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Vehicle-Based Countermeasures For Signal and Stop Sign Violation

Task 1. Intersection Control Violation Crash Analyses

Task 2. Top-Level System and Human Factors Requirements

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Kerrin Bressant was the NHTSA COTR for this project.

16. Abstract

This report provides the first two major task reports for a study to develop performance specifications and perform supporting objective tests for a planned field operational test (FOT) of a vehicle-based countermeasure to intersection crashes associated with light vehicle violations of stop signs and traffic signals (red lights). The envisioned system will warn drivers if they are in imminent danger of running a stop sign or signal, and is called the Intersection Crash Avoidance, Violation warning (ICAV) system. Task 1 consisted of database analyses employing primarily 1999 and 2000 General Estimates System data. This included a crossing-path crash problem size description by injury severity level, followed by increasingly detailed analyses of crash type, traffic-control devices, violation distributions and types, causal factors, speed behavior, and infrastructure components. An estimated 261,000 light vehicle crashes in 1999 and 162,000 in 2000 occurred at intersections where one of the two vehicles had a stop sign and was charged with a violation. There were an estimated 133,000 crashes in 1999 and 99,000 crashes in 2000 involving traffic signal violations. These crash populations could be target crashes for ICAV. The Task 2 report includes a review of past literature relating to the stop sign/signal violation crash problem and proposed countermeasures, as well as top-level system requirements and preliminary specifications for future deployment and FOT systems, and for a testbed system to be fabricated under this project. The ICAV system for stop-sign violations is conceived as consisting of four functional subsystems: positioning, in-vehicle sensors, computations (dynamic algorithm), and driver-vehicle interface. The signal-violation system requires these same four subsystems and, in addition, a communications link with the infrastructure (the traffic signal) to determine signal phase and timing. Using this functional system concept, the report outlines the fundamental performance requirements of the deployment system and identifies knowledge gaps in these performance requirements.

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EXECUTIVE SUMMARY

PROJECT AND REPORT OVERVIEW

The Virginia Tech Transportation Institute (VTTI) is conducting a 30-month study (Contract No. DTNH22-00-C-07007, Task Order 12) for the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation to develop performance specifications and supporting objective tests for a field test of a vehicle-based countermeasure to intersection crashes. The study is targeting intersection crashes associated with violations of stop signs and traffic signals (red lights). The envisioned system will provide in-vehicle intersection control violation warnings to drivers; that is, it will warn drivers if they are in danger of running a stop sign or red light. The system is called the Intersection Crash Avoidance, Violation warning (ICAV) system. The ICAV system for stop-sign violations is conceived as consisting of four subsystems: positioning, in-vehicle sensors, computations (dynamic algorithm), and driver-vehicle interface. The signal-violation system requires these same four subsystems and, in addition, a communications link with the infrastructure (the traffic signal) to determine signal phase and timing.

Significant past research has been performed on these crash-prevention concepts, and thus a primary goal for the current project is to move the ICAV concept rapidly forward for testing, evaluation, and deployment. This project is designed to complete the preliminary research and development (R&D) required to prepare for an ICAV field operational test and subsequent deployment. Specifically, the objectives of the project are to develop technology-independent performance specifications for an ICAV system and to perform objective tests of countermeasure performance. A system testbed will be fabricated to enable the conduct of the test and refinement of functional specifications. In the process, the project will also develop a human factors database to assist designers and system evaluators in assessing countermeasure designs and, in general, to create an R&D basis for a future field operational test (FOT) of this crash countermeasure.

The systems-engineering approach to the project will be to determine system requirements and then to develop performance specifications for three ICAV systems to be developed:

- A *testbed system*, to be fabricated under the contract and used to conduct tests to determine minimum acceptable performance specifications for a successful ICAV FOT system.
- An *FOT system*, which may be ready in approximately five years. The FOT system will likely be very similar to the deployment system but may be constrained by technology availability or practical considerations.
- A *deployment system*, which may exist in approximately 10 years.

The project consists of five major tasks, as follows:

- Task 1: Perform Intersection Control Violation Crash Analysis
- Task 2: Determine Top-Level Requirements for Countermeasures

- Task 3: Develop and Validate Testbed System
    - Phase A: Stop Sign Violation Warning System
    - Phase B: Signal Violation Warning System
- Task 4: Develop Performance Specifications and Objective Tests for FOT System
- Task 5: Final Project Reporting.

Tasks 1 and 2 of the study were performed, and completed, concurrently. This document is a unified interim report containing reports on each of these two tasks. The two task reports contained in this document are, thus, as follows:

- Task 1 Report: Intersection Control Violation Crash Analyses (Project Deliverable 8)
- Task 2 Report: Top-Level System and Human Factors Requirements (Project Deliverable 11).

