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

DOT HS 808 143
DOT-VNTSC-NHTSA-94-1

Final Report
August 1994

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

# REPORT DOCUMENTATION PAGE

*Form Approved OMB No.0704-0188*



**1. AGENCY USE ONLY (Leave blank)**

**2. REPORT DATE**
August 1994

**3. REPORT TYPE AND DATES COVERED**
Final Report
October 1992 - April 1994

**4. TITLE AND SUBTITLE**
Examination of Signalized Intersection, Straight Crossing Path Crashes and Potential IVHS Countermeasures

**5. FUNDING NUMBERS**
HS421/S4007

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

**8. PERFORMING ORGANIZATION REPORT NUMBER**
DOT-VNTSC-NHTSA-94-l

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

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
DOT HS 808 143

**11. SUPPLEMENTARY NOTES**
Firm Contracting to RSPA/VNTSC:

| | |
|---|---|
| Battelle | Celspan Corp. |
| 505 King Ave. | P.O. Box 400 |
| Columbus, OH 43201-2693 | Buffalo, NY 14225 |

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**

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

**12b. DISTRIBUTION CODE**

**13. ABSTRACT (Maximum 200 words)**

This report provides a preliminary analysis of signalized intersection, straight crossing path (SI/SCP) crashes to support development of crash avoidance system (CAS) functional concepts as part of the Intelligent Vehicle Highway System (IVHS). An SI/SCP crash is defined as a crash at a signalized intersection in which two vehicles, one with and one without right-of-way, collide in straight crossing paths. A detailed analysis of 50 such crashes shows that 41% of these crashes are caused by drivers who were unaware of the signal presence and its status, and that 16% were caused by drivers who attempted to beat the amber phase. The CAS concepts discussed in this report are driver alerts, driver warnings, partially automatic control systems, fully automatic control systems, and a hybrid system that incorporates the previous four concepts and transitions among them. The report also provides kinematic models to determine the time and distance available for crash avoidance under various vehicle operating conditions. The report concludes with a number of research needs to better understand SI/SCP crashes and guide CAS development.

**14. SUBJECT TERMS**
vehicle crash analysis, crash countermeasures, IVHS, kinematic models, crash circumstances

**15. NUMBER OF PAGES**
60

**16. PRICE COOE**

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

# 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 signalized intersection, straight crossing path crash study. The results are based on the analysis of 37 hard copy reports and 13 police accident reports, which were selected from the 1992 Crashworthiness Data System (CDS) and from the 1991 General Estimates System (GES), respectively. 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 Louis Tijerina and John D. Chovan of Battelle and John 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-Shiarn Wang of IMC, Inc., provided technical guidance and reviewed the report.

The contributions of the following Battelle staff are also acknowledged: John C. Allen, Jeffrey H. Everson, and Nathan Browning for their technical assistance and review; Laura K. Brendon for serving as technical writer and editor; Christina A. Anagnost and Suzanne W. Mckeown for serving as copy editors; and Viki L. Breckenridge for providing secretarial services. Their support is much appreciated.

## METRIC/ENGLISH CONVERSION FACTORS

### ENGLISH TO METRIC

**LENGTH (APPROXIMATE)**

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

**AREA (APPROXIMATE)**

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

**MASS - WEIGHT (APPROXIMATE)**

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

**VOLUME (APPROXIMATE)**

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

**TEMPERATURE (EXACT)**

[(x-32)(5/9)] $^o$F ❑ y $^o$C

### METRIC TO ENGLISH

**LENGTH (APPROXIMATE)**

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

**AREA (APPROXIMATE)**

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

**MASS - WEIGHT (APPROXIMATE)**

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

**VOLUME (APPROXIMATE)**

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

**TEMPERATURE (EXACT)**

[(9/5) y + 32] $^o$C ❑ x $^o$F

### QUICK INCH-CENTIMETER LENGTH CONVERSION

| INCHES | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|

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

### QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

| °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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## LIST OF ILLUSTRATIONS (continued)



## LIST OF TABLES

## ABBREVIATIONS AND ACRONYMS

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

| | |
|---|---|
| a | SV deceleration, $ft/s^2$ |
| ATIS | Advanced Traveler Information System |
| ATMS | Advanced Traffic Management System |
| CAS | crash avoidance system |
| CDS | Crashworthiness Data System |
| D | distance traveled with soft braking applied, ft |
| $D_{stop}$ | required SV braking distance to stop by the Stop Line, ft |
| $D_{stop(min)}$ | minimum required stopping distance without delays, ft |
| $D_{CZ}$ | distance from the beginning of the Clearance Zone to the intersection Stop Line, 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 |
| $D_{loc}$ | SV distance (location) from the Stop Line when the CAS warning is delivered, ft |
| FACS | fully automatic control system |
| ft | foot, feet |
| g | unit force of gravity, 32 $ft/s^2$ |
| GES | General Estimates System |
| $L_{SV}$ | length of SV, ft |
| $LD_{min}$ | minimum longitudinal distance from intersection for POV to collide with SV, ft |
| $LD_{max}$ | maximum longitudinal distance from intersection for POV to collide with SV, ft |
| $L_{POV}$ | length of POV, ft |
| lw | lane width, ft |
| IVHS | Intelligent Vehicle Highway System |
| mph | miles per hour |
| NASS | National Accident Sampling System |
| NHTSA | National Highway Traffic Safety Administration |
| NPR | nonpolice-reported |
| $P_{driver\ failure}$ | failure to brake at signalized intersections |
| PAR | police accident report |
| POV | principal other vehicle |
| $R_{driver}$ | driver reliability in braking at signalized intersections |
| RT | reaction time, s |
| s | second, seconds |
| SI/LTAP/IPD | signalized intersection, left turn across path, initial perpendicular direction |

ABBREVIATIONS AND ACRONYMS (continued)

| | |
|---|---|
| SI/PCP | signalized intersection, perpendicular crossing path |
| SI/SCP | signalized intersection, straight crossing path |
| S V | subject vehicle |
| $t$ | elapsed time, s |
| $t_{amber}$ | remaining duration of amber light, s |
| $t_{max\ available}$ | time available to accommodate driver and machine delays, s |
| $t_{design\ amber}$ | design amber duration (duration of the amber light, as designed into the signal status), s |
| $t_{design\ delay}$ | design delay 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 at which SV crosses the leading edge of the POV travel lane, s |
| $T_2$ | time when the SV clears the POV travel lane, s |
| $V_{final}$ | final travel velocity after a constant deceleration is applied over a given distance, ft/s |
| $V_0$ | initial travel velocity before a constant deceleration is applied, ft/s |
| $V_{SV}$ | SV velocity, ft/s |
| $V_{POV}$ | POV velocity, ft/s |
| W | intersection width, ft |

EXECUTIVESUMMARY

This report provides a preliminary analysis of signalized intersection, straight crossing path (SI/SCP) crashes to support development of SI/SCP crash avoidance system (CAS) functional concepts that might be developed as part of the Intelligent Vehicle Highway System (IVHS). The SI/SCP crash is defined as a crash at a signalized intersection in which two vehicles, one with and one without right-of-way, collide in straight crossing paths. An analytic model of intersection negotiation behavior at signalized intersections is presented to indicate possible sources of driver error that might contribute to the crashes. These possible sources include inattention to the presence of the intersection, improper detection or interpretation of the signal status, time estimation errors associated with signal changes, lack of cross traffic detection, and visual obstruction problems.

SI/SCP crashes accounted for 203,000 police-reported crashes in 1991; this is roughly 3 percent of all crashes in 1991. SI/SCP crash characteristics indicate that it is largely a dry pavement, good weather, daylight phenomenon involving predominantly people under 54 years of age traveling over a wide range of travel velocities. From a causal standpoint, a detailed analysis of 50 such crashes suggests that roughly one out of four such crashes occurs due to deliberate violation of the signal to stop. Over half of such crashes may be attributed to driver "unawareness" of the crash hazard, either because of inattention, obstructed vision, or misjudgment of the signal status and/or other traffic patterns. Driver intoxication, vehicle defects, and various other conditions make up the remaining causal factors.

Some drivers are so motivated to get to their destination that they will drive recklessly to do so. The view taken here is that IVHS technologies are unlikely to change such behaviors. Instead, the focus of functional CAS concepts presented in this report is to address the driver unawareness problem. It is assumed that the rational driver, if alerted, warned, or otherwise assisted to avoid the crash, will respond in appropriate ways.

The CAS concepts discussed in this report are: driver alerts, driver warnings, partially automatic control systems, fully automatic control systems, and a hybrid system that incorporates the others 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 called for in situations where driver delay or inadequate braking performance cannot be tolerated. Control intervention for the SI/SCP crash is presented 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 SI/SCP crashes and begins the assessment of alternative CAS concepts. Driver alerts are modeled, by way of an example, in terms of both parallel and series system reliability models. In a parallel system, the system performs satisfactorily if at least one of the components performs satisfactorily. In a series system, the system fails if any component fails. One important theoretical result is that, if the driver and CAS work as a series system, the reliability of the two will be less than the reliability of the driver alone. Reasons for this include false and nuisance alarm effects and other human factors phenomena. Due to lack of important driver behavior data, it is not clear what formulation is most appropriate for the unaware driver. However, the example provides an illustration of the technique and should motivate further inquiry into this important research area. Driver warnings are analyzed in terms of the maximum time available for driver and vehicle/CAS delays under various kinematic conditions. An alternative assessment examines the notion of constant warning time and the trigger points implied by various kinematic conditions. Intersection maneuvers can be anticipated or predicted sufficiently in advance to support constant warning times. This is not necessarily the case in, for example, lane change crashes wherein a vehicle suddenly and sharply cuts in front of another vehicle. The potential of warning the principal other vehicle (POV) driver that the subject vehicle (SV) will violate its signal is assessed in terms of graded warnings. For the scenarios assessed, modeling results suggest that graded warnings will not be feasible. Furthermore, even if POV drivers are warned when the SV fails to exhibit nominal (average) braking, 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. Finally, the minimum distance trigger points for fully automatic control systems at selected decelerations are presented along with a single example of the contribution soft braking may make to providing additional time for driver delays. All of the kinematic analyses assume vehicles traveling at constant velocity and applying uniform deceleration. The implications of more complex motion profiles and the need to better represent true driver behavior at intersections are noted.

This report concludes with a number of research needs to better understand SI/SCP crashes and guide CAS development. The clinical analysis should be verified by analyzing additional cases. There are many driver human factors research needs and some of those peculiar to this crash type are presented. CAS algorithm needs for SI/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 modeling 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'a preliminary analysis of signalized intersection, straight crossing path (SI/SCP) crashes. The SI/SCP crash is defined and a driver model of intersection negotiation is presented to identify sources of possible driver actions that could lead to SI/SCP crashes. The size of the SI/SCP problem is presented in terms of accident statistics. A detailed analysis of crash cases follows to determine the underlying causes of SI/SCP crashes. This analysis then guides the definition of SI/SCP crash. avoidance system (CAS) functional concepts that might be developed as part of the Intelligent Vehicle Highway System (IVHS). The CAS concepts that are presented follow a theme that concerns time to collision and the required intensity of crash avoidance maneuver. The signalized intersection maneuver is then modeled in a simple way so that the maximum time available for driver and machine delays after alert or warning onset can be assessed for the CAS concepts presented. In addition, the notion of constant warning time is also evaluated. Finally, the analysis concludes with research needs that will further an understanding of SI/SCP crashes and the development of crash countermeasures.

## 1.2 DEFINITION OF SIGNALIZED INTERSECTION, STRAIGHT CROSSING PATH (SI/SCP) CRASHES

In this report, "SI/SCP crash" refers to a collision that occurs at a signalized intersection. Two vehicles (one with right-of-way and one without) travel through the intersection in straight paths perpendicular to each other and collide. The vehicle without right-of-way, the subject vehicle (SV), may either strike or be struck by the principal other vehicle (POV). Figure l-1 illustrates a prototypical SI/SCP precrash scenario.

Figure 1-2 shows a simple model of intersection negotiation behavior at signalized intersections, adapted from the work of McKnight and Adams (1970). This model suggests possible sources of driver error that can contribute to SI/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 observe traffic signals. The driver who is unaware of the intersection for whatever reason might fail to slow down. Similarly, the driver, who is unaware of the traffic signal status or who makes erroneous assumptions about it, is prone to cross the intersection at inopportune times.

