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Examination of Unsignalized Intersection, Straight Crossing Path Crashes and Potential IVHS Countermeasures

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13. ABSTRACT (Maximum 200 words)

This report provides a preliminary analysis of unsignalized intersection, straight crossing path (UI/SCP) crashes and applicable countermeasure concepts for the Intelligent Vehicle Highway System (IVHS) program. A UI/SCP crash occurs when two vehicles, one with the right-of-way and one without, collide at right angles while both are attempting to pass straight through an intersection controlled by stop signs. A detailed analysis of 100 such crashes showed that drivers ran the stop sign in about 42% of these crashes and that the remaining crashes involved drivers who stopped and then proceeded against cross traffic. Moreover, about 75% of UI/SCP crashes were caused by drivers who were unaware of the presence of either the stop sign or crossing traffic. The crash avoidance system (CAS) concepts discussed in this report include driver alerts, driver warnings, partially automatic control systems, fully automatic control systems, and a hybrid system that incorporates these concepts and transitions among them. This report concludes with a number of research needs to better understand UI/SCP 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), John A. 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 unsignalized intersection, straight crossing path crash study. The results' are based on the analysis of 100 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 and Louis Tijerina 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., and Mark Mironer of the Volpe Center; William A. Leasure, Jr., Ronald R. Knipling, and August Burgett of NHTSA OCAR; and Jing-Shiam Wang of IMC, Inc., provided technical guidance and reviewed the report.

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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)] ^{0}F ❑ y ^{0}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

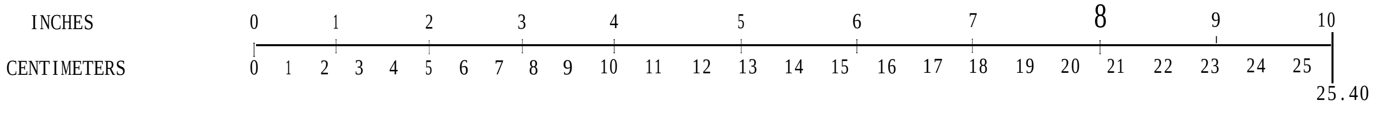
VOLUME (APPROXIMATE)

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] ^{0}C ❑ x ^{0}F

QUICK INCH-CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-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.

a_{POV}	*POV acceleration, ft/s*^{2}
a_{SV}	SV deceleration/acceleration, ft/s^2
CAS	crash avoidance system
CDS	Crashworthiness Data System
D_1	distance from the front of the SV prior to maneuver to the leading edge of the POV travel lane, ft
D_2	distance from the front of the SV prior to maneuver to the far edge of the POV travel lane, ft
d_L	distance from Stop Line to the leading edge of the first travel lane, ft
D_{lane}	distance from the front of the SV, at a given braking distance, to the leading edge of the POV travel lane, ft
$D_{location}$	SV location from the Stop Line at any given instant, ft
$D_{remaining}$	SV location to the minimum braking distance, ft
D_{stop}	SV braking distance required to stop by the Stop Line, ft
$D_{stop(min)}$	required SV braking distance assuming zero driver and machine delays, ft
FACS	fully automatic control system
FARS	Fatal Accident Reporting System
ft	foot, feet
g	unit force of gravity, 32 ft/s^2
GES	General Estimates System
L_{SV}	length of SV, ft
L_{POV}	length of POV, ft
LD_{max}	maximum longitudinal distance for the POV from the beginning of collision field, ft
LD_{min}	minimum longitudinal distance for the POV from the beginning of the collision field, ft
lw	lane width, ft
IVHS	Intelligent Vehicle Highway System
NASS	National Accident Sampling System
NHTSA	National Highway Traffic Safety Administration
NPR	nonpolice-reported
PAR	police accident report
POV	principal other vehicle
RT	reaction time, s
s	second, seconds
SV	subject vehicle
t	elapsed time, s

ABBREVIATIONS AND ACRONYMS (continued)

$t_{available}$	time remaining to accommodate driver and machine delays, s
$t_{driver\ RT}$	SV driver brake reaction time, s
$t_{machine\ delay}$	vehicle delay plus IVHS delay, s
T_1	time until SV crosses the nearest edge of the POV travel lane, s
T_1*	time required for the front of the SV to cross the nearest edge of the POV travel lane, assuming uniform acceleration from a stop, s
T_2	time required for SV to clear the POV travel lane, s
T_2*	time required for the SV to clear the POV travel lane, assuming uniform acceleration from a stop, s
UI/LTAP/IPD	unsignalized intersection, left turn across path, initial perpendicular direction
UI/SCP	unsignalized intersection, straight crossing path
V_{SV}	SV velocity, ft/s
V_{POV}	POV velocity, ft/s
W	intersection width, ft

EXECUTIVE SUMMARY

This report provides a preliminary analysis of unsignalized intersection, straight crossing path (UI/SCP) crashes to support development of crash countermeasure concepts for the Intelligent Vehicle Highway System (IVHS) program Unsignalized intersections can be defined as intersections with stop signs, intersections where signals are no longer functioning due to loss of power, or intersections where the driver must judge whether stopping is appropriate (such as at yield signs and at intersections without any traffic control). This report focuses on crashes that occur at unsignalized intersections controlled by stop signs. Two vehicles, one with the right-of-way and one without, travel' through the intersection in straight paths perpendicular to each other and collide. An analytic model of intersection negotiation behavior at unsignalized intersections is presented to indicate possible sources of driver actions that might contribute to such crashes. The possible sources include unawareness of the intersection during an approach; misinterpreting signage; failure to anticipate sudden braking by a lead vehicle; failure to recognize crash hazards posed by cross traffic either by inattention, misperception, or failure to register the presence of a threat; and unawareness caused by vision obstruction; among others.

UI/SCP crashes accounted for approximately 375,000 police-reported crashes in 1991; this is roughly 6 percent of all crashes in 1991. UI/SCP crash characteristics indicate this is largely a dry pavement, good weather, daylight phenomenon predominantly involving people 54 years of age or younger traveling over a wide range of posted travel speeds, though the majority of crashes occur at posted speeds of 45 mph or less. A detailed analysis of 100 cases in which the subject vehicle (SV) had a stop sign and the principal other vehicle (POV) had right-of-way uncovered two types of UI/SCP crashes: Subtype 1, where the SV driver ran the stop sign, and Subtype 2, where the SV stopped and then proceeded across the intersection at an inopportune time. From a causal factors standpoint, driver inattention (56.4 percent) and obstructed vision (18.7 percent) are predominantly associated with crash Subtype 1. Driver inattention is not involved in crash Subtype 2, instead faulty perception (81.7 percent) and vision obstruction (14 percent) predominate. Collectively, these suggest that a significant proportion of UI/SCP crashes arise due to driver "unawareness" of the crash hazard at the intersection. A variety of other causal factors (such as driver intoxication and adverse weather) also contribute to the UI/SCP crash problem.

The crash avoidance system (CAS) concepts discussed in this report are: driver alerts, driver warnings, partially automatic control systems, fully automatic control systems (FACS), and a hybrid system that incorporates these concepts and transitions among them. The concepts were developed in consideration of the relationship between time to collision and required intensity of avoidance action. Driver alerts are non-directive, in-vehicle signs that indicate the driver is approaching an intersection. These alerts are intended to be presented both early on and frequently in an effort to prevent a crash hazard from ever forming. Driver warnings are directive indications that the driver must stop and, in principle, may be graded in urgency or crash likelihood. Partially automatic control systems and fully automatic control systems are then presented as control intervention schemes that may be appropriate in

situations where driver delay and/or braking performance cannot be tolerated. Control intervention for the UI/SCP crash is introduced in terms of soft braking as well as moderate and graded braking systems.

The analysis presented in this report is aimed at better understanding crash avoidance requirements associated with UI/SCP crashes. It also begins the assessment of alternative CAS concepts. Driver alerts are modeled, by way of an example, in terms of a series system reliability model. In a series system, the system fails if any of its components fails. The need for data on human reliability in the face of CAS is noted. Driver warnings are analyzed in terms of the maximum time available to prevent a crash for driver and vehicle/CAS delays under various kinematic conditions. Both warnings to the SV driver and the POV driver are noted. An alternative assessment examines the notion of constant warning time and the trigger points implied by various kinematic conditions. The presence of intersection stop signs can be anticipated or predicted sufficiently in advance to support constant warning times for the SV driver. This is not necessarily the case in, for example, lane change crashes where a vehicle suddenly and sharply cuts in front of another vehicle. This latter example is more similar to the situation the POV driver is confronted with, especially in Subtype 2, when the POV is close to the intersection. For this reason, constant warning times for the POV driver are not evaluated in this report. The potential of warning the POV driver that the SV is entering the intersection is assessed. For the scenarios assessed, POV warnings may work for crash Subtype 1 and for crash Subtype 2. However, even if POV drivers are warned when the SV fails to exhibit expected braking or begins accelerating from a stop into the intersection, this may lead to false alarms, secondary safety consequences such as rear-end crashes with the POV as lead vehicle, and the like. The need for further research is underscored. Control intervention, which includes partially automatic and fully automatic control systems, is not explicitly modeled here. However, the minimum stopping distances required in the absence of appreciable driver or machine delays indicate possible CAS trigger points for control intervention. All of the kinematic analyses assume vehicles traveling at constant velocity and applying uniform deceleration or uniform acceleration. The need to explore the implications of more complex motion profiles and to better represent true driver behavior at intersections is noted.

This report concludes with a number of research needs to better understand UI/SCP crashes and guide CAS development. The clinical analysis should be verified by analyzing additional cases and possibly comparing the assessments of different clinical analysts for concordance. There are many driver human factors research needs and some of those peculiar to this crash type are presented. Of particular concern are the questions of how drivers will interact with CAS systems, the potentially disruptive effects of false alarms, and the inability to visually verify a threat. CAS algorithm needs for UI/SCP crash avoidance are discussed, including research on the attenuating factors of reliability and measurement error (accuracy or timeliness) to algorithm success and the use of variable setpoints tailored to individual drivers. Additional research needs include an analysis of safety implications of CAS concepts in the context of a traffic system and interaction between SV and POV drivers during the precrash phase.

1. BACKGROUND

1.1 OUTLINE

This report provides an analysis of unsignalized intersection, straight crossing path (UI/SCP) crashes. It introduces the problem of UI/SCP crashes, indicates the problem size, describes the crash characteristics, and identifies causal factors derived from an assessment of a sample of UI/SCP crash cases. These data are used in this report to identify crash countermeasure concepts for the Intelligent Vehicle Highway System (IVHS). These concepts are organized in terms of time-to-collision and required intensity of crash avoidance action. The report presents an analysis of crash countermeasure requirements and opportunities for crash avoidance. It concludes with a discussion of key research needed to extend the analysis presented here.

1.2 DEFINITION OF UNSIGNALIZED INTERSECTION, STAIGHT CROSSING PATH (UI/SCP) CRASHES

Unsignalized intersections can be defined as intersections with stop signs, intersections where signals are no longer functioning due to loss of power, or intersections where the driver must judge whether stopping is appropriate (such as at yield signs and at intersections without any traffic control). This report focuses on crashes that occur at unsignalized intersections controlled by stop signs. Two vehicles, one with the right-of-way and one without, travel through the intersection in straight paths perpendicular to each other and collide. The intruding or subject vehicle (SV), the vehicle without right-of-way, may either strike or be struck by the other involved or principal other vehicle (POV). Figure l-1 illustrates a prototypical UI/SCP precrash scenario at a two-way stop sign.

Figure l-2 shows a model of intersection negotiation behavior at unsignalized intersections, adapted from the work of McKnight and Adams (1970). This model suggests possible sources of driver actions that can contribute to UI/SCP crashes and, therefore, is helpful in identifying crash countermeasure concepts that address those problems. It is also the basis of intelligent driver support in the European DRIVE program (Michon, 1993).

The driver should decelerate when the vehicle approaches the intersection and should prepare to stop. The driver who is unaware of the intersection for whatever reason might fail to slow down. Similarly, the driver who makes erroneous assumptions about the meaning of signs (e.g., assumes that a four-way stop is in effect) might cross the intersection at inopportune times.

The driver who intends to proceed across the intersection must observe other traffic and pedestrians and must watch lead vehicles to anticipate sudden stops. The driver might misperceive cross traffic with respect to speed, acceleration, distance to the intersection, or direction of travel (straight versus turn). Alternatively, a POV driver of a cross traffic vehicle might suddenly apply the brakes in a manner that places the POV across the SV's travel

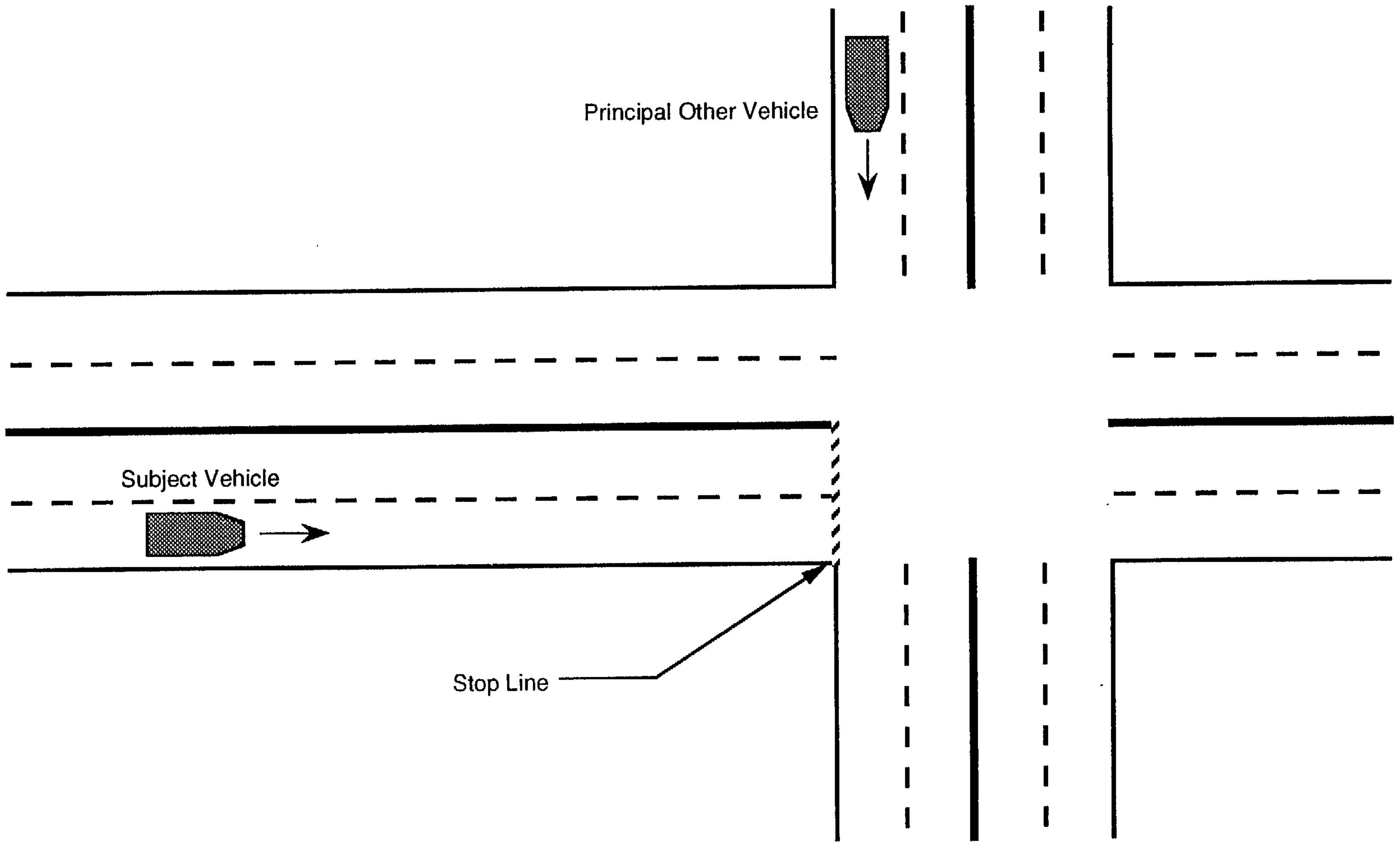
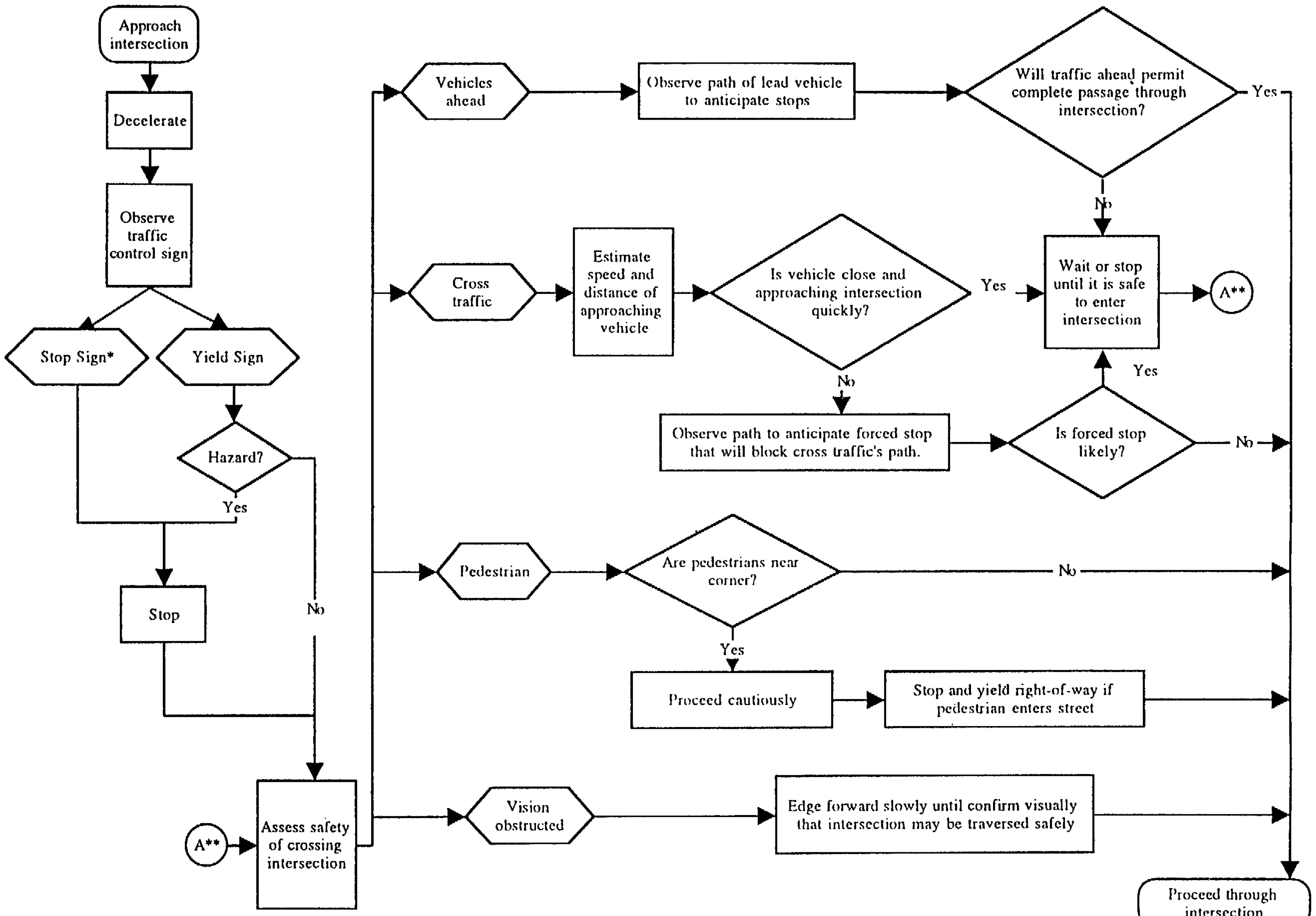