TASK 1 REPORT OVERVIEW: INTERSECTION CONTROL VIOLATION CRASH ANALYSES

Task 1 of this project involved a series of database analyses aimed at creating a clear problem definition for intersection-violation crashes. The goal was to characterize light-vehicle violation crashes so that intersection-violation countermeasures could be developed in subsequent project tasks. The analyses included an overall crossing-path crash problem size description by injury severity level, followed by increasingly detailed analyses of crash type, traffic-control devices, violation distributions and types, causal factors, speed behavior, and infrastructure components. The analyses included identification of major causal factors for each subtype of intersection-control violation. In accordance with the contract SOW, VTTI used the NHTSA General Estimates System (GES) database to characterize the violation crossing-path (CP) crash problem for the years 1999 and 2000.

The Task 1 analyses were performed in a top-down fashion, beginning with defining the overall crash problem (Subtask 1.1) and then refining the analyses in later subtasks (Subtasks 1.2. through 1.7). Thus, the purpose of the first analysis was to determine the overall size of the crossing-path crash problem by scenario and maximum severity level. This was accomplished by considering the frequency of crossing-path (CP) crashes involving only light vehicles for 1999 and 2000. Subtask 1.1 showed that there were 1,698,000 CP crashes for 1999. Given that there were an estimated 6,271,000 crashes of all types in 1999, these CP crashes accounted for 27% of all the crashes. In 2000, there were 1,667,000 CP crashes out of an estimated 6,389,000 crashes (26%).

Analysis of the overall CP crash problem in Subtask 1.1 showed that:

- Left-turn crashes make up the majority (about 52%) of crossing-path crash types.
- The next most prevalent type is the straight crossing-path crash type (30-35%).
- Other CP types include right-turn crashes (about 6%) and unknown (7-11%).

In terms of maximum injury severity, property damage only (PDO) crashes made up the majority of CP crashes at approximately 56%, followed by injury crashes (including fatality crashes) at approximately 39%. About 5% had unknown severities.

In Subtask 1.2, the variable for traffic-control device (TCD) was introduced. TCDs were divided fairly evenly between three-color signals and stop signs. In terms of crash severity, CP crashes occurring at three-color signalized intersections were fairly evenly divided between PDO (50%) and injury crashes (46%; the remainder were unknown). Stop-sign CP crashes had more PDO crashes (58%) than injury crashes (39%; the remainder were unknown).

Subtask 1.3 looked at stop-sign crashes in greater detail and found that stop-sign CP crashes in which only one vehicle had a stop sign were four or five times more prevalent than crashes in which both vehicles had a stop sign.

Subtask 1.4 identified the crash population of light vehicles cited with violations. This analysis utilized 1999 and 2000 GES datasets containing new variables with vehicle-level data on pre-crash maneuvers for signalized-intersection crashes and cited violation types for all CP crashes. Those citation types deemed most amenable to the ICAV countermeasures were speeding, reckless driving, failure to yield right of way, and running a stop sign or traffic signal. For 1999, 63% of all three-color signal CP crashes with these violations involved a straight pre-crash maneuver by the violating vehicle; for 2000, the percentage was 53%. For stop-sign crashes, drivers in the one-stop-sign case were more likely to be cited than drivers in the two-stop-sign case.

Subtask 1.5 attempted to understand the primary contributing factors for cited CP crashes, along with related environmental and roadway factors. A factor priority scheme was used to examine each variable in turn. Among all crash types and injury levels, driver distraction and inattention was the largest primary contributing factor, at 37%. Driver's vision obscured was indicated in about 10%. For environmental and roadway factors, weather was the largest at 13%, followed by road surface at 4%.

Subtask 1.6 examined speeding behavior in cited CP crashes, including the distributions of posted speed limits, traveling speed (when known), and whether or not the crash was speed related. A high majority (93%) of CP crashes with violations are coded as "not speed related."

Subtask 1.7 explored the infrastructure characteristics (including trafficway flow and number of lanes) for signalized-intersection, CP crashes with violation citations. Results showed that:

- 45 to 50% occurred on undivided, two-way roadways.
- 35 to 40% occurred on 3- and 4-lane roadways.

Subtask 1.8 consisted primarily of an economic analysis of the CP crashes identified for 2000. Using recently updated NHTSA crash-cost estimates for 2000, the analysis showed costs of approximately $47,025,000,000 for the 1,667,000 CP crashes in the year 2000. Dividing the overall cost by the number of crashes resulted in an approximate estimated cost per CP crash of $28,200. The analysis provides further breakdowns for violation crashes with various pre-crash maneuvers.