The traffic signal status indicates what the driver should do. A red light or flashing red light means "stop." (See the discussion of jurisdictional differences in Section 5.1 of this report.) Some hurried drivers may anticipate that the red light will change to green (perhaps by glancing at the cross traffic signal status) and will not stop. An amber light means "clear

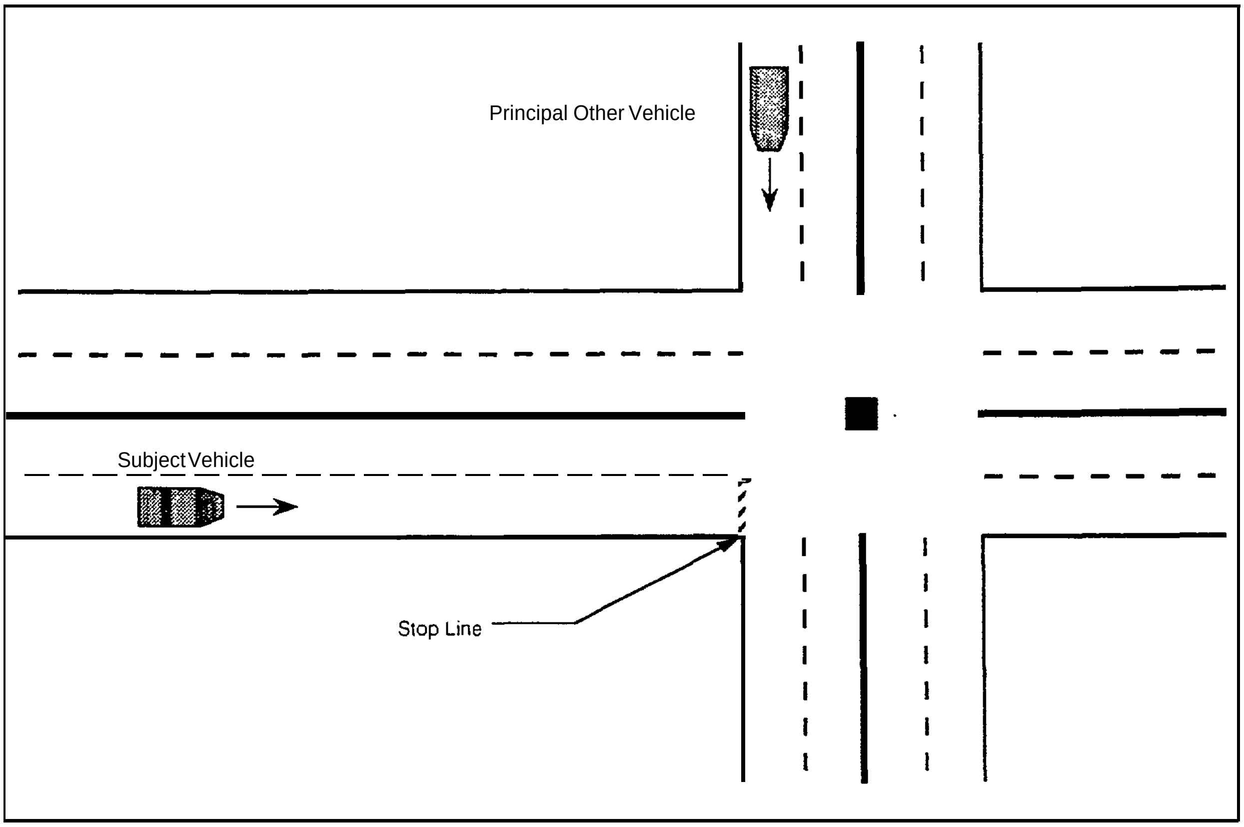


Figure l-l. SI/SCP Precrnsh Scenario

the intersection" (the driver should either traverse through the intersection, if possible, or should stop before the vehicle reaches the intersection). Drivers must judge their ability to clear the intersection by the time that the light turns red and act accordingly. Such judgements may be faulty due to miscalculation of the duration of the amber light and the remaining travel distance through the intersection with respect to their own vehicle travel speed.

For the flashing amber light, the driver must detect, recognize, and identify a hazard before stopping the vehicle; otherwise, the driver will proceed through the intersection. The driver's errors in hazard assessment might have several causes, such as misperception of the presence of cross traffic and inaccurate estimates of the distance, approach speed, and intended direction of cross traffic. A driver highly motivated to avoid waiting at a traffic light might incorrectly evaluate such information and become involved in an intersection crash.

Even when there is a green light, the driver should estimate how long the light has been green and anticipate when it will turn amber, and then red. Driver errors might arise because the driver does not know how long the light has been green, is unfamiliar with the signal status at a particular intersection, or has poor time estimation skills. The SV driver might not brake if other vehicles are following too closely behind or if the driver believes that there is insufficient stopping distance.

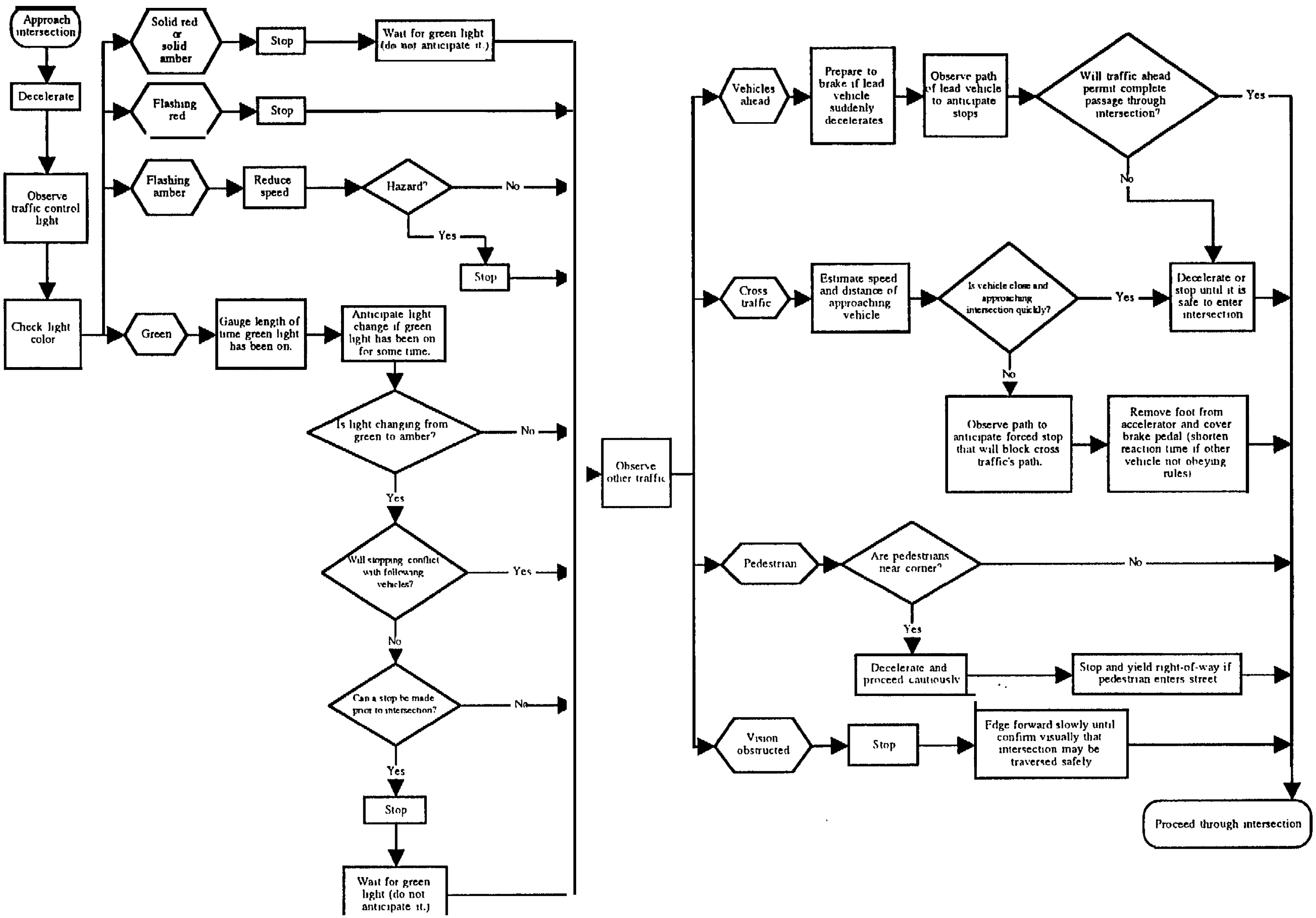


**Figure 1-2. Simple Model of Intersection Negotiation Behavior**

The driver who intends to proceed across the intersection must observe other traffic and pedestrians and must pay attention to lead vehicles to anticipate sudden stops. Drivers must also pay attention to pedestrians because they are often highly unpredictable. However, pedestrians might also attract attention by their dress or manner and, therefore, might distract the driver. Cross traffic (the chief concern of this report) might be misperceived with respect to speed, distance to the intersection, or direction of travel (straight versus turn). Alternatively, the driver of a cross traffic vehicle (POV) might suddenly brake for lead traffic or pedestrians, which might place the POV across the SV's travel lane. Finally, it is possible that 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 error sources can lead an otherwise rational driver to enter into an unsafe driving situation.

In summary, the ideal driver negotiating an intersection must:

- Detect the presence of the intersection during an approach and slow down
- Detect and interpret the signal status correctly
- Estimate, when the light changes from green to amber, if it is safe to proceed through the intersection
- Anticipate sudden deceleration from lead vehicle(s)
- Detect the presence of cross traffic
- Recognize crash hazards posed by cross traffic, perhaps by estimating the speed and distance of the approaching vehicles
- Identify vision obstruction problems and attempt to overcome such problems
- Watch for and anticipate other traffic or pedestrians that may cause a cross traffic vehicle to suddenly stop in the SV travel lane

Although this simple model of driver behavior does not define how a driver accomplishes these tasks, it introduces the problem and suggests opportunities for crash avoidance assistance. The next section describes the crash problem size.

# 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 SI/SCP crash problem. The data are based on police accident reports (PARs) derived from the NHTSA General Estimates System (GES) 1991 statistics. Approximately 3 percent of PARs were SI/SCP crashes, which represents approximately 203,000 crashes. In addition, based on an estimation algorithm developed by NHTSA (Knipling, Wang, & Yin, 1993), there were nearly 200,000 nonpolice-reported (NPR) SI/SCP crashes. The Sl/SCP crash type accounted for roughly 4 percent, or 18.1 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.

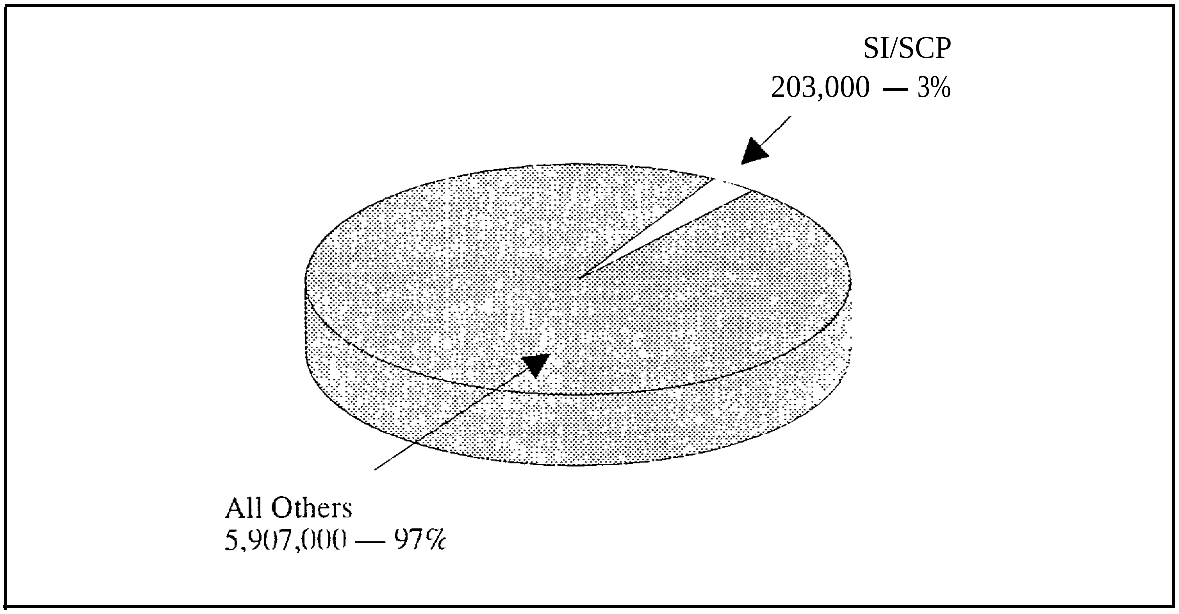


Figure 2-1. Problem Size, 1991 GES Data

## 2.2 DISCUSSION

The SI/SCP crash problem represents a relatively small percentage of the crash population. However, 203,000 crashes are not insignificant, nor are the related economic consequences. Available technologies might be able to provide affordable SI/SCP crash countermeasures, thereby adding to highway safety and providing technology transfer to other crash types.

1991 GES data indicate that roadway conditions do not need to be a priority consideration for a first-order assessment (see Table 2-l). These data indicate that 79 percent of SI/SCP crashes occur on dry pavement, 19 percent on wet pivement, and only 2 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 although future work should examine poor traction impacts. Table 2-l also shows that good ambient lighting predominates in SI/SCP crashes (e.g., 72 percent occur in daylight). In addition, the majority of drivers (81 percent) involved in SI/SCP crashes are under 54 years of age, although elderly drivers are over-represented in intersection crashes (Smith, Meshkati, & Robertson, 1993), and future research should address elderly drivers and their limitations. Speed profiles, when modeled, should span a wide range of speeds to represent a variety of posted speed limits. The distribution in Table 2-1 indicates, however, that the majority of SVs were traveling 35 mph or less, possibly due to emergency braking that was applied too late. The statistics on the obstruction of driver vision and on driver distraction are considered to be conservative because PAR data do not reliably capture the involvement of these factors in crashes.

