Examination of Intersection, Left Turn Across Path Crashes and Potential IVHS Countermeasures

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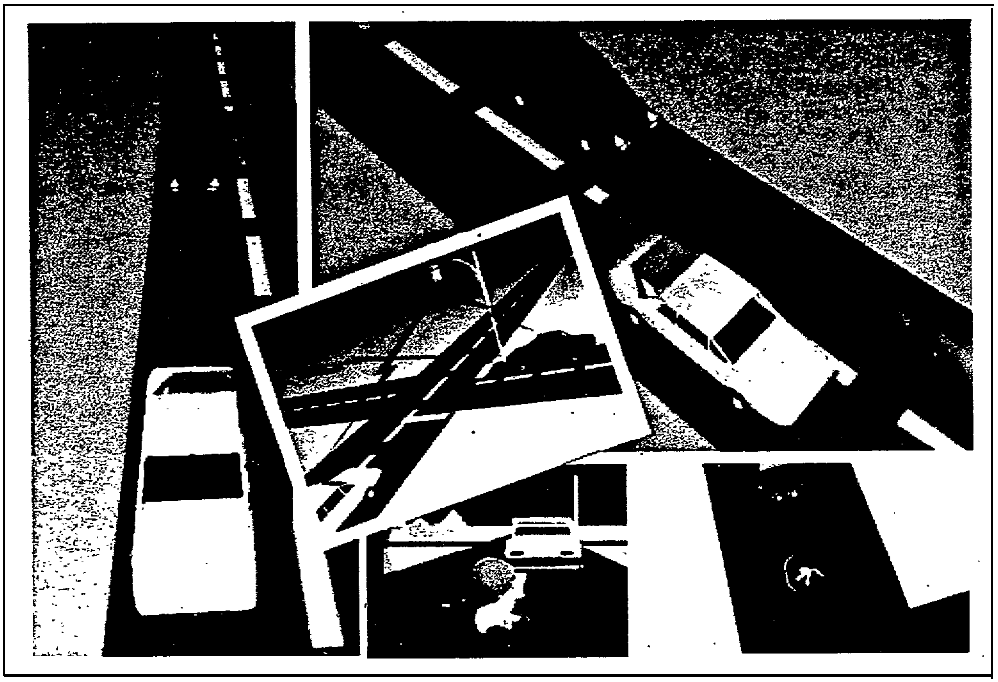
September 1994



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13. ABSTRACT (Maximum 200 words)

This report provides a preliminary analysis of intersection-related, left turn across path (LTAP) crashes and applicable countermeasure concepts for the Intelligent Vehicle Highway System (IVHS) program. An LTAP crash occurs when the subject vehicle (SV) approaches an intersection, attempts to turn left, and either strikes or is struck by the principal other vehicle (POV) traveling in the opposing traffic lanes. A detailed analysis of 154 such crashes showed that 49 percent are caused by drivers who were unaware of the oncoming vehicle, and that 30 percent were caused by drivers who saw but misjudged the velocity/gap of the oncuning vehicle. Moreover, two LTAP crash subtypes are identified: the SV slow, but does not stop, begins the Left turn, and strikes or is struck by the oncoming POV in 71.6 percent of these crashes; and the SV stops, then proceeds with the left turn, and strikes or is struck by the POV in the remaining 28.4 percent of these crashes. The crash avoidance system (CAS) concepts discussed in this report include driver warnings, partially automatic vehicle control systems, end fully automatic vehicle control systems. This report concludes uith a number of research needs to better understand LTAP crashes and guide CAS development.

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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 (Volpe Center), 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 and data needs.

Under this program, nine target crash types are examined, including the following:

- Rear-End
- Backing
- Single Vehicle Roadway Departure
- Lane Change/Merge
- Signalized Intersection, Straight Crossing Path
- Unsignalized Intersection, Straight Crossing Path
- Intersection, Left Turn Across Path
- Reduced Visibility (Night/Inclement Weather)
- Opposite Direction

This report presents the results of the intersection, left turn across path crash study. The results are based on the analysis of 154 hard copy reports that were selected from the 1992 Crashworthiness Data System (CDS). The crashes analyzed in this report 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 Jeffrey H. Everson of Battelle and John A. Pierowicz and Donald L. Hendricks of Calspan.

Wassim Najm of the Volpe Center served as the technical monitor for this report John Hitz, Joseph S. Koziol, Jr., Mark Mironer, and Lynn Fraser of the Volpe Center; William A. Leasure, Jr., Ronald R. Knipling, Robert M. Clarke, and August L. Burgett of NHTSA OCAR; and Jing-Shiarn Wang of IMC, Inc. provided technical guidance and reviewed this report.

The contributions of the following Battelle staff are also acknowledged: John C. Allen and Nathan Browning for their technical assistance and review; Suzanne W. McKeown for serving as editor; Laura K. Brendon for graphics support; and Viki L. Breckenridge for word processing and 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

INCHES: 0 1 2 3 4 5 6 7 8 9 10
CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

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. Cl3 10286.

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ABBREVIATIONS AND ACRONYMS

The following list contains abbreviations and acronyms used in this report, together with their definitions.

u	coefficient of friction
a	normal deceleration, ft/s^2
a^*	emergency deceleration, ft/s^2
CAS	crash avoidance system
CDS	Crashworthiness Data System
$D_{available}$	distance available for crash avoidance braking maneuver, ft
D_{clear}	distance for the SV to clear the intersection, ft
D_{POV}	distance of POV from the intersection Stop Line, ft
D_{slow}	distance to slow from V_0 to $V_{max\ turn}$, ft
$D(t_d)_{loc}$	distance traveled during the td time delay, ft
$D(t_d)_{stop}$	distance required to stop after the td time delay, ft
$D_{required}$	distance required to stop, ft
DUI	driving under the influence
FACS	fully automatic control system
ft	foot, feet
g	unit force of gravity, ft/s^2 (32 ft/s^2)
GES	General Estimates System
IVHS	Intelligent Vehicle Highway System
LTAP	left turn across path
LTAP/IPD	left turn across path, initial perpendicular direction
L	vehicle length, ft (16 ft assumed)
lw	lane width, ft (12 ft assumed)
mph	miles per hour
NASS	National Accident Sampling System
NHTSA	National Highway Traffic Safety Administration
NPR	nonpolice-reported
PAR	police accident report
POV	principal other vehicle
PSU	Primary Sampling Unit
R	radius of turn, ft
R_a	actual radius of turn, ft.
R_m	maximum radius of turn, ft
s	second, second?
t_{clear}	time for the left-turning vehicle to clear the intersection, s
t_d	time delay available for driver, vehicle, and CAS latencies, s
SV	subject vehicle
t_{slow}	time required to slow down from V_0 to $V_{max\ turn}$, s
TCD	traffic control device

ABBREVIATIONS AND ACRONYMS (continued)

V_0	initial travel velocity of SV, ft/s
$V_{max\ turn}$	maximum turn velocity without skidding at a given maximum turn radius (R_m) and coefficient of friction (p), ft/s
V_{POV}	POV velocity, ft/s
V	SV velocity; ft/s
$V(t_d)$	velocity of SV after the time delay (t_d), ft/s

EXECUTIVE SUMMARY

This report presents a preliminary analysis of left turn across path (LTAP) crashes at intersections and potential Intelligent Vehicle Highway System (IVHS) measures to avoid them. The LTAP crash is defined as a collision where the subject vehicle (SV) approaches an intersection and attempts to turn left across an opposing lane of traffic. It either strikes or is struck by the principal other vehicle (POV), which is traveling in an opposing lane. An analytic model of LTAP behavior at intersections is presented to indicate possible sources of driver error that might contribute to crashes. The possible sources include misjudgment of traffic velocity, gap, or behavior; unawareness caused by vision obstruction or other factors; and deliberate violation of a signal; among others.

The LTAP crash accounted for nearly 7 percent of police-reported crashes in 1991, approximately 413,000 crashes. Some features of the LTAP crash type are noted from a detailed analysis of 154 cases. Most LTAP crashes occur on roadways with posted speed limits of 35 mph or greater. Additionally, the SV is more likely to be the vehicle that has been struck rather than the striking vehicle at both signalized and unsignalized intersections. There are two types of LTAP crashes identified: Subtype 1, which accounts for 7 1.6 percent of LTAP crashes, where the SV slows, but does not stop, begins the left turn, and strikes or is struck by the oncoming POV; and Subtype 2, which accounts for the remaining 28.4 percent of LTAP crashes, where the SV stops, then proceeds with the left turn, and strikes or is struck by the POV. For signalized and unsignalized intersections combined, 49 percent of LTAP crashes are caused by drivers who are unaware of the oncoming vehicle, and 30 percent are caused by drivers who see but misjudge the velocity/gap of the oncoming vehicle. For signalized intersections, violation of the signal by the SV or POV, or both, accounts for 15.4 percent of LTAP crashes. Other factors, such as an attempt to beat the other vehidle and driver intoxication, also contribute to the LTAP crash problem.

A framework is presented for IVHS crash avoidance concepts regarding LTAP crashes. This framework is based on a series of sequential countermeasure steps, staring with driver alerts, then working up to higher intensity driver warnings, partially automated control crash avoidance maneuvers, and, finally, fully automatic control maneuvers. The LTAP crash avoidance system (CAS) concepts are based on the relationship between time to collision and the intensity of action required to avoid the crash. In a hybrid system incorporating all of these concepts, the level of the warning would reflect circumstances occurring at the intersection (such as the status of the light of a signal) and the presence of other vehicles that could be potential threats in the case of an LTAP maneuver. For instance, a driver would be alerted if a hazard existed due to the presence of a straight crossing, oncoming vehicle. If the driver did not respond to the alert, a more intense driver warning could be issued. If the driver still did not respond, the system could provide a partially automated control, such as soft braking. If the crash were still impending, a fully automated control system could intervene.

The analysis introduced in this report is intended to increase understanding of crash avoidance requirements associated with LTAP crashes. A simple LTAP model is presented in which driver warnings are analyzed in terms of POV time headway. The model assumes that

(1) the SV follows a quarter-circle turn through the intersection, and (2) the POV travels at constant velocity in a straight-line approach to the intersection. The modeling is divided into two subtypes based on whether the SV does or does not come to a complete stop before entering the intersection. When the SV driver first stops, the time to clear the intersection is calculated on the basis of a typical acceleration and turning radius. If the SV cannot complete the LTAP maneuver before the POV arrives at the intersection, crash avoidance measures are taken to keep the SV from moving until the POV passes through the intersection. In cases where the SV driver does not stop completely, the model assumes that the SV driver begins to decelerate in anticipation of making an LTAP. After a nominal level of deceleration has occurred, if a hazard exists, an in-vehicle warning is given to indicate that an additional degree of braking is required to stop at the intersection. With an assumed level of increased deceleration, the amount of driver/vehicle/CAS delay time that is required to stop within an available distance of the intersection is calculated. The intent of this analysis is to provide a better understanding of crash avoidance opportunities and to illustrate design challenges for LTAP crash countermeasures. The analytic model represented can be used to identify critical countermeasure functional requirements and data needs.

The report concludes with a discussion of research needs to support further refinement of the LTAP scenario and other crash avoidance concepts. These include expanding the causal analysis using other crash data sources; learning more about driver behavior at left turns and their decision processes, investigating potential types of displays, and assessing driver brake reaction time distribution. Also, driver behavior and gap acceptance need to be studied to reduce nuisance alarms, and algorithms need to be examined to incorporate the characteristics that best describe LTAP scenarios. Finally, additional modeling and analyses are needed to address situations involving more than two vehicles.