The final aspect of Subtask 1.8 was to identify further areas of data analysis that could lead to a greater understanding of driver behavior or vehicle kinematics in CP crashes or intersection violations. The following five areas have been identified as candidates for future analyses: the

SAVME database, the naturalistic driving study database, the large-truck crash causation study, case study using Crashworthiness Data System (CDS) data, and in-depth analysis of distraction and inattention cases. None of these approaches holds promise given their current state (i.e., some are in progress), and are not being pursued as of the writing of this report.

Although an ICAV-target crash population could not be defined and determined with specificity in Task 1 based on GES variables, populations likely to be addressable by the countermeasure concept were identified as part of Subtask 1.4. An estimated 261,000 light vehicle CP crashes in 1999 and 162,000 in 2000 occurred at intersections where one of the two vehicles had a stop sign and was charged with a violation. There were an estimated 133,000 crashes in 1999 and 99,000 crashes in 2000 involving traffic signal violations. These crash populations could be target crashes for ICAV.

TASK 2 REPORT OVERVIEW:
TOP-LEVEL SYSTEM AND HUMAN FACTORS REQUIREMENTS

Task 2 determined the high-level requirements for a countermeasure system to address the intersection-control violation problem. Originally, five subtasks were envisioned:

- Subtask 2.1: Literature Gathering and Review
- Subtask 2.2: Vehicle Requirements Analysis
- Subtask 2.3: Initial In-Vehicle System Performance Specifications
- Subtask 2.4: Joint Communications Link Design with Infrastructure
- Subtask 2.5: Document Conclusions and Results (this report).

As part of the project planning and task re-scheduling after contract award, Subtask 2.4 (Joint Communications Link Design with Infrastructure) was postponed and moved to Task 3B (Development of Testbed Warning System and Performance Specifications for Signal Violations). The workshop will focus on the infrastructure-vehicle communications link for signal-violation warnings in the FOT. As such, it is more appropriate and timely in Task 3B and is now scheduled for October 2003. This subtask is not addressed in the present report.

Literature Review

The Task 2 report literature review, the output of Subtask 2.1, is based on a review of more than 60 reports and other publications relating to intersection crashes and countermeasures. Major topics addressed include the following:

- Intersection-crash problem description
  - Previous analytic studies of crash data
  - Studies of red light running and camera enforcement
- Computation algorithm parameters (e.g., brake reaction time, models of braking performance)
- Driver-vehicle interface (DVI) considerations (also see Appendix A)
- Behavioral adaptation to countermeasures.
- Previously-tested vehicle-based countermeasures for intersection crashes/violations (with emphasis on the NHTSA-sponsored Veridian Intersection Collision Avoidance program).

Top-Level System Description and Preliminary Requirements and Specifications

This section of the report is the product of project Subtasks 2.2 and 2.3. Subtask 2.2 was the ICAV requirements analysis and included consideration of countermeasure requirements from the crash avoidance, systems engineering, and driver human factors perspectives. Subtask 2.3 was the development of initial performance specifications.

As briefly described earlier, five functional subsystems are envisioned as essential ICAV components:

- A *positioning* subsystem to determine the vehicle's current position and positional relationship to intersection features (e.g., the stop line) and geometry.
- *In-vehicle sensors* or data links to assess vehicle dynamic parameters, most notably vehicle speed, and to provide data for computations.
- *Computations* to integrate and process data, determine whether an imminent violation warning should be issued, and activate the driver-vehicle interface.
- A *driver-vehicle interface* (DVI) to present the warning to the driver.
- For the signal-violation system but not the stop sign violation system, a *communications* subsystem to receive a data transmission from the infrastructure (i.e., the traffic signal) containing critical information such as signal phase and timing data.

The stop-sign violation system consists of the first four subsystems above and, thus, is totally vehicle-based. The signal-violation system requires the fifth, communications subsystem, which includes both an infrastructure component (i.e., transmitter from the traffic signal) and a vehicle-based component (i.e., a receiver).

Using the functional system concept above, the report outlines the fundamental performance requirements of the deployment system and identifies knowledge gaps in these performance requirements. Many knowledge gaps relate to the identification of specific, refined quantitative values for the various subsystem parameters; these values will be assessed by the FOT system and/or the ICAV testbed. Next, recommended performance requirements for the FOT system are provided, reflecting system development, technology readiness, and economic constraints. Finally, knowledge gaps in the FOT system performance requirements are delineated. These knowledge gaps will be addressed during Task 3 testing, primarily involving the ICAV testbed. The testbed will be an over-performing and adaptable system capable of supporting tests to determine minimum acceptable performance specifications.