Note that one other crash type is similar to the SI/SCP scenario, but is not included in the problem size statistics presented here. This is the signalized intersection, left turn across path, initial perpendicular direction (SI/LTAP/IPD) crash scenario. Figure 2-2 shows a simple schematic of this crash type. In the SI/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. There were an estimated 49,000 such crashes in 1991, representing approximately 0.8 percent of all crashes. Some of the SI/SCP analyses in this report might apply in part to SI/LTAP/IPD crashes as well, although in an effort to maintain homogeneity of the crash sample, no attempt has been made to formally address this crash subtype. Finally, in 1991 there were an additional 8,000 crashes that were coded in GES as “straight intersecting paths, specifics unknown” or “specifics other.” Thus, although the conservative 203,000 SI/SCP crash problem’size is cited for the purposes of this report, a liberal definition of the target crash problem size yields an estimate of approximately 260,000 crashes for 1991. The next section discusses the additional circumstances and causes surrounding SI/SCP crashes.

**Table 2-1**
**Characteristics of SI/SCP Crashes**

| Characteristic | Percent Occurrence |
|---|---|
| Pavement conditions | |
| Dry | 79 % |
| Wet | 19% |
| Snowy or icy | 2 % |
| Ambient weather conditions | |
| No adverse weather | 66 % |
| Rain | 12 % |
| **Snow or sleet** | 2 % |
| Ambient light conditions | |
| Daylight | 72 % |
| Dark, lighted | 22 % |
| Dark, unlighted | 3 % |
| Dawn or dusk | 3 % |
| Alcohol involved in crash | 6 % |
| Age distribution of involved drivers | |
| 15-24 | 25 % |
| 25-54 | 56 % |
| 55-64 | 9 % |
| 65+ | 10 % |
| Sex distribution of involved drivers | |
| Female | 40 % |
| Male | 60 % |
| Travel velocity (mph), all involved vehicles | |
| o-5 | 11% |
| 6-10 | 11% |
| 11-15 | 6% |
| 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+ | 2% |
| Indication (on PAR) of driver vision obstruction | 1 % |
| Indication (on PAR) of driver distraction | 1 % |

Notes:
Figures from 1991 GES data. Unknowns have been distributed proportionally. The percentage of unknowns for vehicle travel velocity is quite high (71 percent).

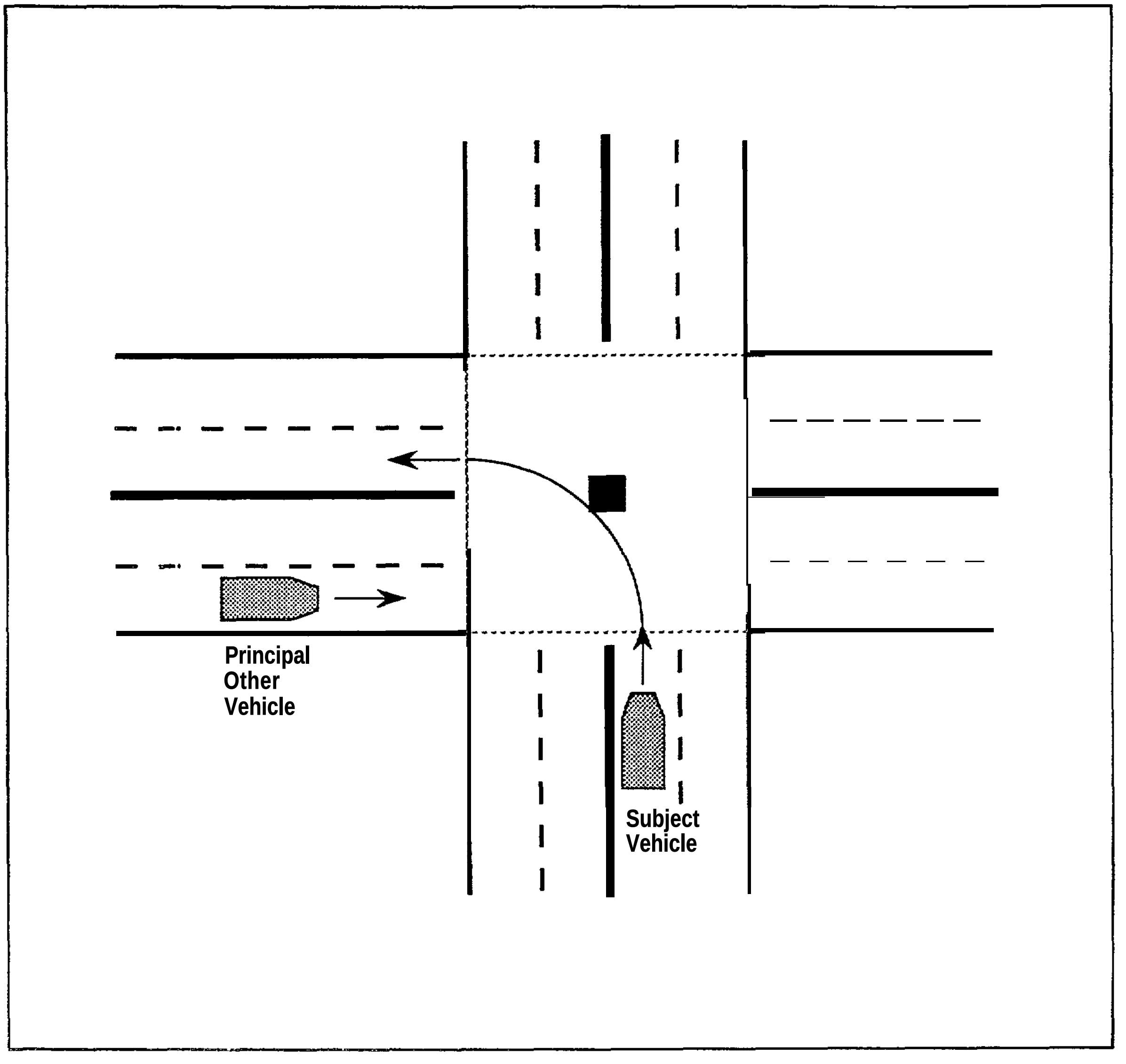


**Figure 2-2. Depiction of SI/LTAP/lPD Crash Scenario**

# 3. ANALYSIS OF SI/SCP CRASH CIRCUMSTANCES

## 3.1 INTRODUCTION

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

## 3.2 CLINICAL DATA SETS AND ANALYSIS METHOD

In this analysis, two accident data sets were drawn, one each from the Crashworthiness Data System (CDS) and 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. The GES sample 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 of PARs, crash investigations, and interviews of all persons involved in the crash. CDS accident cases are a subset of the GES accident cases.

For this report, the CDS data set consisted of 37 unsanitized hardcopy reports selected from the first, second, and third quarters of 1992. The GES data set consisted of 13 PARs from the third and fourth quarters of 1991. These data sets were clinically analyzed.

The clinical analysis approach adopted in this study entails subjective assessment by an expert analyst. The analysis involves content analysis of narrative statements (including keywords and phrases) and kinematic assessment to cross-check narratives. The analyst develops an impression of the crash subtypes or causal factors, or both, from the reviews. Error sources 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 error sources. Furthermore, despite these potential error sources, clinical analysis of detailed case files represents an invaluable aid to understanding the nature of crashes. This analysis also opens up data sources (additional uncoded information in the PARs) that are otherwise unavailable.

The unsanitized NASS CDS cases provide a rich body of data from which to reconstruct accidents and analyze causal factors. The cases include the following:

PARs

Driver statements

Witness statements

Scaled schematic diagrams depicting crash events and physical evidence generated during the crash sequence

Case slides documenting vehicles, damage sustained, and other physical evidence

The number of CDS files is limited, and the data selection process from CDS oversamples crashes that are more severe. Thus, the CDS data are weighted by severity and are used for characterizing the problem statistically. Appendix A discusses the weighting scheme. Causal data in the GES were limited to coded elements and narrative statements contained in each PAR.

## 3.3 CLINICAL ANALYSIS RESULTS: CRASH CHARACTERISTICS

An SI/SCP crash occurs when one vehicle at a signalized intersection strikes or is struck by a second vehicle traveling in a path perpendicular to the first vehicle. The SI/SCP crash population could not be subdivided into separate crash subtypes because most of the crashes characterized in the CDS data set of 37 cases and in the GES data set of 13 cases were similar. Based on the clinical data, common features of this crash type are as follows:

Feature 1. The encroaching driver in the SV was unaware of (or disregarded) the intersection signal, or signal status, and entered the intersection without having the right-of-way. The POV, which had the right-of-way, obeyed the traffic signal and also entered the intersection.

Feature 2. The SV could either be the vehicle that has struck another vehicle or the vehicle that has been struck.

Feature 3. The velocity of the vehicle that violated the signal status was generally close to the surrounding speed limit, suggesting that the SV driver did not attempt to stop for the signal.

## 3.4 CLINICAL ANALYSIS RESULTS: CAUSAL FACTOR OVERVIEW

Because both data sets were small, the causal analysis of the SI/SCP crash problem reported here may not be complete. In addition, the GES sample was limited by the nature of

PARs; the police assessments tended to lack precision with regard to defining causal factors (e.g., "failed to obey signal," "driver inattention"). Despite these limitations, a general picture of causal factors emerged.

Table 3-l and Figure 3-l summarize the causal assessments contained in the narrative or coded portions of the NASS CDS or the GES PARs samples. The percentages cited here and in the remainder of the report are weighted based on crash severity. Appendix A explains the case weighting scheme. Appendix B provides a description of the set of causal factors,

Table 3-1
Cousnl Factors Associated with SI/SCP Crashes

| Causal Factors | NASSCDS | GES PARs | Total | Weighted %[1] |
|---|---|---|---|---|
| Deliberately Ran Signal | | | | |
| Failed to obey signal | 7 | 5 | 12 | 23.2 |
| Tried to beat signal | 6 | 2 | 8 | 16.2 |
| Driver Inattention | 14 | 3 | 17 | 36.4 |
| Driver Intoxication | 6 | 1 | 7 | 12.6 |
| Vision Obstructed | | | | |
| Intervening vehicles | 1 | 0 | 1 | 0.8 |
| Roadway appurtenances | 0 | 1 | 1 | 3.5 |
| Vehicle Defect | 0 | 1 | 1 | 1.6 |
| Other[2] | | | | |
| Hit-and-run | 2 | 0 | 2 | 2.4 |
| Emergency vehicle | 1 | 0 | 1 | 3.5 |
| Total | 37 | 13 | 50 | 100.2 |

Notes:
1 Case weighting scheme described in Appendix A.
2 Category contains two hit-and-run cases and one case where a police vehicle on emergency call entered an intersection against a red signal.

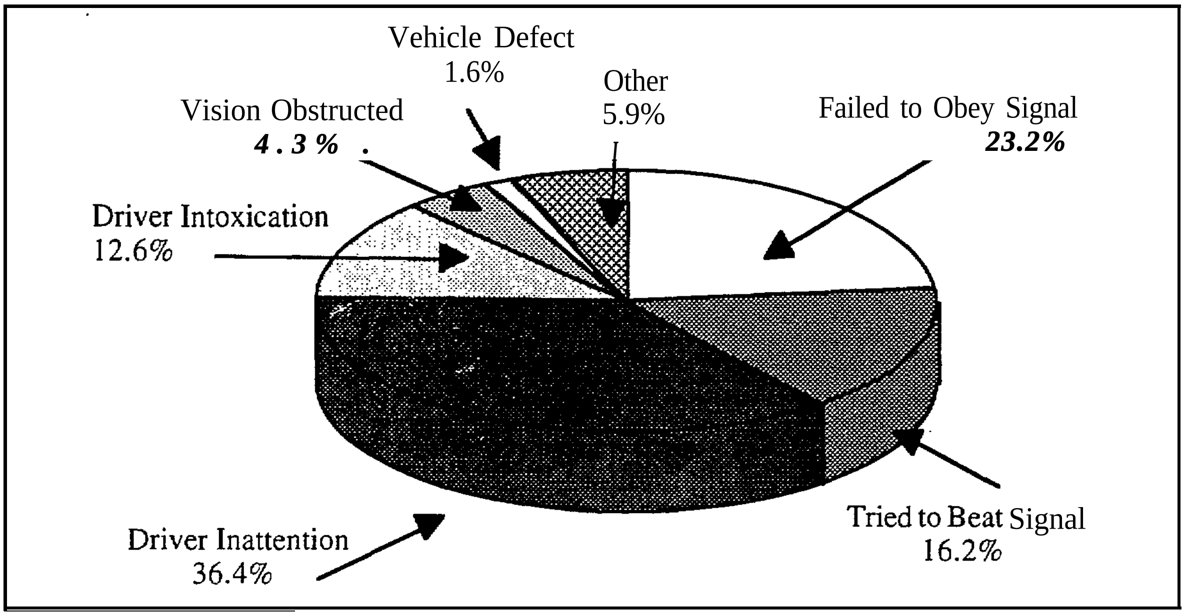


**Figure 3-1. Distribution of Causal Factors Associated with SI/SCP Crashes**

## 3.5 DISCUSSION

The SI/SCP crash causal factor categories provide useful guidance for IVHS crash countermeasure functional concepts. The categories, ***deliberately ran signal*** and ***driver inattention*** were the two most frequently occurring causes in the clinical analysis, accounting for over 75 percent of the crashes.