Figure 1-1. Idealized UI/SCP Precrash Scenario



* Includes implied stops such as a four-way stop at a disabled signal head.
** The circled letter A's represent a feedback loop

Figure 1-2. Simple Model of Unsignalized Intersection Negotiation Driver Behavior lane. Drivers must also watch pedestrians because they are often highly unpredictable. However, pedestrians might also attract attention by their dress or manner and, therefore. might distract the driver. Finally, the SV driver might not have a good line-of-sight for observing cross traffic and might proceed across the intersection unaware that a vehicle is approaching on a collision course. All of these potential sources of error might cause an otherwise rational driver to enter into an unsafe driving situation.

In summary, the ideal driver negotiating an unsignnlized intersection must perform the steps shown in Table 1-1. Although this simple model of driver behavior does not define how a driver accomplishes these tasks, this list suggests opportunities for crash-avoidance assistance. Such opportunities are based on a combination of crash subtype characteristics and causal factors. The next section describes the crash problem size.

Table 1-1
Steps Used by Drivers to Negotiate Unsignalized Intersections

1.	Detect the presence of the intersection during an approach
2.	Correctly identify signage
3.	Anticipate sudden deceleration from lead vehicle(s)
4.	Detect the presence of cross traffic
5.	Recognize crash hazards posed by cross traffic, perhaps by estimating the speed, acceleration, and distance of the approaching vehicles
6.	Watch for and anticipate other traffic or pedestrians that may cause a cross traffic vehicle to suddenly stop in the SV travel lane
7.	Identify problems that might obstruct the driver’s vision and attempt to overcome such problems
8.	Stop the vehicle
9.	Estimate when it is safe to proceed through the intersection

2. CRASH PROBLEM SIZE

2.1 PROBLEM OVERVIEW

Figure 2-1, based on data from the National Highway Traffic Safety Administration (NHTSA) accident data systems, presents a pie chart indicating the magnitude of the UI/SCP crash problem. The data are based on police accident reports (PARs) derived from the NHTSA General Estimates System (GES) 1991 statistics. Approximately 6 percent of PARs were UI/SCP crashes, which represent approximately 375,000 crashes. An analogous and accurate determination of fatal crashes and fatalities due to UI/SCP crashes is not possible at this time since the 1991 Fatal Accident Reporting System (FARS) does not contain the same defining data variables and elements used for GES data retrievals. Additionally, an estimated 436,000 nonpolice-reported (NPR) UI/SCP crashes occurred. The UI/SCP crash type accounted for roughly 3.6 percent, or 16 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.

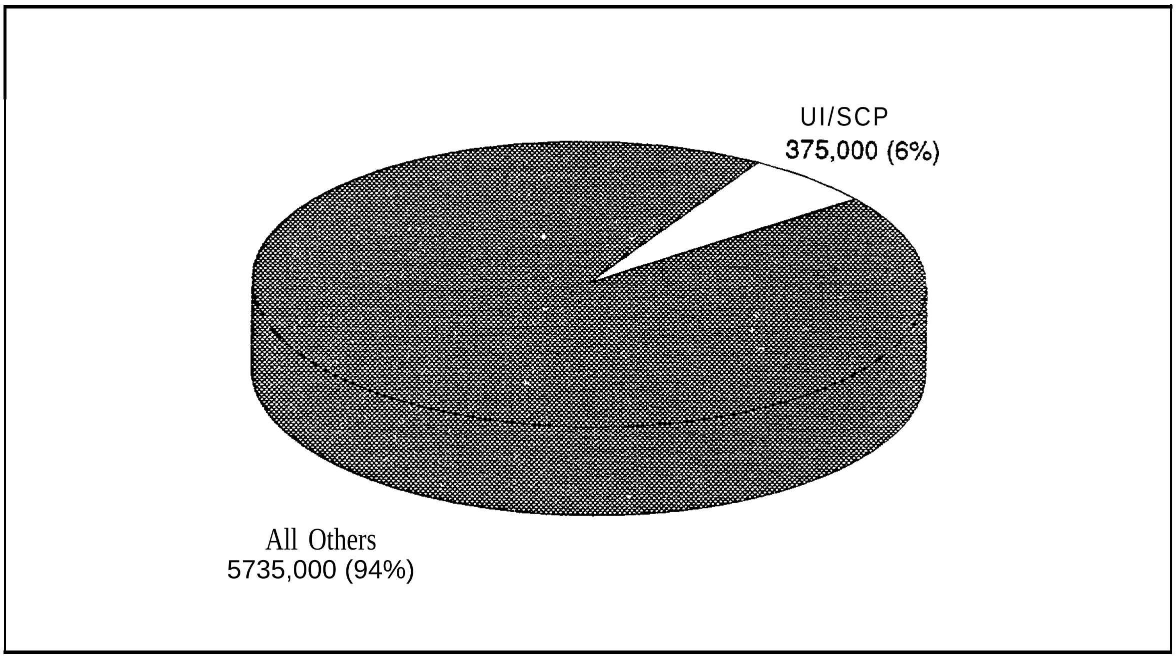


Figure 2-1. Problem Size, 1991 GES Data

The above problem size estimate of 375,000 police-reported target crashes for 1991 is conservative. In addition to these UI/SCP crashes, in 1991 there were 17,000 crashes occurring at unsignalized intersections and coded in GES as “straight crossing paths, specifics unknown” or “specifics other.” More importantly, there were an estimated 229,000 crashes at unsignalized intersections categorized as the unsignalized intersection, left turn across path, initial perpendicular direction (UI/LTAP/IPD) crash type. Figure 2-2 shows a simple schematic of this crash type. In the UI/LTAP/IPD crash type, the two vehicles approach each other at a perpendicular angle, and the vehicle approaching from the right turns left across the path of the other vehicle. These additional crashes may have many of the same causal factors and dynamics as the straight crossing crashes addressed in this report. Altogether, a liberal definition of target crashes yields a problem size estimate of 621,000 police-reported crashes and 743,000 NPR crashes for 1991. Some of the UI/SCP analyses in this report might apply in part to UI/LTAP/IPD crashes as well, although in an effort to maintain homogeneity of the crash sample, this crash subtype has not been formally addressed.

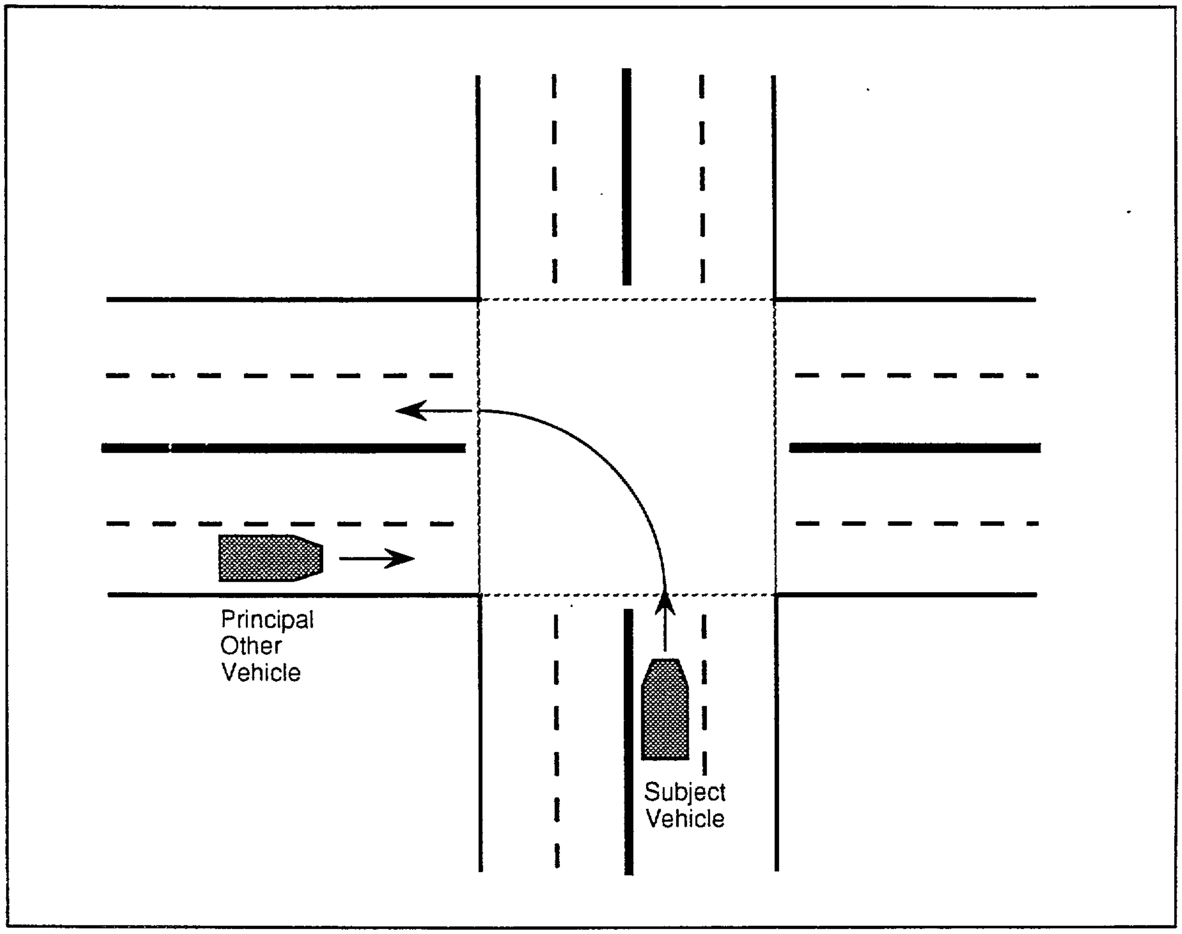


Figure 2-2. Depiction of UI/LTAP/IPD Crash Scenario

2.2 DISCUSSION

The UI/SCP crash problem represented about 6 percent of the total crash population in 1991. Available technologies may be able to provide affordable UI/SCP crash countermeasures, thereby adding to highway safety and providing technology transfer to other crash types.

1991 GES data obtained from NHTSA indicate that roadway conditions are not a priority consideration for a first-order assessment (see Table 2-l). These data indicate that 74 percent of UI/SCP crashes occur on dry pavement, 19 percent on wet pavement, and only 6 percent occur on snowy or icy pavement. The high incidence of dry pavement crashes suggests that the primary modeling of braking or steering maneuvers should assume good traction. The data also show that good ambient lighting predominates in UI/SCP crashes (e.g., 80 percent occur in daylight). While elderly drivers are overrepresented in intersection crashes (Peacock & Karwowski, 1993), the majority of drivers (81 percent) involved in UI/SCP crashes are 54 years of age or younger. Speed profiles, when modeled, should span a wide range of speeds to represent a variety of posted speed limits, though the distribution in Table 2-l indicates the majority of involved vehicles were traveling 35 mph or less. The statistics concerning the obstruction of driver vision and the distraction of driver attention are considered conservative because PAR data do not reliably capture the involvement of these factors in crashes. Also, Table 2-l data imply a limited role for loss of control factors such as snowy or icy roadways or alcohol-intoxicated drivers. The next section discusses the circumstances surrounding UI/SCP crashes.

Table 2-1
Characteristics of UI/SCP Crashes

Characteristic	Percent Occurrence
Pavement conditions	
Dry	74%
Wet	19%
Snowy or icy	6%
Other	1%
Ambient weather conditions	
No adverse weather	84%
Rain	12%
Snow or sleet	3%
Fog or smog	1%
Ambient light conditions	
Daylight	80%
Dark, lighted	12%
Dark, unlighted	5%
Dawn or dusk	3%
Alcohol involved in crash	4%
Age distribution of involved drivers	
15-24	28%
25-54	53%
55-64	8%
65+	11%
Sex distribution of involved drivers	
Female	42%
Male	58%
Travel velocity (mph), all involved vehicles	
0-5	11%
6-10	11%
11-15	8%
16-20	10%
21-25	16%
26-30	13%
31-35	14%
36-40	6%
41-45	5%
46-50	2%
51-55	2%
56+	1%
Indication (on PAR) of driver vision obstruction	3%
Indication (on PAR) of distraction of driver attention	1%

Notes: Figures are from 1991 GES data. Unknowns were distributed proportionally.

3. ANALYSIS OF UI/SCP CRASH CIRCUMSTANCES

3.1 INTRODUCTION

This section describes the UI/SCP crash characteristics and identifies causal factors that contribute to the UI/SCP crash problem.

3.2 CLINICAL DATA SETS AND ANALYSIS METHOD

In this analysis, 100 cases sampled from the Crashworthiness Data System (CDS) were used, along with severity weightings obtained from the General Estimates System (GES). These data sets are part of the National Accident Sampling System (NASS), which is designed to support the development, implementation, and assessment of highway safety programs.