1. BACKGROUND

1.1 OUTLINE

This report provides a preliminary analysis of intersection-related, left turn across path (LTAP) crashes. The objective of this report is to provide a better understanding of the nature and characteristics of LTAP crashes and to determine the potential application of Intelligent Vehicle Highway System (IVHS) countermeasures. The LTAP crash is defined and a driver model of left turn negotiation is presented to identify sources of possible driver actions that could lead to LTAP crashes, The size of the LTAP problem is presented in terms of accident statistics. A detailed analysis of underlying causes and scenarios of LTAP crashes follows, which guides the suggestions for LTAP crash avoidance system (CAS) functional concepts. The CAS concepts presented follow a theme that concerns time to collision and the required intensity of crash avoidance maneuver. The left turn maneuver is then modeled in a simple way so that the maximum time available for driver and vehicle/CAS delays after alert or warning onset can be assessed for the CAS concepts presented. The report concludes with recommended research needsthat will further an understanding of LTAP crashes, and the development of crash countermeasures.

1.2 DEFINITION OF LEFT TURN ACROSS PATH (LTAP) CRASHES

In this report, the LTAP crash refers to a crash that occurs at an intersection where one vehicle, the subject vehicle (SV), approaches an intersection and attempts to turn left across traffic traveling in the opposite direction. The crash occurs when the SV either strikes or is struck by a principal other vehicle (POV) traveling in the opposing traffic lanes. Crashes of this, type can occur at signalized or unsignalized intersections. Figure l-l is a simplified diagram of an LTAP maneuver.

Figure l-2 shows a simple model of driver behavior during left turns, adapted from the work of McKnight and Adams (1970). This model suggests possible sources of driver error (see Table l-l) that can contribute to LTAP crashes and is helpful in identifying possible crash countermeasure concepts that might ameliorate these errors, The European DRIVE program (Michon, 1993) also uses McKnight and Adams (1970) as the basis for intelligent driver support

In the simple model, the SV driver approaches the intersection, signals the intent to turn, and decelerates. The driver might fail to slow down sufficiently at this point in the process. If a traffic control device (TCD) is present, then the appropriate behavior is taken, depending on the characteristics of the device. The unaware driver might not observe the TCD. If the device is a stop sign, then, ideally, the driver will observe it and stop before entering the intersection and continuing with the left turn. If the TCD is a traffic light, then the color and status of the light indicate the appropriate behavior for the driver to exhibit, within the constraints of the driver's judgement. The driver who is unaware of the signal status might make erroneous assumptions and might make a left turn at an inopportune time.

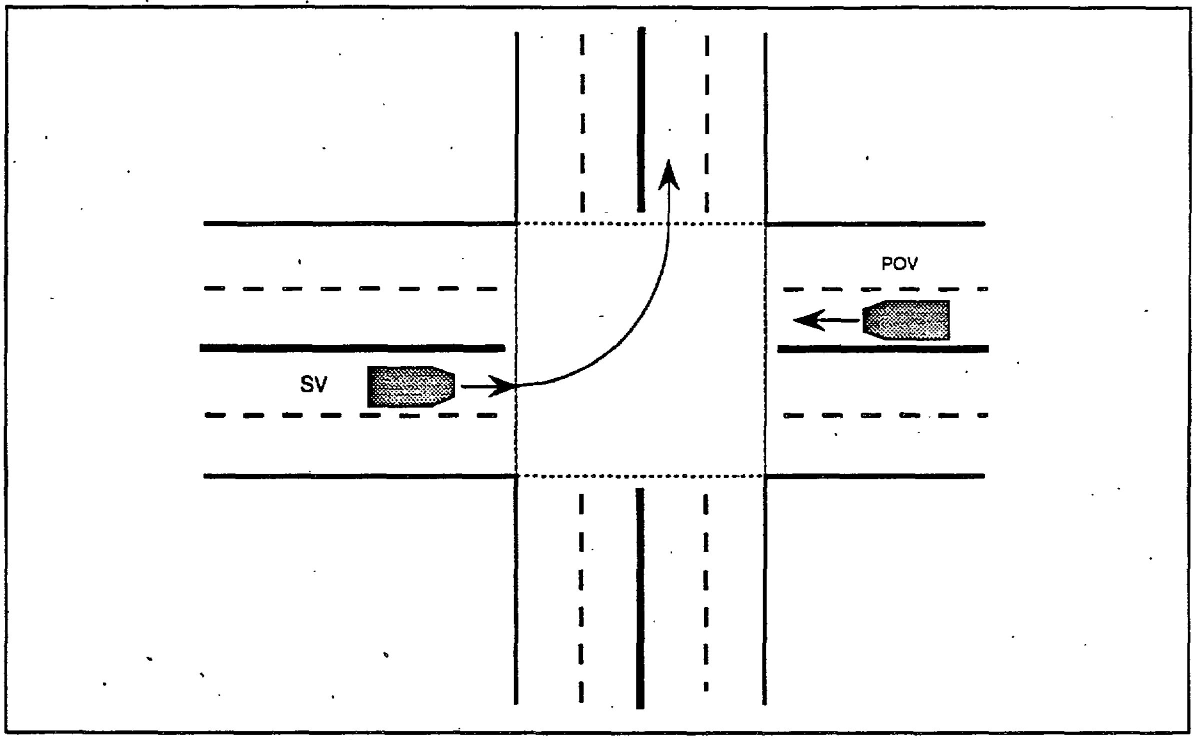


Figure 1-1. Simplified Diagram of an LTAP Maneuver

Once the information from the TCD is processed by the driver, the driver observes other traffic. If no oncoming or cross traffic exists, then the driver continues. A driver might fail to detect traffic, which could create a hazardous situation. If traffic is oncoming, then the available gap is judged as to its sufficiency for a safe left turn. The driver who misjudges the gap or velocity of oncoming traffic might cause a crash. Similarly, the gap between the driver's vehicle and any cross traffic must be judged appropriately. If the driver's vision is obstructed, the driver should slow or stop the vehicle and edge out slowly into traffic to visually confirm that the pathway is safe. If other vehicles are obstructing the driver's vision, then additional awareness and action must be engaged before the left turn can be made safely. When the pathway is judged to be clear (which could be an erroneous judgement) and the turn can be made safely, then the driver assumes the correct velocity and makes the turn.

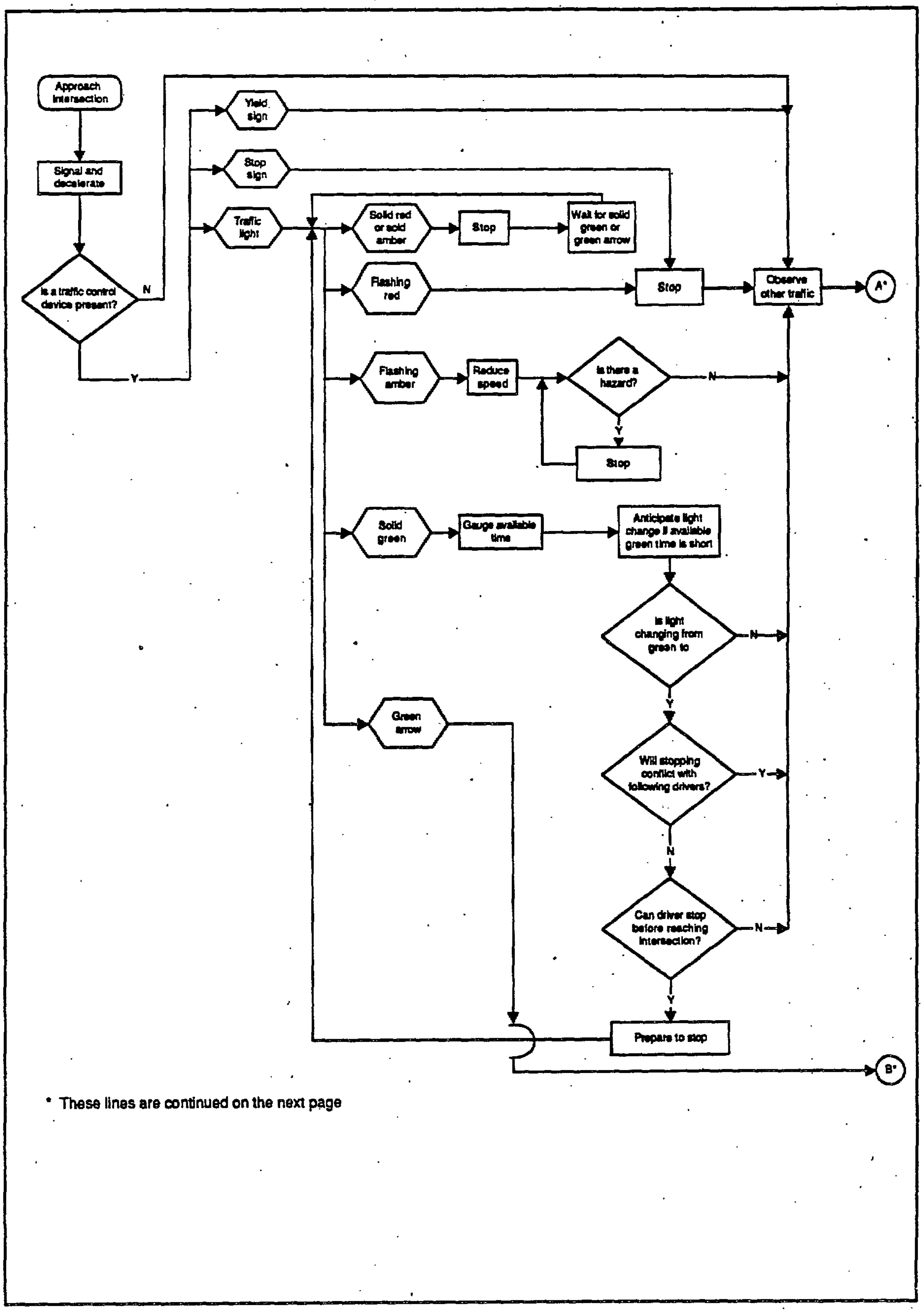
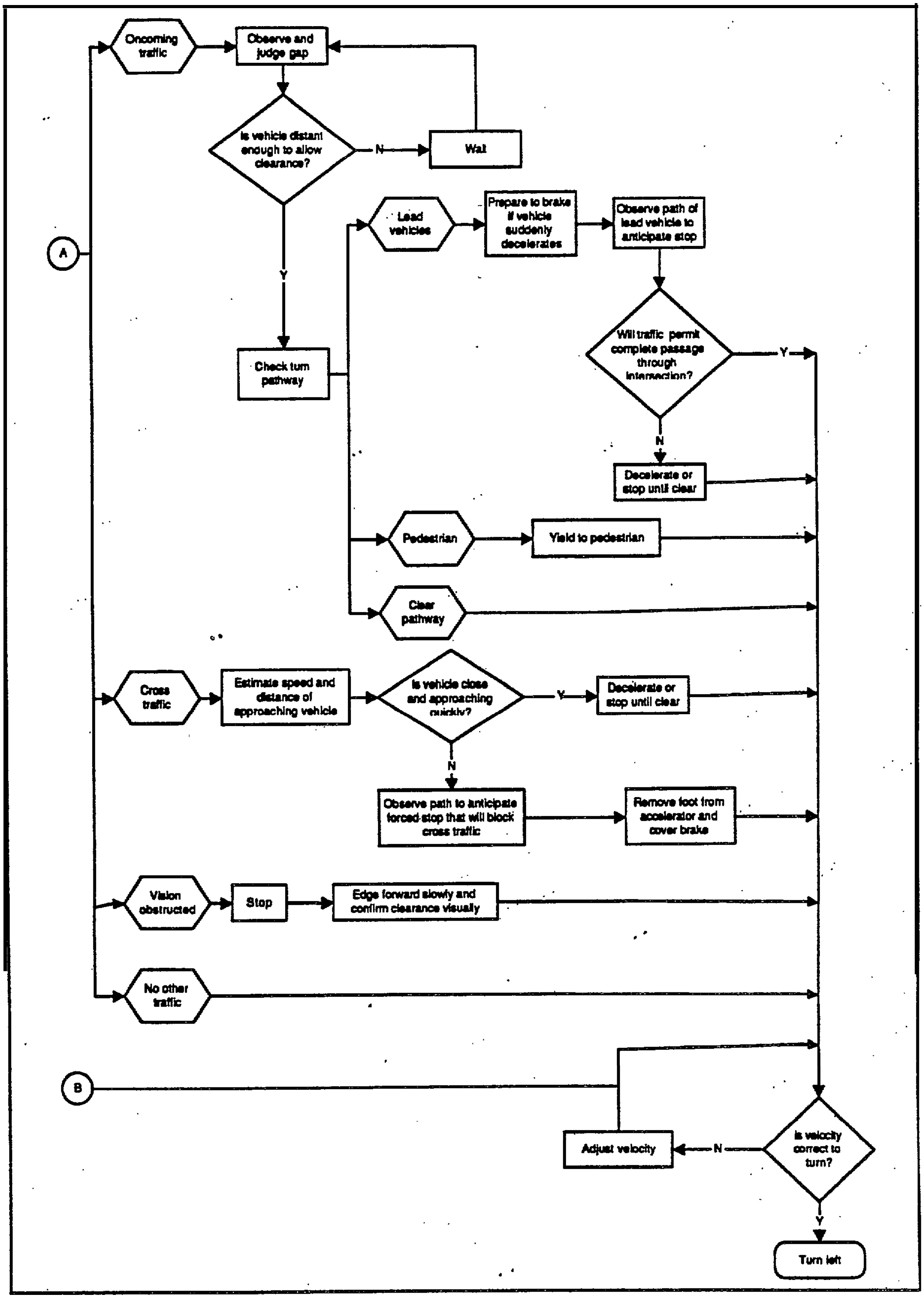