The ***deliberately ran signal*** category can be divided into two subcategories: ***failed to obey the signal*** and ***tried to beat the signal.*** Clearly, drivers who deliberately violated the red light were highly motivated to avoid stopping at the intersection.

If such drivers are assumed to be rational within the limits of their situational assessment, they might ***fail*** to obey the signal for the following reasons:

- The driver's subjective probability of succeeding at this risky maneuver is greater than some go/no-go threshold. This may be due to failure to see cross traffic, misperception of cross traffic speed and distance, or false expectations that the other driver will yield the right-of-way. A driver's assessment of the probability of safely traversing an intersection might be aided by an IVHS warning system that alerts or informs the driver that the vehicle will not clear the intersection in time.

- Alternatively, the driver's motivation to get through the intersection might lower the go/no-go threshold momentarily and lead to more risky behavior, with all other things being equal. This explanation suggests that the driver might ignore a warning system in favor of risky behavior. Changing such motivations is difficult and is outside the scope of an IVHS warning system.

The subcategory of drivers who ***tried to heat the signal*** probably consists of otherwise rational drivers who attempt to travel through the intersection because they thought that the amber light would last long enough to allow it. An IVHS warning system that is keyed to the amber light might alleviate such crashes.

***The driver inattention*** category probably consists of drivers not fully aware of the intersection and signal status because of distractions inside or outside of the vehicle or because the drivers' minds wander. An IVHS warning system that alerts drivers to the presence and status of the signalized intersection might be useful if the warning system can focus the driver's attention back to the intersection.

The driver's vision was obstructed in a small percentage of the cases. This obstruction, created by intervening vehicles or roadway appurtenances, might be considered another cause of driver unawareness. As such, it may be alleviated by using an IVHS countermeasure designed to address driver inattention.

The remaining three categories (driver intoxication, vehicle defects, and other circumstances) are general in nature and probably contribute to multiple crash types. Solutions to these are not likely to be specific to the SI/SCP crash problem and, therefore, do not depend on the SI/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 causal factors.

# 4. IVHS CRASH COUNTERMEASURE CONCEPTS FOR SI/SCP CRASHES

## 4.1 INTRODUCTION

The causal factor results suggest that over half of all SI/SCP crashes are due to SV driver unawareness of the crash hazard. This unawareness may be due to driver inattention (36.4 percent), vision obstruction (4.3 percent), or lack of information that would keep an otherwise rational driver from trying to beat the signal (16.2 percent). Thus, the focus of this section will be CAS concepts that could be used to inform the unaware driver about the impending hazard and assist the driver in crash avoidance maneuvers by means of alerts, warnings, and control intervention.

Figure 4-l provides a time-intensity graph of crash avoidance requirements (National Highway Traffic Safety Administration, 1992). In the context of SI/SCP crashes, 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 control intervention 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 might not be effective if the kinematics of the situation are too unforgiving. The characteristics of a given crash countermeasure system will depend largely on the time available to take evasive action and the intensity of action needed to avoid a crash. This figure will be used as a convenient framework for IVHS SI/SCP crash countermeasure systen concepts.

## 4.2 INTERSECTION 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 means to do this is to alert the driver to the presence of the intersection or signal ahead. For example, a waymark processed some distance from the intersection could trigger an alert to an in-vehicle system that effectively indicates that “there’s an intersection ahead.” An effective alerting device or signal must inform the driver of the critical intersection information, yet must not be perceived as a nuisance or be an in-vehicle distraction. Since drivers will usually be aware of approaching intersections, such a presence indicator provides redundant information. However, for the unaware driver, 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). Since drivers usually negotiate intersections safely, this simple alert should be very effective in preventing a hazardous condition from developing. The appropriate modeling scheme for this case’s crash avoidance effectiveness involves reliability models rather than kinematic models. An example of such a reliability analysis appears in Section 5.0.

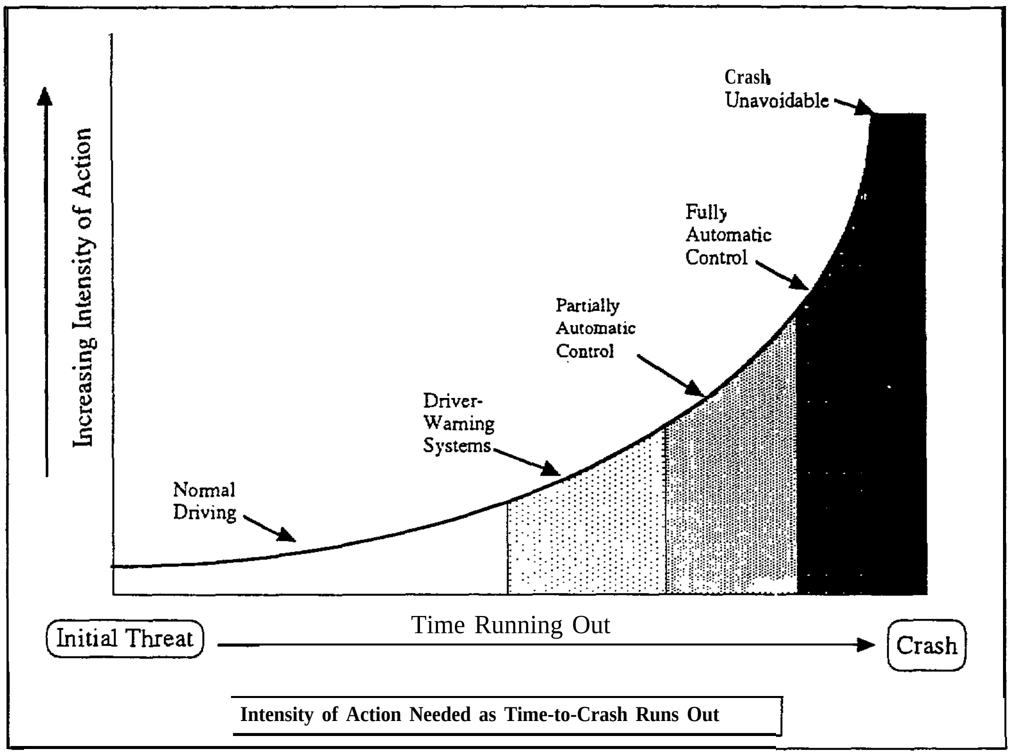


**Figure 4-1. Time-intensity Graph of Crash Avoidance Requirements (Source: NHTSA, 1992)**

## 4.3 DRIVER WARNING SYSTEMS

A modification of the concept presented in Section 4.2 would replace the simple intersection alert with warnings (e.g., the system would warn the driver to begin braking) that depend on the signal status (i.e., when the light turns amber or red). For a warning system, intersection signal status and geometry (intersection width) as well as SV velocity and distance to the intersection must be processed. The logic for this warning system might consist of the following rules:

- If the light is green, no warning is issued

- If the light is amber, then

  if the SV can clear the intersection by the time that the light turns red, no warning is issued

  otherwise, a warning is issued

- If the light is red, a warning is issued

Since, by definition, the SV must yield the right-of-way by the time that it reaches the intersection, warnings must be issued to the SV instead of to any other vehicle in the vicinity. Such a system concept would help the inattentive driver, the driver whose view of the signal is obstructed, and the driver who tries to beat the signal. This warning concept would likely not help those drivers who fail to obey the signal because they do not perceive a hazard from cross traffic. This is because the algorithm is tied solely to signal status, and such drivers have a demonstrated proclivity to deliberately ignore the signal status.

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 signal status of the signalized intersection 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.

It may be possible to warn the POV driver that the SV will likely not stop in time or will otherwise intrude on the intersection. For example, the POV driver could be warned of the direction of the approaching SV. If the IVHS crash countermeasure system has information about the position, velocity, and deceleration of the SV and POV, POV driver warnings could be graded to indicate a possible, probable, or imminent crash threat. The POV driver, given sufficient warning, could then be on the lookout for the intruding SV and slow, brake, or steer the vehicle to avoid the crash. The 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.

## 4.4 PARTIALLY AUTOMATIC CONTROL SYSTEMS

Partially automatic control systems (driver-in-the-loop) may 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 may not be braking sufficiently to stop in time. Here, partial-control systems that allow semiautomatic vehicle control could be used appropriately.

The most relevant example of a partially automatic control system for the SI/SCP case is soft braking (e.g., 0.1 or 0.2 g). In this situation, certain driving conditions would prompt on-vehicle automation to apply moderate braking that the driver could increase by pressing on the brake pedal. Like cruise control, the driver could also disengage the soft braking (for example, by tapping the brake pedal or stepping on the accelerator) 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 by 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. Such concepts are being experimentally investigated in the European DRIVE program (Michon, 1993; Parkes & Franzen, 1993).

## 4.5 FULLY AUTOMATIC CONTROL SYSTEMS (FACS)

The last portion of the time-intensity graph indicates time budgets that are the least forgiving of delays. At some point, FACS (driver not in the loop) can be used to avoid a crash. FACS concepts for SI/SCP crash avoidance involve automatic hard braking (e.g., 0.5 g level of braking). Since FACS is a natural extension of partially automatic control, the data needs for FACS concepts are similar to those given earlier. A distance threshold and associated time, based on vehicle and system delays alone (i.e., no driver delay allowed), serve as the precursor for FACS onset. Such a system would allow time for the driver to react to a warning or to be assisted by partial automatic control before braking. But beyond the threshold – if there was insufficient deceleration to brake at or before the Stop Line – FACS would respond by automatic hard braking at a higher level of braking up to some limit (e.g., 0.5 g). To be fully effective, the FACS should have information about the performance capabilities of the vehicle-roadway combination. Preliminary studies on FACS in the DRIVE program indicate that FACS may enhance safe driving, yet be perceived as intrusive and disturbing to most drivers, thereby threatening CAS acceptance (Nilsson, Alm, & Jansson, 1991).

## 4.6 HYBRID SYSTEMS

In principle, a hybrid concept that uses all of the previous concepts provides smooth transitions 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 warning. If the driver does not respond in time, or responds inadequately, partial automatic control would commence. This might provide soft braking for a period or gradually increased levels of braking until the SV stops. If necessary, it might utilize the hard braking provided by FACS. Fuzzy control 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 a smooth transition from one braking level to another.

The control intervention system concept in particular leads 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 control intervention systems must be carefully designed to minimize or eliminate the potential for harm. For instance, automatic hard braking might cause a rear-end crash with a closely following vehicle. The effect of such systems on traffic flow also merits attention and poses interesting analytic challenges in the context of multiple vehicles, some with IVHS capability and others without.

The hybrid system concept might address several SI/SCP causal factors such as attempts to beat the signal, driver inattention, and vision obstruction. At a minimum, safety and driver acceptance require that 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 have a way to deal with IVHS system problems, such as false or nuisance alarms.

Table 4-l summarizes the functional CAS 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 at a fixed time interval. | Early-on indication of intersection and/or signal state should prevent SI/SCP crash hazard from occurring. | Alerts must be both effective at informing drivers with usually redundant information and should not be obnoxious 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 trmes required to avord the crash could be provided. | Warnings will occur less frequently than alerts. If maximum time available when a warning is given IS sufficient for driver reactron 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 intellrgence 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, graded braking. A system with and without driver override could be designed | Control Interventlon will presumably be benefictal 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 comprehensrve 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

In this section, the signalized intersection maneuver is analyzed in terms of the Clearance Zone, the Dilemma Zone, and the Brake Zone, which are defined based on travel speed, duration of the amber light, level of braking, and driver-plus-machine delays. SV driver alerts are also analyzed using two models (i.e., parallel and series models) to estimate the reliability of the CAS-driver system. SV and POV warning analyses are then conducted in this section to determine the time and distance budgets required for these warnings to be effective in helping these drivers avoid crashes. Finally, control intervention is analyzed to determine the minimum trigger distance for automatic braking to be effective and the effects of soft braking on time available for driver and/or machine delays. The ensuing analysis considers only constant velocity approaches to the intersection. As drivers negotiate the intersection, any changes in velocity may affect the outcome. The impact of changes in nominal velocities is not considered in this report but should be a focus of future analysis.

## 5.1 ANALYSIS OF THE SIGNALIZED INTERSECTION MANEUVER

In this section, the signalized intersection maneuver is analyzed for straight crossing paths. An assumption of this analysis is that the SV clears the intersection before the light turns red. Under some jurisdictions, the SV is permitted to enter the intersection throughout the amber light and to clear the intersection after the light turns red (Rach, 1982). However, in these jurisdictions, a delay in the cross-traffic green light must allow for last-minute clearances to avoid collisions (Wilshire, 1992). The jurisdictional assumption used here considers the most general case since it accounts for the time needed for the SV to clear the intersection.