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TASK 1. INTERSECTION CONTROL VIOLATION CRASH ANALYSES

Numerous studies have attempted to quantify and characterize crossing-path crashes. Many of these efforts were reviewed in the literature review performed for Task 2 of this project and are included later in this report. The Intersection Crash Avoidance – Violation (ICAV) project approaches the problem of crossing-path crashes by warning the driver when a violation is about to occur. None of the previous efforts to characterize crossing-path crashes looked specifically at violation crashes, so Task 1 of this project involved a series of database analyses aimed at creating a clear problem definition for intersection-violation crashes. The goal of Task 1 was to define violation crashes so that intersection-violation countermeasures could be developed in subsequent project tasks. The analyses included an overall crossing-path crash problem-size description by injury severity level, followed by increasingly detailed analyses of crash type, traffic-control devices, violation distributions and types, contributing factors, speed behavior, and infrastructure components. The analysis included identification of major contributing factors for each subtype of intersection-control violation. VTTI was assisted in this task by the creation of a new General Estimates System (GES) database by NHTSA's National Center for Statistics and Analysis. VTTI used this GES database to characterize the crash problem for the years 1999 and 2000. Crash frequencies based on the GES and reported here reflect the number of police-reported crashes estimated by the GES.

It should be recognized that the full extent of the crossing-path crash problem size cannot be grasped simply by reading the results of these Task 1 analyses. Further details of the overall crossing-path problem size can be obtained from the literature review section of this report. In addition, there are several recently released reports that complement the intersection-violation analyses reported here. More detail on pedestrian crossing-path crashes can be found in daSilva, Smith, and Najm (2003). For example, the second largest scenario category of crashes in this analysis was "Vehicle is going straight and pedestrian is crossing the roadway at intersection," at 18.5% of all pedestrian crashes. For pedalcyclists, daSilva, Campbell, Smith, and Najm (2002) found that the largest crash scenario was "Vehicle traveling straight on a crossing path with the pedalcyclist" (40.2% of all pedalcyclist crashes). Finally, fatal intersection-violation crashes, including pedalcyclist and pedestrian crashes, were analyzed in depth by Noga, Smith, and Najm (2003), using the FARS system. A few of their results are included in the earlier sections of the current report for comparison purposes. Together, these sources should provide the interested reader with a solid grasp of the crossing-path violation problem, with particular emphasis on those crashes in which at least one driver received a citation.

SUBTASK 1.1. DISTRIBUTION OF CROSSING-PATH CRASH SCENARIOS BY *CRASH SEVERITY*

The Task 1 analyses were performed in a top-down fashion, beginning with defining the overall crash problem in Subtask 1.1 and then refining the analyses in later subtasks. The purpose of the first analysis was to determine the overall size of the crossing-path crash problem by scenario and maximum severity level. This was accomplished by considering the frequency of crossing-path crashes involving only light vehicles, as shown in Tables 1 and 2 for 1999 and 2000, respectively. Note that all tables for Subtasks 1.1 through 1.7 are presented at the crash level (rather than the person or vehicle level) and that crash severity refers to the maximum injury severity for that crash. The analyses for each year are presented separately, rather than combined, so that future researchers can use these numbers to double-check their own work (a method that was used extensively for this report).

Five crossing-path types of interest for this report were examined as follows: Straight Crossing Path (SCP); Left Turn Across Path – Opposite Direction Conflict (LTAP-OD); Left Turn Across Path – Lateral Direction Conflict (LTAP-LD); Right Turn Into Path (RTIP); and Left Turn Into Path (LTIP). For most sections of the report, the three left turn types were combined under the term Left Turn (LT). Likewise, the two possible types of Right Turn Into Path (Opposite Direction and Lateral Direction) were called, simply, Right Turn Into Path (RTIP). The remaining crash type is SCP; therefore, three crash types (LT, RTIP, and SCP) are discussed in most sections of this report. Figure 1 illustrates these crash types.