Figure 1-2. **Simplified Model of Driver Behavior When Negotiating a Left Turn Across Path (continued next page)**



Figure, l-2. Simplified Model of Driver Behavior When Negotiating a Left Turn Across Path (continued) . .

Table l-l
Possible Sources of Driver Error
When Making a Left Turn Across Path

Driver Task	Possible Errors
Approach the intersection	Driver might be unaware of the intersection ahead and its geometry.
Signal	Driver might not signal to other traffic.
Decelerate	Driver might not decelerate sufficiently to process intersection information properly.
Perceive TCD	Driver might be unaware 0f TCD altogether or might be unaware of signal characteristics.
Heed TCD	Driver might not perceive correct device characteristics.
Perceive the color of the traffic light	Driver might be unaware of the status (flashing versus solid) or color (red, amber, green) of a light.
Respond appropriately to the color of the light	Driver might exhibit incorrect behavior to a particular light characteristic.
Observe other traffic	Driver might be unaware of other traffic (crossing or oncoming).
Judge the gap in oncoming traffic	Driver might misjudge the gap in or velocity of oncoming traffic.
Judge the gap in cross traffic	Driver might misjudge the distance of the gap in traffic or the velocity of oncoming traffic if he or she is distracted by cross traffic.
Edge out into traffic to confirm clearance when the driver's vision is obstructed	Driver might not realize that vision is obstructed or might edge out into traffic without confirming information.
Check the pathway	Driver might not check the pathway or might misperceive objects (vehicles or pedestrians) in the pathway. Driver might not anticipate other traffic behavior properly.
Adjust velocity to turn	Driver might turn too fast or too slow.
Complete the left turn	Driver might stop before the turn is completed.

2: CRASH PROBLEM SIZE

This section describes the magnitude of the LTAP crash problem. Statistics from national databases are presented and discussed.

2.1 PROBLEM OVERVIEW

Figure 2-1, based on data from the National Highway Traffic Safety Administration (NHTSA) accident data systems, presents the size of the LTAP crash problem. These data are based on police accident reports (PARs) derived from the NHTSA General Estimates System (GES) 1991 statistics. Nearly 7 percent of PARs were LTAP crashes, representing approximately 413,000 crashes. A rough estimate of 1991 nonpolice-reported (NPR) LTAP crashes is 462,000; this rough estimate was derived by applying the proportion of police-reported, low severity (property damage only) crashes that are LTAP to the estimated total population of NPR crashes. The LTAP crash type accounted for roughly 8 percent or 37 million hours of crash-caused delay in 1991. Crash-caused delay, measured in vehicle hours, estimates the delay of noninvolved vehicles caught in the congestion that results from a crash. Furthermore, 51.2 percent of LTAP crashes occurred at signalized intersections, whereas 48.8 percent occurred at unsignalized intersections.

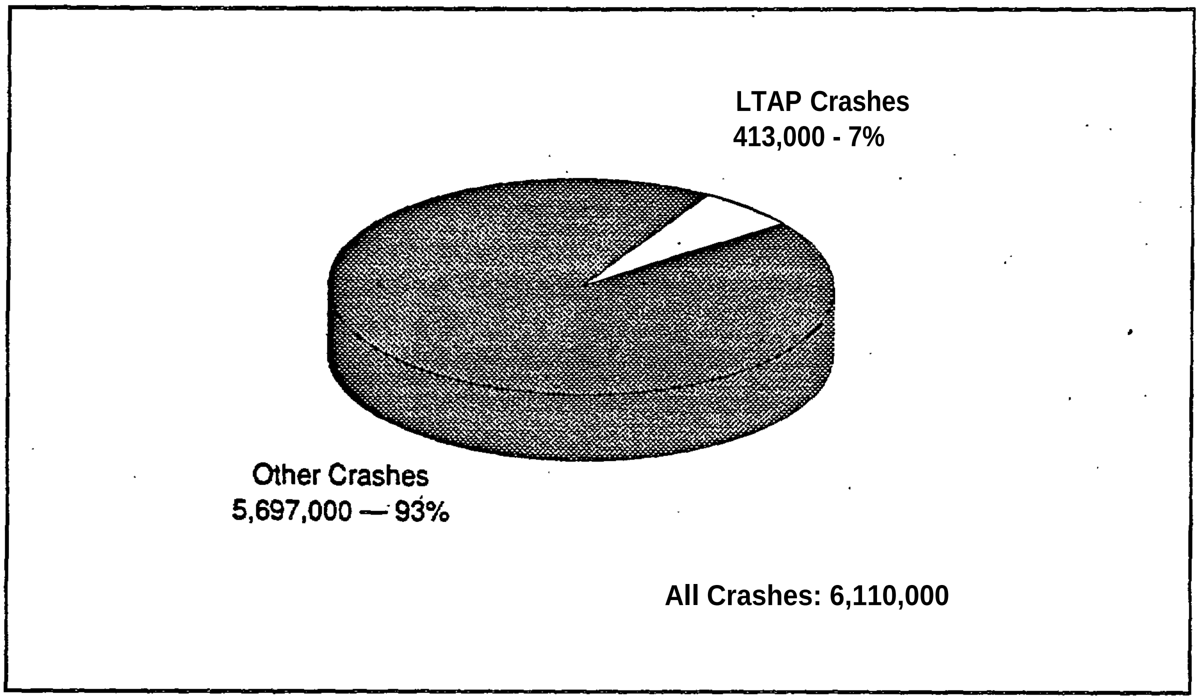


Figure 2-1. LTAP Crash Problem Size, 1991 GES Data

2.2 DISCUSSION

The LTAP crash problem represents a substantial number of crashes and related economic consequences. IVHS technologies might be able to provide effective LTAP crash countermeasures, thereby adding to highway safety.

Table 2-1 presents the characteristics of LTAP crashes and the percentage occurrence of these characteristics. The data indicate that most LTAP crashes occur on dry pavement and in no adverse weather conditions, 80 and 86 percent, respectively. Table 2-l also shows that good ambient lighting predominates in LTAP crashes (e.g., 73 percent occur in daylight). In addition, the majority of drivers (82 percent) involved in LTAP crashes are under 54 years of age, although elderly drivers are over-represented in statistics on intersection crashes (Peacock & Karwowski, 1993). Also, the distribution of travel velocities in Table 2-l indicates that the majority of SVs (59 percent) were traveling at 10 mph or less, probably due to the need to slow down to make the left turn. The statistics on the obstruction of driver vision and on driver distraction are considered to be conservative because PAR data do not reliably capture the involvement of these factors in crashes.

Note that one other crash type is similar to the LTAP scenario, but is not included in the problem-size statistics presented in-this report. This crash type is the left turn across path, initial perpendicular direction (LTAP/IPD) crash. Figure 2-2 shows a simple diagram of this precrash scenario. In the LTAP/IPD crash type, the two vehicles approach each other at a perpendicular angle, and the vehicle approaching from the right of the POV (i.e., the SV) turns left across the path of. the other vehicle. An estimated 278,000 crashes of this type occurred in 1991, representing approximately 2.9 percent of all crashes. Some of the LTAP analyses in this report might apply in part to LTAP/IPD crashes as well. No attempt was made, however, to formally address this crash subtype in this report. Finally, in 1991, an additional 307,000 crashes in GES were coded as "turn across path, specifics other," "turn into path, specifics other," "turn across path, specifics unknown," or "turn into path, specifics unknown." Thus, although the more conservative figure of 413,000 LTAP crashes is used as the crash problem size in this report, a more liberal definition of the target crash problem size yields an estimate that is much larger.

The next section discusses the circumstances and causes of the LTAP crash type derived from analysis of detailed crash case files.

Table 2-1
LTAP Crash Characteristics
(from 1991 GES Data)

Characteristics	Percent Occurrence	
Pavement conditions		
Dry	80.0%	
Wet	17.0%	
Snowy or icy	3.0%	
Ambient weather conditions		
No adverse weather	86.0%	
Rain	11.0%	
Snow or sleet	3.0%	
Ambient light conditions		
Daylight	73.0%	
Dark, lighted	19.0%	
Dark, unlighted	5.0%	
Dawn or dusk	3.0%	
Alcohol involved in crash	5.0%	
Age distribution of involved drivers		
15-24	28.0%	
25-54	54.0%	
55-64	7.0%	
65+	11.0%	
Sex distribution of involved drivers		
Female	42.0%	
Male	58.0%	
Travel velocity (mph)	**SV**	**POV**
0-5	31.0%	4.0%
6-10	28.0%	3.0%
11-15	15.0%	3.0%
16-20	10.0%	6.0%
21-25	6.0%	12.0%
26-30	4.0%	16.0%
31-35	3.0%	24.0%
36-40	2.0%	13.0%
41-45	0.6%	11.0%
46-50	0.4%	3.0%
51-55	0.7%	5.0%
56+	0.2%	0.0%
Indication (on PAR) of driver vision obstruction	6.0%	
Indication (on PAR) of driver distraction	3.0%	

Note: Unknowns were distributed proportionally.