The signalized intersection maneuver can be considered in terms of a Clearance Zone, a Dilemma Zone, and a Brake Zone. These zones are defined based on travel speed, duration of the amber light, level of braking, and driver-plus-machine time delays. These zones change from moment to moment. At any time. a vehicle's location within a zone determines possible outcomes for the intersection maneuver.

An SV driver is considered to be in the ***Clearance*** Zone when, traveling at constant velocity, he or she can clear the intersection (the intersection width plus the SV's length) by the time that the signal turns red. In the ***Dilemma Zone,*** the SV cannot stop in time or clear the intersection before the light turns red. In the ***Brake*** Zone, the SV can stop at or before the Stop Line for some proportion of drivers, depending on the level of braking applied and driver-plus-machine delays. From Figure 5-1, the leftmost boundary of the Clearance Zone ($D_{CZ}$), and the rightmost boundary of the Brake Zone ($D_{Stop}$) are defined as follows:

$$D_{CZ} = V_{SV}\, t_{amber} - (W + L_{SV}) \tag{1}$$

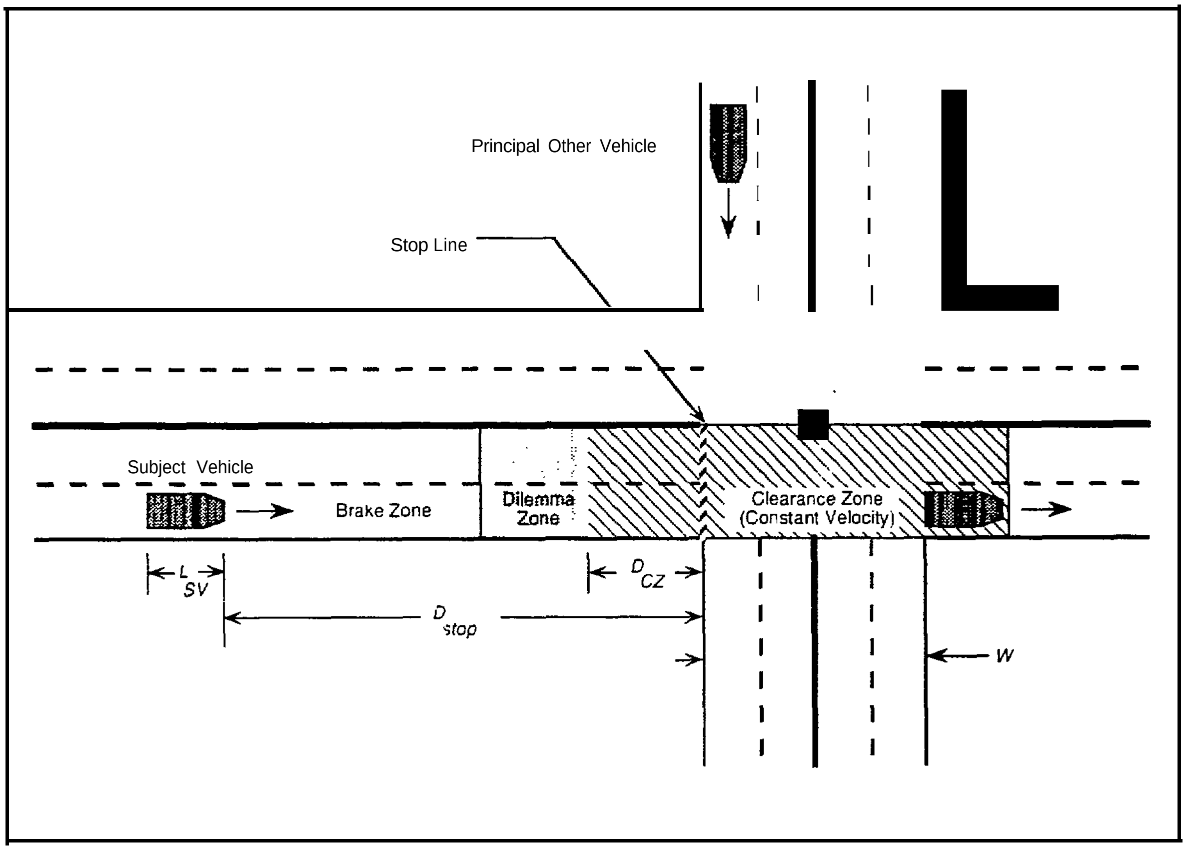


**Figure 5-1. Depiction of the SI/SCP Maneuver**

$$D_{Stop} = \frac{V_{SV}^2}{2a} + (t_{Driver\ RT} + t_{machine\ delay})V_{SV} \qquad (2)$$

where

| | | |
|---|---|---|
| $D_{CZ}$ | = | distance from the beginning of the Clearance Zone to the intersection Stop Line, ft |
| $V_{SV}$ | = | ‘SV velocity, ft/s |
| $t_{amber}$ | = | remaining duration of amber light, s |
| $W$ | = | intersection width, ft |
| $L_{SV}$ | = | SV length, ft |
| $D_{stop}$ | = | required SV braking distance to stop by the Stop Line, ft |
| $a$ | = | SV braking deceleration, ft/s$^2$ |
| $t_{Driver\ RT}$ | = | SV driver brake reaction time, s |
| $t_{machine\ delay}$ | = | $t_{vehicle\ delay} + t_{IVHS\ delays}$ s |

Normally, the driver will not brake if the vehicle is within the Clearance Zone and will brake to a stop when the SV is within the Brake Zone. The Dilemma Zone, which depends on the remaining duration of the amber light, is a no-win situation for drivers. In fact, traffic engineers try to eliminate the Dilemma Zone by optimizing the duration of the amber light with respect to the travel velocities expected at the intersection. Gazis et al. (1960) analyzed the problem and determined the following equation for minimum duration of the amber light:

$$t_{design\ amber} = t_{design\ delay} + \frac{V_{SV}}{2a} + \frac{W + L_{SV}}{V_{SV}} \tag{3}$$

| | | |
|---|---|---|
| where $t_{design\ amber}$ | = | duration of the amber light, designed into the signal status, s |
| $t_{design\ delay}$ | = | delay assumed by the traffic engineer to accommodate driver and machine delays, s |
| $V_{SV}$ | = | SV velocity, ft/s |
| $a$ | = | SV braking deceleration, ft/s$^2$ |
| $W$ | = | intersection width, ft |
| $L_{SV}$ | = | SV length, ft |

According to Rach (1982), $t_{design\ amber}$ is actually the minimum clearance interval. Those jurisdictions in which laws require vehicles to cross the intersection before the light turns red use a minimum clearance interval as the amber interval. An all-red phase is recommended in jurisdictions in which vehicle codes permit vehicles to enter the intersection throughout the duration of the amber light and to clear it after the red light has appeared. In these cases, the all-red phase is equal to $(W+L)/V$, and $t_{design\ amber} = t_{design\ delay} + V/2a$. Thus, the two approaches are equivalent with respect to the time available to the SV.

Wilshire (1992) recommends that $t_{design\ delay} = 1.0$ s, $a = 10$ ft/s$^2$, and $L = 20$ ft be assumed when the design amber duration for a particular intersection is determined. For these values and a 48-ft-wide intersection ($W = 48$ ft), Figure 5-2 plots the design amber durations required as a function of posted speed limit. At 20 mph, a design amber duration of 4.8 s is needed. At 60 mph, a design amber duration of 6.2 s is needed. These values will be used in Section 5.2 to assess the opportunities for CAS driver warnings.

## 5.2 RELIABILITY ANALYSIS OF SV DRIVER ALERTS

As mentioned in Section 4.2, the concept of a driver alert may prevent an SI/SCP crash hazard situation. Thus, the most appropriate modeling scheme for this concept is reliability modeling rather than kinematic modeling. Drivers usually negotiate intersections safely. According to data from the 1991 GES on signalized intersection, perpendicular crossing path (SI/PCP) crashes (of which SI/SCP are a subset), the expected number of

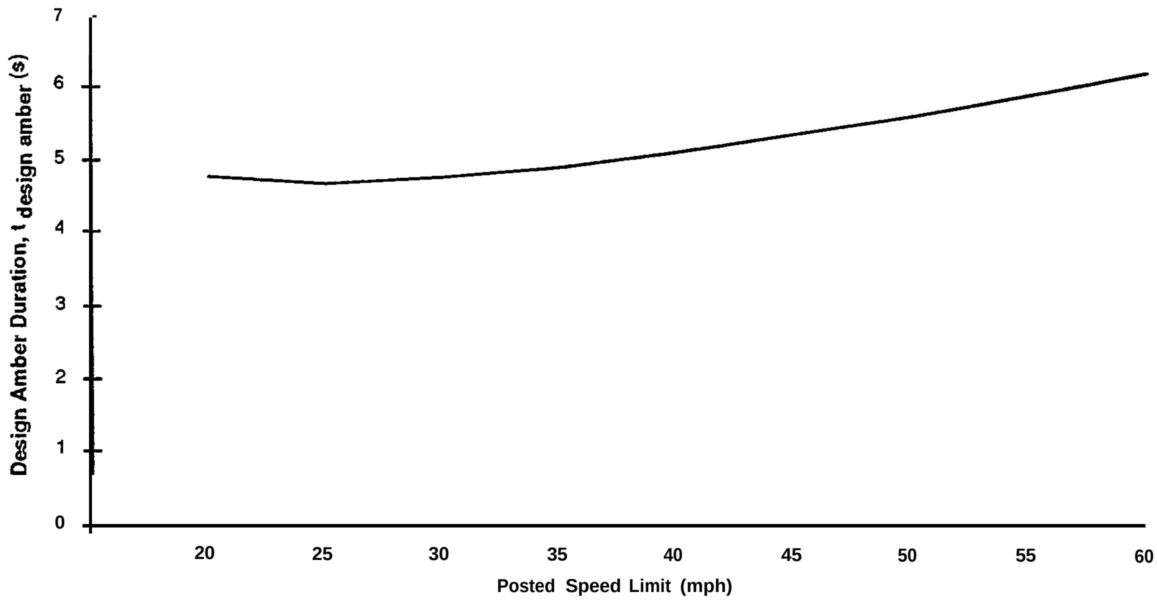


**Figure 5-2. Design Amber Times Associated With Various SV Travel Velocities**

passenger vehicle crash involvements during an average lo-year vehicle life is calculated as follows:

$$E\ [\textit{SV crash involvements per 10-year vehicle life}] = .0354 \times (0.5) \times \frac{203{,}000}{260{,}000} = .0138 \qquad (4)$$

The first term is the expected number of SI/PCP crash involvements per IO-year vehicle life for all vehicles. One-half of these are assumed to be the SV; this is captured by the second term. The third term indicates the proportion of SIIPCP crashes that are SI/SCP crashes. This implies that passenger vehicle drivers in the U.S. average less than about one reportable SI/SCP crash every 725 years (Wang & Knipling, in press).

Drivers brake about 50,000 times per year (Farber, 1991), and some fraction of those braking actions are initialized to stop vehicles at signalized intersections. For illustrative purposes only, assume that on the average only 5 out of every 100 brakings are initiated to stop the vehicles at signalized intersections. Following Farber (1991), driver reliability in braking at signalized intersections, *R(driver),* might be estimated as 1 minus the failure to brake at signalized intersections ("driver failure"):

$$P(\textit{driver failure}) = \frac{1}{725 \textit{ years/crash} \times 2{,}500 \textit{ SI/SCP brakings/year}} = \frac{1}{1{,}812{,}500} \qquad (5)$$

$$R(driver) = 1 - \frac{1}{1{,}812{,}500} = .9999994 \qquad (6)$$

This illustration suggests that drivers are very reliable at stopping at intersections. Furthermore, this level of human reliability is also consistent with other sources of human reliability estimates (e.g., Swain & Guttmann, 1983).