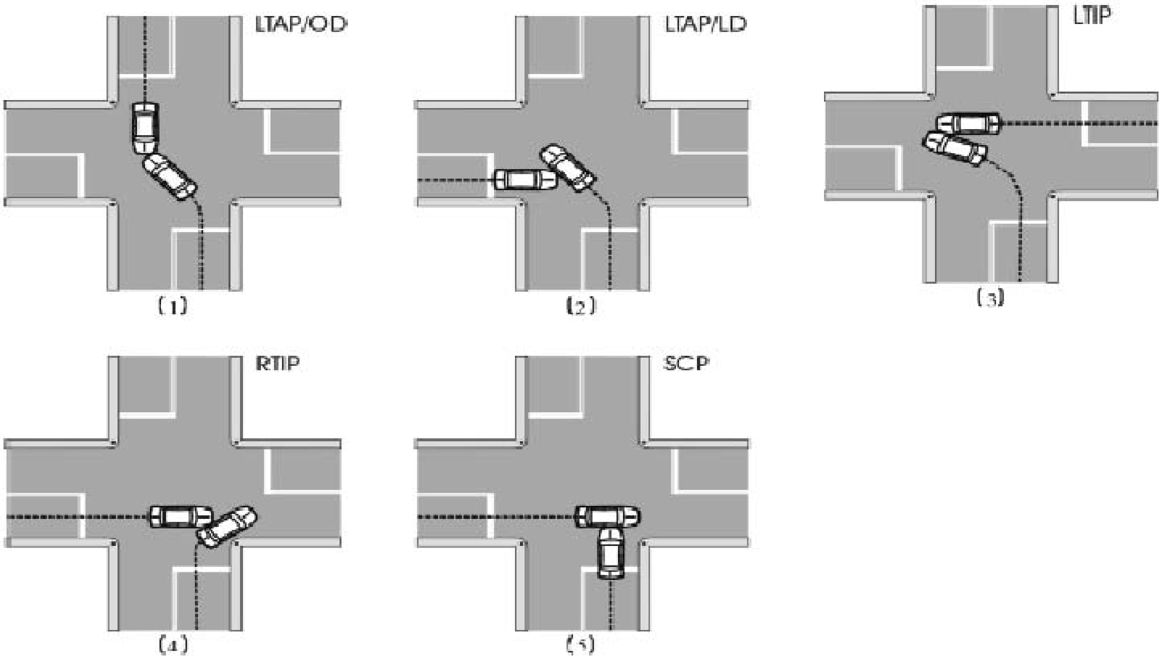

Figure 1: Crossing-Path Scenarios (figure reprinted from Najm, Smith, and Smith, 2001).

The results in Tables 1 and 2 are restricted to light vehicles, as defined by Najm et al. (2001; page B-1), and scenarios were restricted to the type defined by the same source (page 5). Special-use vehicle crashes and emergency-vehicle crashes were excluded. Note that Najm et al. were able to use the imputed Body Type variable, which does not exist in the new GES databases. Therefore, the unknown code (99) was included in the light-vehicle total in the tables below. These unknown body types comprised 1.2% of the total crossing-path crashes shown in the tables. Figures 2 and 3 graphically present the information outlined in Tables 1 and 2.

An examination of the lower right-hand corner of Table 1 shows that in 1999, there were 1,698,000 crossing-path (CP) crashes. Given that there were an estimated 6,271,000 crashes of all types in 1999, these CP crashes accounted for 27% of all crashes. In 2000, there were 1,667,000 CP crashes out of estimated 6,389,000 crashes, or 26%.

Table 1. Frequency of Crossing-Path Crashes Involving *Light* Vehicles, 1999 GES data.

Crash Severity	(LT/OD + LT/LD + LT)	SCP	RTIP	Unknown CP	All CP
Property Damage Only	501,000 30%	308,000 18%	71,000 4%	85,000 5%	**965,000** **57%**
Injury (all levels)	363,000 21%	240,000 14%	24,000 1%	26,000 2%	**653,000** **38%**
Unknown Severity	34,000 2%	32,000 2%	5,000 0%	9,000 1%	**79,000** **5%**
All Severities	**898,000** **53%**	**580,000** **34%**	**100,000** **6%**	**120,000** **7%**	**1,698,000** **100%**

Table 2. Frequency of Crossing-Path Crashes Involving *Light* Vehicles, 2000 GES data.

Crash Severity	(LT/OD + LT/LD + LT)	SCP	RTIP	Unknown CP	All CP
Property Damage Only	479,000 29%	293,000 18%	71,000 4%	95,000 6%	**937,000** **56%**
Injury (all levels)	349,000 21%	255,000 15%	23,000 1%	26,000 2%	**653,000** **39%**
Unknown Severity	33,000 2%	30,000 2%	4,000 0%	11,000 1%	**78,000** **5%**
All Severities	**861,000** **52%**	**578,000** **35%**	**97,000** **6%**	**131,000** **8%**	**1,667,000** **100%**

Note: VTTI did the following when performing this analysis, as required by the statement of work (SOW) and subsequent instructions:

1. Used the Najm et al. definition of "Light" vehicles and "Scenarios" of Crossing Path crashes as described in the recent report, "Analysis of Crossing Path Crashes" available from the TOM (except that the Imputed Body Type variable was not available).
2. Utilized the maximum injury severity reported in a crash (Accident Level) as coded in the GES (except that Imputed Maximum Severity was not available) for the "Crash Severity" definition.
3. Included fatality crash estimates in the injury counts, but only as taken from the GES.
4. Used terms defined by Najm et. Al (2001): SCP – Straight Crossing Path; LTAP/OD – Left Turn Across Path – Opposite Direction Conflict; LTAP/LD – Left Turn Across Path – Lateral Direction Conflict; RTIP – Right Turn Into Path; LTIP – Left Turn Into Path.
5. Rounded GES estimates to the nearest 1,000, and used asterisks to represent estimates between 0 and 500.

Note: In the above and all of the following Task 1 tables, rounding errors based on note 5 (above) may occasionally cause numbers in the Total columns or rows to seem to be too high or too low by 1,000. Likewise, percentages may sometimes total 99% or 101% but are always represented as 100% in the totals.

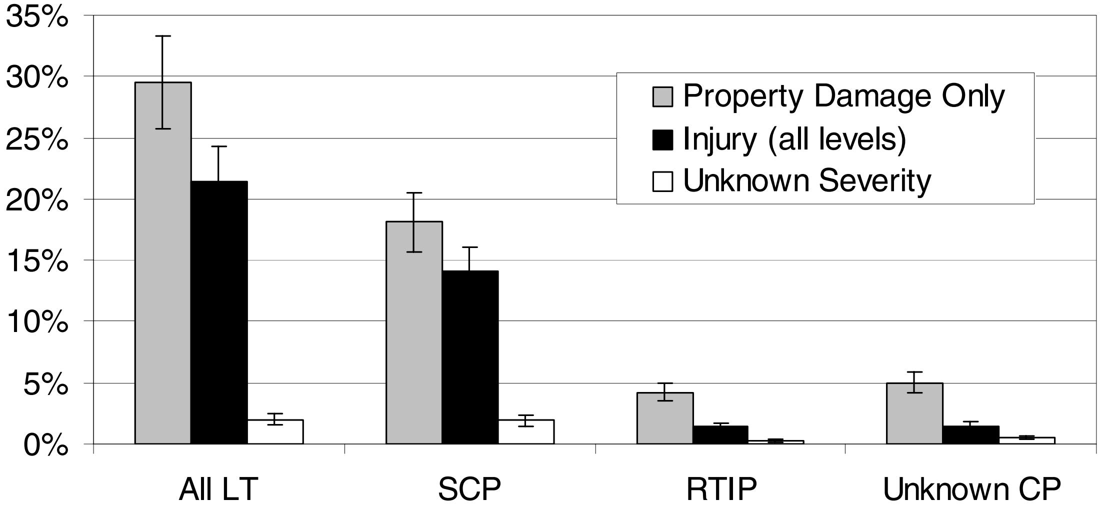

Figure 2. Percentage of Crossing-Path Crashes by Type and Severity Level, 1999 GES (bars represent 95% confidence interval).

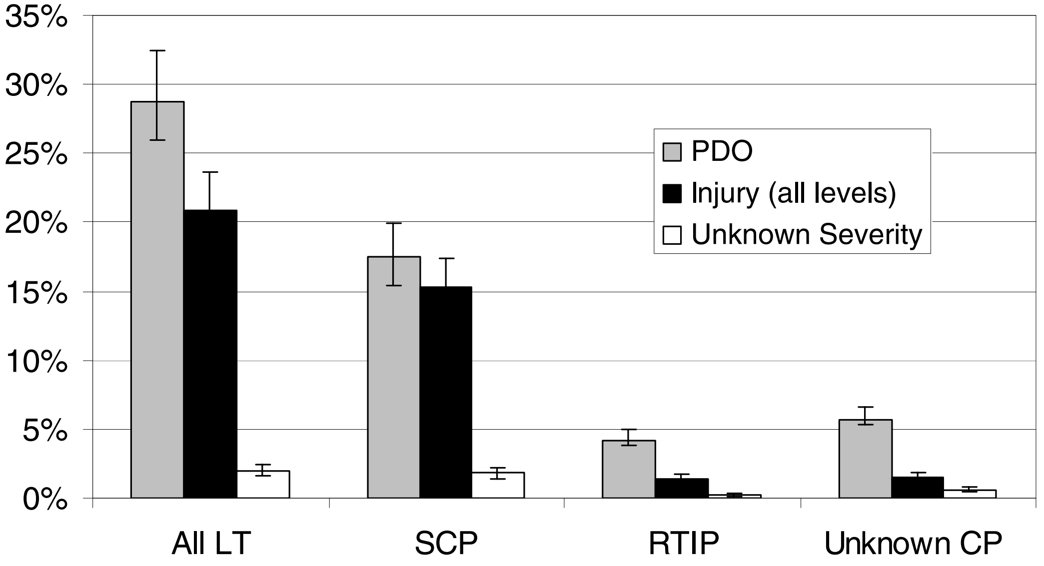

Figure 3. Percentage of Crossing-Path Crashes by Type and Severity Level, 2000 GES (bars represent 95% confidence interval).