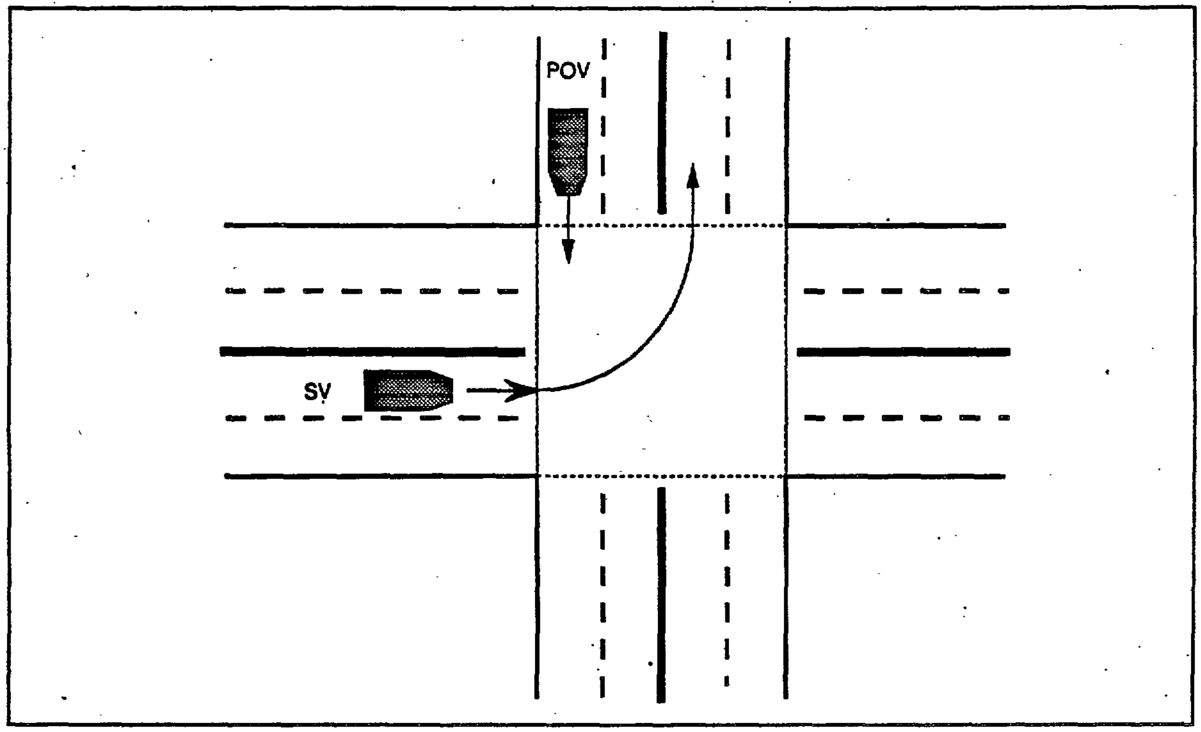


Figure 2-2. LTAP/IPD Precrash Scenario

3. ANALYSIS OF LTAP CRASH CIRCUMSTANCES

This section describes characteristics of LTAP crashes and identifies causal factors that contribute to the LTAP crash problem. First, the data set and the analysis methodology are described. Then the results of the clinical analysis are presented. These results include crash characteristics and causal factors. The section concludes with a discussion of the LTAP crash circumstances.

3.1 CLINICAL DATA SET AN ANALYSIS METHOD

In this analysis, accident data were drawn from the Crashworthiness Data System (CDS). This database system is part of the National Accident Sampling System (NASS), which is designed to support the development, implementation, and assessment of highway safety programs.

The CDS data file consists of a probability sample of police-reported accidents in the United States. These accidents are characterized by a harmful event, such as property damage or personal injury, and must involve passenger cars, light trucks, or vans that were towed from the scene because of damage. CDS data are obtained from a review by research accident investigation personnel of PARs, crash investigations, and interviews of all persons involved in the crash. For this report, the CDS, data set consisted of 184 unsanitized hardcopy reports selected from the first, second, and third quarters of 1992. The unsanitized NASS CDS cases provide data from which to reconstruct crashes and analyze causal factors. The cases include the following:

- 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

The CDS data set was subjected to a clinical analysis. This methodology entails subjective assessment by an expert analyst. It involves content analysis of narrative statements (including keywords and phrases) and kinematic assessment to crosscheck narratives. The analyst develops an impression of the crash subtypes or causal factors, or both, from the reviews. Error sources in this process might include limited sample size, incomplete case files, and analyst decision processes that are subject to cognitive heuristics and biases in judgement (Wickens, 1992). As an example of the error sources, confirmation bias may lead 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. Furthermore, despite these potential sources of error, clinical analysis of detailed case files represents an invaluable aid to understanding the nature of crashes. This methodology also opens up data sources (additional uncoded information in the PARs) that are otherwise unavailable.

3.2 CLINICAL ANALYSIS RESULTS: CAUSAL FACTORS

A general picture of the causal, factors of LTAP crashes emerged from the analysis of the 184 cases. Of these, 30 cases had insufficient detail for further analysis; thus, 154 cases remained for analysis. Table 3-l summarizes the causal assessments derived from the narrative or coded portions of the NASS CDS sampled cases. The percentages cited hereand in the remainder of the report are weighted based on crash severity of LTAP crashes in the GES. Appendix A explains the case weighting scheme. Definitions of the causal factors are presented in Appendix B.

At both signalized and unsignalized intersections, the SV driver was often unaware of the crash hazard. In the case of faulty perception, either the SV driver misjudged how fast the POV was approaching or how close the POV was to the intersection, or did not perceive that the POV was in his or her vicinity. A potentially harmful situation was not obvious to the SV driver. Furthermore, when the SV driver's view was obstructed, the driver could not be cognizant of the crash hazard, since the oncoming POV was not in view. In these cases, the SV driver's unawareness of the crash hazard contributed to the crash.

3.3 CLINICAL ANALYSIS RESULTS: CRASH CHARACTERISTICS

The cases in the clinical sample were distributed by whether the SV was moving (the SV slows down but does not stop before it turns left) or stationary (the SV stops at the intersection and then proceeds later to make the left turn) prior to the crash. Table 3-2 shows this distribution by causal factors. More than two-thirds of the cases in which precrash motion was known were moving prior to the crash. This is significant due to the different kinematic conditions and time budgets that are available under each condition.

From the results of the analysis of the clinical sample, some other features of this crash type were found:

1. The SV is more likely to be the vehicle that has been struck than the vehicle that strikes another vehicle at both signalized (76.3 percent of vehicles that have been struck versus 23.7 percent of vehicles that strike another vehicle) and unsignalized (81.1 percent of vehicles that have been struck versus 18.9 percent of vehicles that strike another vehicle) intersections.

Table 3-1
Summary of Causal Factors of LTAP Crashes

Causal Factors	Signalized		Unsignalized		Signalized + Unsignalized	
	No. of Cases	Weighted %	No. of Cases	Weighted %	No. of Cases	Weighted %
Faulty perception						
Driver looked but misjudged traffic velocity/gap	24	18.3	19	11.6	43	30.0
Driver looked but did not see	22	14.8	11	8.4	33	23.2
View obstructed						
Intervening vehicle(s)	22	12.3	10	9.9	32	22.3
Roadway geometry	0	0.0	2	2.1	2	2.1
Environmental factors (rain, fog)	1	0.1	0	0.0	1	0.1
Violation of signal						
Subject vehicle (SV)	8	2.0	0	0.0	8	2.0
Principal other vehicle (POV)	17	9.9	0	0.0	17	9.9
Both SV and POV	6	3.5	0	0.0	6	3.5
Attempted to beat other vehicle	3	3.2	0	0.0	3	3.2
Driver inattention (distracted)	4	1.4	0	0.0	4	1.4
Improper signaling by POV	1	1.5	1	0.1	2	1.7
Driving under the influence (DUI)	2	0.3	1	0.1	3	0.4
Total	110	67.3	44	32.2	154	99.8

Note: 30 unknown cases were eliminated.

Table 3-2
SV Precrash Motion in LTAP Cases

Causal Fadtor	Moving		Stationary	
	No. of Cases	Weighted %	No. of Cases	Weighted %
Attempted to "beat" other vehicle	3	5.0	0	0.0
Violation of signal				
Both	1	0.8	5	4.4
POV	11	12.5	4	1.9
sv	4	0.8	4	2.0
Driver inattention (distracted)	3	1.8	1	0.2
DUI	1	0.2	1	0.2
Faulty perception				
Looked - Did. not see	14	17.6	8	4.9
Looked - Misjudged velocity/gap.	20	21.7	4	5.9
View obstructed				
Intervening vehicle(s)	9	8.6	12	8.9
Environmental	1	0.2	0	0.0
Improper signaling by POV	1	2.4	0	0.0
Total	68	71.6	39	28.4

Note: 47 unknown cases were deleted

2. Although LTAP crashes occurred on roadways with posted speed limits between 25 mph and 55 mph, most LTAP crashes occurred on roadways with posted speed limits greater than or equal to 35 mph.

3.4 DISCUSSION

The causal factor categories provide useful guidance for IVHS CAS functional concepts. The categories of ***faulty perception*** and ***obstruction of view*** were the two most frequently occurring causes, accounting for nearly 78 percent of the LTAP crashes.

The ***obstruction of view*** category is primarily caused by intervening vehicles. A CAS that displays relative position and approach parameters of all approaching vehicles in the vicinity of the intersection could be effective in alerting the SV driver. This is particularly true when vehicles are lined up in oncoming traffic lanes. Alternatively, warning of a traffic hazard could be sufficient.

At signalized intersections, the ***violation of signal*** category suggests that POV drivers might fail to obey a TCD because their motivations for traveling through the intersection outweigh the perceived risks or because the drivers believe that there is a high probability that they will traverse the intersection unharmed (Tijerina, Chovan, Pierowicz, & Hendricks, 1993). In the first instance, a driver is unlikely to heed a warning system. In the second case, the driver might benefit from a system that warned of certain hazard. This category might ***also*** be a part of the ***faulty perception*** category since an SV driver might attempt to beat the signal if the gap or POV approach velocity was judged incorrectly.

Since the remaining categories are of unsubstantial quantity or are general in nature, they are not discussed further in this report. The next section discusses potential IVHS crash countermeasure concepts in light of the identified crash characteristics and causal factors.

4. 1VHS CRASH AVOIDANCE CONCEPTS FOR LTAP CRASHES

4.1 INTRODUCTION

The LTAP crash avoidance system concepts in this section are devised with respect to the two SV precrash maneuvers identified in the previous section. Figure 4-1, which illustrates the need for increasing intensity of crash avoidance action as time progresses from the emergence of the initial threat to the actual crash occurring (NHTSA, 1992), will be used in this report as a framework for IVHS LTAP CAS concepts. This framework was also adopted in earlier reports (Tijerina et al., 1993). As the SV driver approaches the intersection to make a left turn, the driver has time to react to alerts and warnings. As the vehicle comes closer to the intersection, driver assistance in the form of driver-vehicle partially automated control systems is necessary since the time available to react is decreased. As the car comes, even closer, driver delays or inadequate braking are not tolerable, and a fully automatic control system (FACS) must be used. Sometimes, even the FACS might not be effective if the kinematics of the situation are too unforgiving. As NHTSA (1992) pointed out, the characteristics of a given CAS will depend largely on the time available to take evasive action and the intensity of action needed to avoid the crash.

For the SV, the intent to turn might be necessary for triggering the countermeasure system. Three behaviors on the part of the SV driver could be used to indicate intent to turn left. When approaching the intersection, the driver might activate the left turn signal to indicate intent. As the vehicle approaches the turn, it will need to be moving slowly enough to make the turn. Deceleration, therefore, might be used to indicate the SV driver's intent to turn left. Thirdly, when roadway geometry includes turning lanes, the presence of the SV in the left turning lane may also indicate intent to turn left.

4.2 DRIVER WARNING SYSTEMS

The best way, to avoid crashes is to prevent the start of a hazardous situation. When the situation warrants, the SV driver must judge whether it is safe to traverse opposing traffic lanes at both signalized and unsignalized intersections. If the intersection is signalized, the SV driver must also consider the signal status. If the SV does not have right-of-way when opposing traffic is oncoming, the warning would be issued to the SV driver (for example, warnings to brake or to not steer) when a hazard exists. However, the POV driver might also be warned to slow down or to stop if a crossing SV is in its path.