Given a driver reliability estimate, it is necessary to estimate the reliability of the CAS alone and the reliability of drivers with the CAS in the vehicle. The CAS may actually reduce the reliability of the driver, perhaps by promoting less attention to the driving conditions because of a driver's faith that the CAS will provide necessary protection. The CAS will likely be considerably less reliable than the driver. For illustrative purposes, assume that the CAS is only l/100 as reliable as the average driver and that the driver with the CAS is only l/100 as reliable as the average driver without a CAS:

$$P(driver\ failure/CAS) = P(CAS\ failure) = 100\ P(driver\ failure)$$

$$100 \frac{1}{(725 \times 2{,}500)} = 0.0000552 \qquad (7)$$

To determine the reliability of the CAS-driver system, either a parallel or a series system can be used (Hillier & Lieberman, 1986). In a parallel system, the system performs satisfactorily if at least one of the components performs satisfactorily. This model, favored by Farber (1991), assumes that the driver continues to monitor the driving situation along with the CAS. Thus, a mishap can be avoided if either the CAS works or the driver notices the hazard. Implicit is the notion that the driver will respond appropriately to a CAS alert or warning. As indicated below, if the parallel system model holds, the CAS should provide improved safety protection to the driver:

$$R(driver + CAS) = 1 - P(driver\ failure/CAS) \times P(CAS\ failure)$$

$$= 1 - \left(\frac{100}{725 \times 2{,}500}\right)\left(\frac{100}{725 \times 2{,}500}\right) = .999999997 \qquad (8)$$

In a series system, the system fails if any component fails. Thus, a crash is avoided only if the CAS alerts the driver and the driver responds appropriately to the CAS alert. This model may be more appropriate for the unaware driver who is not monitoring the driving situation in parallel with the CAS and who may be less reliable at responding to the CAS than without it, say, due to the effects of false or nuisance alarms. The probability that the driver will brake in response to the CAS is unknown. However, for the purposes of exposition, a reliability statement can be generated by assuming that the driver with CAS is

100 times less reliable than the driver without the CAS. For the example provided here, the CAS-driver system reliability estimate has been reduced compared to that of the driver alone:

$$R(driver + CAS) = (1 - P(driver\ failure/CAS))(1 - P(CAS\ failure))$$
$$= \left(1 - \left(\frac{100}{725 \times 2{,}500}\right)\right)\left(1 - \left(\frac{100}{725 \times 2{,}500}\right)\right) \quad (9)$$
$$= .9998897$$

This is only an illustration of the reliability modeling approach. More information is needed on the effectiveness of driver alerts or warning systems. However, this example analysis indicates the need to better understand the nature of the driver-CAS system (parallel or series). It also provides a means to assess the sensitivity of the system to changes in the probability estimates for driver or CAS failure. For example, the driver may not respect the CAS alert because of false or nuisance alarms. If the series model of reliability holds, this human factors phenomenon may compromise the benefits that such a system could provide.

## 5.3 ANALYSIS OF SI/SCP CRASH AVOIDANCE FROM SV DRIVER WARNINGS

The following analysis involves CAS warnings issued to an SV driver who is "unaware" of the intersection or signal status due to inattention or obstructed vision. The analysis also relates to those drivers who "tried to beat the signal," but who would not have done so, given appropriate information about the signal status. An IVHS crash countermeasure system would require moment-to-moment data on the signal status, particularly the remaining time of the amber phase. The system also requires data on the given intersection geometry (e.g., number of lanes, lane width). These data might be provided by vehicle-to-roadway communication with the signal box, by Advanced Traveler Information System (ATIS) databases for the particular intersection geometry, or by other means. The SV length, velocity, and moment-to-moment location from the Stop Line must also be available to the CAS.

To assess the maximum available time ($t_{max\ available}$) for crash avoidance, the design amber duration appropriate for a given SV travel velocity is used. The CAS could then use the following simple rules to warn the unaware SV driver approaching the intersection at constant velocity:

- If the light is green, no warning is issued
- If the light is amber, then
  - if the SV is within the Clearance Zone, no warning is issued
  - if the SV is further than Clearance Zone, then a warning is issued

• If the light is red, a warning is issued

Since the SV could be located anywhere along the approach path to the intersection, the CAS should poll its relevant set of parameters regularly.

At the onset of the warning, the maximum time available for driver and machine time delays given the SV is at a distance ($D_{loc}$) from the Stop Line at warning onset is as follows:

$$t_{\max\ available} = \frac{D_{loc} - \left(\frac{V_{SV}^2}{2a}\right)}{V_{SV}} \tag{10}$$

| | | | |
|---|---|---|---|
| where | $t_{max\ available}$ | = | the maximum time delay available for driver and machine response, s |
| | $D_{loc}$ | = | SV distance (location) from the Stop Line when the CAS warning is delivered, ft |
| | $V_{SV}$ | = | SV velocity, ft/s |
| | $a$ | = | SV braking deceleration, ft/s$^2$ |

To analyze the time budgets in this scenario, the maximum allowable time delay for coming to a stop by the Stop Line can be assessed from the Clearance Zone border to the CAS range limit, $R$. This is reasonable since a well-designed CAS should provide ample warning to an SV to stop if that SV will not be able to clear the intersection in time. This implies assessing the maximum time available to brake up to the maximum $D_{CZ}$ point. The onset of the amber or red light presumably can occur with equal likelihood when the vehicle is at any location within the system. Thus, up to $D_{CZ}$, the analysis evaluates the maximum time available for driver and machine delays when the warning onset occurs at various distances from the intersection.

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 48-ft-wide intersection and a 16-ft SV length (i.e., $W + L_{SV} = 64$ ft).

To determine the proportion of drivers who could brake as fast or faster than $t_{max\ available}$, subtract the machine time delay budget and look up the remaining value on the cumulative probability plot in Figure 5-4. This plot contains the theoretical data for the surprise brake reaction time of Sivak, Olson, & 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). This corresponds to a 50th percentile value of 1.07 s and a standard deviation of 0.63 s. Thus, if 2.0 s are available for the driver to respond, then approximately 90 percent of drivers should be able to respond in time to avoid the crash and, therefore, can benefit from such a CAS.

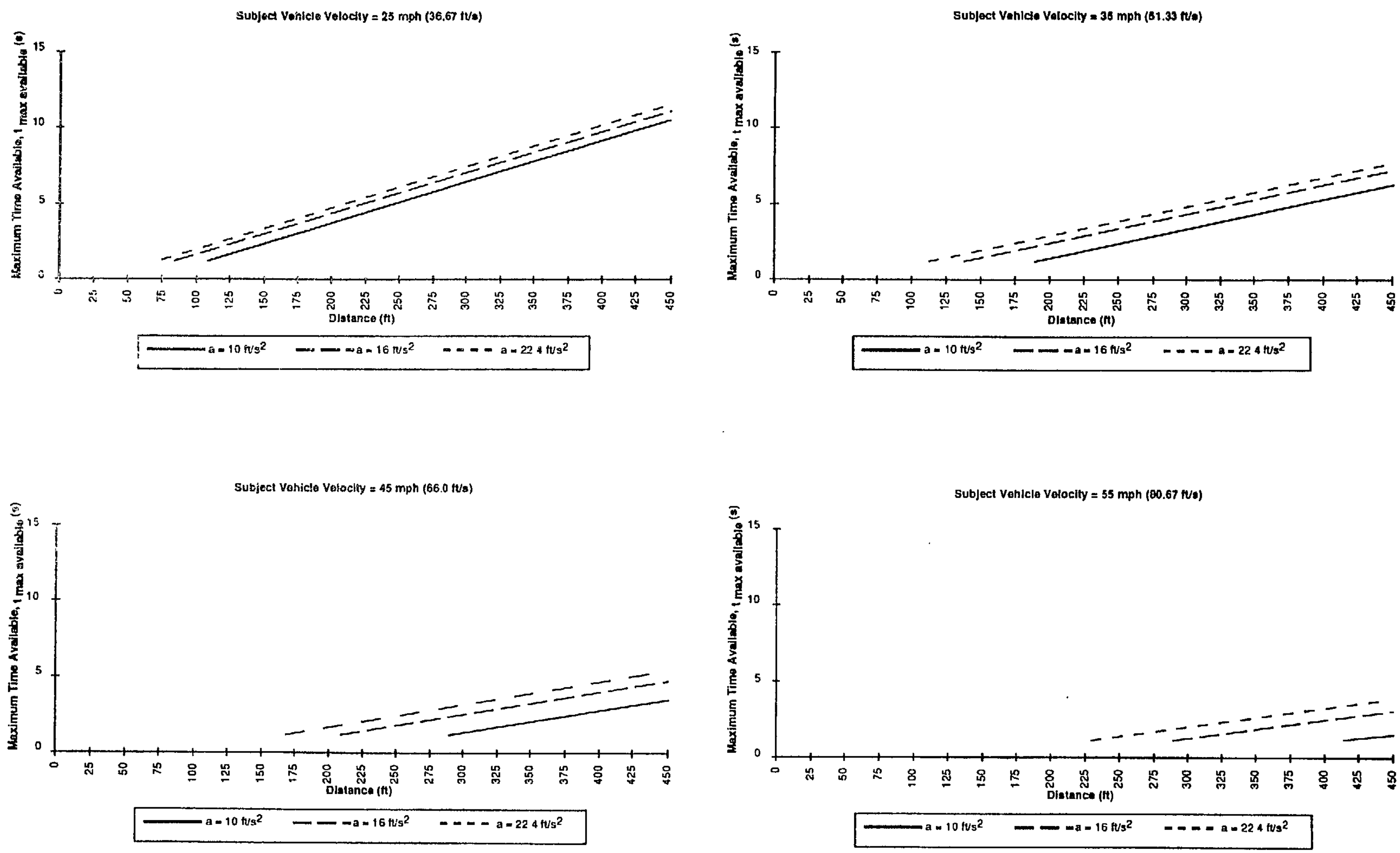


**Figure 5-3.** **Maximum Time Available for Driver and Machine Delays as a Function of Travel Velocity, Deceleration, and Distance from the Intersection at CAS Warning Onset (up to the Clearance Zone Limit, $D_{CZ}$)**

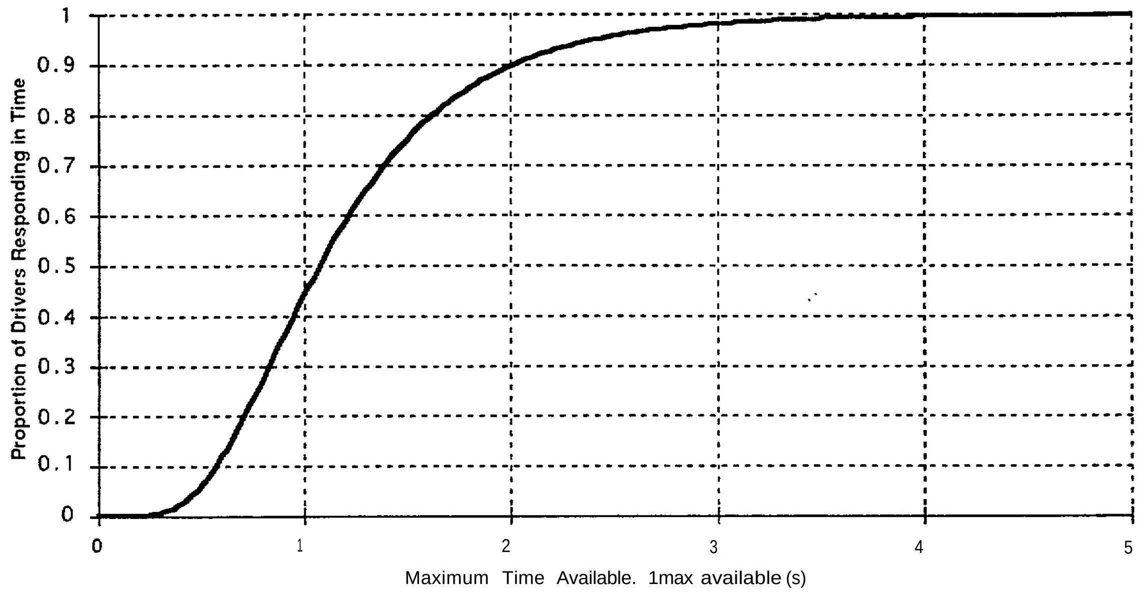


Figure 5-4. Theoretical Proportion of Unaware Drivers Who Can Brake as Fast or Faster Than $t_{max\ available}$

This analysis can also he used to assess the minimum CAS range required for a given posted speed limit and intersection geometry. For example, assume a CAS design goal is to accommodate 90 percent of the driver population. The CAS should allow for driver delay (assume 2.0 s) and machine delay (assume 0.5 s) for a total delay of 2.5 s. In this example, let the braking level equal 0.31 g. If the driver approaches an intersection with posted speed limits of 35 mph, then from Figure 5-3, the driver-vehicle system must be warned by 158 ft. At a posted speed limit of 55 mph, on the other hand. the driver-vehicle system must be warned by 527 ft.

Consider a refinement of this CAS concept. The SV driver should have an opportunity to demonstrate normal braking behavior. This allows the CAS to withhold warnings when, in fact, the SV driver is already doing what is needed. Wortman and Mathias (1983) report on the nominal decelerations applied by drivers approaching an intersection to stop. The 50th percentile value is approximately 10 $ft/s^2$. This value might be used to determine the point where the CAS first provides a driver warning. At a given velocity, the CAS can determine the distance at which the SV would have to begin decelerating by this amount. If the vehicle is decelerating, no warning would be presented; otherwise, a warning to brake would be delivered. For example, at an SV velocity of 66 ft/s (45 mph), the driver warning would be presented approximately 218 ft from the Stop Line, the latest point at which 10 braking should begin.

If the driver needs to be warned to brake when the car is located at the nominal deceleration point, it is too late for normal deceleration, because when the warning trigger distance was determined no driver or machine delays were assumed. Now a greater deceleration is needed (e.g., 16 $ft/s^2$). The CAS can determine whether the SV is slowing at that level by the latest distance where 16 $ft/s^2$ braking will bring the vehicle to a stop. In the 66 ft/s velocity example, this point is 136 ft from the Stop Line. A second, more urgent warning could be delivered to the SV driver if necessary, and this would arrive about 1.24 s ((218 ft - 136 ft)/66 ft/s) after the first warning. Alternatively, control intervention could involve initiation of moderately hard (OS g) automatic braking to bring the vehicle to a stop.