The GES file is a nationally representative probability sample of police-reported crashes that occur annually in the United States. It includes police-reported crashes that result in a fatality or injury and those that involve major property damage. GES data are limited to information provided on the PARs.

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 and are a subset of the GES accident cases. The NASS CDS cases used in this analysis provide a rich body of data from which to reconstruct accidents and analyze causal factors. These 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 number of CDS files is limited and the data selection process from CDS, by design, oversamples crashes that are more severe. Thus, CDS data are weighted by severity, as reflected in GES cases of the same crash type. These weightings are used to characterize the problem statistically. Appendix A shows the case weighting scheme.

The clinical analysis adopted in this study entails subjective evaluation by an expert analyst. The analysis 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. Sources of error in the clinical analysis 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). 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 sources of error. Furthermore, despite these potential sources of error, clinical analysis of detailed case files represents an invaluable aid to understanding the nature of crashes. This analysis also includes data sources (additional uncoded information in the PARs) that are otherwise unavailable.

3.3 CLINICAL ANALYSIS RESULTS: CRASH CHARACTERISTICS

In the clinical sample of 100 cases, UI/SCP crashes occur when one vehicle at a unsignalized intersection strikes or is struck by a second vehicle that is traveling in a path perpendicular to the first vehicle. As indicated in Table 3-1, the following two subtypes of the UI/SCP crash were identified:

- Subtype 1: The SV driver ran the stop sign at an unsignalized intersection.
- Subtype 2: The SV driver proceeded against cross traffic after the SV driver stopped at the stop **sign** at an unsignalized intersection.

Table 3-1
Distribution of Crash Subtypes in Clinical Sample

Crash Subtypes	Number of Cases	Weighted % of Sample
Subtype 1: SV driver ran the stop sign	51	42.3
Subtype 2: SV driver proceeded against cross traffic	49	57.6
TOTAL	100	99.9

Note: The weighting scheme used for the CDS sample appears in Appendix A.

The two crash subtypes were examined for the following characteristics:

- ***Speed distribution.*** This characteristic was similar for both subtypes. UI/SCP crashes occurred in the sample at speed limits that are common in urban or suburban locations (25 to 35 mph) as opposed to rural locations (40 mph and above). Figure 3-1 illustrates the distribution; the posted speed limit for six cases (three each of the two subtypes) was unknown.

- ***POV travel direction.*** This refers to the POV's approach direction with respect to the SV's left or right side. Table 3-2 lists the distributions. In both subtypes the POV is about equally likely to be approaching from the left or right.

Table 3-2
Distribution of POV Approach Direction in Clinical Sample

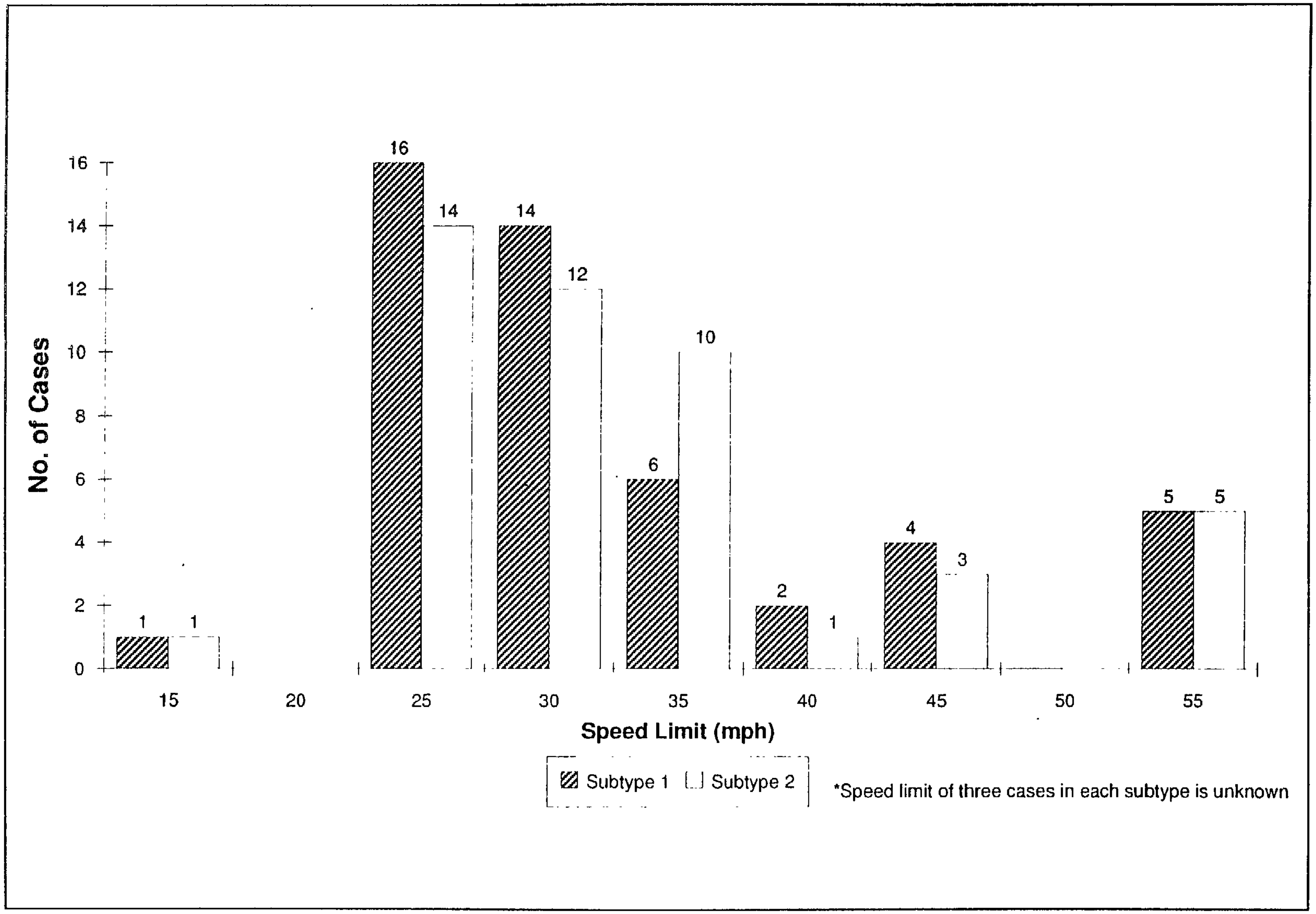
Crash Subtypes	POV Approached from SV Left	POV Approached from SV Right
Subtype 1: SV driver ran the stop sign	52.1 %	47.9 %
Subtype 2: SV driver proceeded against cross traffic	47.9 %	52.2 %

Note: The case weighting scheme used for the CDS sample appears in Appendix A.

- ***SV's role in the crash event.*** This characteristic shows whether the SV was the striking or the struck vehicle. Table 3-3 summarizes this analysis. For Subtype 1, the distribution was close to a 50/50 percent split, so warning the SV driver and/or the POV driver may be appropriate here. For Subtype 2, the SV accelerated into the intersection and was struck by the POV in 74 percent of the cases. This suggests warning the POV driver may be worthwhile. Although the percentages for striking/struck and left/right approaches are the same for Subtype 1, the two characteristics are not linked; the SV was not the striking vehicle in each case where the POV approached from the left.

3.4 CLINICAL ANALYSIS RESULTS: CAUSAL FACTOR OVERVIEW

The CDS data set contained many causal factors. Appendix B contains descriptions of all causal factors. However, these factors tended to be grouped within the defined subtypes in distinctive patterns. Table 3-4 lists the distribution of causal factors by crash subtype and by total sample. Six unknowns were eliminated from crash Subtype 1 and three unknowns were eliminated from crash Subtype 2.



*Speed limit of three cases in each subtype is unknown

Figure 3-1. Distribution of SV Posted Speed Limits, UI/SCP Crashes

Table 3-3
Role of SV

Crash Subtypes	Striking	Struck
Subtype 1: SV driver ran the stop sign	52.1 %	47.9 %
Subtype 2: SV driver proceeded aaainst cross traffic	26.1 %	73.9 %

Note: The case weighting scheme used for the CDS sample appears in Appendix A,

For Subtype 1, driver inattention was the major causal factor (56.4 percent) followed by obstructed vision and adverse environmental conditions. These three factors accounted for approximately 86 percent of the crashes in Subtype 1.

Faulty perception was associated with the majority of Subtype 2 crashes (81.7 percent). For this causal factor, two distinct types of perceptual difficulties were noted: drivers who looked, but did not see the POV (62.1 percent) and drivers who looked, but misjudged the POV's distance from the intersection or its approach velocity, (19.6 percent). In seven of the eight cases in this latter category, the POV was approaching from the right. Obstructed vision was also a significant causal factor for Subtype 2 (14 percent).

3.5 DISCUSSION

The crash subtypes and causal factor categories provide useful guidance for IVHS crash avoidance system functional concepts. Although the categories of driver inattention, obstructed vision, and ***faulty perception*** accounted for approximately 80 percent of the UI/SCP crashes, the profiles of the two crash subtypes implicate different causal factors.

The primary causal factor of Subtype 1 crashes (an SV driver ran stop sign) is ***driver inattention,*** followed by ***obstructed vision.*** A driver may be unaware of an approaching intersection or its 'control signs due to inattention or obstructed vision. In these cases, an WI-IS crash avoidance system that warns drivers of the intersection's presence might be effective.

The primary causal factor for Subtype 2 crashes (an SV driver proceeded against cross traffic) is ***faulty perception.*** In this case, the crash avoidance system (CAS) would need to detect the presence and lateral distance of other vehicles with respect to the SV's location and to aid the SV driver in judging acceptable gaps. The SV driver may also proceed because of

Table 3-4
UI/SCP Crash Causal Factor Analysis Results

Causal Factor	Crash Subtype #1	Weighted Percentage	Crash Subtype #2	Weighted Percentage	Total Sample	Weighted Percentage
Driver Inattention	29	56.4	0	0.0	29	22.6
Faulty Perception						
Looked - Did Not See	0	0.0	31	62.1	31	36.7
Looked - Misjudged Velocity/Gap	0	0.0	8	19.6	8	12.2
Vision Obstructed/Impaired						
Roadside Trees	1	2.0	0	0.0	1	0.8
Roadside Geometry	1	8.0	1	0.6	2	3.2
Intervening Vehicles	1	8.0	4	12.1	5	10.3
Sunlight	1	0.7	1	1.3	2	1.1
Deliberate Violation of Sign						
Subject Vehicle	4	8.0	0	0.0	4	3.4
Driving Under the Influence (DUI)	5	6.1	0	0.0	5	2.7
Adverse Environmental Conditions (Low-Friction Pavement)						
Ice-Covered Roads	2	10.0	1	4.4	3	6.7
Wet Roads	1	0.7	0	0.0	1	0.3
TOTAL	45	99.9	46	100.1	91	100.0

Note: Six unknowns were eliminated from Crash Subtype #1 and three unknowns were eliminated from Crash Subtype #2.

obstructed vision. In this case, a CAS that warns the driver of cross traffic might be effective.

The deliberate violation of sign category is similar to the deliberately ran signal category discussed in Tijerina et al. (1994), who suggested that drivers might fail to obey. a traffic control signal 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. 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.

The last two categories ***(driving under the influence*** and ***adverse environmental conditions)*** are general in nature and probably contribute to multiple crash types. Solutions to these are not likely to be specific to the UI/SCP crash problem and, therefore, do not depend on the UI/SCP crash etiology. For this reason, they are not discussed further in this report.

The next section will discuss potential IVHS crash countermeasure concepts in light of the identified crash subtypes and causal factors.

4. IVHS CRASH AVOIDANCE CONCEPTS FOR UI/SCP CRASHES

4.1 INTRODUCTION

Figure 4-1 provides a time-intensity graph of crash avoidance requirements (National Highway Traffic Safety Administration, 1992). As the car approaches the intersection, the driver has time to react to alerts and warnings. As the car comes closer to the intersection, driver assistance in the form of driver-vehicle partially automatic control systems is necessary. 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 may not be effective if the kinematics of the situation are too unforgiving. As NHTSA (1992) pointed out, the characteristics of a given crash avoidance system will depend largely on the time available to take evasive action and the intensity of action needed to avoid the crash. This figure will be used as a convenient framework for IVHS UI/SCp crash avoidance system concepts.

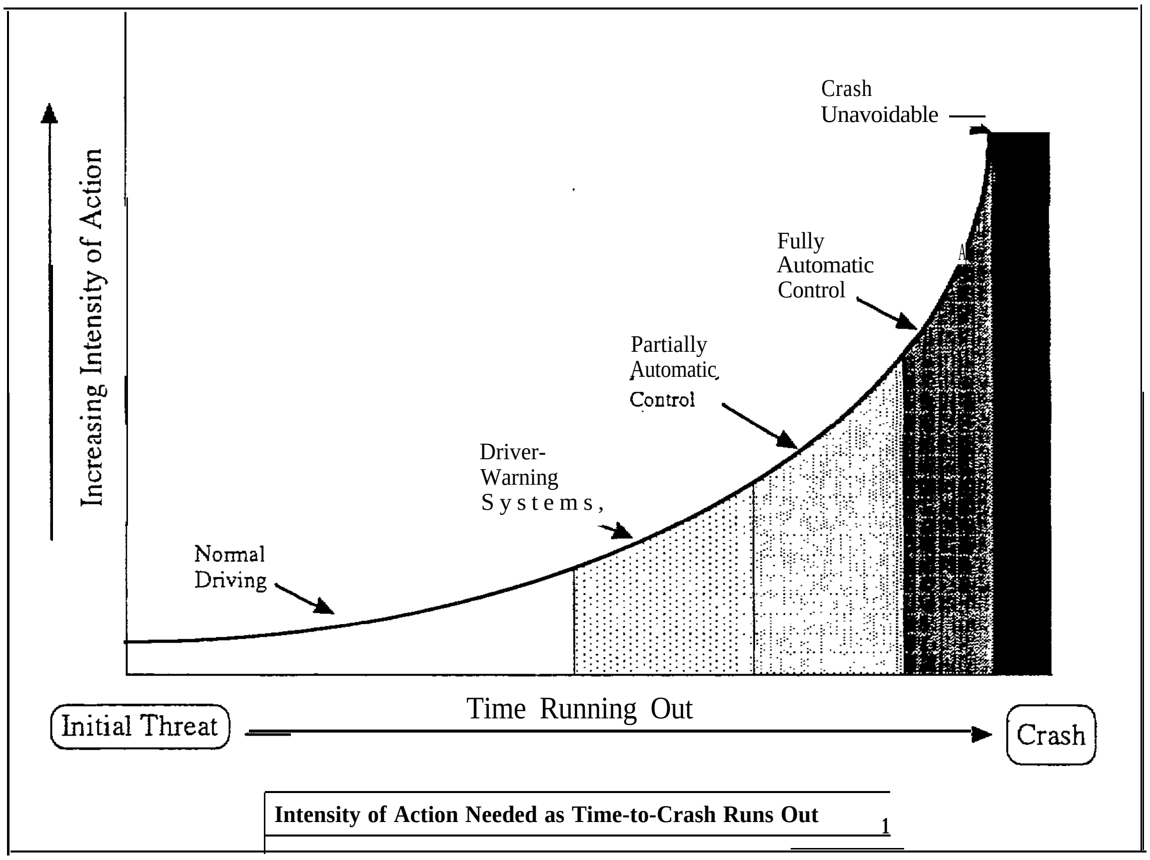


Figure 4.1 **Time-intensity Graph of Crash Avoidance Requirements (Source: , NHTSA, 1992)**

4.2 DRIVER ALERTS

As shown from left to right in the time-intensity graph, the best way to avoid crashes is to prevent the start of a hazardous situation. One simple way to do this is to alert the SV driver to the presence of the intersection or stop sign ahead. For example, a waymark processed some distance from the stop sign could trigger an alert that effectively indicates that there is a stop sign ahead. The location of the vehicle where this alert is provided should give the driver ample opportunity to complete a normal deceleration to a full stop. This is an application of alerts to avoid Subtype 1 crashes.

Another way to prevent the start of a hazardous situation is to alert the SV driver to the presence of a POV in an oncoming traffic lane. When the POV passes its waymark, the SV alert system could indicate that a vehicle is approaching the intersection. No information about the POV's instantaneous distance from the intersection or its velocity would be processed to provide this level of alert. This information might be helpful in Subtype 2 UI/SCP crashes because it alerts drivers in the Subtype 2 category about the potential hazards of an approaching vehicle.

