESENTATION 23

5.1 Introduction 23
5.2 ProximityCaseModel 23
5.3 Proximity Case Crash Avoidance Modeling Results 29

-

TABLE OF CONTENTS (continued)

Section Page

6. RESEARCHNEEDS 37

6.1 Problem Size Area 37
6.2 Clinical Analysis Area 37
6.3 Lane Change Driver Behavior Area 38
6.4 Driver Warning Area Needs 39
6.5 Further Modeling Research Needs 39

7. SUMMARY 41

APPENDIXA-WEIGHTINGSCHEMES 42

APPENDIX B - EXAMPLE LANE CHANGE CALCULATIONS 44

APPENDIX C - README.TXT FILE . . . . , ... , ... 47

REFERENCES 49

LIST OF ILLUSTRATIONS

Figure Page

1-l Simple Model of Ideal Lane Change Behavior 2

2-l Problem Size, 1991 GES Data 5

2-2 Fatalities, 1991 FARS Data 6

3-l Distribution of Maneuver Types in a Clinical Data Set 11

3-2 Lane Change Crash Subtypes and Variations 12

3-3 Distribution of Lane Change Crash Subtypes and Variations 14

3-4 Distribution of SV Drivers Who Saw the POV Prior to Impact 15

4-l Time-intensity Graph of Pre-crash Avoidance Requirements 17

5-l Distribution of Lane Positions at Start and End of Lane Change Maneuver 2 5

5-2 Trajectory and Acceleration Profile of SV With and Without Crash Avoidance 26

5-3 Maximum Response Time to Allow a Driver to Avoid a Lane Change Crash Under Stated Conditions 30

LIST OF TABLES

Table Page

3-1 NASS CDS Pre-crash Vehicle Maneuver Cluster Variables Pre-crash Avoidance Maneuvers 13

5-l Summary of Modeling Parameters 29

ABBREVIATIONS AND ACRONYMS

The following is a list of abbreviations and acronyms used in this report and their definition.

ω	lane change frequency, radians/s
a	instantaneous lateral acceleration, ft/s^2
A	peak acceleration, ft/s^2
a_0	initial lateral acceleration, ft/s^2
a_0'	lateral acceleration at beginning of recovery maneuver, ft/s^2
a_{POV}	braking efficiency of the principal other vehicle, ft/s^2
A_r	maximum recovery acceleration, ft/s^2
CDS	Crashworthiness Data System
d	lateral position, ft
$d_{available}$	distance traveled during system and driver lags, ft
d_{brake}	distance traveled during braking, ft
d_0	initial lateral position, ft
d_0'	lateral distance at beginning of recovery maneuver, ft
d_0''	lateral distance when maximum recovery acceleration is achieved, ft
D_{slow}	longitudinal distance required to slow down, ft
D_{SV}	distance SV travels while POV slows, ft
D_{warn}	minimal distance to provide a warning, ft
FACS	fully automatic control systems
FARS	Fatal Accident Reporting System
ft	foot, feet
g	unit force of gravity, 1 g = 32.0 ft/s^2
GES	General Estimates System
ILCD	intended lane change distance, ft
IVHS	Intelligent Vehicle Highway System
k	rate of change in acceleration, ft/s^2/s
LAD	likelihood alarm display
LATGAP	lateral intervehicle gap, ft
NASS	National Accident Sampling System
NHTSA	National Highway Traffic Safety Administration
NPR	non-police reported
p	probability
PAR	police accident report
$P_{crash\ avoidance}$	probability of crash avoidance
$P_{driver\ detects}$	probability that the driver detects the issued warning
$P_{driver\ reacts}$	probability that the driver reacts appropriately to an alert
$P_{driver\ recognizes}$	probability that the driver recognizes the crash hazard
$P_{IVHS\ system\ works}$	probability that the IVHS system works correctly
POV	principal other vehicle
PSU	Primary Sampling Unit

RT	reaction time, s
s	second, seconds
SV	subject vehicle
t	elapsed time, s
$t_{available}$	maximum available time, s
t_{close}	time to close lateral intervehicle lateral gap, s
$t_{driver\ RT}$	reaction time of the driver, s
$t_{IVHS\ delay}$	warning system lag, s
t_{LC}	total time to complete a lane change, s
v	instantaneous lateral velocity, ft/s
v_0	initial lateral velocity, ft/s
v_0'	lateral velocity at beginning of recovery maneuver, ft/s
v_0''	lateral velocity when maximum recovery acceleration is achieved, ft/s
x	x-axis
y	y-axis
z	z-axis
Z	normalized distribution

1. BACKGROUND

1.1 INTRODUCTION

This report provides an analysis of lane change crashes to guide the development of Intelligent Vehicle Highway System (IVHS) crash avoidance systems. It introduces the problem of lane change crashes. Two crash subtypes are identified and causal factors that contribute to lane change crashes are assessed clinically from a sample of lane change crash cases.From these data, functional goals for IVHS lane change crash avoidance systems are described.A simple kinematic model of crash avoidance requirements introduces key pre-crash variables and outlines the space of time and distance available for crash avoidance from a kinematic perspective. The report concludes with a discussion of key research needed to extend the analysis presented here. Included with the report is a diskette of the kinematic models developed for this crash type and files for data tables used in generating data plots contained in the report. The file README.TXT is an ASCII file that describes the program and data files on this diskette. The file is also transcribed in Appendix C.

1.2 DEFINITION OF LANE CHANGE MANEUVERS AND CRASHES

In this report, "lane change" refers to a family of maneuvers that includes simple lane change, merge, exit, pass, and weave maneuvers. For purposes of this study, lane changes are defined as a deliberate and substantial shift in lateral position of a vehicle. A "lane change crash" occurs when a driver attempts to change lanes and strikes or is struck by a vehicle in the adjacent lane. Variations in lane change maneuvers are described below.

Figure l-l shows a simple model of ideal lane change behavior, based in part on the work of McKnight and Adams (1970). Once the driver wishes to change lanes, the driver first checks traffic control devices (signs, signals, pavement markings) to see if a lane change is legal. Driver error might arise here if such signs are unnoticed or unheeded.

If the lane change is legal, the driver engages in information gathering and decision making about driving conditions and determines if conditions are favorable for a lane change. The driver checks mirrors for vehicles passing in the destination lane, following vehicles closing fast in the destination lane, and following vehicles beginning to enter the destination lane. The driver checks the blind spot, perhaps by varying speed to bring into view any vehicles traveling at the same speed in the blind spot. The driver scans ahead for any lead vehicles in the destination lane and assesses the driving situation for rear-end crash potential. On a multilane highway, the driver looks to the far-adjacent lane for any vehicles moving into the destination lane. The driver also assesses the roadway for any limitations to lane changing, e.g., curves, intersections, narrow bridges, and so forth. Information-gathering errors might result because the driver fails to collect critical information (e.g., fails to sample mirrors, check the blind spot). The driver might sample but, because of faulty sampling strategies, fail to perceive or misperceive critical information.

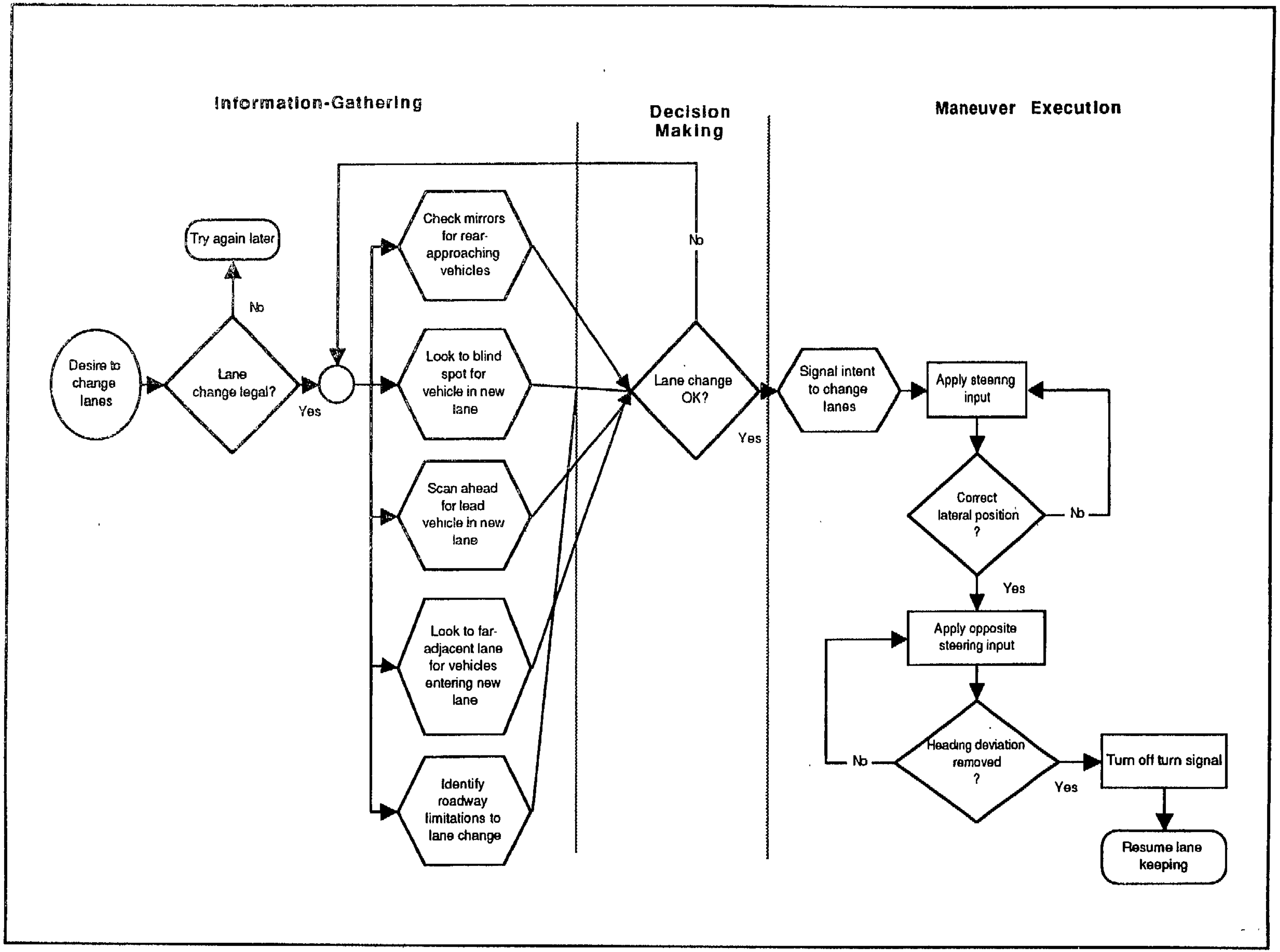


Figure 1-1. Simple Model of Ideal Lane Change Behavior

Decision-making errors might include problems in assessing the information gathered, deciding to halt information gathering prematurely, or ascribing a higher likelihood of successful lane change than is warranted.

If the driver decides the lane change can be successfully completed, the ideal driver signals the intent to change lanes with turn signals. A driver might err by failing to provide such signals to other vehicles in the surrounding roadway, thereby depriving the other drivers of an opportunity to take corrective action if required.

The driver then executes the lane change maneuver. Wierwille (1984) described the execution of the lane change maneuver as follows. The driver applies a steering input, which introduces a heading deviation that results in a buildup of lateral deviation. As the vehicle approaches the correct lateral position in the adjacent or destination lane, the driver removes the heading deviation by apply a steering correction in the direction opposite that of the initial steering input. The vehicle may be traveling at constant longitudinal velocity or may be accelerating longitudinally. Once in the correct lateral position, the driver turns off the turn signal and resumes lanekeeping behavior.

The merge and exit maneuvers are kinematically similar to a lane change. However, the merge often involves subject vehicle (SV) entry into a faster-moving traffic stream. This implies that the SV is probably accelerating longitudinally. An exit may involve transition to a slower-moving traffic stream, which implies the SV is probably decelerating longitudinally.

As Wierwille (1984) explains, passing involves two successive lane changes, once to the adjacent lane to overtake and then once to return to the original lane. Passing is made up of four maneuver segments: heading deviation in the direction of the adjacent lane, removal of the heading deviation in that direction, heading deviation introduced back in the direction of the original lane, and removal of that heading deviation. The subject vehicle may be accelerating longitudinally or may be traveling at constant longitudinal velocity.

The Transportation Research Board (1985) defined weaving as the crossing of two or more traffic streams traveling in the same general direction without the aid of traffic control devices. Yoo (1987) indicates that weaving occurs when a merge area is closely followed by a diverge area or when an on-ramp and an off-ramp are closely spaced and joined by an auxiliary lane. Weaving requires intense lane changing since many vehicles may be changing lanes at once.

Lane change maneuvers can be further classified by their direction (to the left, to the right) and by whether the maneuver is essential (because of a lane-drop, lane-closure, or to maintain a route) or nonessential (e.g., to avoid a slow-moving lead vehicle).

The next section describes the crash problem size with respect to a number of factors.

2. CRASH PROBLEM SIZE

2.1 PROBLEM OVERVIEW

Figure 2-1, based on Wang and Knipling (1993), indicates the magnitude of the lane change crash problem based on police accident reports (PARs) derived from the National Highway Traffic Safety Administration (NHTSA) General Estimates System (GES) 1991 statistics. There were approximately 244,000 lane change/merge crashes[1], which represents about four percent of all crashes that occurred in 1991. Figure 2-2 presents the magnitude of the lane change/merge crash problem in terms of fatalities. Data from the Fatal Accident Reporting System (FARS) indicate that 224 fatalities resulted from lane change/merge crashes in 1991. This represents 0.5 percent of the fatalities in the FARS data base. Additionally, approximately 386,000 non-police reported (NPR) lane change/merge crashes occurred. This crash type is estimated to account for roughly 10 percent, or 41.2 million hours, of crash-caused delay in 1991. Crash-caused delay, measured in vehicle-hours, estimates the delay experienced by noninvolved vehicles caught in the congestion that results from a crash.