In principle, the signal status of an upcoming intersection can be known to a CAS in advance. In this sense, the SI/SCP crash is different from lane change crashes. Lane change crashes occur because one vehicle suddenly and unexpectedly cuts in front of another vehicle, which is not the case for SI/SCP crashes.

Constant ***warning times*** might be provided to the SV driver in the SI/SCP case during any light status, given a sufficient CAS range and knowledge of the intersection signal status. This might be in the form of a ***driver alert*** presented at a fixed time interval (e.g., 2.0 s) prior to the point where normal (10 $ft/s^2$) deceleration should begin. Constant warning times imply that warning (or alert) onset will vary as a function of SV travel speed and the deceleration that will be applied subsequently. Figure 5-5 depicts the distances required for braking and for 2.0 s of alerting at different travel velocities assuming two different decelerations are applied no later than the end of the 2.0 s period. Such graphs provide an indication of the CAS range or trigger distances needed for constant warning times. For the example discussed thus far, a 2.0 s constant warning requires an alert at 66 ft/s x 2.0 s or 132 ft prior to the nominal deceleration point (218 ft) from the intersection. Thus, the driver alert should be presented 132 ft + 218 ft or 350 ft from the intersection Stop Line if the driver must brake. This alert should not be obnoxious to the driver or embarrass the driver when other passengers are in the vehicle. Since the notion of driver alert involves frequent CAS alerts, the presentation mode must be socially and psychologically acceptable to the SV driver. Kinesthetic-tactile displays such as active pedals might provide such a display (Michon, l993).

Figure 5-6 presents these notions within the context of both the time-intensity graph and the signalized intersection schematic. For this figure, the SV is traveling at 45 mph (66 ft/s). The point at which 10 $ft/s^2$ normal braking deceleration must begin (218 ft), the point 2.0 s earlier where driver alert would be presented (350 ft), and the point at which urgent warning and/or control intervention (0.5 g braking) would commence (136 ft) are depicted. The notion of constant warning time is being applied as part of the European DRIVE program for crash avoidance systems (Vetwey et al. 1993), This concept deserves further analysis and assessment in future CAS studies.

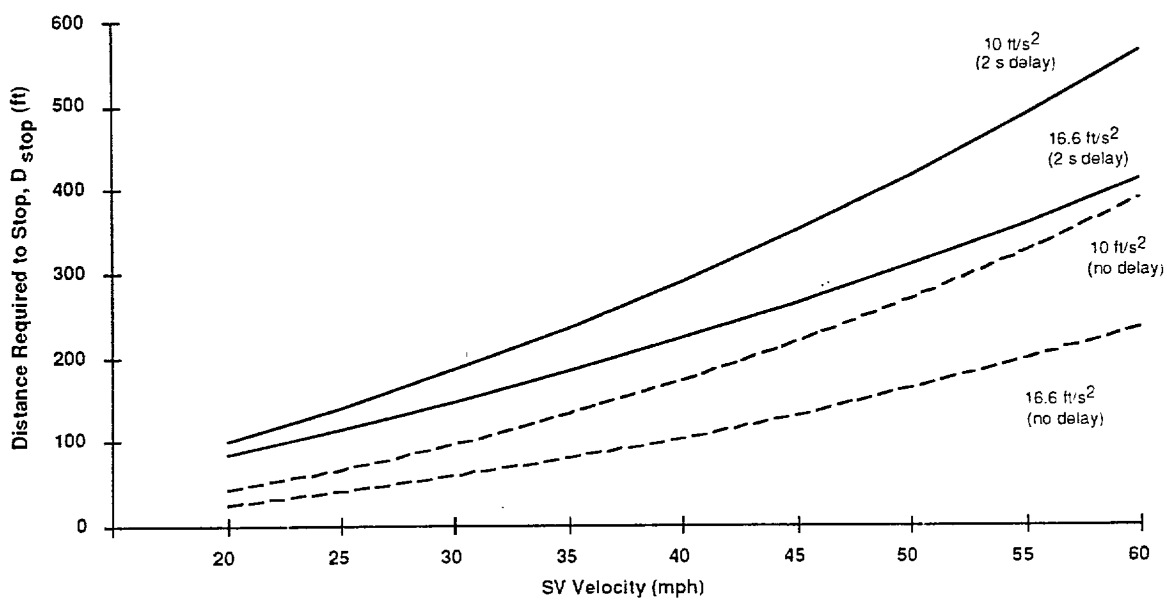


**Figure 5-5. Distances Required for Braking and for 2.0 s of Alerting at Different Travel Velocities, Assuming Different Braking Decelerations.**

## 5.4 ANALYSIS OF SI/SCP CRASH AVOIDANCE FROM THE POV DRIVER WARNINGS

The POV driver might be warned that an approaching SV will not stop as it should. A crash can occur when the SV and POV occupy the intersection at the same time. This concept will be used to assess whether a POV driver warning might be viable. The analysis that follows assumes the simplest case in which both the SV and POV are traveling at constant velocity and at the same speed.

The equations that follow use the terms defined below:

| | | |
|---|---|---|
| $D_{lane}$ | = | distance from the front of the SV to the leading edge of a POV travel lane, ft |
| $lw$ | = | lane width, ft |
| $V_{SV}$ | = | SV velocity, ft/s |
| $V_{POV}$ | = | POV velocity, ft/s |
| $L_{POV}$ | = | POV length, ft |
| $T_1$ | = | time that the SV crosses the leading edge of the POV travel lane, s |
| $T_2$ | = | time that the SV clears the POV travel lane, s |
| $L_{SV}$ | = | SV length, ft |

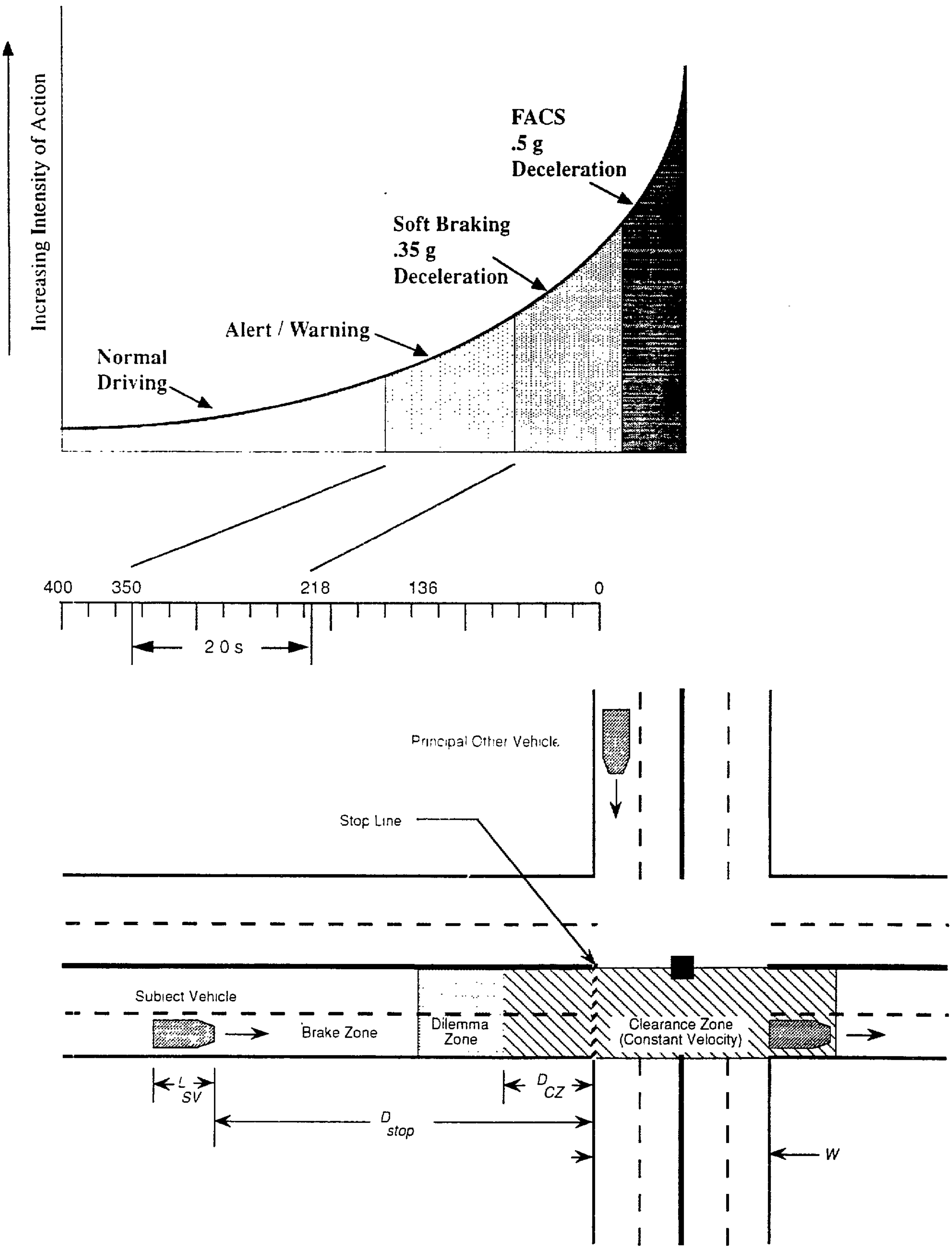


**Figure 5-6. IVHS Crash Avoidance Concepts in the Context of 45 mph SV Travel**

Assuming that the SV travels at constant velocity,

$$T_1 = \frac{D_{lane}}{V_{SV}} \tag{11}$$

$$T_2 = \frac{D_{lane} + lw + L_{SV}}{V_{SV}} = T_1 + \frac{lw + L_{SV}}{V_{SV}} \tag{12}$$

$T_1$ and $T_2$ define a time interval when the SV occupies the intersection across the POV travel lane. To avoid a crash, the POV must clear the intersection either before the SV enters the POV travel lane (before $T_1$) or must not arrive until after the SV has cleared the intersection (after $T_2$). Therefore, $T_1$ and $T_2$ can be used to define the location of the POV when it poses a crash hazard.

The minimum longitudinal distance ($LD_{min}$) that the POV must be from the intersection to just clear the intersection before the SV arrives is the product of $V_{POV}$ and $T_1$, adjusted for the fact that the POV must also clear the SV lane width ($lw$) and its own vehicle length ($L_{POV}$). The maximum longitudinal distance ($LD_{max}$) that the POV must be from the intersection to just avoid the crash is the product of $V_{POV}$ and $T_2$. The POV vehicle locations between $LD_{min}$ and $LD_{max}$ can be considered a hazard zone. Thus,

$$LD_{\min} = V_{POV}T_1 - (lw + L_{POV}) \tag{13}$$

$$LD_{\max} = V_{POV}T_2 \tag{14}$$

The SV driver should be able to exhibit stopping behavior before a CAS warns the POV driver. The CAS might track the approaching SV and assess its deceleration from moment to moment. As the SV nears the intersection, it crosses a distance where normal braking (e.g., 0.31 g) should begin for the SV to stop by the Stop Line. If the SV does not exhibit this deceleration, the POV driver might be alerted that a crash is ***possible.*** If the SV continues past the point where moderately hard braking (e.g., 0.5 g) is needed to stop the vehicle, the POV is warned that a crash is ***probable.*** Finally, if the SV continues past the point where emergency braking (e.g., 0.7 g) must begin to stop in time, the POV is warned that a crash is ***imminent.***

The effectiveness of this logic depends on the time and distance budgets available to the POV driver to apply emergency braking when the driver is warned. To analyze the viability of POV driver warning, a representative range of SV and POV travel velocities (25, 35, 45, and 55 mph) were assessed using the $T_1$, $T_2$, $LD_{min}$, and $LD_{max}$ concepts at each of three SV braking decelerations (0.31 g, 0.5 g, and 0.7 g). Table 5-1 shows the results along with the maximum time available to the POV for 0.7-g emergency braking at $LD_{max}$ and $LD_{min}$.

## Table 5-1
## Sample Calculations for Vehicles Travelling at Various Velocities

| 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.

To assess the theoretical proportion of drivers who could stop in time, refer to the lognormal distribution of surprise brake reaction times (Taoka, 1989) in Figure 5-4. Thus, if the maximum time available to the POV driver was, for example, 2.0 s, excluding vehicle and CAS time delays, then theoretically about 90 percent of drivers could stop in time.

The analysis in Table 5-1 assumes a drastic evasive maneuver. Given the limited time budgets associated with even a 0.7 g-braking maneuver, simple slowing is not likely to be feasible and, therefore, is not analyzed in this report. 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.

## 5.5 CONTROL-INTERVENTION EFFECTIVENESS FOR SV DRIVERS

The notion of control intervention is most applicable when there is insufficient time for the driver to respond. It is also potentially applicable when the driver response may not be adequate when braking to a stop with no driver or machine delays. The equation for minimum stopping distance without delays is as follows:

$$D_{stop(\min)} = \frac{V^2}{2a} \quad (15)$$

The distance budgets for a representative range of travel speeds are depicted in Figure 5-7 for decelerations of 10 ft/s$^2$, 16 ft/s$^2$, and 22.4 ft/s$^2$. This figure provides guidance for determining the minimum trigger distances needed for FACS braking. If a machine delay is desired, add the product of $V_{SV}$ and ($t_{machine\ delay}$), ft, to the plotted value of interest.