An effective alert presents challenges because it must inform the driver of the critical intersection information, yet not be perceived as a nuisance or be an in-vehicle distraction. Since drivers will usually be aware that they are approaching a stop sign, such an indicator provides redundant information. However, for the unaware driver in crash Subtype 1, this alert could be quite useful. This notion of repeating a signal inside the vehicle has recently been proposed by De Vaulx (1991).

The alert, if effective, will keep a hazardous condition from developing. The alert should allow the driver to decide how to respond (e.g., maintain constant velocity, take foot off the accelerator, begin braking now). Since drivers usually negotiate intersections safely, this simple alert should prevent development of the hazardous conditions. The appropriate modeling scheme for this case's crash avoidance effectiveness involves reliability models rather than kinematic models. For example, the effectiveness of the stop sign alert might be modeled as a series system in which the probability of crash avoidance is the product of the probability that the system works properly, the probability that the driver detects the alert, the probability that the driver recognizes the potential hazard, and the probability that the driver reacts appropriately. That is,

$$P_{crash\ avoidance} = P_{IVHS\ system\ works} \times P_{driver\ detects} \times P_{driver\ recognizes} \times P_{driver\ reacts\ appropriately} \qquad (1)$$

As an illustration, assume that the CAS works 99 percent of the time, the driver detects 99 percent of alerts from it, recognizes the hazard 90 percent of the time, and obeys the warning 90 percent of the time. The probability for crash avoidance will nominally be

$$P_{crash\ avoidance} = (.99)\ (.99)\ (.90)\ (.90) = .79 \qquad (2)$$

or about 79 percent. Although more information is needed to model such a system, the model clearly indicates the driver's importance to the effectiveness of the stop sign alert. Even a near-perfect detection and presentation CAS will be degraded if the driver does not respect the alert and obey its advice.

4.3 DRIVER WARNING SYSTEMS

A modification of the concept presented in Section 4.2 would replace or follow up the simple stop sign alert with directive warnings to brake.

For crash Subtype 1, an SV driver warning could work something like this. Wortman and Mathias (1983) reported a range of nominal decelerations at signalized intersections and reported a 50th percentile value of 10 ft/s^2 (or about 0.31 g.) Thus, given the current SV travel velocity, a braking deceleration of 10 ft/s^2 (or some other value indicative of normal, alert driver behavior) could be used to determine the minimum required stopping distance. If the SV is not decelerating sufficiently at that distance, the warning to stop ahead could be presented. Such an IVHS warning system would require moment-to-moment updates on SV locations (or distance) with respect to the intersection Stop Line, travel velocity, and deceleration profile. This system concept would help the inattentive SV driver and the SV driver whose view of the stop sign is obstructed. This warning concept would likely not help those drivers who fail to obey the stop sign because they do not perceive a hazard from cross traffic.

An expansion of this warning logic gives the driver ***graded warnings.*** If the SV should prepare to stop, the CAS could check for normal deceleration (e.g., 10 ft/s^2) at the appropriate distance from the intersection and provide a warning if this is not exhibited. Should the SV continue without appropriate slowing, the CAS would deliver a more urgent warning to the driver at some later point (e.g., the minimum distance needed for braking to a stop at 16 ft/s^2). The notion of graded alarms for intersection crash avoidance has recently been reported by Enkelmann et al. (1993) for the PROMETHEUS program in Europe.

Since, in principle, the presence of a stop sign can be known in advance, it should be possible to also provide a ***constant warning time*** to the SV driver. If the CAS determines that the SV driver must stop, then a warning to prepare to stop can be provided at a fixed period of time prior to some event (e.g., 2.0 s before the SV reaches the point at which normal braking should be in effect). Constant warning time may be more feasible in intersection negotiation than in, say, lane change crashes (where a vehicle suddenly cuts in front of or collides with a POV). The constant warning time might provide guidance about when to deliver the intersection alert or when to provide the first of the graded warnings.

For crash Subtypes 1 and 2, it is possible to warn the POV driver of a potential crash. The POV driver could be warned of the direction of the intruding SV, and vice versa. If the IVHS crash avoidance system has information about the position, velocity, and acceleration of the SV and POV, the driver warnings could be graded to indicate a possible, probable, or imminent crash threat. The POV driver, given sufficient warning, could be prepared for the intruding SV and could slow, brake, or steer the car to avoid the crash. Effectiveness of POV warnings will depend largely on how early the POV driver can be warned to avoid striking or being struck by the SV. The POV warning, however, would usually provide redundant information since the POV driver typically sees the SV maneuver and is prewarned about a potential hazard.

If the SV driver in Subtype 2 is warned of vehicles approaching from the left or right, the driver could wait until it was safe to pass through the intersection. The warning could be presented only when the SV driver removes a foot from the brake pedal and the SV is in motion. This concept might be beneficial for the unaware driver. It is less clear if the driver who misperceives the cross traffic would exercise extra caution, given this type of alarm. An ideal gap acceptance aid would indicate to the SV driver when it is safe to cross the intersection. However. the go/no-go indication depends on knowing when the driver will. begin the maneuver and what acceleration will be applied. Neither can be known with certainty. Alternatively, the CAS could provide a warning to the SV driver when the POV time headway is less than some threshold tied to the time needed to cross the intersection (e.g., 5 s) (see Ueno & Ochiai, 1993, for an application of time headway to left-turn maneuvers).

4.4 PARTIALLY AUTOMATIC CONTROL SYSTEMS

Partially automatic control systems (driver-in-the-loop) might be appropriate at points along the time-to-crash continuum where driver action alone is insufficient. For example, the driver might not respond to a warning soon enough or might not be braking sufficiently to stop in time. Here partially automatic control systems that allow semiautomatic vehicle control could be used appropriately.

The most relevant example of a partially automatic control system for the UI/SCP Subtype 1 crash is soft braking. In this situation, certain driving conditions could prompt in-vehicle automation to apply moderate braking that the driver could increase by pressing on the brake or gas pedal. Like cruise control, the driver could also disengage the soft braking by tapping the brake pedal in the event of a false alarm. This type of system might be engaged in a number of ways. One method might be to constantly monitor the driver’s velocity and distance to the intersection, perhaps monitoring for typical decelerations indicative of normal and aware driver braking behavior. If the driver does not apply braking by a certain point, calculated with respect to that driver’s typical deceleration, soft braking at that deceleration would begin. Alternatively, even softer braking could begin earlier, at some indifference threshold, and be acceptable to the driver. This earlier braking could provide added safety benefits.

Control intervention schemes can also be proposed for crash Subtype 2. For example, an “intelligent throttle” might be used to move the vehicle through the intersection when the cross traffic conditions permit. Although the safety of such a system is highly questionable, it would require data on cross traffic vehicle location, speed, and motion profile to predict when the POV would occupy the intersection. The system would also require data on SV performance capabilities such as maximum acceleration. Beyond these data needs, human factors and safety issues are associated with this type of system. Drivers might resist automatic negotiation of a hazardous maneuver. Any loss of traction due to an ice patch or oil slick would cause a delay that could be disastrous. Problems in registering cross traffic could also prove fatal. For these reasons. the intelligent throttle may not be a viable control-intervention option.

4.5 FULLY AUTOMATIC CONTROL SYSTEMS

The last portion of the time-intensity graph indicates time budgets that are the least forgiving of delays. At some point, FACS provide the means of last resort to avoid a crash. FACS concepts for UI/SCP Subtype 1 and Subtype 2 crash avoidance involve automatic hard braking. Since FACS are natural extensions of control intervention, the data needs for FACS concepts are similar to those given in Section 4.4. A distance threshold and associated time, based on vehicle and system delays alone (no driver involvement), serve as precursors for FACS onset. FACS would respond by automatic hard braking up to some limit (for example, 0.5 g). To be fully effective, the FACS should know the performance capabilities of the vehicle-roadway combination.

4.6 HYBRID SYSTEMS

In principle, a hybrid concept that uses all of the previous categories of concepts provides a smooth transition from the driver to the automation and back to the driver. The driver could be given the opportunity to negotiate the intersection via driver alert and driver warning. If the driver does not respond in time, or responds inadequately, control-intervention would commence. This might provide soft braking for a period or gradually increased braking until the SV stops. If necessary. it might utilize the hard braking level provided by FACS for emergencies. Fuzzy logic (i.e., control logic that has many intermediary stages between control states) or similar technologies could be incorporated into such a system to provide smooth transition from one braking level to another.

FACS in general and the hybrid system concept in particular lead to a host of research questions. Driver acceptance and cooperative behavior with the IVHS automation are major areas of needed research. A systems analysis of the impacts of such system concepts would be warranted. The FACS must be carefully designed to minimize or eliminate the potential for harm. For instance, automatic braking might cause a rear-end crash though other, nonintersection-specific systems such as “Headway Detection” could alleviate this. The effect of such systems on traffic flow also merits attention. The effects of such FACS in the context of multiple vehicles, some with IVHS capability and others without, pose interesting analytic challenges.

The hybrid system concept might address several UI/SCP causal factors, such as attempts to run the stop sign, driver inattention, and vision obstruction. At a minimum, safety and driver acceptance require that the automatic braking be disengaged if the driver judges it appropriate to do so. The foolhardy driver might use this design feature to override the system and drive unsafely. This risk must be weighed against the needs of drivers who must contend with IVHS system problems, including false or nuisance alarms.

As a summary, Table 4-l shows a matrix of countermeasure concepts presented here.

Table 4-1
Summary Table of Functional CAS Concepts

CAS Concept	Description	Potential Benefits	Potential Drawbacks
In-Vehicle Alerts	In-vehicle signing that provides early indication of an intersection ahead. These alerts could, in principle, provide an earlier indication by a fixed time interval.	Early-on indication of intersection and/or stop sign should prevent UI/SCP crash hazard from occurring.	Alerts must be effective at informing drivers with usually redundant information and should not be too intrusive since the alerts will be given frequently.
Driver Warnings	A more intrusive version of the alert concept. Graded warnings to the SV or POV driver and constant warning times required to avoid the crash could be provided.	Warnings should occur less frequently than alerts. If maximum time available when a warning is given is sufficient for driver reaction time and machine delays, the warning should promote safety.	False alarm warnings will likely degrade CAS effectiveness. Warning thresholds are problematic to set and may require artificial intelligence methods to tailor the warnings to individual types of drivers. Warnings will be ineffective if they are delivered to the driver too late.
Control-Intervention Systems	Includes concepts such as soft braking, moderate braking, and graded braking. A system with and without driver override could be designed.	Control intervention will presumably be beneficial when driver delay cannot be tolerated.	CAS with control intervention will have to be extremely reliable. Driver acceptance is a major issue. Driver-CAS interaction to transition from driver to FACS and back to driver is poorly understood. Control intervention may have adverse secondary consequences on highway safety by causing other types of crashes (e.g., rear-end crashes).
Hybrid Systems	A comprehensive system concept that incorporates the previous concepts in a time-phased manner.	Hybrid systems could provide the adaptive driver support necessary for optimum safety and driver acceptance.	All the previous drawbacks apply here and may be compounded by the need to smoothly transition from one CAS state to another.

5. MODELING REPRESENTATION

5.1 INTRODUCTION

In this section, the unsignalized intersection maneuver is analyzed for straight crossing paths. The analysis explains the key factors that will influence IVHS crash avoidance system design and effectiveness.

The unsignalized intersection maneuver can be considered in terms of the distance required to stop at the Stop Line (see Figure 5-1). This distance is based on travel speed, vehicle braking ability, and driver-plus-machine time delays. At any point in time, a vehicle's location determines possible outcomes for the intersection maneuver and IVHS crash avoidance system effectiveness. When the SV is traveling through the intersection, it remains in a potentially hazardous posture until it completely clears the intersection, including its own vehicle length. Based on these considerations, the analysis is presented for each of the two UI/SCP crash subtypes: Subtype 1, where the SV driver ran the stop sign and Subtype 2, where the SV driver stopped and then proceeded through the intersection against cross traffic. For each subtype, there are separate sections for warnings to the SV driver and warnings to the POV driver.

5.2 SUBTYPE 1: SV RAN THE STOP SIGN - WARNING THE SV DRIVER

In this subtype, the driver of the SV is often unaware of the stop sign and/or the intersection ahead due to inattention or obstructed vision (63 percent of the UI/SCP crashes in Subtype 1). To avoid a crash with a POV in a crossing lane, an alert or warning signal must be issued to the SV driver at some distance from the stop sign so that the vehicle can be brought to a stop. The distance required to brake to a complete stop is defined as follows:

$$D_{stop} = \frac{V_{SV}^2}{2a_{SV}} + (t_{driver\ RT} + t_{machine\ delay})V_{SV} \tag{3}$$

where D_{stop} = SV braking distance required to stop by the Stop Line, ft

V_{SV} = SV velocity, ft/s

a_{SV} = SV deceleration, ft/s^2

$t_{driver\ RT}$ = SV driver brake reaction time, s

$t_{machine\ delay}$ = $t_{vehicle\ delay} + t_{IVHS\ delay}$, s

The IVHS crash avoidance system would alert or warn drivers or the control intervention would engage when the vehicle is no closer to the intersection than the distance defined above, assuming some time budget for driver and machine delays. The farther away the vehicle is from the Stop Line when braking is applied, or the greater the deceleration applied, the more stopping distance is available. (For reference, Wortman and Mathias (1983)

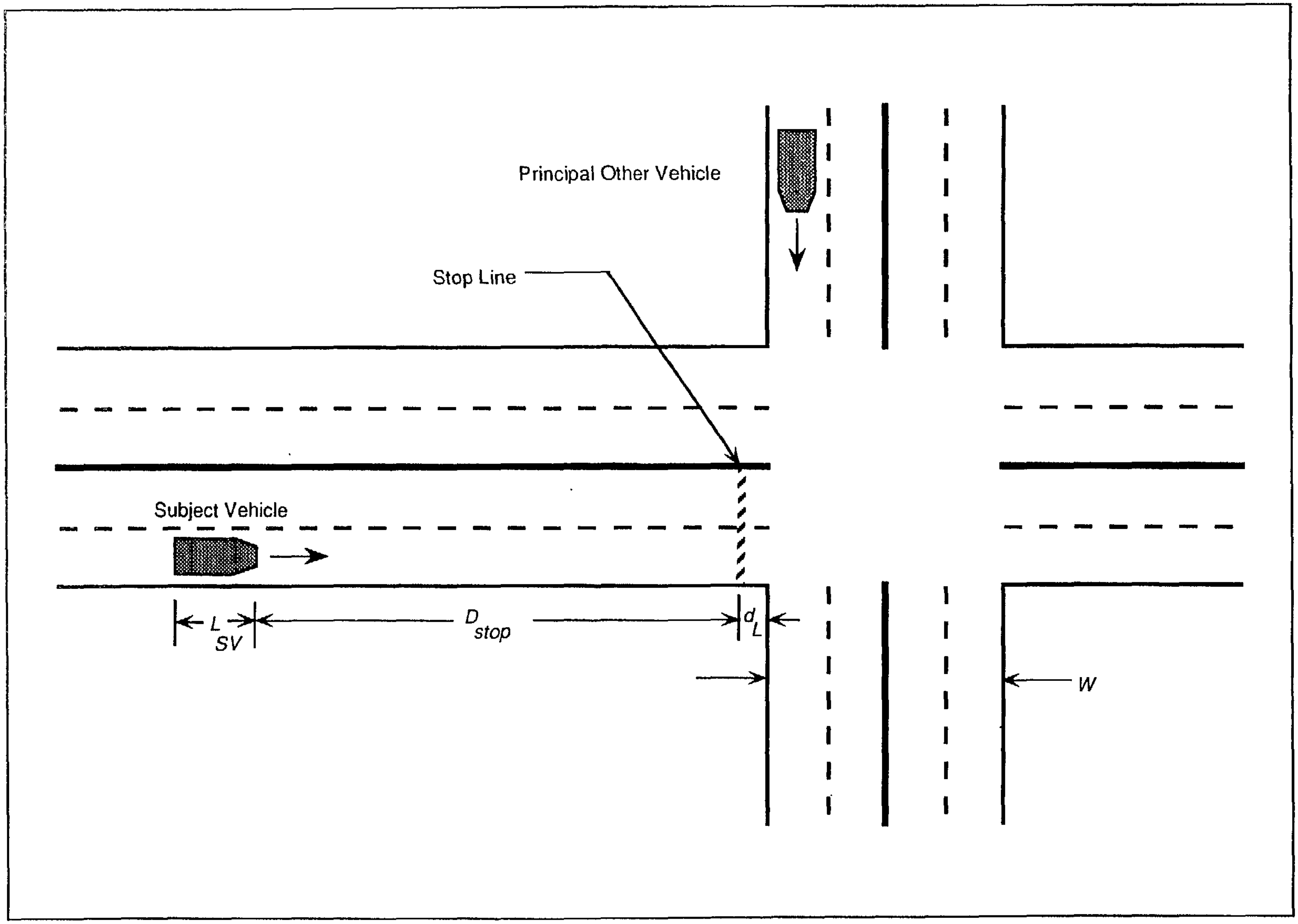


Figure 5-1. The UI/SCP Scenario When the POV is Approaching from the Left (symbols defined in text)

reported a 50th percentile nominal deceleration rate of 10 ft/s^2 or about 0.31 g for normal stops at signalized intersections.) Normal stopping deceleration at an intersection is a very conservative basis for a warning system since braking after a warning may be higher than normal. The IVHS CAS range sets the outer limit to when warnings occur or when control intervention is operational.