Since the analysis techniques used to create Tables 1 and 2 were based heavily on the work performed by Najm et al. (2001), Tables D-1 and D-2 from their report were combined and replicated here in Table 3 for comparison to Tables 1 and 2, above (Najm et al., 2001; page D-1). Note that Najm et al. used Imputed Body type and the 1998 GES database in the older format. There was also no breakdown by severity in the Najm et al. (2001) report. Despite the differences in years, databases, and variables, both the overall totals and percentages are quite comparable between the two tables. Note that, in the absence of instructions otherwise in the SOW, Tables 1 and 2 do include crashes at both driveways and intersections. Table 4 presents the comparison across years by crossing-path crash type.

Table 3. Frequency of Crossing-Path Crashes involving *Light* Vehicles, 1998 GES data, from Najm et al. (2001).

Location	(LT/OD + LT/LD + LT)	SCP	RTIP	Unknown CP	All CP
Intersection	615,000 (37.4%)	472,000 (28.7%)	62,000 (3.8%)	141,000 (8.6%)	**1,290,000 (78.5%)**
Driveway	253,000 (15.4%)	20,000 (1.2%)	34,000 (2.1%)	46,000 (2.8%)	**353,000 (21.5%)**
All Locations	**868,000 (52.8%)**	**492,000 (29.9%)**	**96,000 (5.9%)**	**187,000 (11.4%)**	**1,643,000 (100%)**

Table 4. Comparison of 1999 and 2000 Crossing-Path Crash Type Frequencies and Percentages to Najm et al. (2001).

Year	All Left Turn	SCP	RTIP	Unknown CP
1998 (Najm et al., 2001)	868,000 (53%)	492,000 (30%)	96,000 (6%)	187,000 (11%)
1999 GES – this study	898,000 (53%)	580,000 (34%)	100,000 (6%)	120,000 (7%)
2000 GES – this study	861,000 (51%)	578,000 (35%)	97,000 (6%)	131,000 (8%)

A more detailed breakdown of severity was then performed, using the KABCO scale. These results are presented in Table 5 for the 1999 GES data and in Table 6 for the 2000 GES data. In Table 7, the overall KABCO percentages for crossing-path crashes presented in Tables 5 and 6 are compared to the KABCO percentages reported by Wang and Knipling (1994; page 3-10) based on 1991 GES data. As can be seen, the percentages have not changed greatly over the span of eight or nine years.

Table 5. Reprise of Table 1 (1999 GES) broken down by KABCO Maximum Injury Severity Levels.

Crash Severity	All LT	SCP	RTIP	Unknown CP	All CP
Fatal Injury (K)	3,000 0%	3,000 0%	* 0%	* 0%	**6,000** **0%**
Incapacitating injury (A)	54,000 3%	36,000 2%	3,000 0%	2,000 0%	**95,000** **6%**
Non-incapacitating injury (B)	111,000 7%	67,000 4%	6,000 0%	6,000 0%	**190,000** **11%**
Possible injury (C)	196,000 12%	135,000 8%	15,000 1%	18,000 1%	**363,000** **21%**
No injury (0)	501,000 30%	308,000 18%	71,000 4%	85,000 5%	**965,000** **57%**
Unknown or unknown severity	34,000 2%	32,000 2%	5,000 0%	9,000 1%	**79,000** **5%**
All Severities	**898,000** **53%**	**580,000** **34%**	**100,000** **6%**	**120,000** **7%**	**1,698,000** **100%**

Note that GES estimates have been rounded to the nearest 1,000, and asterisks used to represent estimates between 0 and 500 for this and subsequent tables.

Table 6. Reprise of Table 2 (2000 GES) broken down by KABCO Maximum Injury Severity Levels.