The benefits of soft braking depend very much on when the soft braking begins and how long it is applied. To introduce an example, assume that the CAS can provide soft braking of $a$ = 5 ft/s$^2$ (0.15 g) over a 103-ft segment of approach to the intersection. If the SV is traveling initially at $V_o$ = 51.33 ft/s, then by the end of the $D$ = 103 ft distance segment with soft braking, the new velocity is:

$$\begin{aligned} V_{final} &= \sqrt{(2a)D + V_o^2} \\ &= \sqrt{2 \text{ x } (-5)(103) + 51.33^2} \\ &= 40 \ ft/s \end{aligned} \quad (16)$$

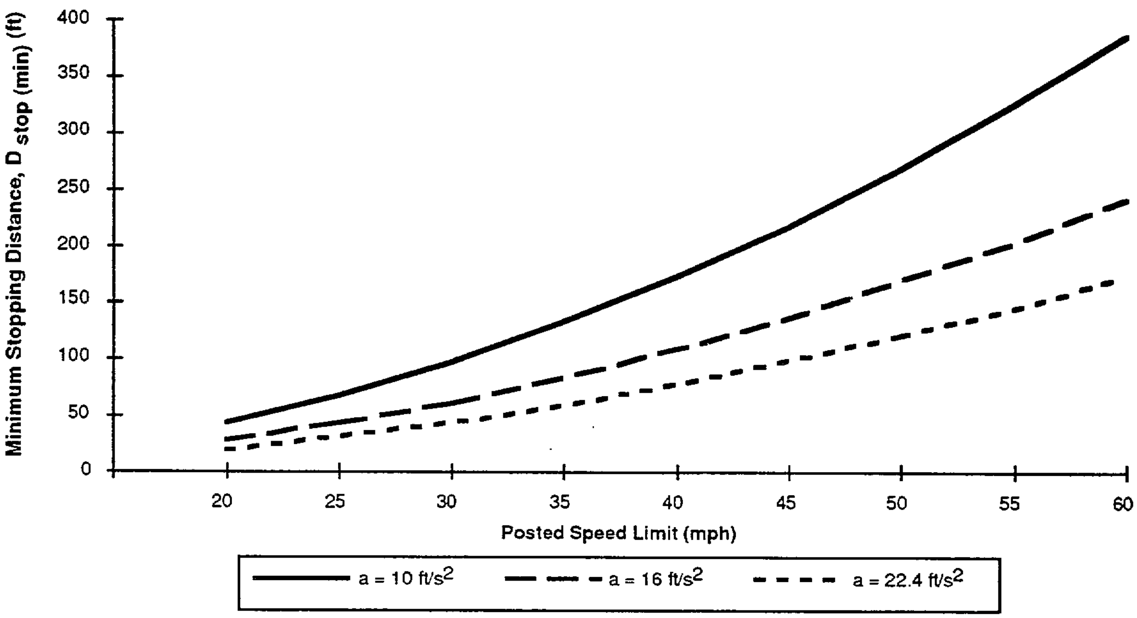


**Figure 5-7. Minimum Stopping Distances for FACS Braking as a Function of Travel Speed and Deceleration Applied. Zero Time Delays Are Assumed**

Without the soft braking, the SV would take 2.0 s to travel the same distance:

$$t = \frac{D}{V_o} = \frac{103}{51.33} = 2.0\ s \tag{17}$$

The time needed to slow down, however, would be as follows:

$$t = \frac{V_{final} - V_0}{a} = \frac{40.0 - 51.33}{-5.0} = 2.25\ s \tag{18}$$

The additional 0.25 s might be used for driver delays.

As mentioned before, driver acceptance of control intervention is very much in question and must be addressed through a systematic program of research. Drivers might find soft braking a nuisance and override it. The application of automatic braking may promote rear-end or other crashes. Moderately hard braking could potentially harm the SV driver or other passengers not prepared for the sudden deceleration. These and other issues related to control intervention merit further investigation.

# 6. MAJOR FINDINGS AND OBSERVATIONS

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

## 6.1 CAUSAL FACTORS

An in-depth analysis of a sample of SI/SCP crashes was conducted to identify crash circumstances and causal factors. The sample comprised 37 CDS reports and 13 GES PARs. The analysis revealed three major causes of SI/SCP crashes, which are listed below in a descending order according to their weighted percentage of occurrence:

1. driver unawareness of the intersection and signal status due to inattention and obstructed vision (40.7%),
2. driver failure to obey the red light signal (23.2%), and
3. driver attempt to beat the amber light signal (16.2%).

## 6.2 CRASH COUNTERMEASURE CONCEPTS

Three IVHS crash countermeasure concepts, specific to the SI/SCP crash scenario, were devised to address the major causal factors listed above. In addition, a hybrid concept was suggested which employs these three concepts and provides timely transitions among them. The three countermeasure concepts are briefly described below.

1. In-vehicle alert: This concept adopts in-vehicle signing to provide the SV driver an early indication of a signalized intersection ahead and signal status. Such a concept is mostly applicable to SI/SCP crashes caused by the SV driver who is inattentive or whose view is obstructed. Thus, about 41% of SI/SCP crashes would be addressed by this particular countermeasure concept.

2. Driver warning: This concept provides graded warnings to the SV driver and constant warning times required to avoid the SI/SCP crash. The logic of such a system concept is tied to the signal status and its time duration. This concept would mostly benefit unaware drivers and drivers who attempt to beat the amber light signal; therefore, it would be applicable to 57% of SI/SCP crashes, Also, warning the POV driver at certain instances is considered.

3. Control intervention: Such a concept is an alternative (or possibly a supplement) to a driver warning system 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 and with or without driver override. This concept addresses the three major causes of the SI/SCP crash. However, in the case of drivers who fail to stop at a red light signal, automatic control intervention in

the form of emergency braking to a stop would appear to be the only countermeasure. Consequently, automatic control intervention would apply to around 80% of SI/SCP crashes.

## 6.3 MODELING REPRESENTATION

Analytical models were formulated to represent the effects of IVHS crash countermeasure concepts on SI/SCP crash avoidance. These models would be used to estimate countermeasure effectiveness and to identify critical countermeasure functional requirements and data needs. Reliability modeling was adopted to assess the in-vehicle alert concept, assuming a parallel or a series CAS-driver system. SV and POV driver warnings and control intervention mechanisms were represented by kinematic models. Next, observations are made with regard to modeling results of SV driver warnings and POV driver warnings.

### 6.3.1 SV Driver Warnings

The analysis of the SV driver warning model reveals that the greater the distance of the SV from the minimum stopping distance point, 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 55 mph (80.67 ft/s), then the SV driver has only 12ms 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 and decreases with increased deceleration. At higher speeds, since more distance is needed to stop, the maximum time delay will remain higher longer the further away that the vehicle is from the intersection. From Equation (10), the maximum time delay becomes zero when the distance is equal to $V^2_{SV}/2a$ For a constant time delay, more intense 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 differences in the maximum time available. For example, given a distance of 350 ft from the intersection, at 25 mph, the difference between the maximum time available for a = 22.4 ft/s$^2$ (8.73 s) and for a = 10 ft/s$^2$ (7.71 s) is 1.02 s. At 55 mph, the difference becomes (2.54 s - 0.31 s) 2.23 s. 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.

**63.2 POV Driver Warnings**

The POV driver warning model 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 S-1, available response times for POV range from 1.79 to 2.61 s for trave1 velocities of 25 to 55 mph, respectively, if the POV warning is received at the $LD_{max}$ distance using 0.31-g (SV deceleration) warning threshold. Note that the analysis assumes that the POV reacts with emergency braking of 0.7-g. If warning is not received until the POV is at the $LD_{min}$ distance, the range of available time for crash avoidance is 0.27 to 1.92 s, for travel velocities of 25 to 55 mph, respectively. Given this early onset, POV driver warning might be effective over at least some distances from the intersection.

At the 0.5-g and 0.7-g warning thresholds, drivers have too little time available to stop. Even the longest time of 1.10 s will leave roughly half of all surprised drivers unable to respond in time since the 50th percentile brake reaction time (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 0.31-g threshold is 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 approximately at the 50th percentile (Wortman & Mathias, 1983), which means that approximately 80 percent of drivers who eventually stop will brake harder, but later. This constitutes a substantial risk of false alarms, which may undermine CAS effectiveness. This **is** an important issue which merits future research.

# 7. RESEARCH AND DEVELOPMENT

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

- The clinical sample did not contain any cases due to loss of traction. The problem size estimate of Section 2.0 indicates that about 21 percent of all SI/SCP crashes occurred on wet and snowy/icy pavements. It is recommended that this type of causal factor be identified in consideration of IVHS crash countermeasures that might contribute to safety in such circumstances, even though it is not specific to the signalized intersection.

## 7.2 DRIVER BEHAVIOR AT SIGNALIZED INTERSECTIONS

- The analysis assumed rudimentary responses by the SV driver, i.e., braking. Information is needed about driver response to traffic signals. For example, if the duration of a red light is excessive, many drivers might be prone to encroach on the intersection, An understanding of the psychology of the signalized intersection negotiation would be useful for more realistic modeling and subsequent design of the IVHS crash countermeasure system.

- It would be beneficial to know the correlation between driver reaction time and nominal braking rate, as well as the correlation between brake reaction time and peak braking deceleration. This could be useful in designing the algorithm for warnings and FACS and in tailoring it to specific individuals.

- The decision processes of both the SV and POV driver should be explored further. This understanding may indicate the manner in which crash avoidance information should be conveyed to the driver.

- Effects of FACS on the driver should be investigated. Studies such as those by Nilsson et al. (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. 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 might 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 countermeasure system information to the driver.

- There is a need to assess how drivers interact with warning systems. Such issues as acceptance, appropriateness of response, and system reliability are in need of further investigation.

## 7.3 SI/SCP ALGORITHM RESEARCH NEEDS

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

- The data needs for an SI/SCP crash avoidance algorithm were discussed at length in Section 5.0. 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 crash countermeasure system algorithm will require multiple setpoints. Alternative setpoints should be systematically assessed to determine how setpoints (e.g., 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 analysis.

## 7.4 FURTHER MODELING RESEARCH NEEDS

- The analysis reported here was from the vantage point of a single vehicle, i.e., the SV or POV. In practice, other vehicles are present on the roadway, and interactions with these other vehicles must be addressed. For example, does rapid deceleration to avoid an SI/SCP crash result in a rear-end crash instead? What is the impact of a series of signalized intersections that might be encountered on a high-traffic city roadway? What is the effect of the duration of the amber light on traffic flow and driver behavior? Questions like these 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. Thr weighting procedure, illustrated in Table A-l, included the following steps:'

- The crashes in each data set were sorted by severity [Crash Severity]. The number of each in the sample [# in Sample] was compared to thr total sample, which gave analysts the percent of the clinical sample represented by each severity [% of Clinical Sample].

- NHTSA provided the percentage of thr GES data represented by each severity level [% of 1990 GES].

- The percent of the national profile that each case representcd [% Rep. Each Case] was determined by dividing [% of 1990 GES] by [# in Sample].

**Table A-l**
**Case Weighting Scheme for Combined NASS CDS and GES PAR Sample**

| Crash Severity | # in Sample | % of Clinical Sample | % of 1990 GES | % Rep. Each Case |
|---|---|---|---|---|
| 0(0) | 15 | 30.0 | 53.04 | 3.54 |
| 1 (C) | 16 | 32.0 | 24.79 | 1.55 |
| 2(B) | 9 | 18.0 | 14.20 | i.58 |
| 3/4(A/K) | 10 | 20.0 | 7.97 | 0.80 |
| Total | 50 | 100.0 | 100.00 | |

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

## APPENDIX B. DESCRIPTION OF CAUSAL FACTORS

***Deliberately Ran Signal***

***Failure to Obey Signal:***

These are cases where the SV driver made the decision to continue forward into the intersection when the signal status was red.

***Tried to Beat Signal:***

These are cases where the signal was typically amber when the SV driver made the decision to continue forward into the intersection and "beat the red."

***Driver Inattention***

These are cases where the SV driver was distracted from the driving task and did not observe the traffic signal during final approach to the intersection. Typical sources of distraction in these cases were looking for a street sign, talking with a passenger in the vehicle, or searching for something in the vehicle interior.

***Driver Intoxicated***

Each of these cases involved an SV driver with a blood alcohol content of 0.10 or greater.

***View Obstructed***

***Intervening Vehicles:***

This case was an instance where the POV was shielded from the view of the SV driver by other vehicles.

***Roadway Appurtenances:***

This case involved an instance where a roadside object obstructed the SV driver's view.

***Other***

"'Other" cases are odd situations. Two cases were hit-and-run cases. One case involved a police vehicle on an emergency call that entered the intersection against a red signal.

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***U.S. GOVERNMENT PRINTING OFFICE: 1994-502-193/00027**