4.3 CONTROL-INTERVENTION SYSTEMS

The most relevant example of a partially automatic control system for the LTAP case is that of soft braking, although other examples, such as some degree of automatic steering control, could be feasible. If the SV is not slowing enough to stop before turning when a potential hazard exists, then the countermeasure would entail applying moderate braking that

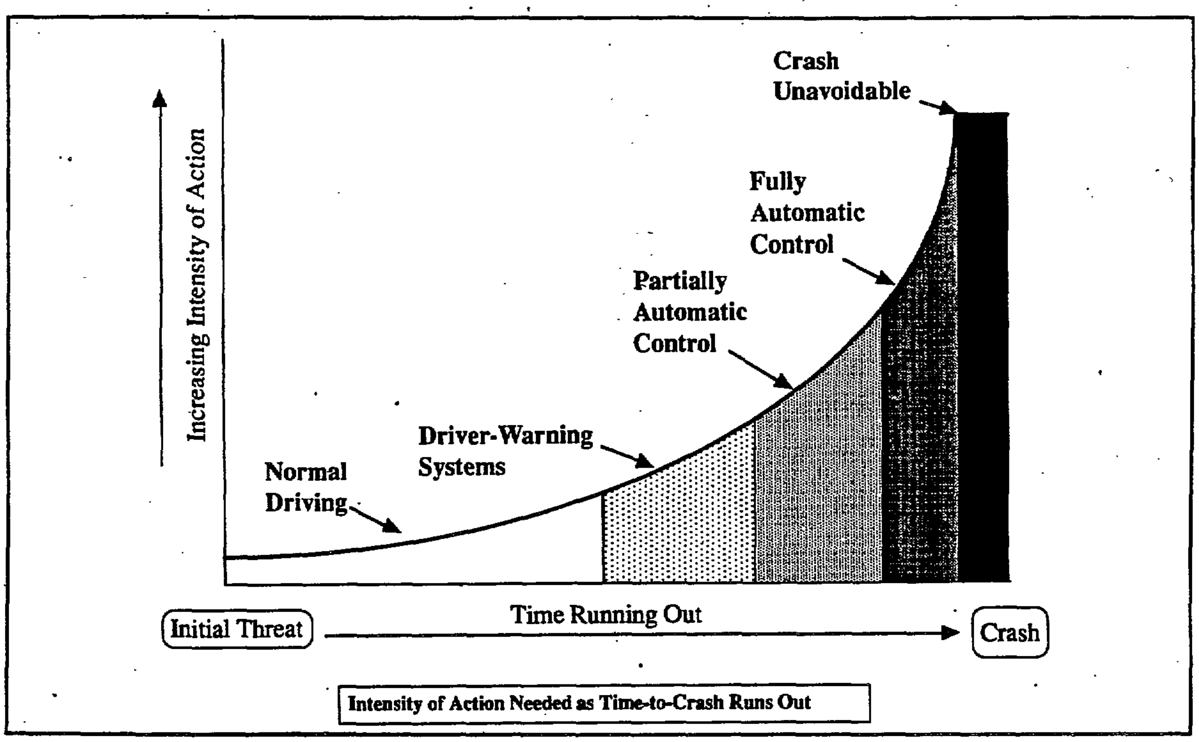


Figure 4-1. Time-Intensity Framework for LTAP Crash Avoidance

the driver would increase by pressing on the brake pedal. Similarly, the POV might be prompted to slow down with soft braking if an SV is in its path and is creating a potential hazard. If the SV is stopped in the intersection, partially automatic steering control might prompt the driver to not proceed (e.g., increased resistance to the steering) instead of turning at inopportune times.

The FACS could provide the last means to avoid a crash. FACS concepts for LTAP crash avoidance involve automatic hard braking (although hard braking may have drawbacks), holding the vehicle at the stopped position until the potential hazard no longer exists, or coupling automatic braking with automatic steering control. The SV would be forced to stop and wait before the vehicle turns left, while the POV passes through the intersection. When the POV approaches an SV, the POV FACS would engage hard braking to prevent it from colliding with the SV or to reduce its speed to decrease impact severity. POV automatic steering could enable controlled swerving to avoid a collision with surrounding vehicles and the SV, although automatic steering may have additional drawbacks.

The next section presents a simplified model of LTAP maneuvering with respect to these crash avoidance concepts.

5. MODELING REPRESENTATION

5.1 INTRODUCTION

A simple LTAP model is presented that assumes the turning vehicle follows a quarter-circle turn of radius R during the maneuver. Information on SV and POV velocity, acceleration, and distance to the Stop Line of the intersection is assumed to be known (see Figure 5-1). The POV is assumed to travel at constant velocity in a straight-line approach to the intersection. Furthermore, the SV driver's intent to turn left is assumed to be known through such indications as turn signal activation, SV position in a turn lane, slowing against a green light, and so forth. The representation in this report, however, uses deceleration as the intent to turn left. Two subtypes of the LTAP crash are modeled based on maneuvers identified in the analysis and by Ueno and Ochiai (1993): the SV does not stop before it turns left (Subtype 1), and the SV stops at the intersection, then proceeds later to make the left turn (Subtype 2).

5.2 SUBTYPE 1: SV DOES NOT STOP

In this LTAP crash subtype, the SV slows, but does not stop, makes the LTAP maneuver, and strikes or is struck by the oncoming POV. A crash could be avoided if the SV stopped before the vehicle turned left to allow the POV to clear the intersection. For simplicity, the SV may be considered to safely stop as far as one lane width (12 ft) beyond the intersection Stop Line into the intersection. CAS concepts for this LTAP crash subtype must support braking to a full stop as the basic evasive maneuver.

The clinical analysis of crash files indicates that LTAP crashes occur at posted speed limits of 25 to 55 mph. However, drivers who wish to turn left must slow down based on the geometry of the intersection. Consider, as an example, the intersection geometry of Figure 5-1. R_m is the maximum turning radius when the left turn is initiated at the Stop Line; but when the SV starts to turn further into the intersection, the turning radius can be as small as R_a. For modeling purposes, 12-ft-wide lanes, no median, and 16 ft vehicle lengths are assumed throughout. In the model, it is assumed that the SV is traveling at some initial speed (V_0), is centered in the inner lane, and will turn left onto the center of the inner cross-traffic lane. Furthermore, the coefficient of friction (μ) between the road surface and the SV tires is assumed to be 0.7, and the maximum turn radius (R_m) is assumed to be 30 ft. Regardless of initial approach velocity, the maximum velocity with which a vehicle can make an unbanked turn without skidding is:

$$V_{max\ turn} = \sqrt{(R_m)\ (\mu)\ (g)} = \sqrt{(30)\ (0.7)\ (32)} = 26 \text{ ft/s} \tag{1}$$

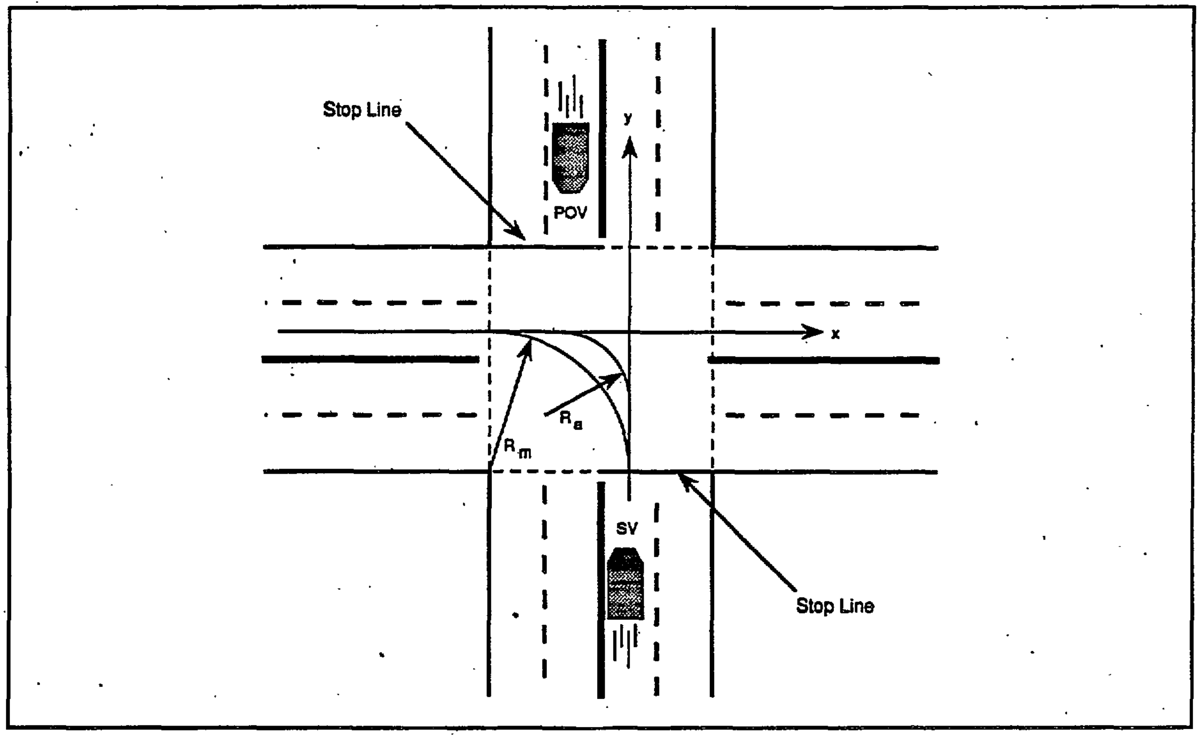


Figure 5-1. Model Intersection Geometry

where,

$V_{max\ turn}$	=	Maximum turning velocity without skidding, for an unbanked turn of radius (R_m) and coefficient of friction (μ), ft/s
μ	=	Coefficient of friction between road surface and vehicle tires
g	=	Acceleration due to gravity, 32 ft/s^2

The rational driver who intends to turn left will start slowing well before the intersection Stop Line is reached. Wortman and Mathias (1983) reported an empirical distribution for nominal decelerations of drivers at signalized intersections with a 50th percentile value of approximately .31 g (a = 9.92 ft/s^2). This study examined full stops at signalized intersections rather than left turn maneuvers. However, for purposes of explanation, a 9.92 ft/s^2 deceleration will be used to determine when the SV driver begins slowing to attain $V_{max\ turn}$ at the start of the quarter-circle turn (i.e., the Stop Line). For example, an SV initially traveling at 35 mph (V_0 = 51.33 ft/s) implies D_{slow} = 98.6 ft to slow down to 26 ft/s, according to the following equation:

$$D_{slow} = \frac{V_{max\ turn}^2 - V_0^2}{2a} \tag{2}$$

where

D_{slow}	=	Distance needed to slow from initial travel velocity (V_0) to maximum turning velocity ($V_{max\ turn}$), ft
$V_{max\ turn}$	=	Maximum turning velocity, ft/s
V_0	=	Initial travel velocity, ft/s
a	=	Braking level to slow, ft/s^2

Drivers must be warned in sufficient time to change from a turning maneuver to an emergency braking maneuver. If the CAS warns the SV driver to stop, the SV will continue the preplanned deceleration until the SV driver realizes that an emergency braking maneuver is required. The time interval between CAS warning onset and emergency braking onset is referred to in this report as t_d. This is the transition time from what the driver planned to do to what the driver is warned to do. The emergency braking deceleration (a^*) is assumed to be greater than the nominal deceleration of the left turn maneuver (a).

To illustrate, consider Figure 5-2, a simplified representation of the SV velocity as a function of the distance from the left turning point. For an SV that is traveling 45 mph (66 ft/s), nominal braking (.31 g) will start at some distance from the turning point such that the maximum turning velocity is reached at the left turning point. If the braking starts any later, then nominal braking levels will not decrease speed enough to reach the maximum turning velocity. Thus, harder braking (.5 g) will be required to slow the vehicle enough to turn.