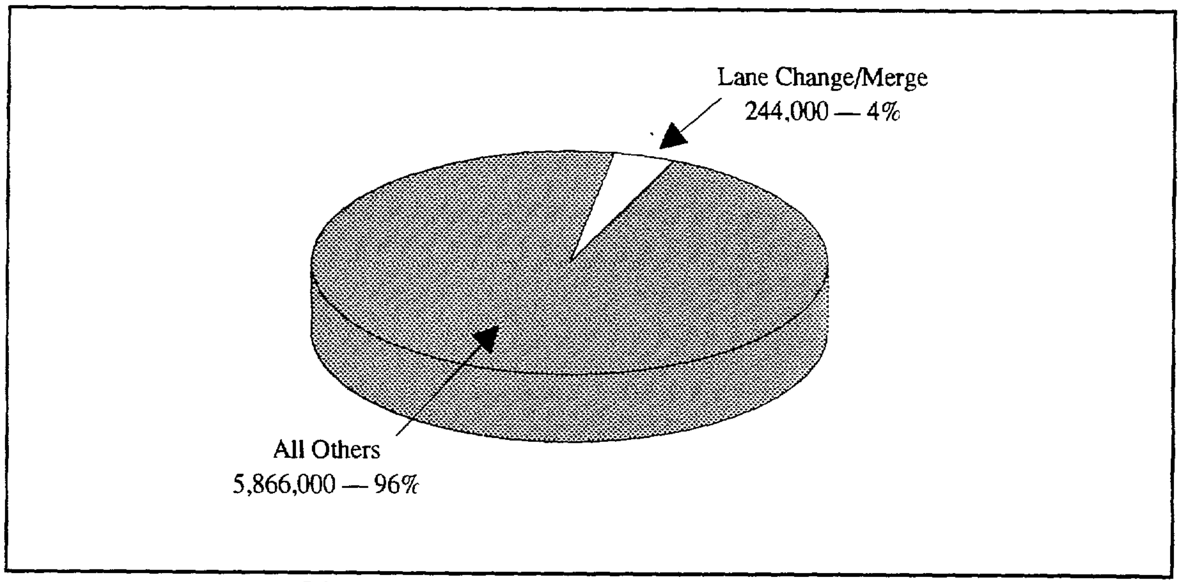


Figure 2-1. Problem Size, 1991 GES Data

Wang and Knipling (1993) provide additional data about lane change/merge crashes that may be of interest to crash avoidance system developers:

---

[1] This report uses the term *lane change/merge* when referring to GES/FARS data because the 1991 databases do not allow disaggregation of lane change from merge.

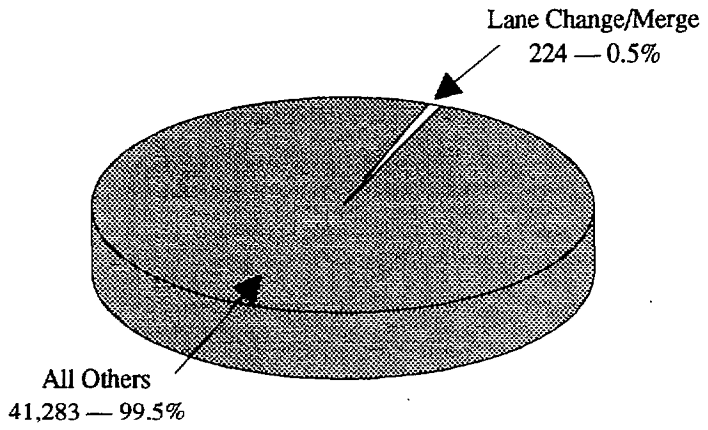


Figure 2-2. Fatalities, 1991 FARS Data

- 77 percent of lane change/merge crashes occurred during daytime hours (0601 to 1830) and an additional 13 percent occurred in the dark but on lighted roadways.
- About 68 percent of the crashes that comprise the "lane change/merge crashes' category were nonjunction crashes, which implies that most were simple lane change maneuvers, as opposed to merge, exit, or weave maneuvers.
- Lane change/merge crashes occurred on roadways with a wide range of speed limits. About three-quarters of passenger vehicle crashes occurred on roads with speed limits of less than 55 mph.
- Unknown rates for vehicle pre-crash travel speeds were high. However, available data indicate that most lane change/merge crashes involved two vehicles traveling at approximately the same speed — that is, within 5 mph of each other.
- Fewer than 15 percent of the lane change/merge crashes occurred under adverse weather conditions.
- Alcohol involvement was noted in approximately 3.5 percent of the lane change/merge crashes.
- Over 77 percent of the lane change/merge crash SV drivers were between 15 and 44 years of age.

- 1991 GES crash statistics indicate that passenger cars are about equally likely to be involved in left-to-right and right-to-left lane change/merge maneuver crashes.

This report does not specifically address or model combination-unit truck (tractor trailer) lane change/merge crashes, although two differences between their crashes and those of passenger vehicles are notable. First, more than two-thirds of combination-unit truck lane change/merge crashes occur on 55 mph or 65 mph roadways. Secondly, among combination-unit trucks, left-to-right lane change/merge crashes appear to be about three times more frequent than right-to-left crashes.

2.2 DISCUSSION

The lane change/merge crash problem is a relatively small percentage of the crash population and the associated proportion of fatal crashes is quite small. On the other hand, a quarter of a million crashes in one year is significant, as is the fact that this one crash type accounts for almost 10 percent of all crash-caused delay, with the attendant economic consequences. Furthermore, available technologies might soon provide affordable lane change/merge crash avoidance countermeasures, with the potential to add incrementally to highway safety, and provide technology transfer to other crash types.

From a crash modeling standpoint, the GE-S data reported by Wang and Knipling (1993) provide the following guidance. Lighting should not be a serious consideration because most crashes occur in the daylight hours or in the dark on lighted roads. More than two-thirds of such crashes do not occur at junctions and so simple lane change/merge models should be a first priority. Speed variation, when modeled, should span a wide range of speeds, ranging from arterial roadway to highway speeds. The high incidence of dry pavement accidents suggests that braking or steering maneuvers should be modeled assuming good traction. Finally, the age distribution of subject vehicle drivers suggests that the majority are younger (i.e., less than 45 years old), so concerns about the performance capabilities of the older driver warrant less emphasis in modeling.

Given these factors, the lane change/merge crash problem warrants further investigation, The next section discusses the circumstances surrounding lane change crashes.

3. ANALYSIS OF LANE CHANGE CRASH CIRCUMSTANCES

3.1 INTRODUCTION

This section describes the major lane change crash subtypes (as distinct from maneuver subtypes described in Section 1.2) and identifies causal factors that contribute to the lane change crash problem.

3.2 CLINICAL DATA SETS AND ANALYSIS METHOD

The data sets that were selected from the Crashworthiness Data System (CDS) and from the GES within the National Accident Sampling System (NASS) were subjected to a clinical analysis. The 1992 CDS data set consisted of 33 hard copy reports that represented all crashes coded as lane change crashes by the Primary Sampling Unit (PSU) teams reporting to Calspan (NASS Zone Center #l). The GES data set consisted of 161 hard copy PARs selected from the 1991 data file. The GES data set was a subsample of lane change/merge crashes selected to ensure representativeness of regional variations including time of day and time of year when crashes occurred. The GES data set was examined and tabulated at the NASS storage facility in Washington, DC, by NHTSA Office of Crash Avoidance personnel under the direction of the contractor team analyst.

The unsanitized NASS CDS cases provide a rich body of data from which to do analysis of causal factors, including:

- PARS
- Driver statements
- Witness statements
- Scaled schematic diagrams depicting crash events and physical evidence generated during the crash sequence
- Case slides documenting vehicles, damage sustained, and other physical evidence

Once sanitized, CDS cases are stripped of driver and witness statements, PARs are censored, case identifiers are removed, etc. This often renders the case file difficult, if not impossible, to use for clinical analysis. Crash reconstruction from the CDS files is not perfect because the files are intended to support crashworthiness research and, therefore, may be missing information needed for a causal factor assessment or pre-crash event reconstruction. The number of CDS files is limited, and, by design, the data set oversamples more severe crashes. Thus, GES data are used for weighting by severity and characterizing the problem statistically (see Appendix A for a discussion of the weighting scheme).

GES PAR crash descriptions, while useful for national accident profiles, typically are highly coded and may lack information, such as driver statements, that would describe pre-crash behaviors and crash events. Therefore, both data sets were used to describe crash subtypes.

The clinical analysis approach implies subjective assessment by an expert analyst. It involves content analysis of narrative statements (keywords, phrases) along with kinematic assessment to cross-check narratives. The analyst develops an impression of the crash subtypes and/or causal factors from this review. Error sources in the clinical analysis process could include limited sample size, incompleteness in the case files, and analyst decision processes that are subject to a number of cognitive heuristics and biases in judgement (Wickens, 1992). For example, confirmation bias leads an individual to seek information that confirms an initial hypothesis and to avoid or discount information that could disconfirm it. The procedures used to select and analyze cases in this study have been designed to minimize or eliminate those error sources. Despite these potential error sources, clinical analysis of detailed case files represents an invaluable aid to understanding the nature of crashes and cannot be readily automated. It also opens up data sources – i.e. additional uncoded information on the PARs – that are otherwise unavailable.

As defined earlier, lane change crashes involve two vehicles. Thus, single vehicle crashes that were coded as lane change maneuvers were dropped from further analysis. Such cases might involve a lane change maneuver that went awry and resulted in a road departure. This reduced the CDS data set from 33 cases to 16 cases and the GES data set from 161 cases to 144 cases.

Lane change maneuvers involve deliberate and controlled maneuvers initiated by the subject vehicle driver, so the remaining cases were analyzed in terms of the categories: controlled, out-of-control, and other (see Figure 3-l). The proportion of controlled maneuvers ranged from approximately 85 percent of the GES sample to nearly 94 percent of the CDS sample. The drift classification signified very gradual encroachment and was considered indicative of driver inattention. While this inattention contradicts the definition of a lane change crash, kinematically the drift cases resemble lane change crashes in general. The out-of-control classification signified that the subject vehicle was in a nontracking attitude (typically skidding) as it approached the point of impact. Such cases might involve a lane change on a slick roadway, Of the 11 (2 CDS cases, 9 GES cases) cases in this category, 6 involved loss of control as a result of an evasive maneuver (typically to avoid a noncontact vehicle), 4 involved a loss of control as a result of vehicle speed and ambient surface conditions (wet), and 1 case involved a loss of control as a result of a vehicle component failure (tire blowout).

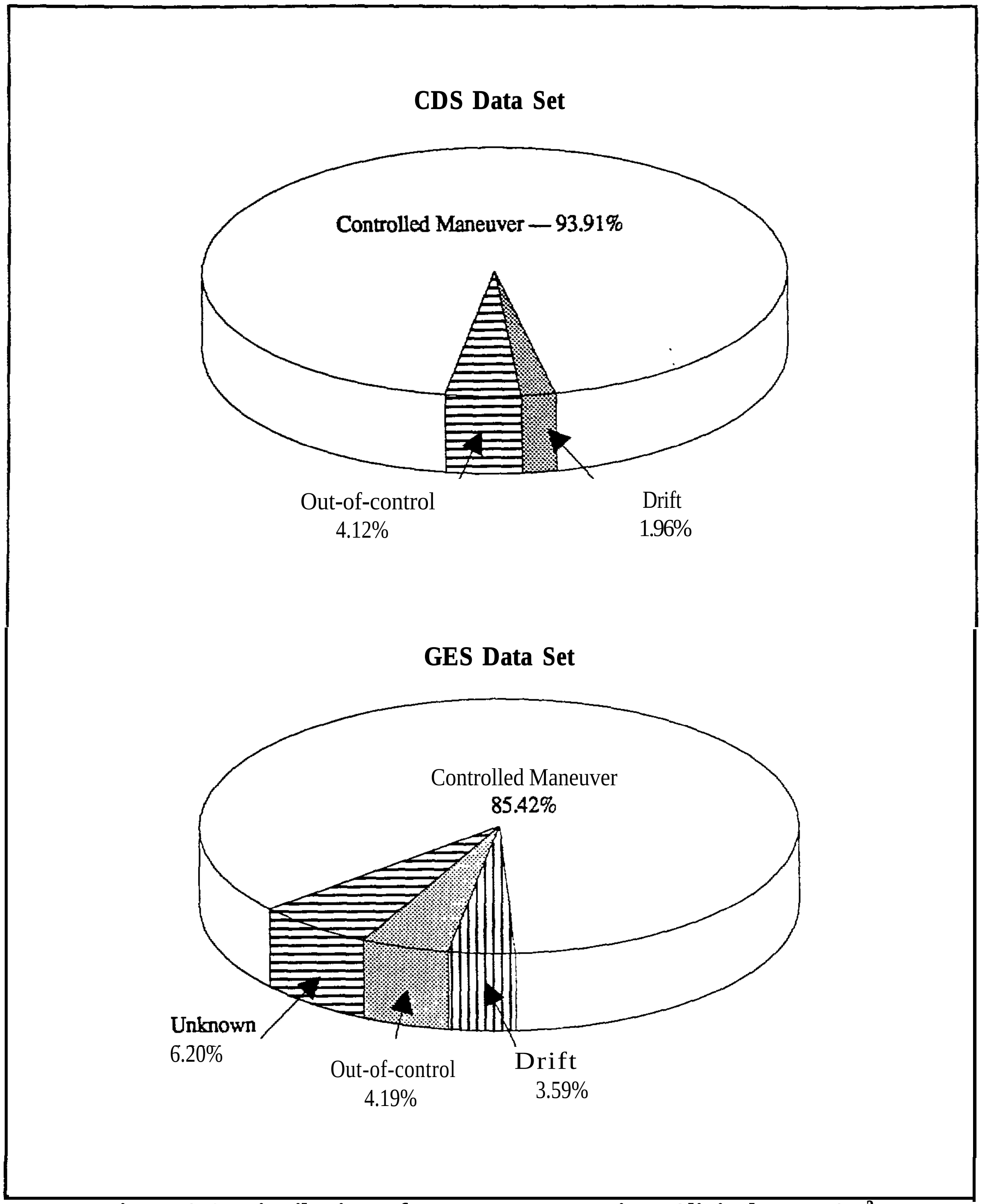


Figure 3-1. Distribution of Maneuver Types in a Clinical Data Set[2]

---

[2] These are weighted percentages. See Appendix A for an explanation.

3.3 CLINICAL ANALYSIS RESULTS: CRASH SUBTYPES

The CDS data set of 16 cases and 66 of the 144 cases in the GES data set were suitable to identify two subtypes of the lane change crash — proximity and fast approach — with variations. See Figure 3-2 for an illustration of these subtypes and their variations. These differ by the relative longitudinal location and velocity differences between the SV and the principal other vehicle (POV) prior to start of the lane change maneuver. In the proximity case, there is little or no longitudinal gap (the SV and the POV laterally overlap) and the velocity differential between the SV and the POV is small.