Figure 5-2 illustrates the effects of constant warning time and braking deceleration on distance required to brake (D_{stop}) for a range of SV velocities. For a given delay value and travel velocity, D_{stop} decreases as braking levels increase. Also, longer delays increase D_{stop} for a given braking deceleration and travel velocity. For example, a moderate braking deceleration of 0.31 g and a total time delay of 3 s would require a braking distance of 570 ft at 55 mph. The CAS range would need to trigger the SV warning at least 570 ft prior to the Stop Line to warn the driver to brake within 3 s. Thus, Figure 5-2 provides guidance on CAS ranges needed for selected constant warning times.

Should constant warning times prove infeasible, other options could be considered. The time available for driver and machine delays, given that the warning might be delivered at any location along the SV approach to the Stop Line, will be considered next. A given SV travel velocity, V_{SV}, and constant deceleration, a_{SV}, yield the minimum braking distance, $D_{stop(min)}$. This quantity is fixed. If the driver is farther than the minimum required stopping distance from the Stop Line, braking must be applied by the $D_{stop(min)}$ distance to successfully stop at the Stop Line. For each instance in time, this means that the time available for driver and machine delays is as follows:

$$t_{available} = \frac{D_{location} - D_{stop(\min)}}{V_{SV}} \tag{4}$$

where $t_{available}$ = time remaining to accommodate driver and machine delays, s

$D_{location}$ = SV location from the Stop Line at any given instant, ft

$D_{stop(min)} = V^2_{SV}/2a_{SV}$ = braking distance needed, given SV velocity and deceleration and no time delays, to stop by or at the Stop Line, ft

V_{SV} = SV velocity, ft/s

a_{SV} = SV deceleration, ft/s^2

At a given velocity, $t_{available}$ is a linear function of distance remaining ($D_{remaining}$, where $D_{remaining} = D_{location} - D_{stop(min)}$).

The results of this analysis are plotted in Figure 5-3. Three different SV response decelerations are each assessed at 25-, 35-, 45-, and 55-mph travel speeds for a 489-ft-wide intersection and a 16-ft SV length (i.e., $W + L_{SV} = 64$ ft).

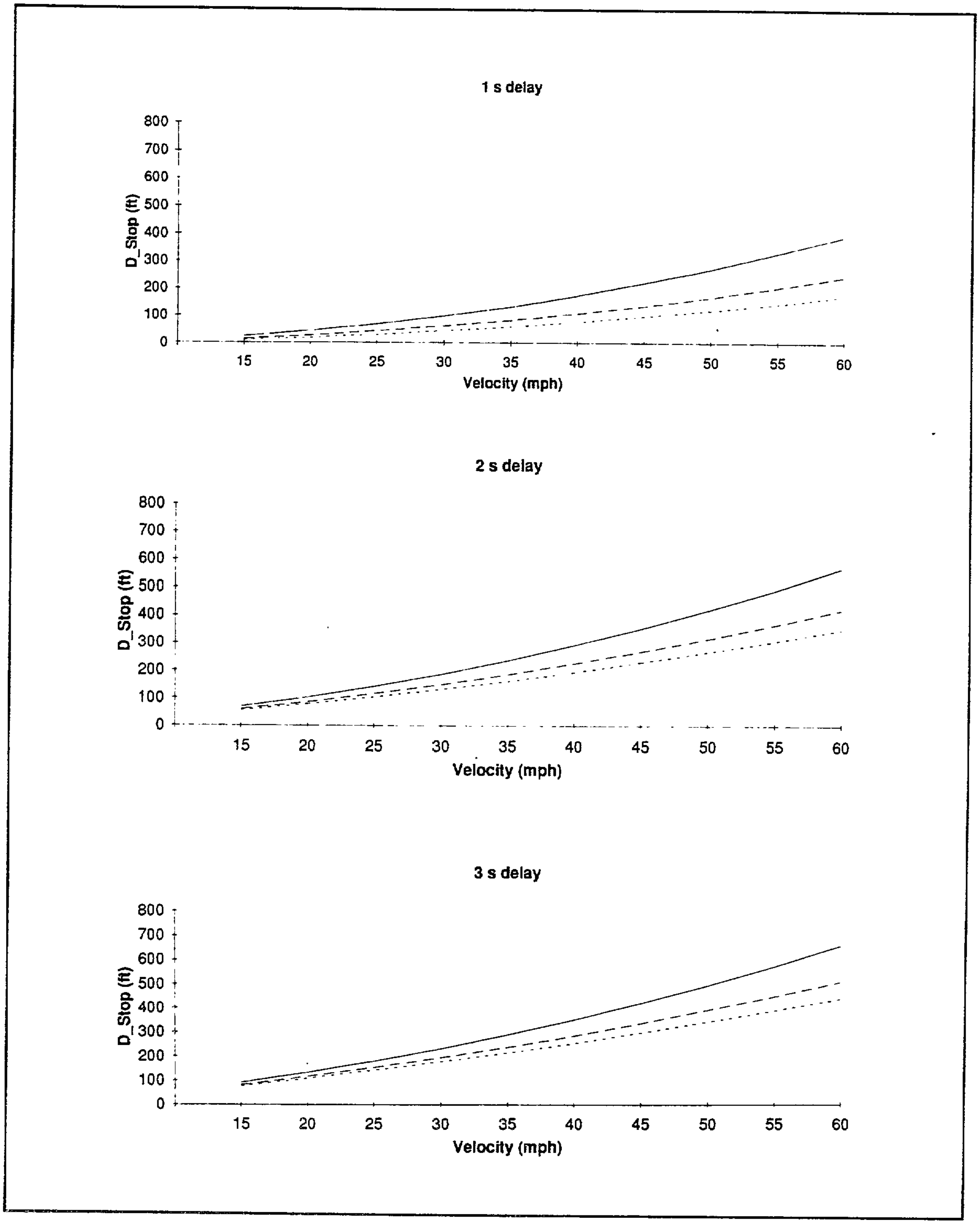


Figure 5-2. Stopping Distance for Various SV Velocity and Deceleration Profiles, for Various Constant Warning Times

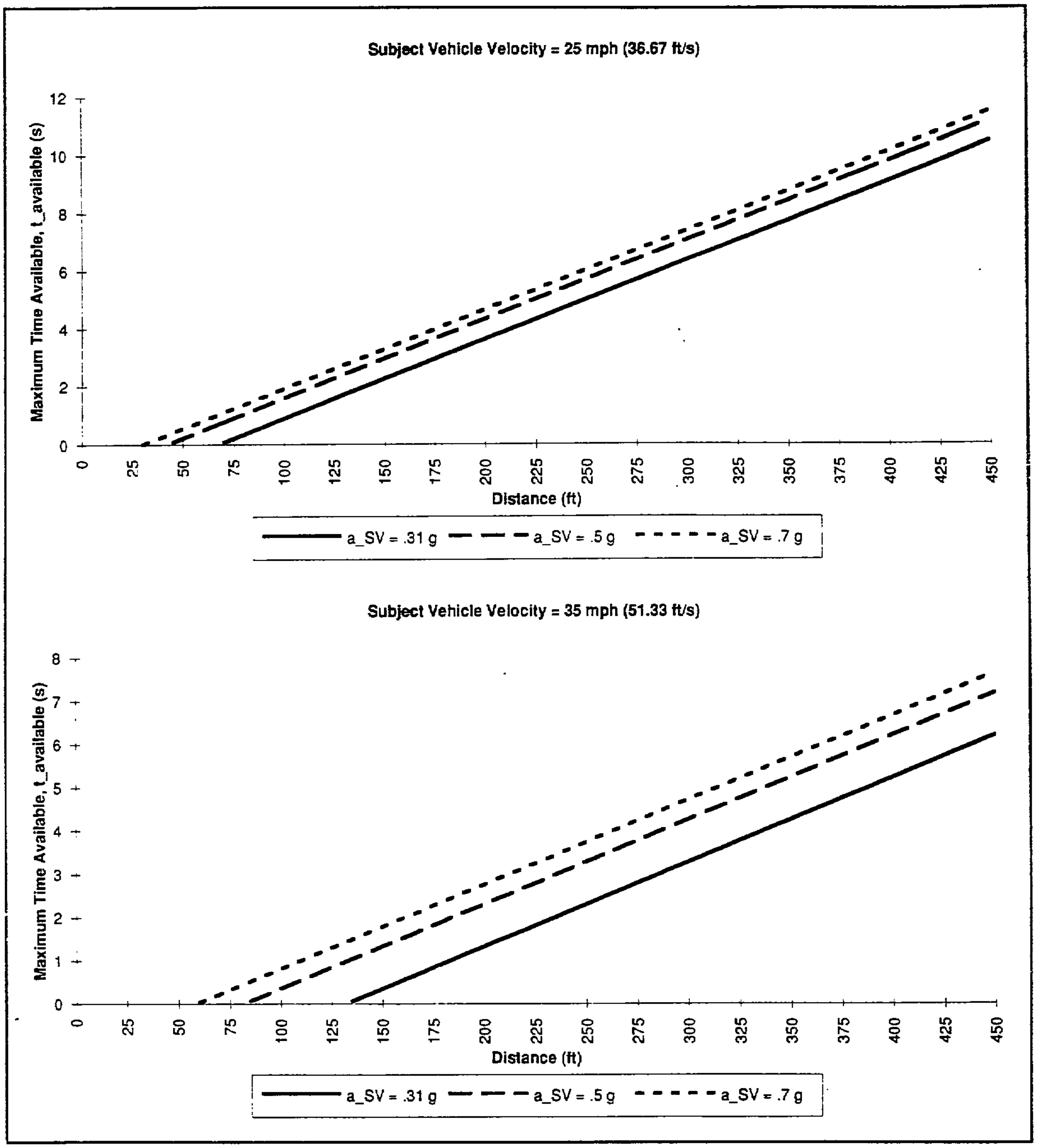


Figure 5-3. Maximum Time Available for Driver and Machine Delays as a Function of Travel Velocity, Deceleration, and Distance from the Intersection at CAS Warning Onset

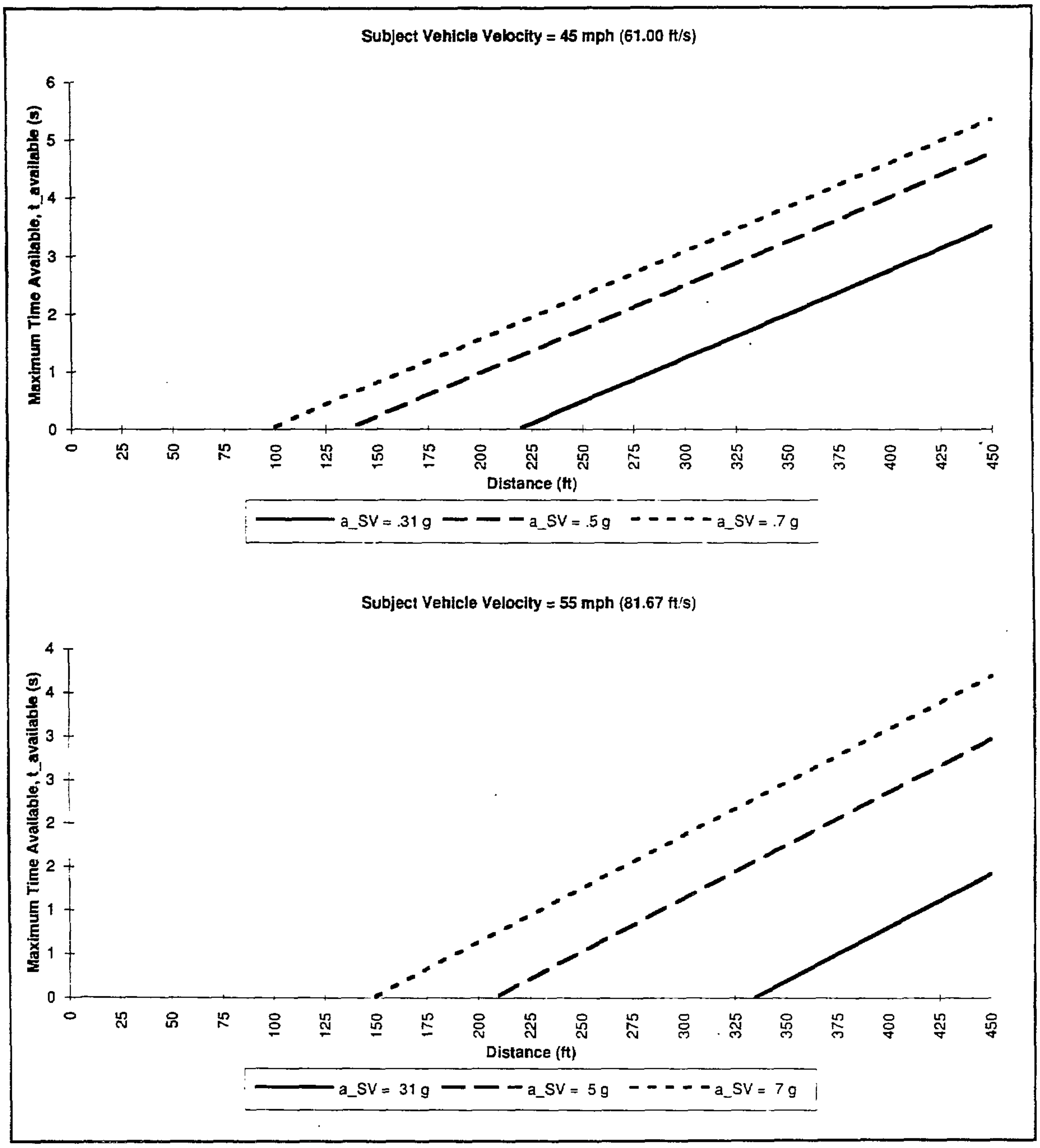


Figure 5-3. Maximum Time Available for Driver and Machine Delays as a Function of Travel Velocity, Deceleration, and Distance from the Intersection at CAS Warning Onset (continued)

To determine the proportion of drivers who could brake as fast or faster than $t_{available}$, the machine time delay budget **is** subtracted out and the remaining value is determined graphically from the cumulative probability plot in Figure 5-4. This plot contains 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 (Taoka, 1989). 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.

Clearly, there would not be enough time for some unaware drivers, alerted by the CAS warning at a given distance from the $D_{stop(min)}$ point, to make a normal stop (e.g., 0.31 g-deceleration). However, this does not mean that there will be a crash, because the driver (or the CAS) might be able to apply harder emergency braking, up to some limit (e.g., 0.7 g).