To estimate the maximum time available for emergency braking, the available distance budgets must be identified. Based on the previous discussion, the distance available ($D_{available}$) includes the distance required to slow the vehicle from an initial SV velocity (V_0) to the maximum turn velocity ($V_{max\ turn}$), using the nominal deceleration (a). For this representation, it is assumed that the SV must stop as far as one lane width (12 ft) into the intersection while awaiting its turn opportunity. Thus, one lane width (lw) is added to the total distance:

$$\begin{aligned} D_{available} &= D_{slow} + lw \\ &= \frac{V_{max\ turn}^2 - V_0^2}{2a} + lw \end{aligned} \tag{3}$$

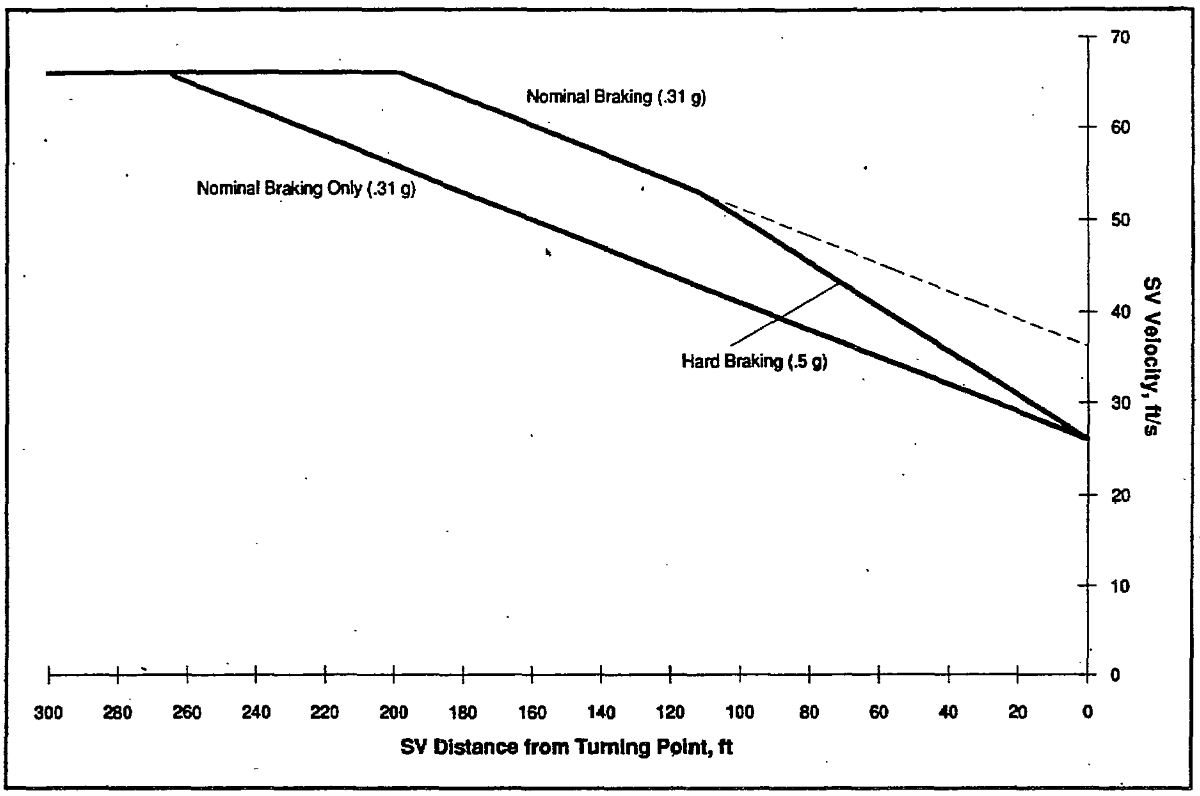


Figure 5-2. Idealized SV Velocity Profile for LTAP Maneuver

where

$D_{available}$	=	Distance available for crash avoidance braking maneuver, ft
a	<	0 (nominal deceleration, negative in sign)
$V_{max\ turn}$	≤	V_0
lw	=	Lane width, ft

All other terms are as previously defined.

In this example, $D_{available}$ = 98.6 ft + 12 ft = 110.6 ft.

The driver begins to decelerate for a left turn without stopping, a CAS warning comes on (as necessary) at the same moment as deceleration begins for the turn, and the nominal deceleration continues until after some time delay, t_d. At this point, the SV is at a new distance from the intersection Stop Line, $D(t_d)_{loc}$, and is traveling at a new velocity, $V(t_d)$. What is the maximum allowable time delay for the driver to react and brake to a full stop no more than 12 ft beyond the intersection Stop Line? Given the developments provided above, the total distance required is the distance traveled during the time delay, $D(t_d)_{loc}$, plus the distance required to decelerate to a stop after the delay, $D(t_d)_{stop}$:

$$D_{required} = D(t_d)_{loc} + D(t_d)_{stop} \tag{4}$$

where

t_d	=	Time delay between warning and action, s
$D(t_d)_{loc}$	=	Distance traveled during the t_d time delay, ft
$D(t_d)_{stop}$	=	Distance required to decelerate to a stop after the t_d time delay, ft

For the maneuver to be successful, we add the following constraint:

$$D_{available} \geq D_{required} \tag{5}$$

Note that, measured from the start of the nominal deceleration for the left turn, the distance the SV will have traveled at $t = t_d$ is as follows:

$$D(t_d)_{loc} = \frac{V(t_d)^2 - V_0^2}{2a} \tag{6}$$

Furthermore, at $t = t_d$ the SV will be traveling at the following velocity:

$$V(t_d) = V_0 + at_d \tag{7}$$

The distance needed to stop after $t = t_d$ is

$$D(t_d)_{stop} = \frac{V(t_d)^2}{2a^*} \tag{8}$$

where all terms have been previously defined. By substituting terms and solving for t_d, the following relationships are derived (recall that a and a^* are treated as negative values):

$$D_{available} = D_{required}$$

$$D_{slow} + lw = D(t_d)_{loc} + D(t_d)_{stop}$$

$$\frac{V^2_{max\ turn}}{2a} - \frac{V_0^2}{2a} + lw = \left[\frac{V(t_d)^2}{2a} - \frac{V_0^2}{2a}\right] - \frac{V(t_d)^2}{2a*}$$

$$\frac{V^2_{max\ turn}}{2a} + lw = \frac{V(t_d)^2}{2a} - \frac{V(t_d)^2}{2a*} = \frac{V(t_d)^2}{2}\left[\frac{1}{a} - \frac{1}{a*}\right]$$

$$= V(t_d)^2\left[\frac{a* - a}{2aa*}\right] \tag{9}$$

$$V(t_d)^2 = \left[\frac{V^2_{max\ turn}}{2a} + lw\right]\left(\frac{2aa*}{a* - a}\right)$$

$$V(t_d) = \sqrt{\left(\frac{V^2_{max\ turn}}{2a} + lw\right)\left(\frac{2aa*}{a* - a}\right)}$$

$$if\ V(t_d) = V_0 + at_d \rightarrow t_d = \frac{V(t_d) - V_0}{a}$$

$$t_d = \frac{\sqrt{\left(\frac{V^2_{max\ turn}}{2a} + lw\right)\left(\frac{2aa*}{a* - a}\right)} - V_0}{a}$$

Now consider the following parameters from the illustration:

V_0	=	51.33 ft/s	
a	=	-.31 g	
	=	-9.92 ft/s^2 ;	typical deceleration left turning driver will use to slow
a^*	=	-.7 g	
	=	-22.4 ft/s^2 ;	emergency braking deceleration applied after driver delay
$V_{max\ turn}$	=	26 ft/s	
lw	=	12 ft	

Using the above equation t_d = 2.33 s. If the SV driver of this illustration stops two lane widths into the intersection, then $D_{available}$ will increase by 12 ft to 122.6 ft. This means that t_d

increases from 2.33 s to 3.25 s. This general representation is proposed for use in assessing LTAP crash avoidance braking maneuvers. Next we consider a model for presenting warnings.

If the POV is located in the SV turning path when the SV is turning, a crash will occur. A crash will not occur, however, if the POV clears the SV turning path before the SV begins the turn, or if it arrives in the SV turning path after the SV has cleared the turn.

The time the SV will arrive in the intersection can be calculated from the time that the driver's intent to turn is known. In this analysis, this time is the time for an SV to slow down to the maximum turning velocity and is calculated from the following equation:

$$t_{slow} = \frac{V_{max\ turn} - V_0}{a} \quad (10)$$

where

t_{slow}	=	Time for the SV to slow down to turn, s
$V_{max\ turn}$	=	Maximum turning velocity, ft/s = 26 ft/s
V_0	=	Initial SV velocity, ft/s
a	=	SV deceleration, ft/s^2

The time it takes the SV to clear the intersection once it has slowed to the maximum turning velocity is calculated as

$$t_{clear} = \frac{R_m \left(\frac{\pi}{2}\right) + L}{V_{SV}} \quad (11)$$

where

t_{clear}	=	Time for the SV to turn and to clear the intersection, s
R_m	=	Maximum turning radius, ft
L	=	Length of the SV, ft
V_{SV}	=	SV velocity, ft/s .

For the parameters from the earlier illustration (V_0 = 51.33 ft/s and a = -.31 g), approximately 2.55 s would be required for the SV to slow down to the maximum turning velocity ($V_{max\ turn}$) of 26 ft/s. That is, after 2.55 s from the start of deceleration, the SV would be at the Stop Line and moving at 26 ft/s. In this illustration, the SV would completely clear the intersection in an additional 2.43 s, for a total maneuver time of $t_{slow} + t_{clear}$ = 4.98 s.

If the POV arrives in the SV turning path before the SV clears it, or if the POV does not clear the SV turning path before the SV enters it, then a crash will occur. A crash will not occur, however, if the time for the SV to slow down to turn is greater than the time for the POV to clear the SV travel path, or if the total SV maneuver time ($t_{slow} + t_{clear}$) is less than the time for the POV to arrive at the SV travel path. A crash will not occur, therefore, if

$$t_{slow} > \frac{D_{POV} + (2lw + L)}{V_{POV}}, \text{ or}$$

$$t_{slow} + t_{clear} < \frac{D_{POV} + lw}{V_{POV}} \tag{12}$$

where

t_{slow}	=	Time for the SV to slow down to turn, s
t_{clear}	=	Time for the SV to turn and to clear the intersection, s
V_{POV}	=	POV velocity, ft/s
D_{POV}	=	POV distance from intersection Stop Line, ft
lw	=	lane width, ft = 12 ft
L	=	POV length, ft = 16 ft

For the illustrative case, the POV would have to clear the SV travel path before 2.55 s from the start of the SV deceleration, or not enter it until 4.98 s from the start of the SV deceleration.

Ueno and Ochiai (1993) present data on driver decisions to turn without stopping or to stop and then turn. These judgements are based on the time headway of the POV to reach the middle of the intersection. In this field study, all drivers stopped when the time headway was 3.0 s or less. Virtually no drivers stopped when the time headway was 8.0 s or more. Between 3.0 s and 8.0 s, the proportion of drivers who turned without stopping was roughly a positive function of time headway. This suggests that time headway might be an important parameter in driver decision-making and warning system design. In the example, if the POV is 3.0 s away from the SV travel path when the SV driver begins the turn, then the SV driver will clear the intersection with 3.0 - 2.43 s = 0.6 s to spare. Psychological factors, however, may make this a very uncomfortable maneuver. Thus, the equation for t_{clear} could be used to indicate the kinematic requirements for POV minimum time headways, yet psychological factors might increase these requirements somewhat.