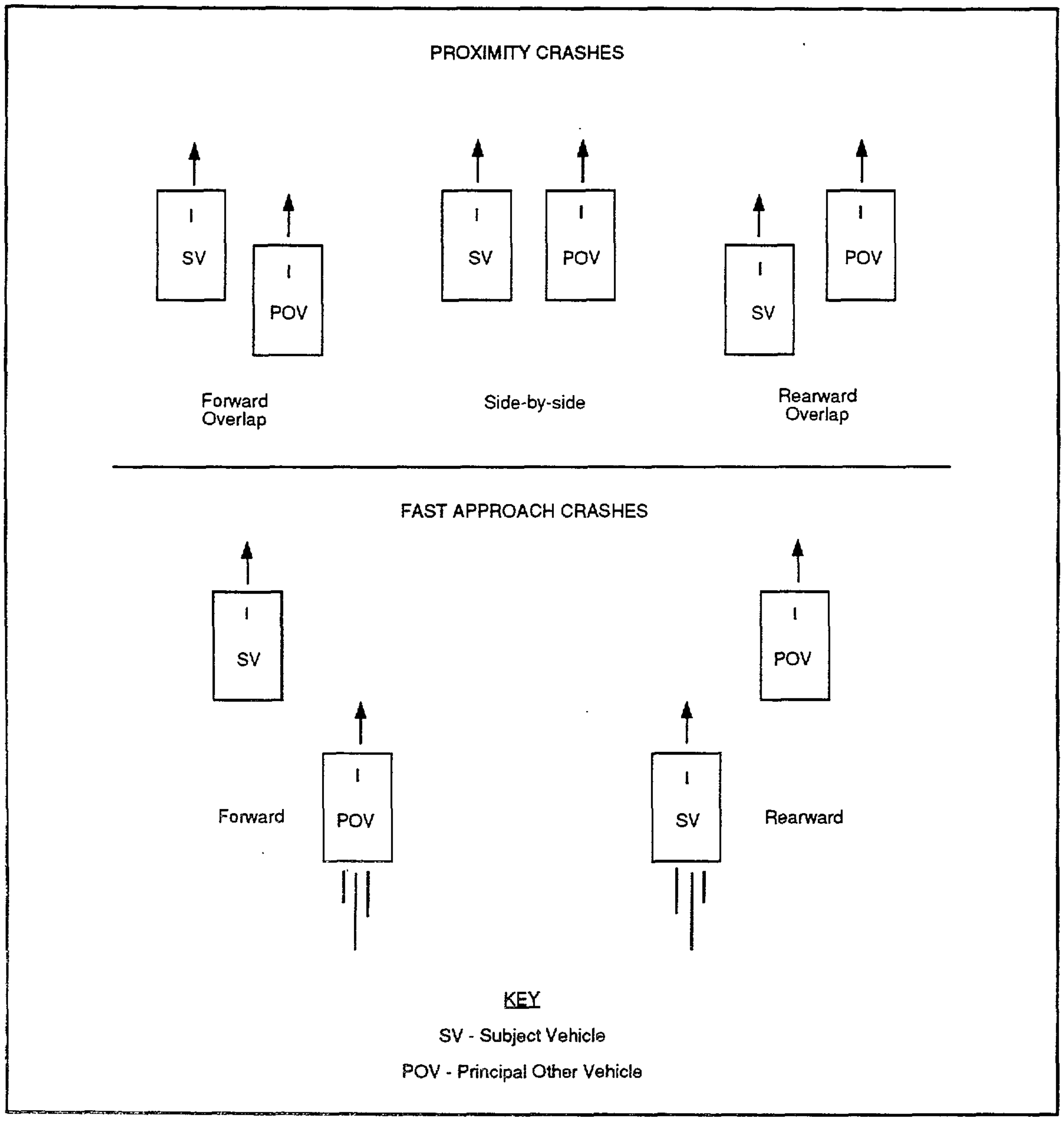


Figure 3-2. Lane Change Crash Subtypes and Variations

Proximity subtype lane change crashes may involve a POV location to the rear, middle, or front lateral area beside the SV.

In the fast approach case, there is a longitudinal gap between the SV and POV prior to the start of the lane change maneuver, and this gap is being closed at a substantial velocity differential between the two vehicles. If the POV is fast approaching as the SV changes lanes, it will strike the SV on the SV rear or side. Similarly, if the SV is fast approaching as the POV changes lanes, it will strike the rear or side of the POV. The distribution of the two crash subtypes and variations is presented in Figure 3-3.

3.4 CLINICAL ANALYSIS RESULTS: CAUSAL FACTOR OVERVIEW

A complete causal analysis could not be conducted on the available clinical sample. The CDS sample was small and driver statements were generally vague (e.g., “did not see other vehicle”). The GES sample was limited by the nature of PARs; the police assessments tended to lack precision with regard to defining causal factors (e.g., “improper lane change,” “improper lookout”). However, despite these limitations, a general picture of causal factors emerged.

The CDS data set included an indication of whether or not (if known) the SV or POV (or both) attempted an avoidance maneuver (see Table 3-l). Of those cases where this information is available, five of eight SV drivers and eight of thirteen POV drivers did not attempt an avoidance maneuver. This finding suggests that the drivers often did not see or were unaware of the presence of the other vehicle. Obviously, the small sample size merits caution in extrapolating such results to the crash population at large.

Table 3-l
NASS CDS Pre-crash Vehicle Maneuver Cluster Variables
Pre-crash Avoidance Maneuvers

Avoidance Maneuver Classification	Subject Vehicle	Weighted %	POV	Weighted %
No Avoidance Maneuver	5	31.5	8	58.2
Avoidance Maneuver	3	6.1	5	37.3
Unknown if Initiated	8	56.4	3	4.4
Totals:	16	100.0	16	99.9

The CDS cases and GES reports were reviewed to determine the point at which the driver of the subject vehicle saw or became aware of the POV; unfortunately, this could be ascertained for only 31 of the GES reports. Figure 3-4 shows that, of these data sets, the driver of the SV never saw the POV prior to impact in approximately 94 percent of the CDS

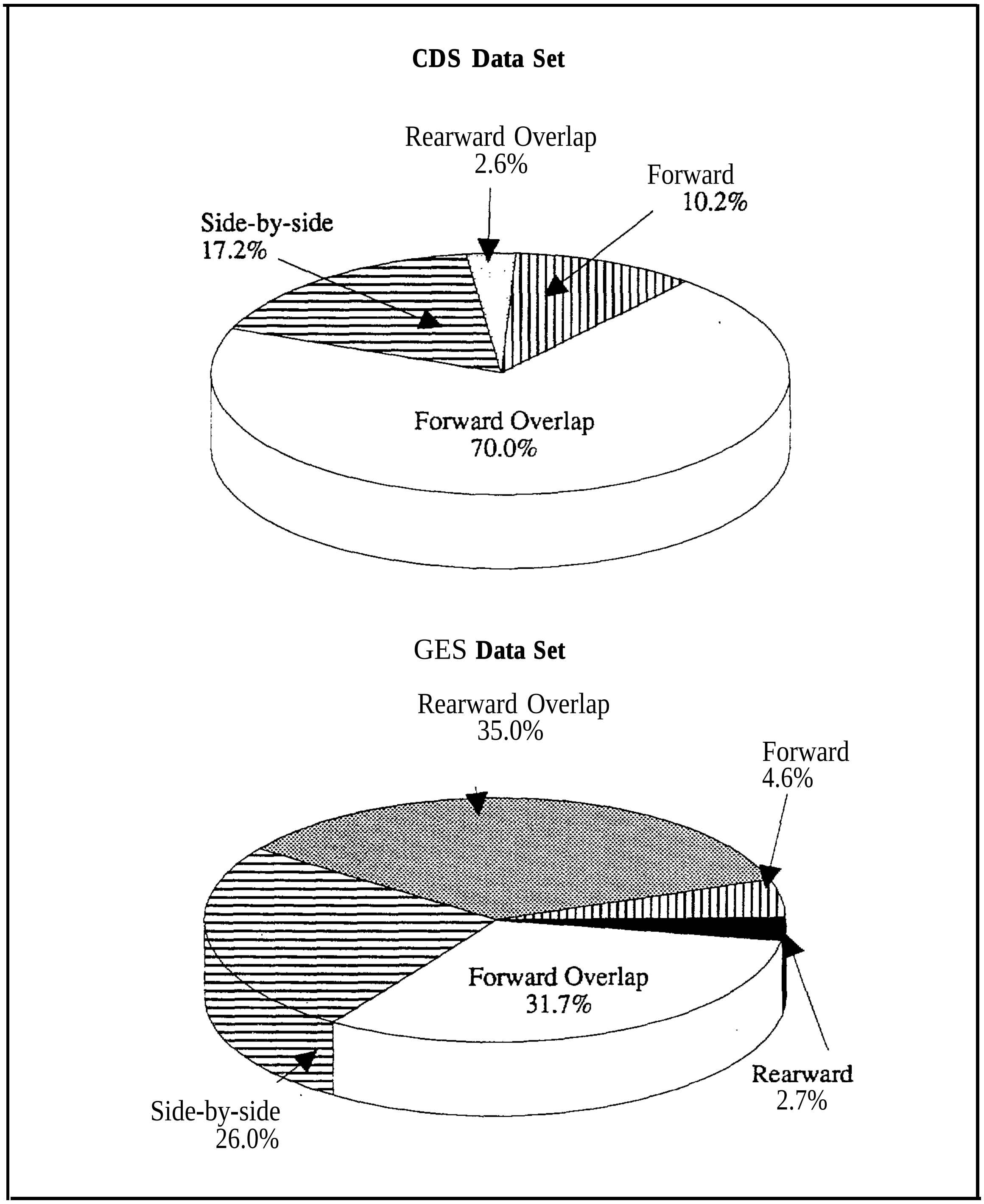


Figure 3-3. Distribution of Lane Change Crash Subtypes and Variations

sample and 64 percent of the GES sample. In those cases where the driver saw the POV prior to starting the lane change maneuver, there was usually an intervening circumstance that the driver did not anticipate. For example, in one case the subject driver was approaching a toll plaza and was attempting to merge into an adjacent lane. The POV in the adjacent lane stopped behind the SV and the SV driver interpreted this action as an indication that the POV driver was allowing him to merge into line. As the SV driver began merging, the POV accelerated forward and struck the rear of the SV.

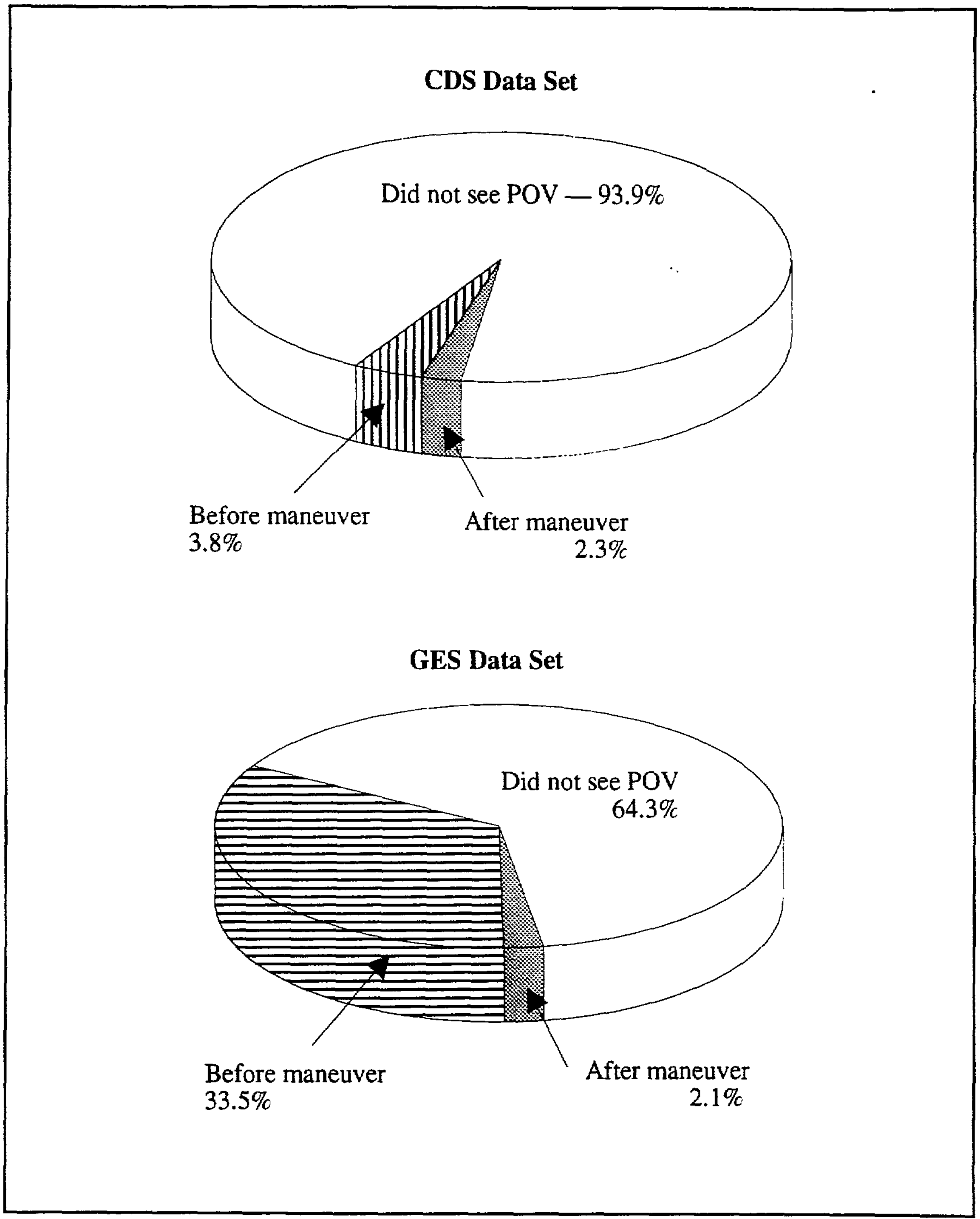


Figure 3-4. Distribution of SV Drivers Who Saw the POV Prior to Impact

3.5 DISCUSSION

The lane change crash subtypes provide useful guidance for IVHS crash avoidance system functional concepts. The proximity subtype was by far the most frequently occurring lane change crash subtype in the clinical analysis. The results underscore the need to detect presence or distance of other vehicles proximal to the SV. The various pre-crash location zones found also indicate that this detection capability must provide coverage over the full length of the SV. Many proximity crashes involve vehicles outside the SV blind zone. Furthermore, 1991 GES crash statistics indicate that passenger cars are about equally likely to be involved in left-to-right and right-to-left lane change maneuver crashes (Wang and Knipling, 1993). Taken together, these data suggest that crash avoidance concepts focused only on blind spot monitoring will not be adequate. Detection coverage over the full length of the SV, on both sides, is needed.