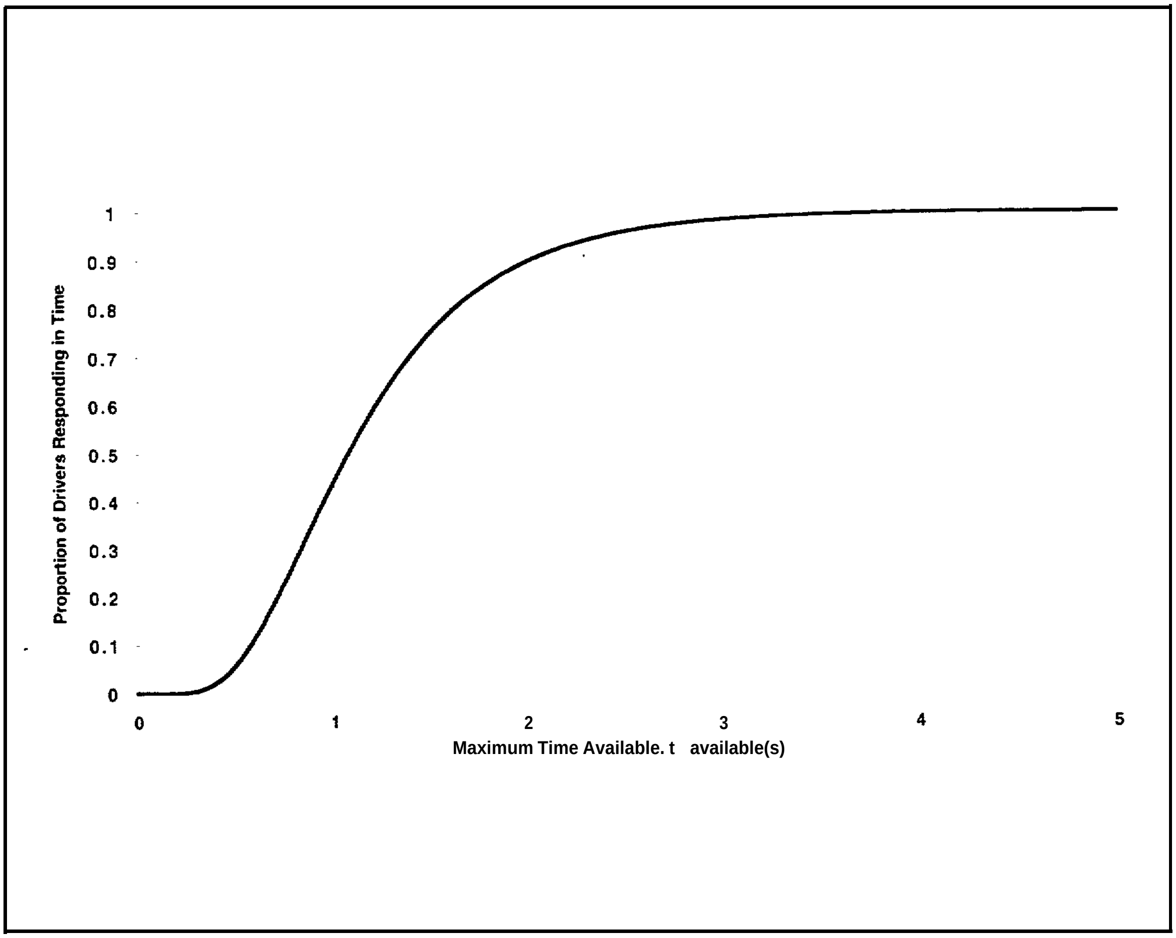


Figure 5-4. Theoretical Proportion of Unaware Drivers Who Can Brake as Fast or Faster than $t_{available}$

Figure 5-5 shows the tradeoff between braking deceleration and alerting distance to maintain a constant 2.0 s to accommodate driver-plus-machine delays. Consider, for example, the 45-mph curve. The graph indicates that for a driver-plus-machine delay of 2.0 s, either an IVHS alert must occur or the driver must become aware of the intersection at 350 ft from the Stop Line with 0.31-g braking deceleration. However, the alert onset, or driver detection, needs only to occur at about 230 ft from the Stop Line if the driver subsequently applies 0.7 g of braking deceleration. Thus, the closer the SV is to the normal $D_{stop(min)}$ point when an alarm first occurs, the greater the subsequent braking must be.

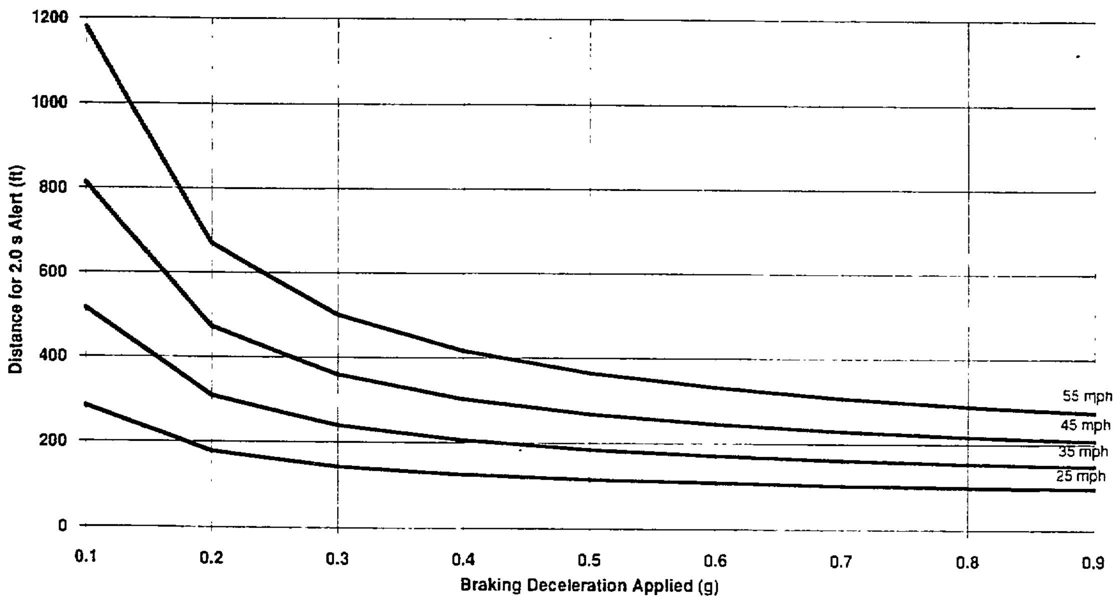


Figure 5-5. Alert Distance as a Function of Brake Deceleration for a Constant 2.0 s of Available Time to Accommodate Driver and Machine Delays

In the case of FACS, the time delays include those generated by the machinery only, without driver reaction time (RT). This has implications for the distance required to brake. The system can react faster by itself than if a driver is responding to a warning, so less time is needed to brake, and thus, the system can respond at a point closer to the intersection.

5.3 SUBTYPE 1: SV RAN THE STOP SIGN - WARNING THE POV DRIVER

The SV and the POV are prone to crash when both vehicles are in the intersection at the same time that the two travel lanes overlap. This is referred to here as the *collision field.* Collision field parameters can describe those occasions when the POV might be warned to take action either to avoid the collision or to reduce its severity if the crash is imminent.

For an SV traveling at constant velocity, T_1 is defined as the time required for the front of the SV to cross the nearest edge of the lane where the POV is located. Assuming that the median width is negligible, T_1 is given by the following equation:

$$T_1 = \frac{D_{lane}}{V_{SV}} \qquad (5)$$

where T_1 = time until SV crosses the nearest edge of the POV travel lane, s
D_{lane} = distance from the front of the SV to the leading edge of the POV travel lane, ft
V_{SV} = SV velocity, ft/s

The time required for the SV to clear the POV travel lane, T_2, is given by

$$T_2 = \frac{D_{lane} + lw + L_{SV}}{V_{SV}} = T_1 + \frac{lw + L_{SV}}{V_{SV}} \qquad (6)$$

where T_2 = time required for SV to clear the POV travel lane, s
D_{lane} = distance from the front of the SV to the leading edge of the POV travel lane, ft
lw = lane width, ft (e.g., 12 ft)
V_{SV} = SV velocity, ft/s
L_{SV} = vehicle length, ft (e.g., 16 ft)

The values for T_1 and T_2 define the time interval when the SV intrudes on the POV travel lane, possibly resulting in a collision. Therefore, a collision will occur if the POV is in the SV travel lane at any time in this interval. To avoid a collision, the POV must clear the intersection prior to the time when the SV enters the travel lane (before T_1) or must not arrive in the travel lane until after the SV clears it (i.e., after T_2). The values of L_{SV} and L_{POV} in Equations (7) and (11) are worst-case estimates since the car widths are only half this distance and the vehicle must only travel 6 ft into the lane to crash with another vehicle. If the velocity of the POV is known and is constant, then the longitudinal distances at which the POV must be from the intersection to avoid a collision can be determined by using this calculated time interval.

A crash is avoided if the POV is closer than the minimum longitudinal distance, LD_{min}, defined as the distance between the POV and the intersection at which the POV can just avoid colliding with the SV. This distance can be calculated using time, T_1. Since distance is the product of velocity and time, then

$$LD_{\min} = V_{POV}\, T_1 - (lw + L_{POV}) \tag{7}$$

where LD_{min} = minimum longitudinal distance for POV from beginning of collision field, ft
L_{POV} = length of the POV, ft
T_1 = time until SV crosses the nearest edge of the POV travel lane, s
lw = lane width, ft
V_{POV} = POV velocity, ft/s

Similarly, a crash is avoided if the POV is farther than the maximum longitudinal distance (LD_{max}), defined as the maximum distance between the POV and the intersection at which the POV can just avoid colliding with the SV. This distance can be derived using time = T_2.

$$LD_{\max} = V_{POV}\, T_2 \tag{8}$$

where LD_{max} = maximum longitudinal distance for POV from the beginning of the collision field, ft
V_{POV} = POV velocity, ft/s
T_2 = time required for SV to clear the POV travel lane, s

If the POV is traveling at constant velocity and is located between LD_{min} and LD_{max} ft away from the intersection, a collision will occur. If, however, at this time the POV that is traveling at constant velocity is closer than LD_{min} from the SV travel lane, or is farther than LD_{max} from the SV travel lane, then a crash will be avoided. Thus, at a minimum, to avoid a collision, the POV must be detected at a range that spans LD_{min} to LD_{max} from the SV lane.

By varying values of the constant velocity for the SV and POV, the detection ranges can be calculated. Once these detection ranges are known, values for warning ranges of the POV can be determined. As the SV approaches the intersection, it crosses the distance where normal braking (e.g., 0.31 g) should begin to stop the vehicle at the Stop Line. At this point, the POV driver is warned that a crash is *possible*. If the SV fails to slow down sufficiently and it continues past the distance required for moderately hard braking (e.g., 0.5 g), the POV is warned that a crash is *probable*. If the SV is still not slowing down appropriately as it passes the point where emergency braking (e.g., 0.7 g) should begin, the POV is warned that a crash is *imminent*.

Table 5-l shows sample stopping distance calculations for vehicles traveling at various constant velocities. For convenience, this table assumes that the velocity of the SV and the velocity of POV are equal. Values are shown only for the first POV lane (i.e., $n = I$). Consider an SV that is approaching a stop sign and a POV approaching the same intersection — both at a constant velocity of 35 mph. When the SV approaches the intersection and reaches a distance of 132.8 ft, normal braking (0.31 g) should begin. If it does not slow down, a "crash possible" warning is issued to the POV if the POV is within 104.8 ft LD_{min} and 160.8 ft LD_{max} of the intersection. If the SV continues past the moderately hard braking (0.5 g) distance (82.3 ft) and the SV is not sufficiently slowing down, a warning is presented to the POV that a crash is probable. As the SV continues, it will pass the emergency braking (0.7 g) distance of 58.8 ft. At this point, the POV receives a warning that a crash is imminent. Once the SV passes through the intersection and clears it, no other warnings regarding its status are broadcast.

5.4 SUBTYPE 2: SV PROCEEDED AGAINST CROSS TRAFFIC - WARNING THE SV DRIVER

If the SV driver is fully aware of the stop sign, the driver may slow down and stop, but then attempt to cross the intersection at an inopportune time because the driver looked but did not see another vehicle (62.1 percent of the cases), misjudged the POV's velocity (19.6 percent of the cases), or because the driver's vision was obstructed (14 percent of the cases). These categories account for about 96 percent of the cases of Subtype 2. The SV driver strikes, or is struck by, the POV, primarily because the SV driver is unaware of oncoming traffic. For this causal factor, driver warning may be helpful.

For Subtype 2 crashes, if the SV driver is unaware of a POV, a countermeasure that notifies the SV driver of the POV's presence might be useful. The POV could cross a marker at a known distance from the intersection. This event could be transmitted through vehicle-to-vehicle or vehicle-to-intersection-to-vehicle communications to the SV. The SV driver would then receive a warning that states "A vehicle is approaching from the left" or "A vehicle is approaching from the right." The logic for such a system might be as follows:

```
If there is an SV brake pedal reversal and if approaching traffic exists,
    Then issue an appropriate warning:
      "A vehicle is approaching from the <left or right>."
```

Alternatively, POV time headway might be used in the following logic:

```
If there is a brake pedal reversal and POV time headway is less than #s,
    Then issue an appropriate warning:
        "A vehicle is approaching from the <left or right>."
```

Either concept should prevent a hazard from occurring, so reliability modeling like that presented in Section 4.2 is appropriate.

Table 5-1
Ranges of Time Available for POV Driver Warning: UI/SCP Subtype 1

POV Velocity (mph)	POV Stop Distance (ft) [1]	T_1 (s)	LD_{min} (ft)	T_2 (s)	LD_{max} (ft)	Max Time Available to POV at LD_{max} (s) [2]	Max Time Available to POV at LD_{min} (s) [3]
a_{SV} = .31 g							
25	67.8	1.8	39.8	2.6	95.8	1.79	0.27
35	132.8	2.6	104.8	3.1	160.8	1.99	0.90
45	219.6	3.3	191.6	3.8	247.6	2.28	1.43
55	328.0	4.1	300.0	4.4	356.0	2.61	1.92
a_{SV} = .50 g							
25	42.0	1.1	14.0	1.9	70.0	1.09	-- [4]
35	82.3	1.6	54.3	2.1	110.3	1.00	--
45	136.1	2.1	108.1	2.5	164.1	1.01	0.16
55	203.3	2.5	175.3	2.9	231.3	1.07	0.37
a_{SV} = .70 g							
25	30.0	0.8	2.0	1.6	58.0	0.76	--
35	58.8	1.1	30.8	1.7	86.8	0.55	--
45	97.2	1.5	69.2	1.9	125.2	0.42	--
55	145.2	1.8	117.2	2.1	173.2	0.35	--

Notes:

1 $D_{stop} = \frac{V_{SV}^2}{2a_{SV}}$

2 $a_{POV} = 0.7\ g;\ t_{available} = \frac{LD_{max} - \frac{V_{POV}^2}{2(.7)(32)}}{V_{POV}}$

3 $a_{POV} = 0.7\ g;\ t_{available} = \frac{LD_{min} - \frac{V_{POV}^2}{2(.7)(32)}}{V_{POV}}$

4 Result $\leq$ 0.0 s, i.e., POV driver would not be warned in time.

5.5 SUBTYPE 2: SV PROCEEDED AGAINST CROSS TRAFFIC - WARNING THE POV DRIVER

Further consideration of this crash subtype yields another possible countermeasure. As in crash Subtype 1, some part of each of the two vehicles must be located in the collision field at the same time for a crash to occur. Using the physical characteristics of the SV and POV and the geometry of the intersection, it can be determined when the SV will be in the collision field if the vehicles are traveling at constant velocities or with constant accelerations or decelerations. The distances that the POV must be from the intersection to avoid an SV in the collision field can be calculated by varying the travel speed of the POV. These distances then provide POV detection ranges that trigger a signal for the POV driver.

The POV would transmit information to the SV, including the discrete event of crossing a waypoint marker, what travel lane it is in, its travel speed, and POV location. These data would presumably be provided by the instruments on the POV (such as its speedometer or odometer) and conveyed to the SV roadside-to-vehicle or vehicle-to-vehicle communications. Using the following set of equations, a system might provide useful warning information to the POV driver.

Assuming uniform acceleration from a stop, T_1* is the time required for the front of the SV to cross the nearest part of the lane in which the POV is traveling. It is given by the following equation:

$$T_1^* = \sqrt{\frac{D_1}{0.5\ a_{SV}}} \tag{9}$$

where D_1 = distance from the front of SV prior to the maneuver to the leading edge of the POV travel lane, ft

= $lw\ (n\text{-}1) + d_L$, where

lw = lane width, ft

n = lane number (1, 2, 3, or 4)

d_L = distance from the Stop Line to the leading edge of first travel lane

a_{SV} = SV acceleration, ft/s^2

The time when the SV clears the POV travel lane, T_2*, is given by

$$T_2^* = \sqrt{\frac{D_2 + L_{SV}}{0.5\ a_{SV}}} \tag{10}$$

where D_2 = distance from the front of the SV prior to the maneuver to the far edge of the POV travel lane, ft

= $lw\,(n) + d_L$, where

lw = lane width, ft

n = lane number (1, 2, 3, or 4)

d_L = distance from the Stop Line to the leading edge of the first travel lane

L_{SV} = length of SV (e.g., 16 ft)

a_{SV} = SV acceleration, ft/s^2

The values for $T_1{*}$ and $T_2{*}$ define the time interval when a collision can occur. Therefore, a collision will occur if the POV is in the SV travel lane at any time in this interval. To avoid a collision, the POV must clear the intersection prior to the time when the SV enters the intersection (i.e., before $T_1{*}$) or must not arrive in the intersection until after the SV clears it (i.e., after $T_2{*}$). If the constant velocity of the POV is known, as can be determined from its speedometer, then the longitudinal distance that the POV must be from the intersection to avoid a collision can be calculated.