If SV drivers find POV time headways, when the SV is at the start of the turn, of less than 3.0 s uncomfortable (as is suggested by Ueno and Ochiai, 1993), and if the start of the left turn is the reference location from which SV drivers are making their go/no-go judgements, then SV drivers should receive a warning of DON'T GO when the POV is at least ($3.0 + t_{slow}$) times V_{POV} ft from the SV turning path. When the SV slows to maximum turning velocity and is at the Stop Line, the POV time headway will still be 3.0 s. Since the SV driver has already started a (nominal) .31 g deceleration, the SV driver could, even with a 2.33 s delay, increase the deceleration up to .7 g and stop the vehicle in time.

This CAS warning and intervention model described above was assessed using the above system of equations, and Table 5-l presents the results. SV velocities were varied from 25 to 55 mph, since this range covers most legal speed limits. The distance required to slow down to the maximum turning velocity (26 ft/s) is given for normal deceleration (0.31 g). The available distance is 12 ft more than the distance required to decrease speed. The maximum time available to react, td, is also given for hard braking and for emergency braking. The maximum time available increases as initial SV velocity increases. This happens because the distance required to slow down is an increasing function of $V0$ *(see* Figure 5-3). Therefore, drivers are applying the nominal deceleration to slow to at least $V_{max\ turn}$ earlier, at higher velocities.

To determine the proportion of drivers who could brake as fast or faster than td, subtract vehicle and IVHS system time delays, and look up the remaining value on a cumulative probability plot of brake reaction time. A first approximation of this distibution could be data from surprise brake reaction times. Figure 5-4 is the theoretical data for the surprise brake reaction time of Sivak, Olson, and Farmer (1982) modeled as a lognormal distribution, with a mean of 0.07 log seconds and a standard deviation of 0.49 log seconds. This corresponds to a 50th percentile value of 1.07 s and a standard deviation of 0.63 s. Thus, if 2.0 s are available for the driver to respond, then approximately 90 percent of drivers should be able to respond in time to avoid the crash and, therefore, can benefit from such a CAS.

5.3 SUBTYPE 2: SV DRIVER STOPS, THEN MAKES A LEFT TURN

The second subtype of LTAP maneuver involves an SV that stops, then proceeds to turn, and is struck by the POV. For this subtype, we assume that the SV stops approximately 12 ft beyond the intersection Stop Line. A model of a CAS warning system may be as follows:

- Assume that the SV will undergo 0.15-g acceleration from a stop when the driver elects to turn left.

- Assume the smaller turning radius in Figure 5-l. This is estimated to be Ra = 18 ft. The total clearance distance is the distance for a quarter-circle turn about this radius (approximately 28.3 ft), plus 12 ft to clear the lane width beside the POV travel lane, plus 16 ft of SV length. The total clearance distance, $Dclear$, therefore, is approximately 56.3 ft.

Table 5-1
Sample Calculations for Subtype 1: SV Does Not Stop

Subject Vehicle Velocity, V_0		Normal Deceleration (a = .31 g)		t_d (s)[3]	
mph	ft/s	D_{slow} (ft)[1]	$D_{available}$ (ft)[2]	Hard Braking (a^* = .5 g)	Emergency Braking (a^* = .7 g)
25	36.7	33.7	45.7	0.3	0.9
30	44.0	63.5	75.5	1.0	1.6
35	51.3	98.7	110.7	1.8	2.3
40	58.7	139.4	151.4	2.5	3.1
45	66.0	185.5	197.5	3.2	3.8
50	73.3	237.0	249.0	4.0	4.6
55	80.7	293.9	305.9	4.7	5.3

Notes:

1) $D_{slow} = \dfrac{V_{max\,turn}^2 - V_0^2}{2a}$; $V_{max\,turn} = 26$ ft / s

2) $D_{available} = D_{slow} + lw; lw = 12$ ft

3) $$t_d = \frac{\sqrt{\left(\dfrac{V_{max\,turn}^2}{2a} + lw\right)\left(\dfrac{2aa^*}{a^* - a}\right)} - V_0}{a}$$

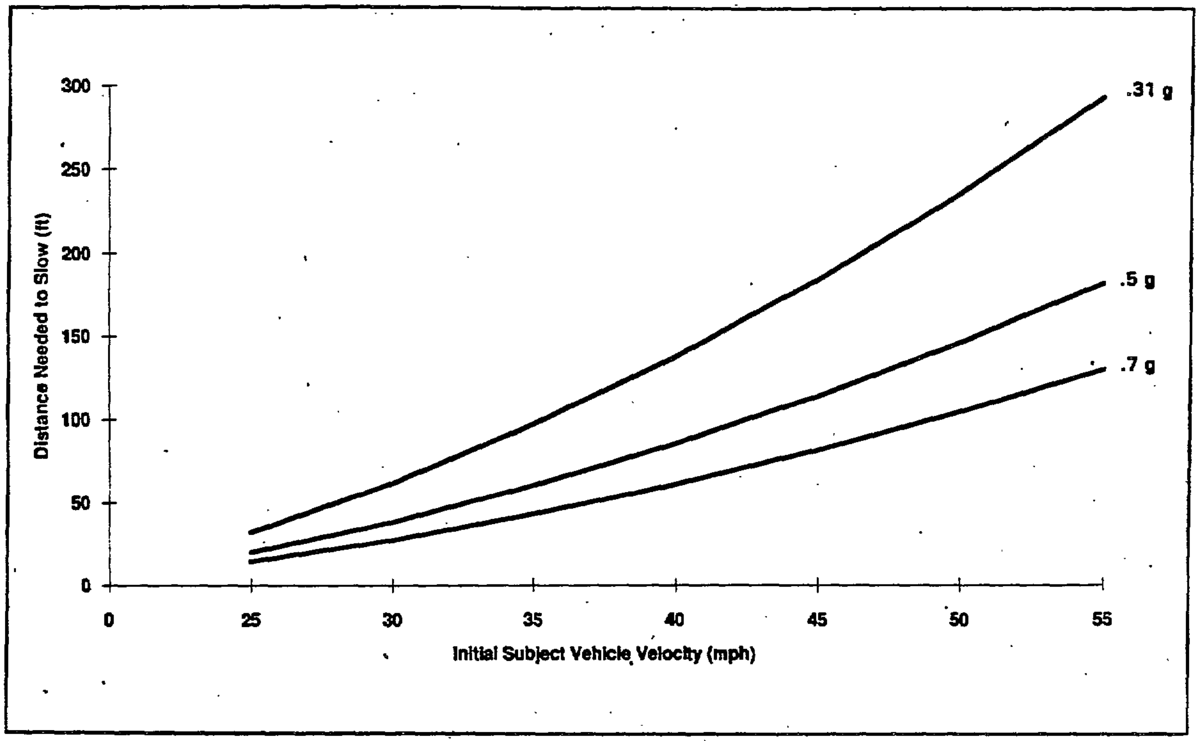


Figure 5-3. Distance Required to Slow to Maximum Turn Velocity (26 ft/s) as a Function of Velocity and Braking Level

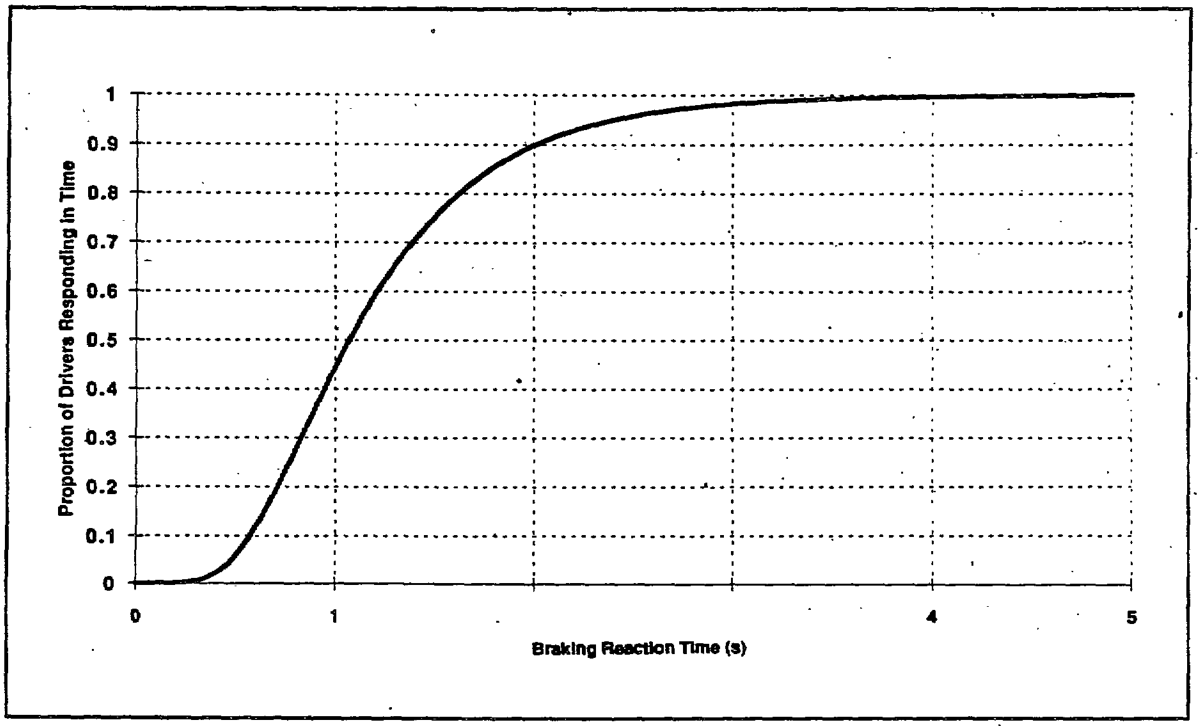


Figure 5-4. Theoretical Distribution for Surprise Brake Reaction Time (from Sivak, et al., 1982)

- Determine, for the above SV trajectory and distance, the time needed to clear the intersection using the following t_{clear} expression:

$$t_{clear} = \sqrt{2\frac{D_{clear}}{a}} \quad (13)$$

- Compare this with POV time headway plus some margin for error. For example, Ueno and Ochiai (1993) used 1.5 s as the driver time allowance for initiating the left turn. This margin is referred to by Enkelmann et al., (1993) as the "warning reserve." If the POV time headway is less than t_{clear}, then the SV cannot clear the intersection.

- If the driver takes a foot off of the brake pedal, provide a warning when the POV time headway is less than the t_{clear} + 1.5 s time allowance.

- If FACS is involved, concurrent with a warning, use control-intervention to provide warning and increased steering resistance to keep the SV from pulling out across the opposing traffic lanes, until all is clear. Alternatively, it may be better to keep the vehicle from moving altogether.

This representation is simple and could work well. The time budget allowed for driver time allowance would be used as the time available for driver-information processing. Since the SV is stationary, this could be adjusted to whatever delay is desired.

Assessing the effectiveness of such a system from a human standpoint will be difficult. Sometimes the appropriate response is "DO NOTHING. WAIT." This is just such a case and so the notion of "reaction time" is inappropriate here. Also, questions will again arise about how drivers will respond to such a system when they "perceive" no problem.

6. RESEARCH NEEDS

The intent of this work has been to identify crash avoidance opportunities and to illustrate design challenges for LTAP crash countermeasures. This section describes the research needs suggested by the analysis. Data needs to support further modeling of the crash circumstances are stressed. Modeling efforts are emphasized to better understand the underlying mechanisms, the crash avoidance parameters, and the potential effectiveness of various NHS crash countermeasures. Thorough analysis and assessment of the crash problem and alternative solutions will minimize risk to the developer and ultimately foster more rapid development of IVHS in general. Furthermore, an in-depth analytical representation of the crash problem will be a key to successful IVHS crash countermeasure system aIgorithm development for both driver indications (alerts and warnings) and FACS implementation.