The fast approach lane change crash subtype emphasizes longitudinal detection of vehicles in adjacent lanes. The fast approaching vehicle should be able to detect other vehicles in front and in both adjacent lanes. Detection capability might also extend behind the vehicle being approached, both to the left and right adjacent lanes. Longitudinal gap distance, SV and POV velocities, and closing velocity are all important to IVHS crash avoidance in this subtype, in addition to lateral gap.

Evidence on causal factors is tentative, but suggests that most lane change crashes involve SV driver unawareness of another vehicle in the adjacent or destination lane. The reasons for this unawareness cannot be determined from the data sets reported here. Driver unawareness suggests that potentially useful IVHS crash avoidance system concepts will detect what the unaware driver does not. They should provide this information so that driver or automatic vehicle crash avoidance maneuvers may take place.

Lane change crash cases designated as not applicable involve numerous causal factors such as vehicle failure (e.g., tire blowout), control loss due to poor traction, and evasive maneuvers to avoid a noncontact vehicle. These causal factors are general in nature and probably contribute to multiple crash types. Solutions to these are not likely to be specific to the lane change crash problem and so do not depend on lane change crash etiology. For this reason they will not be included in further discussion of lane change crash avoidance.

4. IVHS CRASH AVOIDANCE CONCEPTS FOR LANE CHANGE CRASHES

Figure 4-1 provides a time-intensity graph of crash avoidance requirements (National Highway Traffic Safety Administration, 1992). As time runs out, normal driving gives way to some opportunity for driver warning and intervention. As available time shortens, cooperative driver-vehicle evasive maneuvers (control-intervention systems) become mandatory. As available time shortens even further, any driver intervention is too slow and fully automatic control systems (FACS) are needed. Sometimes, even the latter may not be effective if the kinematics of the situation are too demanding. As NHTSA (1992) has pointed out:

> As indicated in the figure, the characteristics of a given crash avoidance system will depend largely on the crash scenario itself, i.e., the time available to take evasive action and the intensity of action needed to avoid the crash (p. 22).

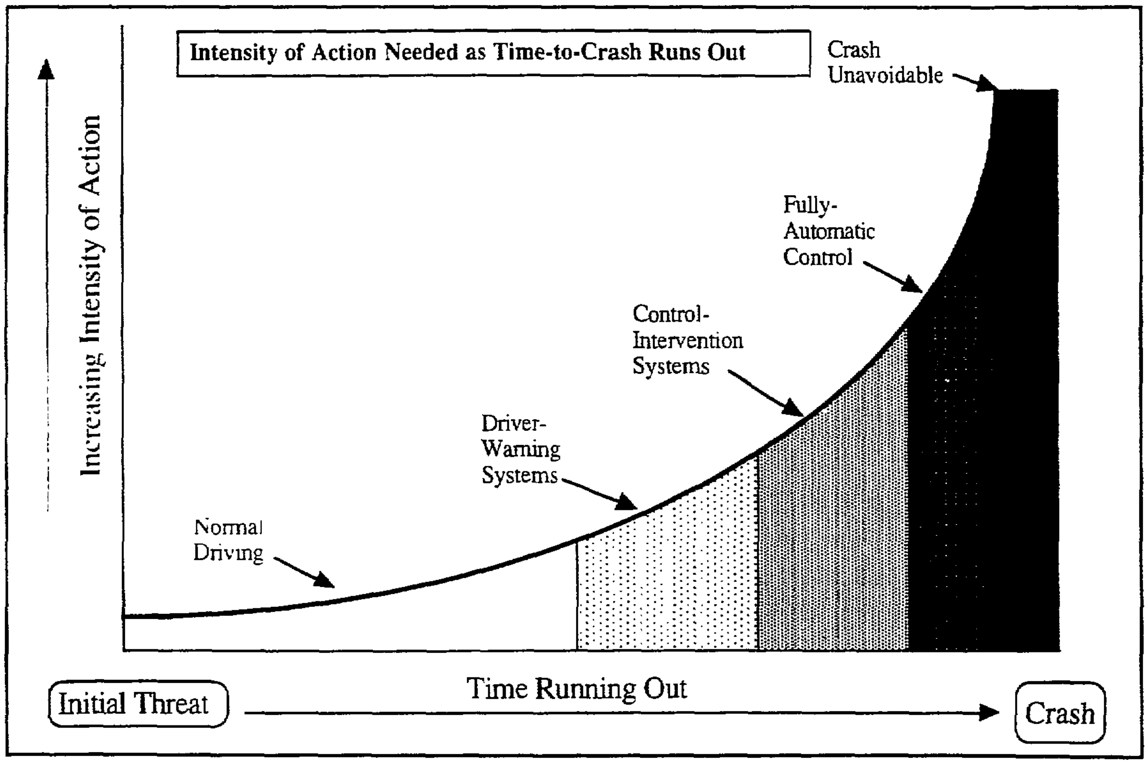


Figure 4-1. Time-intensity Graph of Pre-crash Avoidance Requirements (Source: NHTSA, 1992)

This figure will be used as a convenient framework to cast IVHS lane change crash avoidance system concepts.

4.1 PRESENCE INDICATION AND DRIVER SITUATION DISPLAY

Moving from left to right on the time-intensity graph, it is clear that the best way to avoid crashes is to prevent the start of the hazardous maneuver. One simple means to do this for lane change crashes is the use of a presence indicator. For proximity crash avoidance, this indicator would inform the driver of the presence of vehicles in adjacent lanes. Such a system might continuously sense other vehicles and provide an information display (visual, auditory, other) when a vehicle is present in an adjacent lane. Such information might aid the driver's decision about whether or when to change lanes. An effective presence indicator presents design challenges; it must inform the driver of critical information at critical times, yet avoid being a nuisance or an in-vehicle distraction.

A variant on the presence indicator is a turn-signal-activated system. The notion is that the driver would signal an intent to change lanes (see Figure l-l) sometime before beginning the maneuver. Activation of the turn signals causes the IVHS system to sense for other vehicles in adjacent lanes. This scheme could reduce the risk of nuisance alarms by sensing only when a lane change is imminent. If the driver uses the turn signal (or if other means for assessing driver intent can be developed), and if the signal of intent occurs well before the lane change has begun, it is possible that a hazardous condition can be stopped before it develops. If so, kinematic modeling of such a system to estimate crash avoidance is not necessary. One problem with this concept is that drivers do not always use turn signals. It is possible that the availability of such an IVHS technology would promote greater turn signal use. Since turn signal use conveys SV driver intent to other drivers, an increase in turn signal use would likely produce crash avoidance benefits in itself – independently of the effects of the sensor/warning/control system.

A more sophisticated presence indicator display concept is the driver situation display. A situation display would render the driver's own vehicle as well as surrounding vehicles with[3] a range. This display, if ergonomically designed, would offer the SV driver information on whether or not it is safe to make a lane change and where to watch out for trouble. Judgement on safety of a maneuver would be left to the driver. The display would be supported by a system that detects vehicle locations, vehicle velocities, velocity differences, and perhaps accelerations. The design challenge is to present synthesized or filtered information on a display that can be readily attended by the driver. The driver would use the displayed information to decide when to make the lane change (proximity case), pass (fast approach case), and so on. This situation display would, in principle, provide drivers with situation awareness information to guide judgements about when to and how to engage in lane change maneuvers.

The situation display, as described so far, is a passive information display that assists in the normal driving portion of the time-intensity curve. It might be a visual display, an auditory display, a tactile display, or some hybrid. There are significant human factors issues associated with the design of such a system. These range from collecting and packaging key vehicle information to presenting it in a readily assimilated way. The situation display must not impose undue workload on the driver, else driver inattention to other crash hazards may result. The situation display must be such that it is readily available to the driver and is easily checked prior to initiating the lane change.

The situation display, if effective, will help keep a driver from entering into a pre-crash hazardous condition. The appropriate modeling scheme for crash avoidance effectiveness would involve reliability models. For example, the situation display's effectiveness might be modeled as a series system where the probability of crash avoidance is the product of the probability that the system works properly, the probability that the driver detects the warning, the probability that the driver recognizes the hazard, and the probability that the driver obeys the warning. That is,

$$P_{\text{crash avoidance}} = P_{\text{IVHS system works}} \; P_{\text{Driver Detects}} \; P_{\text{Driver Recognizes}} \; P_{\text{Driver Obeys}} \qquad (1)$$

As an illustration, assume that the IVHS system works 99 percent of the time, the driver detects all of the signals from it, recognizes the hazard 75 percent of the time, but only obeys the warning half of the time. The probability for crash avoidance will nominally be

$$P_{\text{crash avoidance}} = .99 \text{ x } 1.00 \text{ x } .75 \text{ x } .50 = .37125 \qquad (2)$$

or about 37 percent. Unfortunately, no information is available with which to model such a system. However, it clearly indicates the importance of driver polling of the display prior to a lane change (or other) maneuver. Even a perfect detection and presentation TVHS system will be useless if the driver, for example, does not seek out such information ($P_{\text{Driver detects}} = 0$).

The distinction between passive displays and overt/intrusive displays is a fundamental distinction between information displays and warning systems. Recent work on likelihood alarm displays (LADs) (Sorkin and Woods, 1985; Sorkin, Kantowitz, and Kantowitz, 1988) might provide a bridge between passive and overt/intrusive displays. Conceptually, LADs work by displaying graded information; e.g., "crash possible," "crash probable," "crash imminent." The "crash imminent" condition could be augmented by an overt/intrusive warning to the driver. Such a concept may be of value in the driving situation provided graded thresholds can be established that are both reasonable and timely from the driver's standpoint, and provided that the information is presented in a readily consumable way.

4.2 DRIVER WARNING SYSTEMS

Driver warning systems, as indicated in the time-intensity graph, arise later than normal driving, but with enough time that driver intervention alone is feasible for crash avoidance. The causal factor analysis indicated that SV drivers are generally unaware of another vehicle in the adjacent lane. Conceptually, driver warnings are overt/intrusive displays that tell the driver about the presence of another vehicle and possibly what to do about it (steer away, brake, accelerate, as appropriate). Vehicle performance and IVHS system lags consume some of the available time to respond. Variability in driver performance (reaction time to warning and execution of the avoidance maneuver) dictates the proportion of drivers who could respond to a warning in time to avoid the crash. Thus, the effectiveness of a driver warning depends on the time available to the driver versus the time required for the driver-vehicle system to respond.

Conceptually, warnings might produce several reactions in an SV driver, depending on circumstances. (For example, the driver might hold course – i.e., do nothing – while steering or braking or even accelerating, in order to avoid a crash.) The POV driver might be warned to take an evasive action. If both drivers were warned, the warnings would have to be complementary (i.e., not promote a crash). For example, a hazardous SV lane change to the right might involve complementary warnings that prompt the SV driver to veer left and the POV driver to veer right. The warning should also not induce the driver to make a maneuver that prompts another crash with a third vehicle. For example, by warning the POV to suddenly steer away from the oncoming SV, the system might prompt a crash with yet another, third vehicle. There is difficulty in issuing warnings to drivers that tell them how to react. A directive warning’s costs must be compared to the potential benefits of improved driver response speed and reliability of evasive maneuvers that such warnings could provide to the startled driver. As time-to-crash runs out, an IVHS system might first offer nondirective alerts, followed by directive warnings if time is too short. The information and decision processes needed to direct the driver are also required for control-intervention and FACS, which are discussed in the next subsections of this report.

A warning system implies some threshold condition for alarm. This might be lane change start, signaled by some means, and detection of other vehicles that pose hazards. For the proximity subtype of lane change crashes, the warning could be directed to the SV driver with a steering evasive maneuver assumed. The IVHS system would have to detect the SV lane change start and, if there is a POV in the adjacent lane to strike, present an alarm to steer away. Lane change start, POV location, and vehicle travel speeds (for both SV and POV) are all minimal required data needs for such a system.

The fast approach forward case provides an opportunity to warn the POV driver who is fast approaching an SV. The POV driver might be warned to brake (slow down) because the SV is suddenly beginning a lane change. This is precisely what a driver would do if the driver were to naturally notice the lane change start. The IVHS system that deals with the fast approach case will have to detect vehicles in front and to either side of the POV, SV, and POV longitudinal velocities and accelerations; intervehicle longitudinal gap distance; POV braking efficiency and vehicle lags; and the lane change start. Similar concepts could be applied to the fast approaching rearward case as well.

4.3 CONTROL INTERVENTION SYSTEM

Control-intervention systems are appropriate beyond the point where driver warning alone is likely to be effective. Specifically, partial control systems support crash avoidance by allowing semiautomatic vehicle control for crash avoidance. Such systems provide some vehicle deceleration or heading change in the face of a crash hazard, provide additional cues to the driver for crash avoidance, and allow the driver to play a hand in the crash avoidance maneuver. Examples of partial control systems for crash avoidance might be soft braking or variable resistance steering. In the former, driving conditions would prompt moderate deceleration that the driver could increase by simply pressing on the brake pedal. In the event of a false alarm, the driver could also disengage the soft braking by a simple touch of the brake pedal, much like cruise control. Another example of a partial control system would be a steering wheel system that might increase resistance to turning in order to slow or prevent the crash-causing lane change. Such systems are intriguing and, if properly designed, may provide the necessary driver assistance and driver acceptance needed for a system to be viable.

4.4 FACS FOR LANE CHANGE CRASH AVOIDANCE

The last portion of the time-intensity graph indicates the need for fully automatic vehicle control systems for crash avoidance. FACS is the means of last resort if the time available dictates that driver time delays must be near zero. FACS concepts would involve full automatic braking, automatic steering, and perhaps automatic throttle control. The data needs for these concepts are the same as for driver warnings except that a time threshold, based on vehicle subsystem delays alone, must serve as the trigger point for FACS intervention. Such a system would allow the driver to react to a warning but beyond the threshold would attempt to respond by automatic means. To be fully effective, such a system would have to know the performance capabilities of the vehicle-driver-roadway combination.