The minimum longitudinal distance (LD_{min}) that the POV can be from the intersection to collide with the SV can be calculated from time = $T_1{*}$. Since distance is the product of velocity and time, then

$$LD_{\min} = V_{POV}\, T_1^* - \left(lw + L_{POV}\right) \tag{11}$$

where LD_{min} = minimum longitudinal distance for POV to leading edge of collision field, ft

V_{POV} = constant velocity of POV, ft/s

$T_1{*}$ = time until SV crosses the nearest edge of the POV travel lane, s

lw = lane width, ft

L_{POV} = length of the POV, ft

Similarly, the maximum longitudinal distance (LD_{max}) that the POV can be from the intersection to collide with the SV can be derived using time = $T_2{*}$.

$$LD_{\max} = V_{POV}\, T_2^* \tag{12}$$

where LD_{max} = maximum longitudinal distance for POV to leading edge of collision field, ft

V_{POV} = constant velocity of POV, ft/s

$T_2{*}$ = time required for SV to clear the POV travel lane, s

If the POV is closer than LD_{min} to the SV travel lane, or is further than LD_{max} from it, then a crash will be avoided.

As an example, consider the case of a POV approaching from the left of the SV in the nearest lane (lane 1), where the Stop Line is 10 ft from the close edge of lane 1, and the acceleration of the SV is a nominal value of 0.15 g. Using the equation for T_1*, the SV will reach the leading edge of the POV travel lane at

$$T_1^* = \sqrt{\frac{D_1}{0.5\ a_{SV}}} = \sqrt{\frac{lw\ (n - 1) + d_L}{0.5\ a_{SV}}},\ n = 1,\ d_L = 10,\ lw = 12\ ft \qquad (13)$$

$$\approx 2.04\ s$$

and, using the equation for T_2*, the SV will clear the far edge of the POV travel lane at

$$T_2^* = \sqrt{\frac{D_2 + L_{SV}}{0.5\ a_{SV}}} = \sqrt{\frac{lw(n) + d_L + L_{SV}}{0.5\ a_{SV}}},\ n = 1,\ d_L = 10\ ft,\ L_{SV} = 16\ ft \qquad (14)$$

$$\approx 3.98\ s$$

To clear the intersection just prior to the SV entering it, the POV must be at a distance shorter than LD_{min}. If the POV velocity is 35 mph,

$$LD_{\min} = V_{POV}\ T_1^* - (lw + L_{POV}) = 76.8\ ft \qquad (15)$$

or 76.8 ft from the SV travel lane.

To enter the intersection just after the SV clears it, the POV must be at a distance longer than LD_{max},

$$LD_{\max} = V_{POV}\ T_2^* = 204.26\ ft \qquad (16)$$

or 204.26 ft from the SV travel lane.

By varying values for the constant velocity of the POV, various detection ranges can be calculated. Table 5-2 shows sample values for detection ranges at various POV velocities and at different SV accelerations from a stop at a four-lane intersection. The values related to a POV approaching from the left assume the POV is in the closest lane to the SV (i.e., $n = 1$) and that the SV has stopped 10 ft from the beginning of this lane. Also, a lane width of 12 ft with no median present is used. The values related to a POV approaching from the right are derived assuming that the SV must travel an additional two lanes to reach the near edge of the POV lane (i.e., $n = 3$). Throughout, the POV is assumed to brake at 0.7 g to avoid a crash.

5.6 DISCUSSION

Many of the implications of the analysis for IVHS crash avoidance system logic have already been addressed. For this crash type, the notion of constant warning time for the-SV driver seems especially appropriate for crash Subtype 1. A constant 2.0-s alerting period would be desirable to accommodate approximately 90 percent of drivers who may be surprised by an alert onset. Machine delays require additional time in the budget. From Section 4., the system ***alert*** is conceived to be non-directive and relatively benign. It would effectively indicate "stop sign ahead." System design is beyond the scope of this analysis, but auditory, visual, kinesthetic-tactile, or combined displays can be developed and tested for their effectiveness and driver appeal.

The alert must not be perceived as irritating since a given driver may know about the intersection and perceive the alert to be redundant. The alert should also not occur too early or else the driver will learn to ignore it.

The distances for 2.0 s of time available for driver-plus-machine delays before normal deceleration to a stop are provided in Figure S-2. The dotted curves indicate the minimum $D_{stop(min)}$ distances required, assuming no time delay, that is, after the delays are finished. The solid lines indicate the corresponding distances at which the alert must be presented. These solid curves are the sum of the $D_{stop(min)}$, value plus 2.0 s of travel distance at the indicated travel velocity. Note that if the 2.0 s is to accommodate driver delay only, an additional time and system range must be provided for vehicle and IVHS delays.

If the alert is presented, the IVHS crash avoidance system can start monitoring the **driver** and seek driver-vehicle performance data to indicate that the driver is executing a normal deceleration. Assume, for illustrative purposes only, that 0.31 g, or 10 ft/s^2, is a normal deceleration. This defines a $D_{stop(min)}$ point, at a given travel velocity, at or before which braking must commence after driver-plus-machine delays. The system can avoid nuisance alarms if it checks to determine whether the SV is within the braking distance or is decelerating at this point. If not, an intrusive warning is displayed that directs the driver to brake. This warning indicates to the driver, "stop ahead." If FACS is present, control intervention might also begin with automatic braking at the nominal deceleration. In the event of a false alarm, the driver can deactivate the system through some action [e.g., tapping a pedal). The driver can also apply more braking, as desired.

Table 5-2
Ranges of Time Available for POV Driver Warning: UI/SCP Subtype 2

(a) POV approaching from the left of the SV

POV Velocity (mph)	D_1 (ft)	T_1^* (s)	LD_{min} (ft)	D_2 (ft)	T_2^* (s)	LD_{max} (ft)	Max Time Available to POV at LD_{max} (s) [1]	Max Time Available to POV at LD_{min} (s) [2]
a_{SV} = .15 g								
25	10.0	2.0	46.8	22.0	4.0	45.9	3.2	0.5
35	10.0	2.0	76.8	22.0	4.0	204.3	2.8	0.3
45	10.0	2.0	106.7	22.0	4.0	262.6	2.5	0.1
55	10.0	2.0	136.7	22.0	4.0	321.0	2.2	-- [3]
a_{SV} = .20 g								
25	10.0	1.8	36.8	22.0	3.4	126.4	2.6	0.2
35	10.0	1.8	62.7	22.0	3.4	176.9	2.3	0.1
45	10.0	1.8	88.7	22.0	3.4	227.4	2.0	--
55	10.0	1.8	114.6	22.0	3.4	278.0	1.6	--
a_{SV} = .25 g								
25	10.0	1.6	30.0	22.0	3.1	113.0	2.3	--
35	10.0	1.6	53.2	22.0	3.1	158.2	1.9	--
45	10.0	1.6	76.4	22.0	3.1	203.4	1.6	--
55	10.0	1.6	99.5	22.0	3.1	248.6	1.3	--

(b) POV approaching from the right of the SV

POV Velocity (mph)	D_1 (ft)	T_1^* (s)	LD_{min} (ft)	D_2 (ft)	T_2^* (s)	LD_{max} (ft)	Max Time Available to POV at LD_{max} (s)	Max Time Available to POV at LD_{min} (s)
a_{SV} = .15 g								
25	34.0	3.8	110.0	46.0	5.1	186.4	4.3	2.2
35	34.0	3.8	165.2	46.0	5.1	260.9	3.9	2.1
45	34.0	3.8	220.4	46.0	5.1	335.5	3.6	1.9
55	34.0	3.8	275.6	46.0	5.1	410.0	3.3	1.6
a_{SV} = .20 g								
25	34.0	3.3	91.5	46.0	4.4	161.4	3.6	1.7
35	34.0	3.3	139.3	46.0	4.4	226.0	3.3	1.6
45	34.0	3.3	187.1	46.0	4.4	290.5	2.9	1.4
55	34.0	3.3	234.9	46.0	4.4	355.1	2.6	1.1
a_{SV} = .50 g								
25	34.0	2.9	78.9	46.0	3.9	144.4	3.1	1.3
35	34.0	2.9	121.7	46.0	3.9	202.1	2.8	1.2
45	34.0	2.9	164.4	46.0	3.9	259.8	2.5	1.0
55	34.0	2.9	207.2	46.0	3.9	317.6	2.1	0.8

Notes:

[1] $a_{POV} = 0.7\ g;\ t_{available} = \dfrac{LD_{max} - \dfrac{V_{POV}^2}{2(.7)(32)}}{V_{POV}}$

[2] $a_{POV} = 0.7\ g;\ t_{available} = \dfrac{LD_{min} - \dfrac{V_{POV}^2}{2(.7)(32)}}{V_{POV}}$

[3] Result ≤ 0.0 s, i.e., POV driver would not be warned in time.

As mentioned in Section 4.4, it is possible that earlier deceleration could begin with braking decelerations below the nominal deceleration (e.g., 0.2 g). This provides both additional time to respond and kinesthetic cues that a stop is required. Unfortunately, this is also sooner than the driver might normally brake. In this case, there may be no opportunity for the driver to exhibit behaviors indicative of normal performance. Human factors studies must be conducted to determine a soft braking level that does not prompt driver irritation or a feeling of loss of control. This could prove to be problematic in practice since the driver must have an opportunity to exhibit appropriate intersection negotiation behavior and, thus, avoid the IVHS warning or automatic braking. There may be a point of indifference, an indifference threshold, where a given driver does not perceive the earlier onset or deceleration to be unacceptable.

If FACS is not present in the system, or the driver does not begin braking at the nominal deceleration by $D_{stop(min)}$, then more drastic measures are required. For example, the driver may receive an even more urgent warning to brake. This urgent warning might indicate to the driver "STOP!". As discussed earlier, additional time delay may be compensated for by harder braking, up to a limit. An FACS could conceivably be designed to apply this emergency braking (e.g., 0.5 g or higher) if the driver has not responded by the $D_{stop(min)}$ point associated with the higher deceleration rate. While the driver might disengage the braking, this system should prevent encroachment into the intersection in most cases.

The IVHS CAS must also be reset, i.e., the system mutes alerts and alarms, halts automatic braking, and seeks out information about the next intersection. One condition that would allow for the reset is if the SV is beyond the Stop Line at a certain distance.

Figure 5-6 presents these notions in'the context of both the time-intensity graph and the unsignalized intersection schematic. An SV traveling at 45 mph (66 ft/s) is assumed. If, at 10 ft/s^2 normal braking deceleration, $D_{stop(min)}$ is 218 from the Stop Line, then 2.0 s of driver-plus-machine delay to initiate this braking means the alert must be presented 132 feet (2.0 s x 66 ft/s) before the $D_{stop(min)}$ point, i.e., 350 ft from the Stop Line. If the driver is not braking at 218 ft from the Stop Line, the IVHS crash avoidance system initiates a driver warning and soft braking (e.g., 0.35 g), if available. If, at 136 ft from the Stop Line, the vehicle is not decelerating or is not decelerating adequately, the system would initiate a more urgent warning to the driver or the FACS would apply harder emergency braking (i.e., 0.5 g).

For SVs that attempt to proceed against cross traffic, an IVHS collision avoidance system that assists the drivers in judging when it is safe to proceed may be of value. To make this judgement, information about the potential hazard (the approaching POV) can be presented to the SV driver: the direction of approach and perhaps an indication of when the POV will arrive in the intersection. This information would help the SV driver judge the gap that is available to make it safely across the intersection. $T1$ and $T2$ (and $T1^*$ and $T2^*$) provide just this kind of information. The presentation of this gap assessment tool may, however, provide additional workload to the driver, thus making the decision harder to make, Also, the system may not be able to assess when the SV driver will accelerate and at what level, making the situation intractable. A useful alternative may be to warn the SV driver when a POV time headway is less than some safe margin based on time needed by the SV to cross the intersection.

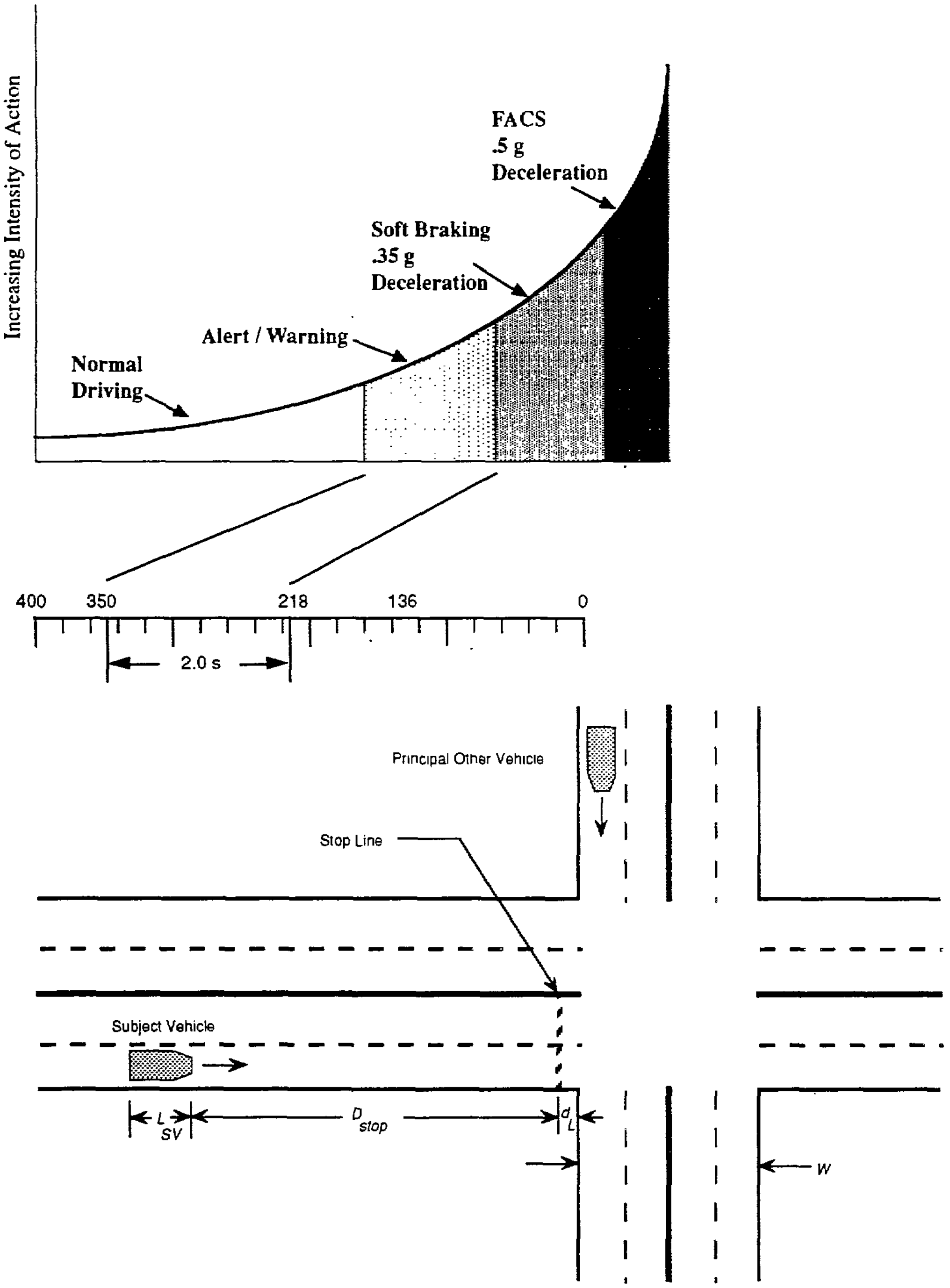


Figure 5-6. IVHS Crash Avoidance System Concepts in the Context of a 45-mph SV Travel Velocity

Since $T1$ (or $T1^*$) is the time when the SV will cross into the collision field, false alarms can be precluded or eliminated such that when the SV is ready to proceed, if the POV is closer than the minimum distance, LD_{min}, from the intersection, no warning is sounded. The POV will pass in front of the SV without incident. Also, if the POV is greater than LD_{max} from the intersection, it will pass behind the SV that is traveling through this intersection. If the POV is between LD,, and LD_{max}, the POV driver will be warned if the SV enters the intersection. The SV driver will thus be aided with gap acceptance information to judge when it is safe to enter the intersection.