6.1 CLINICAL ANALYSIS AREA

- The reported causal analysis (see Section 3.0) showed causal factors within LTAP crash subtypes. This cross-tabulation should be expanded so that different causal factors associated with different subtypes can be more readily understood. Other possible data sources could include NASS, GES data for other years, insurance databases, or other similar databases.

- 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.

- The clinical sample did not contain any cases due to loss of traction. The problem size estimate of Section 2.0 indicates that about 20 percent of all LTAP crashes occurred on wet and snowy/icy pavements. However, this type of causal factor might be identified in support of IVHS crash-avoidance countermeasures that, while not specific to the LTAP maneuver, nevertheless could contribute to safety in such circumstances.

6.2 DRIVER BEHAVIOR AT LEFT TURNS ACROSS PATH

- The analysis assumed a rudimentary response — braking — by the SV driver. Information is needed about driver response to TCDs, as well as to the countermeasure. An understanding of the psychology of left turn negotiation would be useful for more realistic modeling and subsequent design for the IVHS CAS. Useful information might involve an extension of the analytic model of McKnight and Adams (1970). Future research might also examine the social psychology of intersections, i.e., the influence that the behavior of other drivers (making left turns) and pedestrians has on a person's left turn maneuvers. This effect of group behavior on the individual could be extended to compliance with TCDs.

- Knowing the correlation between driver reaction time and, nominal braking rate as well as the correlation between brake reaction time and peak braking level sensitivity would be beneficial. These could be useful in designing the algorithms for warning and FACS and in tailoring them to specific types of individuals.

- The SV and POV drivers' decision processes should be explored further. An understanding of these processes may indicate the manner in which crash-avoidance information should be conveyed to the driver and how adding this information to the driver task impacts workload. Left turn maneuvers at intersections induce high driver workload (Hancock, Wulf, Thorn, and Fassnacht, 1989) and represent decisions under time stress. Data on the effect of intersection geometry, other drivers, environmental conditions, vehicle characteristics, and the SV driver's own decision biases on driver workload and decision-making would be useful in developing effective crash countermeasures. Also, Caird and Hancock (1994) suggest that vehicle-size information is used by drivers in judging POV time headway. Methods to uncover data that are used by drivers might include driver-vehicle performance measures as well as subjective reports by drivers on what they attend to, how they make use of the data, what they consider the decision alternatives to be, and so on.

- The actual maximum turning velocities taken by SV drivers for different geometries, road surface conditions, and vehicle types would provide further insights into driver behavior in LTAP maneuvers.

- Effects of control intervention on the driver should be investigated. Studies such as those by Nilsson, Alm, and Janssen (1991) have reported an overall positive effect on car-following performance. Similar studies of the LTAP maneuver should also be conducted.

- Studies of the interaction between two or more drivers are needed in the context of how the CAS and driver-vehicle behavior- change with multiple vehicles. This is likely to be particularly important in designing and evaluating multiple warnings to the SV and POV drivers. Certain types of conflicts could possibly occur if both drivers are warned of a possible crash. The impact of various driver behaviors on other warning schemes might also be researched.

Alternative displays to convey alerts, warnings, and system feedback to the driver should be explored. In particular, active control devices such as an active gas pedal or torque-shift steering wheel (Schumann, Godthelp, Farber, & Wontorra, 1993) should be explored for conveying IVHS CAS information to the driver.

The left turn maneuver is preplanned. As such, there may be some "cognitive inertia" to shift from one preplanned behavior (i.e., slow and turn without stopping) to an emergency precrash behavior (i.e., emergency stop before the turn). Future research should examine the impact of transitions from preplanned to emergency maneuvers on driver latencies and the accuracy of the response. It is possible that the transition adds considerably to the brake reaction time for any given driver.

- The driver acceptance of an LTAP CAS needs further investigation. For example, drivers will normally negotiate the LTAP successfully. How the driver who cannot see the oncoming POV will react to an LTAP warning to stop is not known. Without visual confirmation of the crash hazard, the warning may not be heeded.

- More information is needed about how the SV driver predicts POV time headway.

- Driver reaction time may not follow the distribution of surprise brake reaction time since the situation in all LTAP maneuvers is not necessarily the same surprise reaction. A better distribution is needed for driver reaction time when the driver's foot is already on the brake pedal.

6.3 LTAP ALGORITHM RESEARCH NEEDS

- Some concepts for an IVHS CAS suitable to the LTAP crash type were discussed. Their presentation in the report is primarily for explication. Additional CAS concepts are needed to enrich the set of alternative system concepts for further analysis and trade studies.

- It is likely that the CAS algorithm will require multiple setpoints. Alternative setpoints should be systematically assessed to determine how setpoints (such as population 50th percentile braking deceleration vs. individual average deceleration) influence driver acceptance and performance. This is an analytical exercise to refine the system design iteratively.

- The impact of various acceleration profiles on algorithm robustness and CAS design should also be explored in more in-depth analyses.

- The false alarm problem should be assessed for LTAP crash avoidance. If it is true that drivers negotiate the LTAP by assessing POV time headways, then there is value to understanding better the psychological aspects of these headways, i.e., their perception, minimum time headways, maximum time headways, and so forth. The work of Ueno and Ochiai (1993) is an important first step. Future work should examine the consistency of their results over a greater variety of travel speeds and intersection geometrics. Such work could promote the development of warning thresholds tailored to specific circumstances.

- The problem of warning familiarity also merits further research. Note that the LTAP problem occurs infrequently (the probability is .03 over the 10-year life of a vehicle that it will be involved in an LTAP crash as the SV). Possibly, this will create unfamiliarity with that will minimize the likelihood of driver warning compliance when the "real" crash hazard is encountered.

- The preferred and most applicable precrash evasive maneuver is braking by the SV. As a last resort, if the SV is beginning the turn, steering away or having a POV evasive maneuver would possibly be appropriate as well. These alternatives should be considered in future research.

- If the POV is also turning, the frequency of false alarms could increase. The development of an LTAP CAS will have to address this possibility, perhaps via vehicle-to-vehicle communications to indicate the POV driver's intent to turn, such as the detection of the POV's turn signal indicator.

6.4 FURTHER MODELING RESEARCH NEEDS

- The analysis reported here was from the vantage point of a single vehicle, that is, the SV. In practice, interactions between SV, POV, and other vehicles present on the roadway must be addressed. For example, does rapid deceleration to avoid an LTAP crash result in a rear-end crash? Questions like this need to be examined in further research1

- Models do not account for all of the parameters of a phenomenon, and the LTAP model presented in this report is no exception. Further refinements of the LTAP model must be addressed that include additional relevant variables for the LTAP maneuver.

- There is a need to understand the actual speed profiles associated with the LTAP maneuver. For example, does the POV tend to speed up or slow down, at intersections rather than maintain a constant velocity? When and what magnitude of deceleration does the left-turning SV exhibit at intersections? Data from Wortman and Mathias (1983) were used for convenience but they represent nominal decelerations to a stop and so may differ from nominal decelerations to slow. What are typical turning velocities for various intersection geometrics? Empirical data on such questions will improve modeling of the LTAP crash circumstances and promote more effective LTAP CAS development.

- The analysis in this report only applies to the case when SV deceleration indicates driver intent to turn left. The effect of other indicators of intent to turn left on the parameters in the model should be studied.

- Normal driving behavior includes some level of crash avoidance. Models should include these characteristics. Modeling more parameters of the crash scenario, such as the effect of yielding or swerving, would provide further insights into the LTAP crash problem. More information about these parameters and their interactions is needed.

One example of current research that may address some of these research needs is the Vehicle Motion Environment (VME) project (Leasure, 1994). The VME project is developing and validating a measurement system that can quantify the specific motions that vehicles exhibit as they move in traffic. The system will establish the locations and motions of all vehicles within the field of view relative to roadway boundaries, other features, and each other. In operation, the VME will gather information on successful collision avoidance maneuvers. Information such as reaction to other drivers cutting in front, normal following distance, typical lane change trajectories, and response to inclement weather will be collected. This information will provide a geometric and kinematic database which can be used to design IVHS countermeasures that intervene and/or provide collision avoidance warnings to the driver. That is, countermeasure parameters can be superimposed analytically on the vehicle motion record to assess their likely performance.

APPENDIX A. CASE WEIGHTING SCHEME

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 Table A-1 and A-2 included the following steps:

- 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 percent of the clinical sample represented by each severity [% of Clinical Sample].
- NHTSA provided the percentage of the GES data represented by each severity [% of 1991 GES].
- The percent of the national profile that each case represented [% Rep. Each Case] was determined by dividing [% of 1991 GES] by [# in Sample].

Table A-l
Case Weighting Scheme For LTAP Crash Causes

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
O(0)	38	24.7	58.7	1.5
1(C)	36	23.4	20.1	0.6
2(B)	24	15.6	13.5	0.6
3/4(A/K)	56	36.4	7.6	0.1
Total	154	100.1	99.9	

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

Table A-2
Case Weighting Scheme For LTAP Crash Subtypes

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	24	22.4	58.7	2.4
1(C)	26	24.3	20.1	0.8
2(B)	16	15.0	13.5	0.8
3/4(A/K)	41	38.3	7.6	0.2
Total	107	100.0	99.9	

Notes:

1) GES crash severity is 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 level 4 (K) severity crashes.

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

APPENDIX B. DESCRIPTION OF CAUSAL FACTORS

Faulty Perception

Looked - Misjudged Velocity/Gap:

The SV driver observes the oncoming POV but still proceeds to initiate a left turn. A typical comment from the subject driver on interview forms and PARs is “the other car must have been speeding because I thought I had plenty of time to turn.”

Looked - Did Not See:

SV driver comments, such as “I never saw the other vehicle,” or “I didn’t see the other vehicle until it hit me,” are included in the documentation of these cases.

View Obstructed

Intervening Vehicles:

These cases are typified by instances where the POV is shielded from the view of the SV driver by other vehicles, traveling in the opposite direction, making a turn. Other circumstances typical of this causal factor are instances on a multi-lane highway where a POV changes lanes to pass a vehicle and impacts the SV making a turn.

Roadway Geometry:

Cases typically where the lead-up to an intersection is an inclined roadway. This shields the subject-driver from observing the POV until the subject vehicle is making its left turn.

Environmental:

Cases where the vision of the SV and POV drivers is reduced by rain or fog.

Violation of Signal

Subject Vehicle:

Cases where the subject vehicle enters the intersection and disregards a red or amber signal status.

Principal Other Vehicle (POV):

Cases where the POV enters the intersection when the SV has a green turn arrow.

Both SV and POV:

Cases where both SV and POV enter the intersection as the signal changes status from green to amber or amber to red.

Attempted to "Beat" Other Vehicle

Cases where the SV driver attempts to perform a left turn ahead of oncoming traffic just as the signal changes from red to green or from green (amber) to red.

Driver Inattention

Cases where the SV or POV driver is distracted from the driving task and does not observe the other vehicle. Typical sources of distraction in these cases are looking for a street sign, talking with a passenger in the vehicle, and searching for something in the vehicle interior.

Improper Signaling

These cases are situations where the SV is at the intersection waiting for traffic to clear to make a left turn. The POV approaches the intersection and signals an intention to turn left. As the SV driver observes the POV's intention to turn, he or she proceeds to initiate a left turn. The POV, instead of making the turn, proceeds straight and impacts the SV.

Driving Under the Influence (DUI)

The driver is operating a motor vehicle with a blood alcohol content (BAC) of over 0.10.

Unknown

Cases where the characteristics of the collision clearly allow them to fit into the crash type but where there is insufficient detail presented to allow determination of the causal factor.

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