FACS concepts lead to a host of research questions. Driver acceptance and cooperation with IVHS automation looms large as an area of needed research. The FACS systems must be carefully designed to minimize or eliminate the potential for their causing more harm than they prevent. Such potential might involve anything from precipitating a rear-end collision (by abrupt automatic braking) to roadway departures (by an automatic steering system gone awry). Analysis is needed to look at the impact of FACS on traffic systems. This type of modeling could examine multiple vehicles, multiple lanes, failure modes, and the impact of IVHS technology infusion in the fleet. In addition to primary effects of crash avoidance, secondary effects (crashes caused, traffic flow impacts, etc.) could be assessed.

Based on the previously presented information, the proximity case was modeled to study the time (and distance) available to avoid a crash. This modeling effort is described next.

5. MODELING REPRESENTATION

5.1 INTRODUCTION

As previously explained, there are two lane change crash subtypes — proximity and fast approach. In the proximity cases, there is little or no longitudinal gap between the SV and the POV. In the fast approach subtype, the POV may be located to the rear, middle, or front lateral area beside the SV. Due to the small number of fast approach cases, this subtype was not modeled.

For the purposes of this report, a simplified model of the lane change maneuver is exercised under a variety of conditions of time and distance. Direction of lane change is considered to be symmetric in effects and so is not considered a critical factor. Merging, exiting, and weaving are all treated as similar from a kinematic standpoint. The SV and the POV involved are assumed to initially travel at constant longitudinal velocity. The simplifying assumption of uniform motion (i.e., constant velocity motion profile for the vehicles) is reasonable as a first approximation. Wang and Knipling (1993) reported that nearly two-thirds of the SVs and POVs have coded travel speeds within ± 5 mph of each other, indicating nearly equivalent velocities for the two vehicles. Lateral motion of the SV during the lane change maneuver and during an evasive steering maneuver are modeled differently as described later in this report. These simplifications are necessary to maintain the high-level perspective appropriate to the scope of this report.

5.2 PROXIMITY CASE MODEL

Wierwille (1984) correctly notes that evasive steering maneuvers have three distinct phases: a large steering input to avoid the crash, a reverse steering input to stop the continued buildup of lateral deviation and correct for vehicle heading, and further steering to return to an appropriate lane and begin normal lanekeeping. The scope of the present analysis is in the first phase and that is the focus of the kinematic representation below.

As a first approximation, normal lane change maneuvers can be modeled as a sine function of time for lateral acceleration (cf. Enke, 1979). That is,

$$a = A sin(\omega t) = \frac{2\pi ILCD}{t_{LC}^2} \sin\left(\frac{2\pi}{t_{LC}} t\right), \tag{3}$$

where, a = instantaneous lateral acceleration
A = $2\pi ILCD / t^2_{LC}$, peak acceleration
ω = $2\pi / t_{LC}$, the lane change frequency
t_{LC} = total time to complete the lane change
t = elapsed time
ILCD = intended lane change distance (see below)

Given this sine function of time for lateral acceleration, lateral velocity and lateral distance traveled during a lane change are derived by successive integration, respectively, as

$$v = \int a \, dt = \frac{A}{\omega} \, [1 - \cos(\omega t)] + v_0 = \frac{ILCD}{t_{LC}}\left[1 - \cos\left(\frac{2\pi}{t_{LC}} \, t\right)\right] + v_0 \tag{4}$$

$$d = \int v \, dt = \frac{At}{\omega} - \frac{A}{\omega^2}\sin(\omega t) + v_0 t + d_0 = \frac{ILCD}{t_{LC}} t - \frac{ILCD}{2\pi}\sin\left(\frac{2\pi}{t_{LC}} t\right) + v_0 t + d_0 \tag{5}$$

where, v_0 = initial lateral velocity (assumed equal to 0 ft/s at lane change start)
d_0 = initial lateral distance (assumed equal to 0 ft at lane change start). d_0 is referenced to the position of the subject vehicle's centerline, at the start of the lane change, with respect to ILCD.

The final expressions in Equations 3, 4, and 5 render lateral acceleration, velocity, and distance in terms of ILCD and t_{LC} and these expressions will be used for the remainder of the modeling presentation. For the proximity case, the longitudinal component of the lateral motion was not considered significant to include in the modeling representation.

Worrall and Bullen (1970) provide empirical data from over 1700 lane changes on multilane highways collected by means of 70 mm aerial photography. Figure 5-1 shows the distribution of lateral placement of the subject vehicles before and after changing lanes. As a first approximation, the five before positions may be cross-tabulated with the three after positions to generate a distribution for ILCD. The 12 ft lane width standard on highways, combined with Worrall and Bullen's data, suggests that ILCD can vary from 9 to 15 ft for modeling lane change crash avoidance requirements.

Worrall and Bullen (1970) also provide data that address total lane change time, t_{LC}. They include average lane change times as a function of SV travel velocity and traffic density. However, the aerial photography technique underestimated total lane change times because of resolution limits and because the sine model predicts that the SV will not move very far laterally during the first and last portions of the maneuver. Discussions with researchers at Calspan, NHTSA's Vehicle Research and Test Center in Ohio, Systems Technology, Inc., and Virginia Polytechnic Institute and State University (VPI & SU) did not uncover any additional sources of normal lane change time data. The collective opinion of these researchers was that lane changes of up to 16 s in duration are not outside the normal

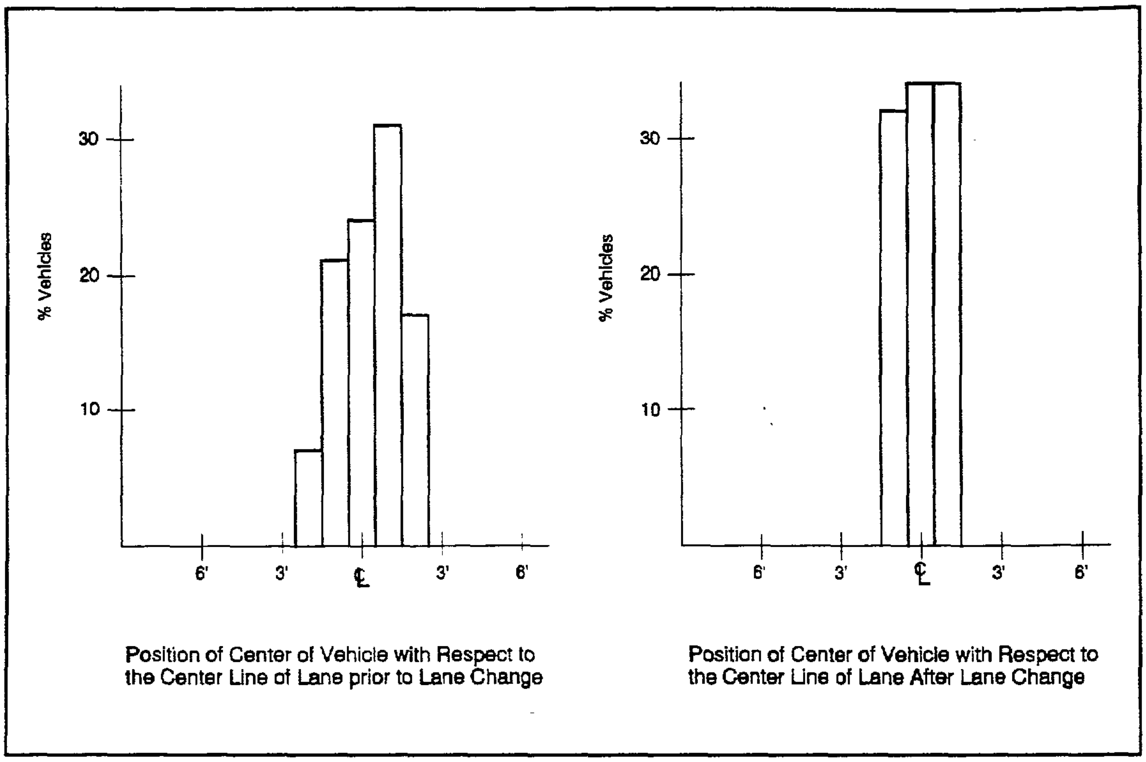


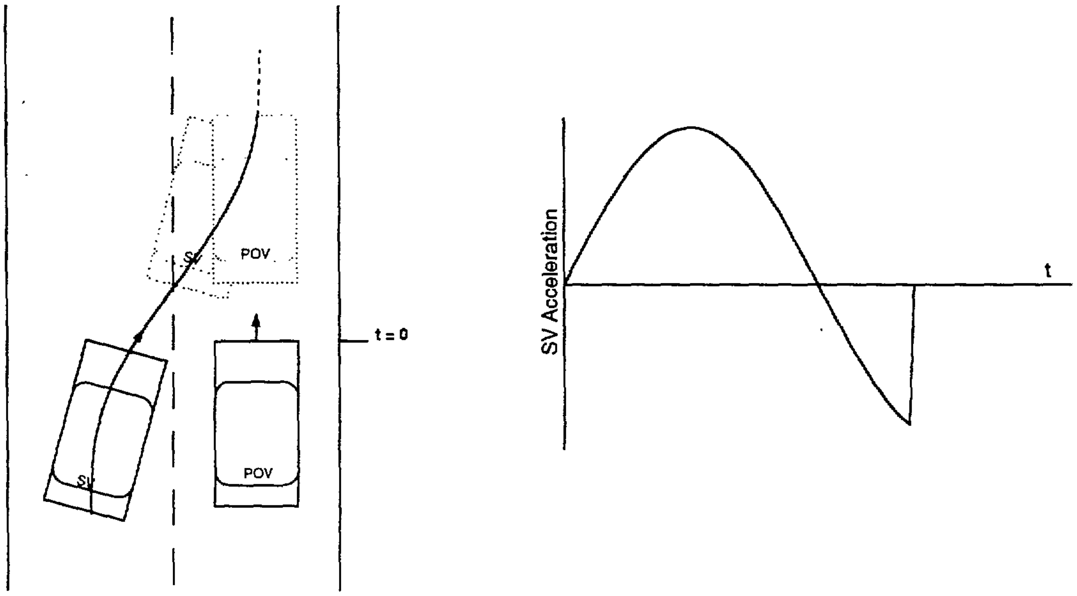
Figure 5-1. Distribution of Lane Positions at Start and End of Lane Change Maneuver. Source: Worrall and Bullen (1970)

range, though most lane changes will be significantly faster. Thus, lane change times from 2 to 16 s are taken as an initial range with which to examine lane change crash avoidance requirements.

The expression for peak acceleration, A, can be determined by substituting ILCD for the final distance, d, and t_{LC} for t in Equation 5. Peak acceleration may be defined in terms of the two variables that define the aggressiveness of the lane change, i.e.,

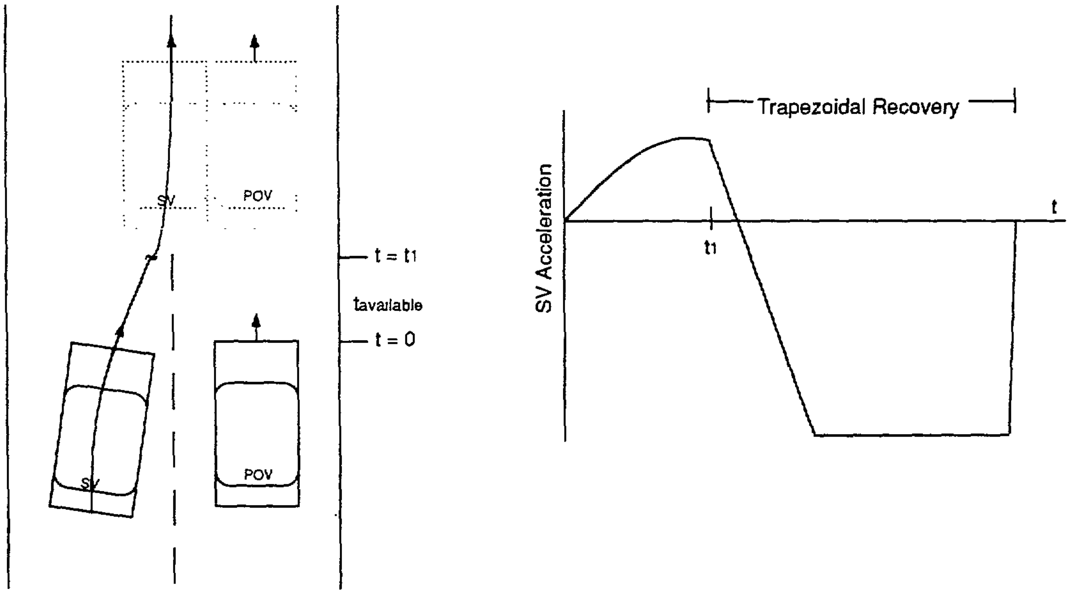
$$A = \frac{2\pi(ILCD)}{t_{LC}^2}. \qquad (6)$$

An IVHS system-initiated crash avoidance steering maneuver in the SV ends the sine model of normal lane change with a step input in steering away from the POV. (See Figure 5-2.) Hereafter, the crash avoidance steering maneuver or "recovery" maneuver may be described by a trapezoidal acceleration model with a maximum recovery acceleration value that the driver does not exceed. This recovery model is used for two reasons. First,



Trajectory *Without*
Collision Avoidance Action

Acceleration Profile
Without Collision Avoidance



Trajectory *With*
Collision Avoidance Action

Acceleration Profile
With Collision Avoidance

Figure 5-2. Trajectory and Acceleration Profile of SV With and Without Crash Avoidance

the trapezoid is an idealized vehicle acceleration for crash avoidance in this case and so is not unrealistic from a driver standpoint. Second, a maximum lateral acceleration that a driver will not exceed is consistent with findings that normal drivers will not use the full steering capability of the vehicle (Malaterre and Lechner, 1990), perhaps because the driver fears losing lateral control (Koppa and Hayes, 1976) or rollover (Wierwille, 1993).