Of course, the input required for such a system is the typical acceleration profile of the individual driver-vehicle combination, which may be elusive for system designers. But, with advancing technologies such as neural networks and fuzzy logic, these profiles may be collected and modified to provide the requisite information for the development of this IVHS crash avoidance technology.

6. MAJOR FINDINGS AND OBSERVATIONS

This section highlights major findings and related observations that resulted from the analysis of UI/SCP crashes and potential IVHS countermeasures.

6.1 CRASH SUBTYPES AND CAUSAL FACTORS

An in-depth analysis of a sample of UI/SCP crashes was conducted to identify crash subtypes and causes. The sample consisted of 100 CDS reports. The analysis revealed two subtypes of UI/SCP crashes: ***ran the stopsign*** (Subtype ***1)*** and ***stopped and then proceeded against cross traffic*** (Subtype 2) which accounted for 42.4% and 57.6% of UI/SCP crashes, respectively. Also, this analysis identified two major causes of UI/SCP crashes, which are listed below in a descending order according to their weighted percentage of occurrence:

1. driver unawareness of POV presence (crash Subtype 2, 45.7%) and of the intersection or its stop sign (crash Subtype 1, 28.9%) due to inattention, failure to see, and obstructed vision: and
2. driver ***misjudgment*** of ***POV velocity/gap*** (crash Subtype 2, 12.2%).

6.2 CRASH COUNTERMEASURE CONCEPTS

IVHS crash countermeasure concepts, specific to UI/SCP crash subtypes, were devised in three different categories to address the major causal factors listed above. In addition, a hybrid concept was suggested which employs concepts of the three previous categories and provides timely transitions among them. IVHS countermeasure concepts are briefly described in each of the three categories below.

1. In-vehicle alert: A Subtype 1 crash countermeasure concept adopts in-vehicle signing to alert the SV driver to the presence of the intersection or stop sign ahead. A Subtype 2 concept provides the SV driver with an in-vehicle situation display of the presence of a POV approaching the intersection. Such concepts are mostly applicable to UI/SCP crashes caused by the SV driver who is inattentive or whose view is obstructed. Thus, the in-vehicle signing and situation display concepts address about 29% and 46% of all UI/SCP crashes, respectively.

2. Driver warning: A Subtype 1 concept provides graded warnings to the SV driver and constant warning times required to avoid this crash subtype. This concept addresses UI/SCP crashes caused by drivers who are unaware of the intersection or stop sign ahead; thus, it would be applicable to about 29% of UI/SCP crashes. A Subtype 2 concept might be a gap acceptance aid that warns the SV driver when it is unsafe to cross the intersection. This concept would mostly benefit drivers who are unaware and misjudge the velocity/gap of the POV. Therefore, about 58% of UI/SCP crashes are addressed by such a concept. Also, warning the POV driver in both crash subtypes at certain instances is considered.

3. Control intervention: This category is an alternative (or possibly a supplement) to driver warning and would be automatically activated, either partially or fully, at points along the time-to-crash continuum where driver action alone is insufficient. This might include soft braking, moderate braking, or graded braking (with or without driver override). This category addresses the two major causes of the UI/SCP crash. In addition, automatic control intervention in the form of emergency braking to a stop might be applicable to Subtype 1 crashes caused by drivers who deliberately violated the stop sign (3.4%). Consequently, automatic control intervention would apply to about 90% of UI/SCP crashes.

6.3 MODELING REPRESENTATION

Analytical models were formulated to represent the effects of IVHS crash countermeasure concepts on UI/SCP crash avoidance. These models would be used to-predict countermeasure effectiveness and to identify critical countermeasure functional requirements and data needs. Reliability modeling was adopted to assess the in-vehicle alert category and the SV driver warning concept in crash Subtype 2, assuming a series GAS-driver system. Other concepts were represented by kinematic models. Next, observations are made with regard to modeling results of SV driver warnings in crash Subtype 1 and POV driver warnings in Subtypes 1 and 2.

6.3.1 Suhtype 1: SV Driver Warnings

The analysis of the SV driver warning model ih crash Subtype 1 reveals that the greater the distance of the SV away from the intersection, the more time that the SV driver has to respond to a warning to stop. For every foot of distance away from the intersection, the maximum time for the driver to respond increases by $1/V_{SV}$ seconds. For example, if the SV is traveling at 25 mph (36.67 ft/s), the SV driver has 27 ms of additional time to respond for every foot that the vehicle is away from the intersection. At faster speeds, this incremental time decreases. If the SV is traveling at 5.5 mph (80.67 ft/s), then the SV driver has only 12 ms of additional time to respond for every foot that the vehicle is away from the intersection. This result demonstrates the sensitivity of the maximum time available to the distance away from the intersection. Seconds of time mean hundreds of feet in distance, implying the need to ensure that the CAS range is as large as possible.

Also, the distance at ‘which the maximum time delay becomes zero increases with increased velocity (since more stopping distance is needed at higher speeds) and decreases with increased deceleration (since harder braking shortens stopping distance). At higher speeds, more distance is needed to stop, so the maximum time delay will remain higher longer as the distance from the intersection increases. The maximum time delay becomes zero when the distance is equal to $V^2_{SV}/2a_{SV}$. For a constant time delay, greater braking implies that the SV can be closer to the intersection when the braking must be initiated to stop the vehicle.

At any given distance and SV velocity, higher deceleration levels mean a larger maximum time available. At faster speeds, this relationship is exaggerated. Although the absolute maximum time available at any given distance decreases across velocities, higher decelerations at greater speeds mean even greater separation of the maximum time available. For example, at 25 mph the difference between the values of maximum time available at a, = 22.4 ft/s^2 and a, = 10 ft/s^2 for distances greater than 75 ft is 1.02 s. At 55 mph the difference becomes 2.24 s for distances greater than about 330 ft. This result demonstrates the sensitivity of the range of maximum time available to the levels of braking applied and travel speed. Greater levels of braking at higher speeds yield substantially greater differences in the maximum time available than do greater levels of braking at lower speeds, implying the criticality of the need for decreased mechanical delays of the braking system at higher speeds.

The UI/SCP crash scenario for Subtype 1 involves several key variables that must be incorporated into an IVHS crash avoidance system for the SV driver. All of these variables are assumed to be monitored moment-to-moment for a given driver response time: IVHS and vehicle delay times, current SV travel velocity, current distance from the Stop Line, and braking deceleration to be applied. From these variables. other factors such as D_{stop} and $D_{stop(min)}$ can be determined.

6.3.2 Subtype 1: POV Driver Warnings

The POV driver warning model in crash Subtype 1 was analyzed to assess the feasibility of warning the POV in case an approaching SV is not decelerating at certain levels as it should. Based on the results shown in Table 5-1, the 0.31 -g (SV deceleration) warning threshold appears to be a potentially viable alternative to trigger an alarm to which a reasonable proportion of drivers can respond. Unfortunately the 0.31 -g nominal deceleration is at approximately the 50th percentile (Wortman & Mathias, 1983), which means that 50 percent of drivers who eventually stop will brake harder and later. This constitutes a substantial risk of false alarms, which may undermine CAS effectiveness.

At the 0.5-g and 0.7-g warning thresholds, drivers have too little time available to stop. Even the longest time of approximately 1.09 s will leave roughly half of all surprised drivers unable to respond in time, since the 50th percentile brake RT (Sivak et al., 1982) is 1.07 s. Since the available time must accommodate system delays as well (which could be substantial), the proportion of drivers who could respond in time grows smaller. Thus, the notion of graded warnings at the thresholds presented above will not work for warning the POV driver.

The analysis in Table 5-1 assumes a drastic evasive maneuver by the POV. Given the limited time budgets associated with even a 0.7-g braking maneuver, simple slowing is not likely to be feasible. Even if 0.7-g emergency braking were allowed, it might have adverse secondary consequences for other vehicles. For example, the CAS system might provide intersection crash avoidance at the expense of an increased risk of a rear-end crash. The POV driver might not be willing or able to apply such hard braking and would therefore be involved in a crash anyway. The POV driver might also use another evasive maneuver, such as steering out of the POV travel lane, and increase the risk of head-on, roadway departure, or other types of crashes. Therefore, the viability of the POV driver warning should be approached with caution and requires further analysis and empirical assessment.

6.3.3 Subtype 2: POV Driver Warnings

Available response times for the POV to avoid a Subtype 2 UI/SCP crash are shown in the last two columns of Table 5-2 under different conditions. Consider first part a) of Table 5-2, which applies to the POV approaching in lane 1 from the left of the SV. In general, there is not enough time for evasive POV maneuvers at or near the LD_{min} point. This makes sense since, in this case, an SV “suddenly” intrudes into the intersection when the POV is very close. Thus, a POV driver warning is unlikely to be effective; warning the SV of approaching POVs may be more appropriate. However, if the POV is at or near $LD_{,,}$ when the SV driver unwittingly pulls out into the intersection, there is sufficient time for driver response in most instances. Between LD_{min} and LD_{max} the POV location at CAS warning onset follows a rectangular distribution. The proportion of drivers who could brake as fast or faster than the maximum available time for delay can be evaluated with reference to Figure 5-4. Thus, there is some potential for POV driver warnings in these circumstances.

Consider next part b) of Table 5-2, which applies to the POV approaching in lane 3 from the right of the SV. In this circumstance, the maximum time available for driver and machine delays at or near LD_{min} varies from 1.1 s to 3.0 s. depending on POV travel velocity and SV acceleration. At or near LD_{max}, the time budgets for driver and machine delay are even greater, from 2.6 to 5.4 s. Given a 90th percentile value for surprise brake reaction time of about 2.0 s, these results suggest POV warnings may be viable in a substantial number of such cases. As in the related analysis for Subtype 1, the viability of the POV driver warning should be approached with caution and requires further analysis and empirical assessment.

7. RESEARCH AND DEVELOPMENT

This section presents research needs suggested by the analysis. Note that in many cases they are similar to the research needs for signalized intersection, crossing path crashes (Tijerina et al., 1994). Data needs to support further crash circumstance modeling are stressed, although understanding the crash causes and mechanisms, as well as driver-vehicle behavior, is also important. Modeling efforts are emphasized because they are important to IVHS crash avoidance systems design. 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 technologies. An in-depth analytical representation of the crash problem will be the key to successful IVHS CAS algorithm development for both driver indications (alerts and warnings) and FACS implementation.

7.1 CLINICAL ANALYSIS AREA

- Only a small clinical sample was used to identify causal factors in this analysis, Consequently, the confidence intervals about the proportions reported are quite broad. If more precise estimates of the proportions of crash causal factors are warranted, then analyzing additional crash cases is recommended.
- 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.

7.2 DRIVER BEHAVIOR AT UNSIGNALIZED INTERSECTIONS

- The analysis assumed a rudimentary response — braking — by the SV driver. Information is needed about driver response to stop signs, as well as to the proposed countermeasures. An understanding of the psychology of the unsignalized intersection negotiation would be useful for more realistic modeling and subsequent design for the IVHS crash avoidance system.
- It would be beneficial to know the correlation between driver reaction time (RT) and nominal braking rate as well as the correlation between brake RT and peak braking deceleration. This 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 the addition of this information to the driver task impacts workload.

- 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 intersection maneuver should also be conducted.

- Studies of the interaction between two or more drivers are needed in the context of how CAS and driver vehicle behavior changes with multiple vehicles. This is likely to be particularly important in designing and evaluating multiple warnings to the SV and POV drivers. It is possible that certain types of instability may arise if both drivers are warned of a possible crash. The impact of various driver behaviors on the graded warning scheme 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 (Schumann, Godthelp, Farber, & Wontorra, 1993) should be explored for conveying IVHS crash avoidance system information to the driver.

7.3 UI/SCP ALGORITHM RESEARCH NEEDS

- Some concepts for an IVHS crash avoidance system suitable to the UI/SCP crash type were discussed. Their presentation in the report is primarily for explication and in no way should be thought of as endorsements. Additional CAS concepts are needed to enrich the set of alternative system concepts for further analysis and trade studies.

- The data needs for an UI/SCP crash avoidance algorithm were discussed at length in Section 5. See Table 7-l for a listing of the variables. Error modeling of the algorithm data should be conducted to assess the impacts of errors (accuracy or timeliness) on hypothetical system effectiveness.

- 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.

- For simplicity, constant travel velocity was assumed in the examples and graphs presented in this report. The impact of various velocity profiles on algorithm robustness should also be explored in more in-depth analyses.

Table 7-1
UI/SCP CAS Data Needs

Variable	Definition
$t_{driverRT}$	SV driver brake reaction time
$t_{machine\ delay}$ • $t_{vehicle\ delay}$ • $t_{IVHS\ delay}$	Vehicle delay plus IVHS delay
$D_{location}$	SV location from the Stop Line at any given instant
d_L	Distance from the Stop Line to the leading edge of the first travel lane
n	Lane number
lw	Travel lane width
V_{SV}	SV velocity
V_{POV}	POV velocity
a_{SV} a_{pov}	SV deceleration/acceleration POV acceleration
Direction of approach	Whether the vehicle is coming from the left or the right
W	Intersection width

7.4 FURTHER MODELING RESEARCH NEEDS

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

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 Tables A-l, A-2, and A-3 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 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
Weighting Scheme For Total Case Sample

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	22	22	60.87	2.77
1(C)	23	23	20.05	0.87
2(B)	16	16	11.16	0.70
3/4(A/K)	39	39	7.92	0.20
Total	100	100	100.00	

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

Table A-2
Weighting Scheme For Subtype 1 Crashes (Ran Stop Sign)

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	8	15.69	60.87	7.61
1 (C)	12	23.53	20.05	1.67
2(B)	7	13.73	11.16	1.59
3/4 (A/K)	24	47.06	7.92	0.33
Total	**51**	**100.01**	100.00	

Table A-3
Weighting Scheme For Subtype 2 Crashes (Proceeded Against Cross Traffic)

Crash Severity	# in Sample	% of Clinical Sample	% of 1991 GES	% Rep. Each Case
0(0)	14	28.57	60.87	4.35
1(C)	11	22.45	20.05	1.82
2(B)	9	18.37	11.16	1.24
3/4(A/K)	15	30.61	7.92	0.53
Total	49	100.00	100.00	

Notes:

1 **GES** crash severity based on cases involving ail 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 Seventy 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 is the ratio (% of 1991 GES)/(# in Sample).

APPENDIX B. CAUSAL FACTOR DESCRIPTIONS

Driver Inattention

Cases where the driver was not attentive to the driving task. These cases are typified by sudden or no actions taken by the subject driver. Many cases involve running the sign because the driver failed to notice the sign.

Faulty Perception

Looked - Did Not See

Cases where the subject vehicle driver looked down the roadway but did not observe the POV. Typical comments from these crashes are “I never saw the other car coming”.

Looked - Misjudged Cap/Velocity

Cases where the driver of the Subject or Principal Other Vehicle did observe the other vehicle, but proceeded with the maneuver. Typical comments in these cases are “They must have been speeding because I thought I had plenty of time to make it across;” or, “I saw the other car but thought I could make it”.

Vision Obstruction/Impairment

Cases where the vision of the driver (SV or POV) is blocked by either intervening vehicle, roadside appurtenances, or roadway geometry (hills or curves). Also included is vision impairment caused by sunlight in the drivers eyes.

Deliberate Violation of Sign

Driver observes sign but knowingly proceeds through it.

Driving Under the Influence

Crashes with a subject driver blood alcohol content (BAC) in excess of 0.10.

Adverse Environmental Conditions

Crashes caused by existing environmental conditions. Typical of these types are crashes where a vehicle approaches an icy intersection, slides into the intersection, and strikes or is struck by another vehicle.

Unknown

Crashes that comply with the criteria of this crash type but with insufficient data present in the file to determine the causal factor.

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