Lateral acceleration for recovery is given as,

$$a = \begin{cases} a_0' - kt, & a < A_r \,. \\ A_r \,, & otherwise. \end{cases} \tag{7}$$

By successive integrations, lateral velocity and distance are given by the following expressions, respectively:

$$v = \int a\, dt = \begin{cases} a_0' t - \dfrac{kt^2}{2} + v_0', & a < A_r \,. \\ A_r t + v_0'' \,, & otherwise. \end{cases} \tag{8}$$

$$d = \int v\, dt = \begin{cases} \dfrac{a_0' t^2}{2} - \dfrac{kt^3}{6} + v_0' t + d_0', & a < A_r \,. \\ \dfrac{A_r t^2}{2} + v_0'' t + d_0'' \,, & otherwise. \end{cases} \tag{9}$$

For all three equations,

a = instantaneous lateral acceleration
k = rate of change in recovery acceleration buildup in $ft/s^2/s$
A, = peak recovery acceleration (away from the POV)
t = elapsed time
a_0' = lateral acceleration at the beginning of the recovery maneuver
v_0' = lateral velocity at the beginning of the recovery maneuver
v_0'' = lateral velocity when maximum recovery acceleration is achieved
d_0' = lateral distance at the beginning of the recovery maneuver
d_0'' = lateral distance when maximum recovery acceleration is achieved

Vehicle delay is represented in the rate of change parameter, k. The value of k must be specified, as must peak recovery acceleration. Mean peak lateral acceleration values during an evasive steering maneuver found in test track studies (Rice and Dell'Amico, 1974) with average drivers ranged from 0.4 g to 0.6 g, approximately. Modem vehicles, however, are capable of generating 0.7 g or higher lateral accelerations. Therefore, a range of A, values (0.4 g, 0.55 g, 0.7 g) will be used to model crash avoidance requirements. These values represent mild, moderate, and aggressive evasive steering maneuvers, respectively.

Different values of k are also used for each A, value. Data from the Rice and Dell'Amico (1974) report indicate that an average mid-1970s passenger car could attain 0.7 g lateral acceleration approximately 1 s after a very rapid, but human-derived, input. For lack of better information, a response of about 80 percent of full vehicle capacity is assumed. This results in a peak lateral acceleration of 0.55 g with a rate of response of 0.65 g/s. To demonstrate the results of a very slow and weak response, an even slower and less forceful response of 75 percent of the previous level of lateral acceleration or a peak of 0.4 g was assumed with an associated rate of 0.4 g/s. Such a response would still be aggressive by normal driving standards, but mild with regard to emergency maneuvers.

The last item needed to estimate crash avoidance requirements for the proximity lane change crash subtype is lateral gap (LATGAP) between the SV and POV at the start of the lane change. Worrall and Bullen's (1970) lane position data at start of lane changing were cross-tabulated with the distribution of ending lane change positions again to generate a distribution of LATGAP values. The ending lane change position, then, is taken as an approximation of normal lanekeeping (suitable for a POV). For modeling, the range of lateral gaps is 3 ft to 9 ft; the vehicle width is assumed to be 6 ft. Table 5-l summarizes the crash model parameters.

Table 5-l
Summary of Modeling Parameters

Parameter	Value
Vehicle Width	6ft
Lane Width	12 ft
Lateral Gap (LATGAP)	3 - 9 ft
Intended Lane Change Distance (ILCD)	9 - 15 ft
Lane Change Time (t,)	2 - 16 s
Peak Acceleration (A)	0.22 - 23.56 ft/s2
Maximum Recovery Acceleration (Ar)	0.4 g 0.55 g 0.7 g
Rate of Recovery Deceleration (k)	0.4 g/s 0.65 g/s 0.7 g/s

5.3 PROXIMITY CASE CRASH AVOIDANCE MODELING RESULTS

The above modeling representation allows for estimation of the time and distance available for crash avoidance via SV steering evasive maneuvers. IVHS crash avoidance system initiation of the steering maneuver must occur within a time budget (and distance/range) for successful crash avoidance. Proximity case lane change crashes by their nature imply a maximum warning range equal to the lateral gap between the SV and the POV. For example, if a vehicle is 10 ft away from the detector, the range of the detector must be at least 10 ft. Thus, the key variable to be evaluated in this subtype is the maximum available time (i.e., maximum allowable time delay) from maneuver start to achieve crash avoidance. This derived variable is maximum available time, $t_{available}$, and represents available time, from lane change start, to accommodate IVHS system delay and driver reaction time.

The value of $t_{available}$ is determined under the two conditions: (1) lateral velocity, v, = 0 and (2) total lateral distance traveled, d, < LATGAP. The crash avoidance requirements are graphically presented as three-dimensional plots (x-axis = t_{LC}, y-axis = ILCD, z-axis = $t_{available}$).

The results are presented in Figure 5-3. For each condition evaluated, a plot indicates the maximum available time ($t_{available}$) in seconds to enable the SV to avoid a crash with the POV by means of an evasive steering maneuver. Each of the three pages of the figure are for different values of maximum recovery acceleration (Ar) = 0.4 g, 0.55 g, and 0.7 g, respectively. On a single page, each plot is for a different inter-vehicle lateral gap

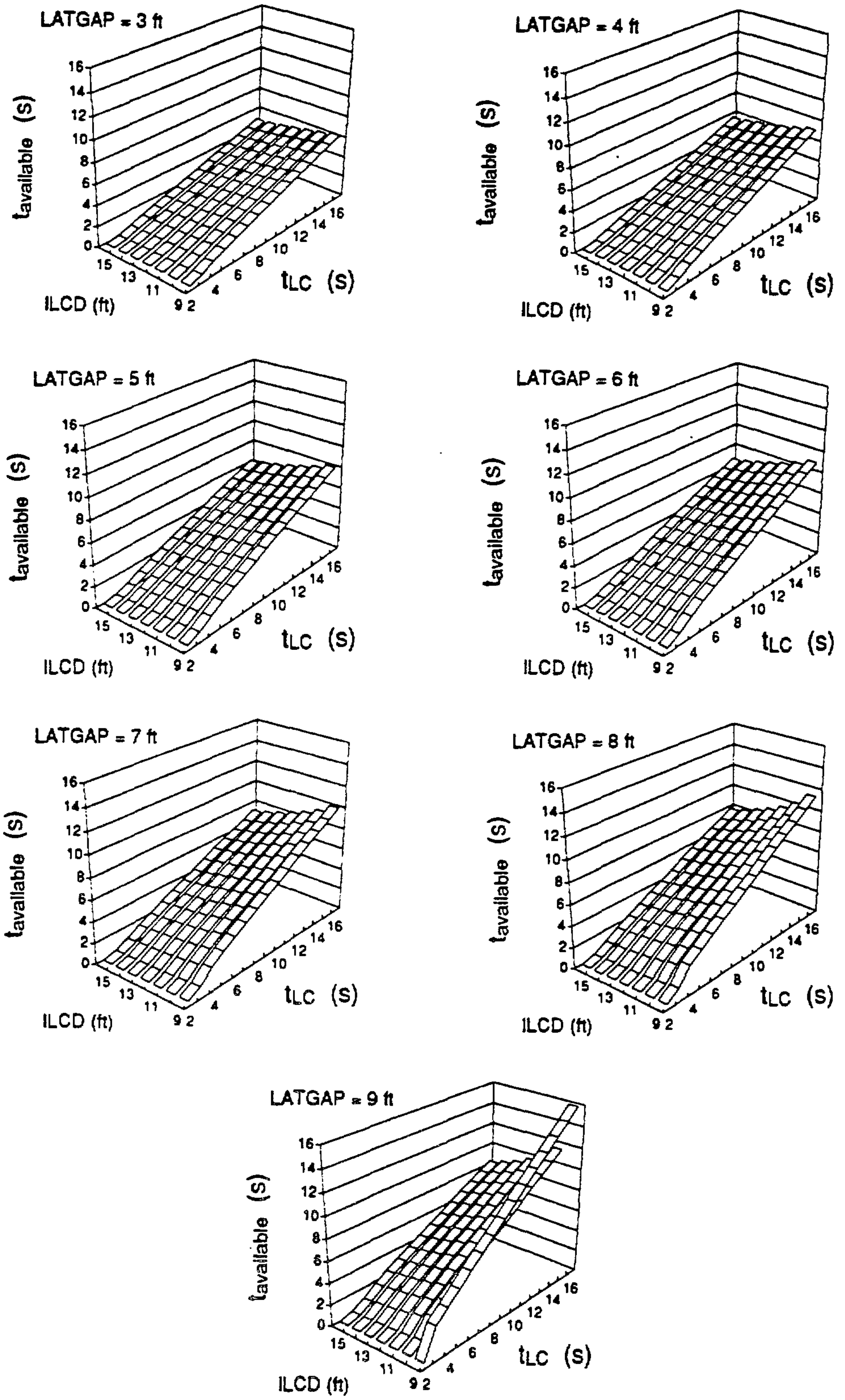


Figure 5-3. Maximum Response Time to Allow a Driver to Avoid a Lane Change Crash Under Stated Conditions. Case I: Maximum Recovery Acceleration (A_r) = 0.4 g.

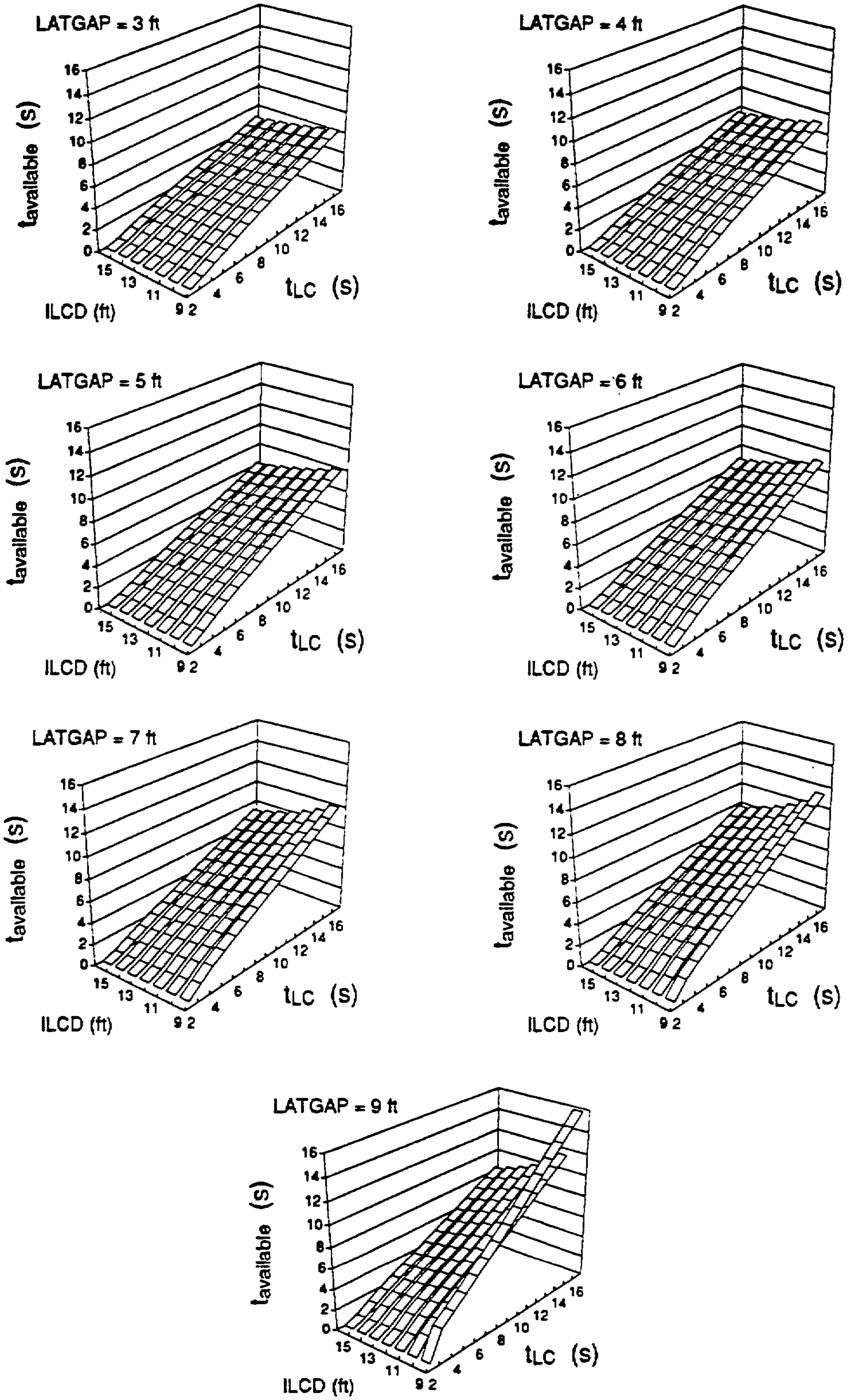


Figure 5-3. Case II: Maximum Recovery Acceleration (A_r) = 0.55 g. (continued)

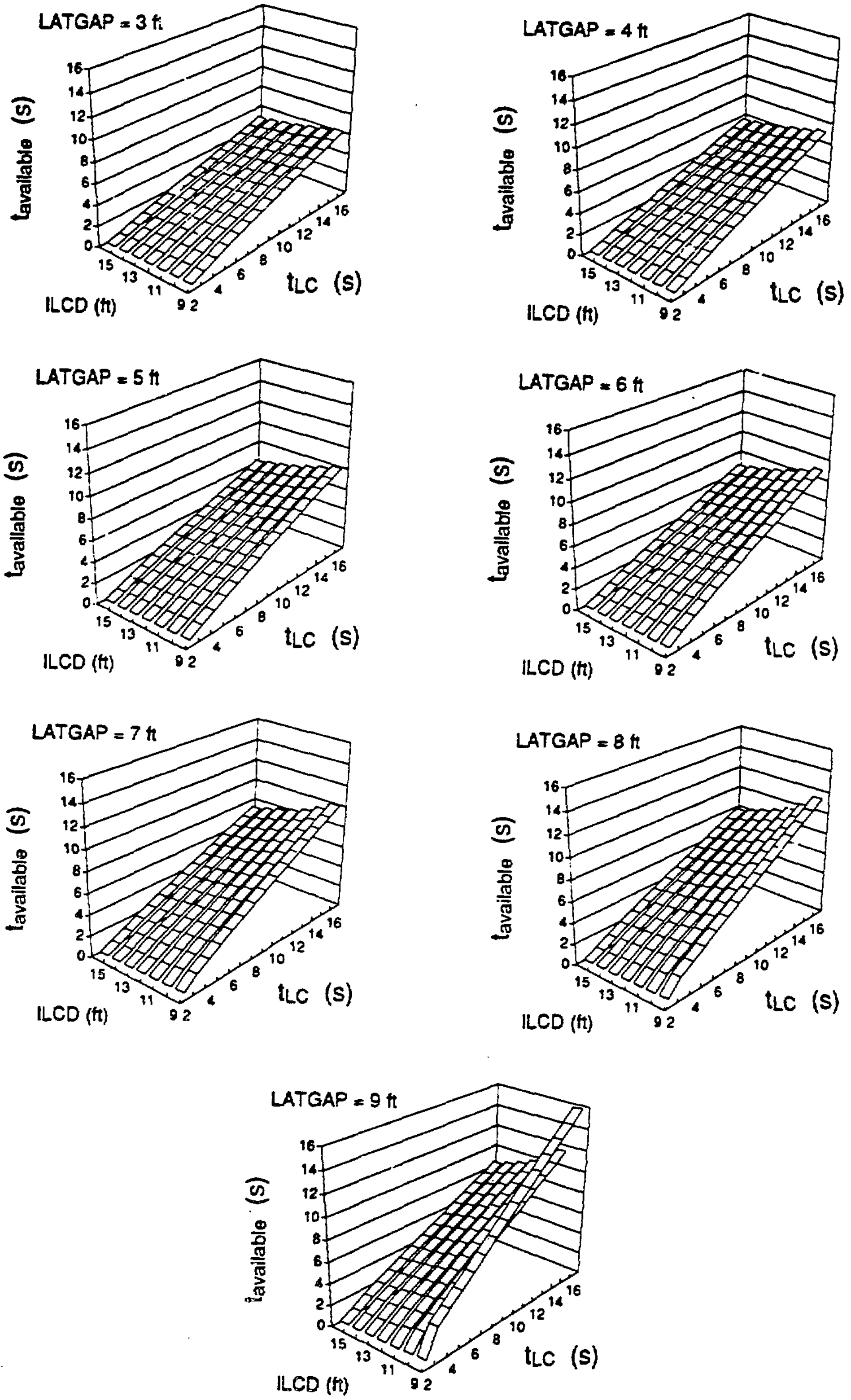


Figure 5-3. Case III: Maximum Recovery Acceleration (A_r) = 0.7 g. (continued)

(LATGAP) = 3 ft, 4 ft, 5 ft, 6 ft, 7 ft, 8 ft, and 9 ft, in order. Each graph shows $t_{available}$ for every combination of intended lane change distance (ILCD) between 9 ft and 15 ft, in 1 ft intervals, and lane change time (t_{LC}), ranging between 2 s and 16 s in 1 s intervals. Values of $t_{available}$ that were less than zero indicated the case when a crash could not be avoided under any circumstances. An example calculation appears in Appendix B.

The following trends were evident in the output data from the model:

(1) For a given intended lane change distance, maximum response time available to avoid a crash increased as lane change time increased. Longer amounts of time used to make the lane change maneuver meant lower lateral velocities, and thus, lower amounts of acceleration to overcome during recovery. Therefore, longer times were available to build up the required levels of deceleration to avoid a crash.

(2) For a given lane change time, maximum response time available to avoid a crash decreased as intended lane change distance increased. When the vehicle traversed longer distances in a fixed amount of time, the lateral velocities and accelerations increased more quickly. Shorter times were available, therefore, to develop the level of lateral recovery acceleration that would be necessary to avoid a collision with the POV.

(3) As intervehicle lateral gap increased, so did maximum response time available to avoid a crash. Although not every crash could be avoided at most intervehicle lateral gaps for all recovery accelerations, more distance was available to be traversed at the larger lateral gaps, and thus more time was available to initiate a recovery response. At larger gaps, the relationship between ILCD and $t_{available}$ became more quadratic, indicating the influence of the higher order terms of the equations – the contributions of velocity and acceleration – to the maximum response time. For these larger gaps, as ILCD increased, $t_{available}$ decreased as the square of ILCD.

(4) Even though the relationship is not obvious in the figure, the computed values show that, as maximum recovery acceleration increased, maximum response time available to avoid a crash increased. This relationship, however, is not strong, with differences in $t_{available}$ on the order of tenths of a second. With lower recovery accelerations, the peak lateral accelerations were reached sooner than with higher recovery accelerations, but their contribution to slowing down the lateral velocity to zero were less. The maximum response time available to avoid colliding with the POV, therefore, was less in vehicles with lower recovery accelerations than those with higher values.

Recall that the available time, $t_{available}$, must accommodate IVHS system delays plus driver steering reaction times, i.e.,

$$t_{available} = t_{IVHS\ delay} + t_{driver\ RT} \tag{10}$$

Thus, the trade-off of available time between system delays and driver delays is linear.

Malaterre and Lechner (1990) provide data on surprisal steering reaction times. The Daimler-Benz simulator in West Berlin was used to present, as an experimental scenario, a journey through open country over various sections of straight and winding roads at travel speeds of between 90 - 100 km/hr. After about 10 minutes of simulator driving, the SV approached a four-legged intersection in open country that was protected by stop signs. Surprisal steering reaction times for 14 subjects were defined as first reaction times to swerve away from another car at the intersection crossroad that suddenly jutted into the SV travel lane. The mean steering reaction time was 0.82 s with a standard deviation of 0.24 s. To develop a distribution of surprise steering reaction times, a log normal model was applied. This decision was based on the success of Taoka (1989) in modeling brake reaction times with the log normal distribution. The log normal mean and dispersion of the log normal distribution of surprise steering reaction times are, respectively, -0.24 log s and 0.287 log s.

To estimate the proportion of people who might be able to respond within a given time budget, a log normal function of driver steering reaction time may be used:

$$Z(t_{driver\ RT}) = \frac{\ln(t_{driver\ RT}) - (-.240)}{.287} \tag{11}$$

Looking up the corresponding value of Z in any table of standard normal deviates determines the proportion of drivers with surprisal steering reaction times less than or equal to $t_{driver\ RT}$. For example, if, for the lane changes of interest, the maximum available time is 1.5 s and the IVHS system time delay is 0.4 s, the maximum allowable driver reaction time, $t_{driver\ RT}$, is

$$t_{driver\ RT} = t_{available} - t_{IVHS\ delay} = 1.5\ s - .4\ s = 1.1\ s \tag{12}$$

And the Z-value of 1.1 s is

$$Z(t_{driver\ RT}) = \frac{\ln(t_{driver\ RT}) - (-.240)}{.287} = \frac{\ln(1.1) + .240}{.287} = 1.17 \tag{13}$$

A Z-value of 1.17, according to a standard normal deviate table, corresponds to a cumulative proportion of .879. So, almost 88 percent of drivers should be able to respond as fast or faster than the maximum available time, provided the steering reaction time distribution is appropriate to surprised/alarmed drivers. More data are needed on surprisal steering reaction times and their distributional properties.

If the $t_{IVHS\ Sytem}$ delay were to be reduced by half, this would increase the time available for driver time delays to 1.3 s. This corresponds to a Z-value of 1.75 that in turn corresponds to a cumulative proportion of .960 or about 96 percent of the driver population. This decrease in IVHS system warning time allowed an additional 8 percent of (slower) drivers to respond to the warning in time to avoid the collision.

As Figure 5-3 illustrates, less time is available as lateral gaps and lane change times shorten. Furthermore, for fixed t_{LC}, shorter ILCDs imply less available time. As the above examples illustrate, if the available time budget for the driver to react is less than about 1.3 s, then less than 96 percent of the driver population is estimated to be able to respond in time. It would be very helpful to know the frequency of occurrence of lane changes that do not allow that much available time. While frequency of occurrence data might be established for ILCD from the histograms provided by Worrall and Bullen (1970), no frequency of occurrence data have yet been uncovered for the distribution of lane change times. Data on these variables (preferably in combination) are sorely needed to bound the requirements for lane change crash avoidance. If most lane changes occur in the 2 s to 4 s range, driver intervention may often not be feasible, In that case, control-intervention systems or FACS for evasive maneuvers may be required. For very fast lane changes, even FACS may be time-limited. This would suggest the need to provide warning to the SV driver-vehicle system prior to lane change start. Warning triggers might then depend on overt signs of SV driver intent – such as turn signal use – or more covert signs – such as to-be-developed predictors of lane change based on driver or vehicle behaviors.

The modeling results of maximum available times are referenced to “lane change start." In reality, detecting the start of a lane change is challenging. This is because of normal variation in lane position that drivers exhibit while lanekeeping. Furthermore, the early portion of lane change maneuver builds lateral acceleration rapidly while changing lateral position relatively little. This makes it hard to discern the start of the maneuver. Thus, an IVHS system must discriminate – with high sensitivity – between lane change start and variations in lanekeeping. In whatever way this design challenge is met, the resulting system is likely to require time to collect and process the needed data for the algorithm. This suggests that the IVHS system delay may be substantial.

What are some implications of this IVHS system delay? Consider first the impact on driver warning and intervention. If one wishes to support 95 percent of the drivers on the road, then approximately 1.3 s should be allowed for driver delay. Assume that the IVHS system delay is 0.5 s. Therefore, any lane change crash hazard that allows less than 1.8 s of delay will be less than 95 percent effective. To illustrate with a crash scenario, a 0.55 g recovery acceleration and initial lateral gap of 6 ft implies that a lane change of 12 ft laterally in 4 s could not result in crash avoidance by warning alone for 95 percent of the drivers in the population. Shorter IVHS delays would improve the situation. Better detection of the lane change start, as well as faster interpretation of the characteristics of the lane change maneuver might shorten the delays.

To evaluate the implications of FACS for crash avoidance, assume that the driver is not a part of the system at all. There will still likely be an appreciable delay for determining lane change start. For example, FACS could theoretically provide crash avoidance against lane changes as aggressive as 12 ft lateral motion in 3.0 s if the IVHS system delay is 0.5 s, the maximum recovery acceleration is 0.55 g, and the initial lateral gap is still 6 ft. On the other hand, a 3 ft lateral gap will barely allow sufficient time for even FACS to detect a lane change start and to provide crash avoidance.

A better alternative for designing lane change crash avoidance systems would be one that was keyed off of a signal of the driver's intent. Turn signals provide this but drivers do not always use them properly. It may be possible to discover other indicators of the driver's intent to change lanes, if not the start of a lane change. However, if such indicators can be found (e.g., idiosyncratic combinations of lane position, steering wheel movements, or eye movements), they may take appreciable time to collect and collate into a warning or signal for FACS intervention. If such indicators are exhibited well in advance of the lane change, then there should be sufficient time for alerting the driver before the maneuver begins. This points to the need for research into driver behaviors that indicate lane change as well as research into signal use and the time interval between signal activation and lane change start. This type of research is a key element to lane change crash avoidance by means of overt warning or FACS if false alarms are to be kept to a minimum.

6. RESEARCH NEEDS

The following research needs are suggested by the analysis reported here. Often a research need is suggested by a gap in current understanding or data. Emphasis is placed on data needs required to support further modeling of the crash circumstances. This modeling effort is emphasized because it is important to IVHS crash avoidance systems design. Thorough analytical assessment of the crash problem, along with IVHS crash avoidance system concepts, will minimize risk to the developer and ultimately speed up the development process of IVHS as a whole. Furthermore, an analytical representation of the crash problem will be a key to successful algorithm development for both driver warning and FACS implementations.

6.1 PROBLEM SIZE AREA

- For the lane change crash problem, additional precision in crash description for each of the following lane change maneuvers would be beneficial: simple lane change, merge, exit, and weave. The present problem size assessment could not clearly distinguish from among all these different maneuver types.

4.2 CLINICAL ANALYSIS AREA

- Only a small number of cases were available for the crash subtype identification and causal factor assessment. Analyzing a larger set of cases and adding to the sample reported herein would be beneficial. The findings could be merged to provide better information on the distribution of various lane change crash subtypes and causal factors, or possibly to uncover additional causal factors or crash subtypes.

- The reported causal analysis could not readily show causal factors within lane change crash subtypes. This cross-tabulation should be pursued in further analyses so that different causal factors differentially associated with different subtypes may be more readily understood. Other possible data sources could include NASS, GES data for other years, the North Carolina data base, insurance data bases, or other similar data bases.

- Given that clinical analysis is a subjective process, a measure of concordance or agreement between two or more analysts working on the same data set would be beneficial. Such a check would provide useful data on the extent to which the causal analysis results can be replicated.

- However tentative, kinematic data reported on crash cases within the subtype-by-causal factor cross-classification would be very helpful. Travel velocities, velocity differences, and similar data would allow for a more focused crash avoidance requirements kinematic model.

6.3 LANE CHANGE DRIVER BEHAVIOR AREA

- Distributional data on initial position and terminal position of SVs before and after lane change, respectively, and the distributions of associated lane change distances during the maneuver would be useful to verify Worrall and Bullen's data or indicate important changes in driver lane change behavior.

- Data are needed on normal lane change times and the distribution of lane change times. Variations in lane change times as a function of travel speed, traffic density, lane change maneuver type (simple lane change, merge, pass, exit, weave), and other driving conditions would be extremely valuable in further characterizing lane change crashes.

- Data are needed on the maximum lateral acceleration normal drivers will use in an evasive steering maneuver. The sources used in this report are over 20 years old and should be updated. More recent data are available from test track studies to generate vehicle performance data. In such tests, however, expert drivers push the vehicle to the limits of its performance envelope. Normal drivers, by contrast, typically do not use the full capability of the vehicle. Therefore, studies of normal volunteer drivers would be very helpful. Variations in scenarios (e.g., by vehicle, driver characteristics, training) might be helpful in better understanding what a driver might reasonably be expected to do in a lane change crash avoidance steering maneuver. Further extensions of these data to include the benefits of 4-wheel steering would also be useful.

- Distributional data on the longitudinal acceleration profiles of vehicles engaged in lane changes would be helpful. The crash avoidance modeling reported here assumed an SV that was traveling with constant velocity longitudinally. It would be helpful to know if vehicles changing lanes (such as when passing) often accelerate so that such a motion profile could be incorporated into future modeling.

- Given that vehicles have changed over the years, empirical data on the rate of lateral acceleration buildup during a maneuver typical for modem automobiles with normal drivers would be helpful. Such studies would also allow for a verification and refinement of the steering recovery maneuver model assumed for the proximity subtype of lane change crash avoidance.

- Data are needed regarding turn signal use and the time between turn signal activation and lane change start. These data would allow further assessment of the effectiveness of a turn-signal-activated warning display.

6.4 DRIVER WARNING AREA NEEDS

- Information on driver steering reaction times in response to warnings of different types (auditory, visual, dual-mode, directional, nondirectional, etc.) are needed to refine the modeling and to support warning algorithm development.

- Driver steering performance data would also be valuable to support effectiveness modeling. Data such as steering ranges (with and without hand-over-hand maneuver), completion times to turn the wheel a given distance, and peak steering velocities would be helpful. These data could be used to more precisely model the feasibility of certain steering recoveries.

- Data are needed to determine indicators of lane change start. If they exist, these indicators might be quite varied. They might include idiosyncratic eye movements (which could be monitored), shifts in lanekeeping (such as a preparatory steering movement away from the direction of the lane change), steering manipulations (e.g, a steering hold), and the like. Obviously, if drivers would learn to always use turn signals before changing lanes, the driver's intent would be known.

6.5 FURTHER MODELING RESEARCH NEEDS

- The models for crash avoidance reported here involved an evasive maneuver on the part of only one driver. If both drivers were warned of the crash hazard, both could be directed to take complementary crash avoidance maneuvers and thus increase the likelihood of crash avoidance. An MIS system that provided such warnings would have to maintain surveillance of the driving conditions to insure that the warning does not, in fact, promote a crash with yet a third vehicle. Further modeling activities should focus on the potential of cooperative avoidance maneuvers (by warning both drivers) and crash avoidance maneuvers not included here (e.g., acceleration to avoid impact).

- The previous research need leads logically to the need to model the lane change IVHS crash avoidance system concepts in traffic systems terms. That is, modeling should be extended to multiple vehicles, multiple IVHS systems (e.g., headway, roadway departure, and so forth), and multiple lanes. Results would provide insights into secondary effects and perhaps their mitigation.

- Results from only one crash avoidance subtype, the proximity subtype, were presented. Modeling of the fast approach subtype may be considered for future work.

7. SUMMARY

The lane change vehicle crash type was analyzed in this report. Types of lane change maneuvers and crashes were described, and the size of the crash problem was estimated from national data bases. Although the lane change crash problem is small relative to other types of crashes and does not account for a high percentage of traffic fatalities, this crash type is responsible for one-tenth of all crash-caused delay. Thus, lane change crashes do have a fiscal impact and may warrant the application of technology to assist in avoiding them.

Lane change crash circumstances were analyzed from a number of crash reports in the CDS and GES data bases to classify the crashes into subtypes and to reveal the factors that were involved in causing them. From these analyses, the proximity and fast approach lane change subtypes emerged, yet a complete causal factor analysis was not possible due to the low numbers of applicable reports in the data base. Some factors did, however, become apparent, such as the driver of the SV not seeing, or otherwise being unaware of, the POV prior to a crash. Implications for the development of IVHS crash avoidance system functional specifications were described and were placed in a framework of time available versus required intensity of an action to avoid a crash as time to impact decreases.

To better understand the kinematics of lane change crashes, the proximity lane change subtype was mathematically modeled. By exercising the model under various conditions of lane change scenario parameters, maximum allowable time delays from the initiation of a lane change to achieve crash avoidance were derived. These maximum allowable time delays, and associated distances or ranges, will be useful for designers of IVHS crash avoidance technologies as they begin to develop concepts for new equipment, and will give the IVHS community a tactical view of how lane change crashes can be avoided.

The need for further research was described in five general areas: developing better size estimates of the lane change crash problem, increasing the robustness of the clinical analysis, securing more accurate data on driver behavior, studying driver-warning interactions, and increasing the representativeness of the models used.

One of the problems with modeling any system is one of representativeness. The models in this report isolate the SV and POV from the remaining traffic in the highway system. Reactions of the drivers in the crash model do not create hazards to other drivers, which can be viewed as unrealistic. Useful modifications to the representation in this report might be to develop models at a systems level. The initial models are isolated terminal events, whereas when more vehicles are involved in the scene, more complex interactions occur. Highways are actually systems of vehicles and a more formal systems analysis would provide an opportunity to view the contribution of these various terminal events to traffic flow and safety system-wide. The first-level approximations in this report do provide a framework to begin this complete system analysis, and will provide information that should be useful to policy makers and system designers.

APPENDIX A

Weighting Schemes

The crashes used in the clinical analysis were weighted for severity so that they might more closely approximate the national profile. The weighting procedure – illustrated in Tables A-l and A-2 – included the following steps[1]:

- The crashes in each data set were sorted by severity [Crash Severity]. The number of each in the sample [# in Sample] was compared to the total sample, which gave analysts the percentage of the clinical sample represented by each severity level [% of Clinical Sample].
- NHTSA provided the percentage of the GES data represented by each severity level [% of 1991 GES].
- The percentage of the national profile that each case represented [% Rep. Each Case] was determined by dividing [% of 1991 GES] by [# in Sample].

---

[1] The phrases enclosed in square brackets refer to headings in the tables - for example, [Crash Severity].

Table A-1
Weighting Scheme Used For 16 Case Applicable NASS CDS Sample

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	5	31.25	82.76	16.55
1(C)	3	18.75	11.39	3.80
2(B)	2	12.50	3.92	1.96
3/4(A/K)	6	37.50	1.93	0.32
Total	16	100.00	100.00	

Table A-2
Weighting Scheme Used For 33 Case Applicable NASS GES Sample

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	7	21.21	82.76	11.82
1(C)	3	9.09	11.39	3.80
2(B)	3	9.09	3.92	1.31
3/4(A/K)	20	60.61	1.93	0.10
Total	33	100.00	100.00	

Notes:

1) GES crash severity based on cases involving all vehicle types. Cases of unknown severity were counted as "0" cases.

2) There was an implicit assumption that, within each severity level, the GES PAR Sample was representative of the national crash experience. In other words, there were no biases in the GES PAR case selection process.

3) Severity levels 3 and 4 (A and K) were combined because of the small number of 4 (K) severity crashes.

4) % Represented by Each Case is the ratio (% of 1991 GES)/(# in Sample).

APPENDIX B

Example Lane Change Calculations

To illustrate the crash avoidance lane change scenario, consider the following example. Two vehicles are traveling in the center of adjacent lanes that are 12 ft in width and the vehicle lengths overlap. The two vehicles are separated laterally by an intervehicle gap (LATGAP) of 6 ft. The driver of the first vehicle (or subject vehicle — SV) intends to make a 12 ft (ILCD) lane change from the center of its travel lane to the center of the adjacent lane in 4 s (t_{LC}), which can be considered as a moderately fast lane change.

The SV driver initiates the lane change maneuver. The subject vehicle follows the inclined sine model for the distance traveled as expressed in Equations 3 through 5, until the driver becomes aware of a crash hazard (the principal other vehicle, or POV). The SV driver begins a recovery maneuver, the maximum recovery acceleration of which will be a moderate level of 0.55 g for this example.

The computer program that was used for modeling iterates by increasing the time at which the recovery maneuver is initiated in increments (the analyst selects the increment size) to determine the maximum time that a recovery maneuver can be initiated to avoid a crash.

Under the conditions of this scenario, the output from the program reveals that the maximum available time ($t_{available}$) during which the SV driver can initiate a recovery maneuver to avoid a crash is 1.38 s. The remainder of this appendix shows how the program determines that a crash does not occur when the recovery maneuver begins at 1.38 s.

The initial conditions of the recovery maneuver — the lateral acceleration, lateral velocity, and lateral distance traveled — are calculated from the inclined sine portion of the model. Using Equation 3, the acceleration $\left(a_0' \right)$ at the initiation of recovery is:

$$a_0' = \frac{2\pi(12)}{4^2} \sin\left(\frac{2\pi}{4} 1.38\right) \tag{B.1}$$

$$\sim 3.9\ ft/s^2$$

The velocity in the lateral orientation when recovery begins $\left(v_0' \right)$ can be calculated using Equation 4 as:

$$v_0' = \frac{12}{4}\left[1 - \cos\left(\frac{2\pi}{4}\,1.38\right)\right] \tag{B.2}$$

$$\approx 4.7\ ft/s$$

And, the distance traveled toward the POV when recovery begins $\left(d_0' \right)$, using Equation 5, is:

$$d_0' = \frac{12}{4}\,1.38 - \frac{12}{2\pi}\sin\left(\frac{2\pi}{4}\,1.38\right) \tag{B.3}$$

$$\approx 2.6\ ft$$

Therefore, the SV will have traveled a lateral distance of 2.6 ft towards the POV when the recovery maneuver is initiated, and is traveling at a velocity of 4.7 ft/s laterally, with an acceleration of 3.9 ft/s^2. The recovery maneuver follows the trapezoidal function as expressed in Equations 7 through 9 and as illustrated in the following table (r = 10 inc/s).

Time from Initiation of Lane Change (s)	**Time from Initiation of Recovery (s)**	**Lateral Acceleration, a (ft/s^2)**	**Lateral Velocity, v (ft/s)**	**Lateral Position, d (ft)**
1.38	0.00	3.90	4.70	2.60
1.48	0.10	1.66	4.98	3.09
1.58	0.20	-0.58	5.03	3.59
1.68	0.30	-2.82	4.86	4.08
1.78	0.40	-5.06	4.47	4.55
1.88	0.50	-7.30	3.85	4.97
1.98	0.60	-9.54	3.01	5.32
2.08	0.70	-11.78	1.94	5.56
2.18	0.80	-14.02	**0.65**	**5.70**
2.28	0.90	-16.26	**-0.86**	**5.69**
2.38	1.00	-17.60	-18.46	-7.21

The program steps time in 0.1 s increments until lateral velocity, v, is equal to zero. In this case, lateral velocity obtains a value of zero between 2.18 s and 2.28 s after the initiation of the lane change maneuver. The maximum lateral position, d — which occurs when lateral velocity is zero – is about 5.70 ft. This value is less than the lateral distance between the two vehicles (LATGAP) of 6 ft. Therefore, a crash has been avoided. Were the distance not less than LATGAP, then a crash would have occurred and the program would stop and the maximum $t_{available}$ would be at the next lower increment.

APPENDIX c

README.TXT File

The following is a transcript of the README.TXT file that is included on the diskette that accompanies this report.

README.TXT

Lane Change Crash Avoidance Model

LCAVOIO (8/93)

LCAVOID calculates the maximum response time necessary to avoid a crash during the lane change maneuver at user specified parameters, as well as the proportion of the population that can generate such a response time. User inputs include:

- Resolution or number of calculation cycles per second. Typical values range from 20 to 100 increments per second.
- Maximum recovery acceleration in g.
- Rate of change in acceleration during recovery in g/s.
- Range of intervehicle gap in ft.
- Range of intended lane change distances in ft.
- Range of lane change times in s.

Once these parameters are entered, the user has the opportunity to confirm their correctness and re-enter any incorrect numbers.

The program writes the output to the screen to give the user feedback during operation, but also saves the output to text files. These files are named according to the following convention:

GAPx. TXT

where x is the value of intervehicle gap. Each file contains four colums of numbers: ILCD in ft, t_LC in s, t-available in s, and p (proportion of drivers who can generate a response time as quick or quicker than t_driverRT).

To run the program, create a directory and copy the file LCAVOID.EXE into it. Then at the DOS prompt, type LCAVOID, press the ENTER key and follow the directions on the screen. When the program has finished execution, three beeps will signal and the message "Run is completed." will be displayed.

The text files on this disk that are named GAPn.m are the output files of a modified version of LCAVOID. The naming convention is such that

```
     n ❑  the intervehicle gap, and

     m  =  an index such that

           uhen m = 1, A_r = .7  g
                m = 2, A-r = .55 g
                m = 3, A_r = .4  g
```

The colums of these text files are ILCD in ft, t_LC in s, t-available in s, t_driverRT in s, and p (proportion of drivers who can generate a response time as quick or quicker than t_driverRT). See the text of the report for definitions of these variables and for more information.

REFERENCES

Enke, K. 1979. "Possibilities for Improving Safety Within the Driver-Vehicle-Environment Control Loop." The 7th International Technical Conference on Experimental Safety Vehicles. Washington, DC: National Highway Traffic Safety Administration.

Koppa, R., and G. G. Hayes. 1976. "Driver Inputs During Emergency or Extreme Vehicle Maneuvers." *Human Factors,* 18: 361-370.

Malaterre, G., and D. Lechner. 1990. "Emergency Maneuvers at Junctions Using a Driving Simulator." *Proceedings of the 11th International Symposium on Transportation and Traffic Theory,* 213-232.

McKnight, A. J., and B. B. Adams. 1970. *Driver Education Task Analysis: Volume I: Task Descriptions.* (Report No. DOT-HS-800-367). Washington, DC: National Highway Traffic Safety Administration.

National Highway Traffic Safety Administration Office of Crash Avoidance Research. 1992. *NHTSA IVHS Plan.* (Report No. DOT-HS-807-850). Washington, DC.

Rice, R. S., and F. Dell'Amico. 1974. *An Experimental Study of Automobile Driver Characteristics and Capabilities* (Calspan Report No. ZS-5208-K-1). Buffalo, NY: Calspan.

Sorkin, R. D., B. H. Kantowitz, and S. C. Kantowitz. 1988. "Likelihood Alarm Displays." *Human Factors, 30(4), 445-459.*

Sorkin, R. D., and D.D. Woods. 1985. "Systems with Human Monitors: A Signal Detection Analysis." *Human-Computer Interaction* 1: 49-75.

Taoka, G. T. 1989. "Brake Reaction Times of Unalerted Drivers." *ITE Journal,* March, 19-21.

Transportation Research Board. 1985. *Highway Capacity Manual* (Special Report No. 209) (Ch. 4 Weaving Areas). Washington, DC: Transportation Research Board. Cited in Yoo (1987).

Wang, J., and R. Knipling. May, 1993. *IVHS/Crash Avoidance Countermeasure Target Crash Problem Size Assessment and Statistical Description: Lane Change/Merge Crashes: Problem Size Assessment and Statistical Description* (DRAFT). Washington, DC: NHTSA Office of Crash Avoidance Research (OCAR).

Wickens, C. D. 1992. *Engineering and Human Performance* (2nd edition). New York: Harper Collins.

Wierwille, W. W. 1984. “Driver Steering Performance.” In G. A. Peters and B. J. Peters editors, *Automotive Engineering and Litigation:* Volume 1: 407-434. New York: Garland Law Publishing.

Wierwille, W. W. 1993. Personal communication. Virginia Polytechnic Institute and State University.

Worrall, R. D., and A. G. R. Bullen. 1970. “An Empirical Analysis of Lane Changing on Multilane Highways.” *Highway Research Board, 303: 30-43.*

Yoo, K. “An Empirical Analysis of the Behavior of Weaving Traffic in a Freeway Weaving Section.” Ph.D diss., Ohio State University, 1987.