Crash Severity	All LT	SCP	RTIP	Unknown CP	All CP
Fatal Injury (K)	3,000 0%	3,000 0%	* 0%	* 0%	**5,000** **0%**
Incapacitating injury (A)	49,000 3%	36,000 2%	2,000 0%	2,000 0%	**89,000** **5%**
Non-incapacitating injury (B)	110,000 7%	83,000 5%	5,000 0%	7,000 0%	**206,000** **12%**
Possible injury (C)	189,000 11%	134,000 8%	15,000 1%	16,000 1%	**353,000** **21%**
No injury (O)	479,000 29%	293,000 18%	71,000 4%	100,000 6%	**937,000** **56%**
Unknown or unknown severity	33,000 2%	30,000 2%	4,000 0%	11,000 1%	**78,000** **5%**
All Severities	**861,000** **52%**	**578,000** **35%**	**97,000** **6%**	**131,000** **8%**	**1,667,000** **100%**

Table 7. Comparison of Table 4 and 5 Percentages to Wang and Knipling's (1994) analysis using imputed Maximum Severity Percentages based on the 1991 GES database.

Crash Severity	Table 4 1999 GES	Table 5 2000 GES	Wang and Knipling 1991 GES
Fatal Injury (K)	0.3%	0.3%	0.3%
Incapacitating injury (A)	5.6%	5.3%	5.5%
Non-incapacitating injury (B)	11.2%	12.3%	10.4%
Possible injury (C)	21.4%	21.2%	18.9%
No injury (0)	56.8%	56.2%	64.9%
Unknown or unknown severity	4.7%	4.7%	---
All Severities	**100%**	**100%**	**100%**

Note: The Wang and Knipling report used the Imputed Maximum Severity variable, so there were no unknowns.

The Volpe Center provided an analysis of fatal crashes based on the same general criteria as for Subtask 1 but using the Fatal Accident Reporting System (FARS) databases (Noga, Smith, and Najm, 2003). A comparison of the Volpe results with the current findings from Tables 5 and 6 is presented in Table 8. There are important differences between the analysis techniques used. For example, the Volpe Center used the first harmful event and the vehicle maneuver to identify crossing-path crashes since the Accident Type variable is not available in FARS, as it is in GES. Also, Volpe's analyses of FARS crashes were limited to intersections and intersection-related locations with stop signs and traffic signals, while the GES crash analyses examined all junctions (including driveways) and all TCDs (or lack thereof). In the Volpe analysis, single vehicle crashes and crashes with more than 2 vehicles were excluded, while they were considered in the GES analysis. In both cases, only crashes with at least one light vehicle were included. Where available, similar tables from the Volpe analysis are included throughout the report to provide insight into the prevalence of fatal CP crashes as compared to all CP crashes.

Table 8. Comparison of Fatal CP Crashes between GES and FARS (from Volpe) for 1999 and 2000.

Crash Severity	All LT	SCP	GES –RTIP FARS – All RT	All CP
1999+2000 Fatal Crashes – GES	5,000	5,000	*	**10,000**
1999+2000 Fatal Crashes – FARS	2,047	4,039	56	**6,142**

Note: The years 1999 and 2000 are summed in this table.

The following points were noted in interpreting the Subtask 1.1 results:

- Left-turn crashes make up the majority of crossing-path crash types, at about 52% of CP crashes for the years 1998 through 2000.
- The next most prevalent type is the straight crossing-path crash type, at about 30-35%, followed by unknown CP crashes at 7-11%.
- Right-turn crashes are the least common type, constituting approximately 6% of all CP crashes for 1998-2000.

- In terms of maximum injury severity, PDO crashes made up the majority of CP crashes, at about 56%, followed by injury crashes (including fatality crashes) at about 39%. There were also a significant number of unknown severity levels, at about 5%.
- The CP crash-type distributions for 1999 and 2000 were very much in agreement with the Najm et al. (2001) results.
- The KABCO distributions were very much in agreement with the Wang and Knipling (1994) results.
- The fatality estimates are known to be highly unreliable in GES. A comparison with the FARS analysis performed by Volpe for the same crash types showed that GES overestimated the fatal CP crashes by a factor of approximately 1.7, although this can be explained to some degree by the different techniques used in analyzing FARS and GES data.

SUBTASK 1.2 DISTRIBUTION OF CRASHES BY *TRAFFIC-CONTROL DE*VICE

The next step for the Task 1 analyses was to further refine the Subtask 1.1findings according to the traffic-control devices involved. There were two traffic-control devices of interest for this subtask: 3-color signals and stop signs, defined as indicated by the GES User's Manual. Tables 9 and 10 include categories for these devices. The dynamics of turning left, going straight, or turning right are segregated because they are very different types of pre-event movements, and each could require a different approach to violation-countermeasure development. Such distinctions are believed at this time to be unnecessary for stop-sign controlled crashes, although stop-sign crashes were analyzed in greater depth in Subtask 1.3. Figures 4 and 5 present the 1999 and 2000 data from Tables 9 and 10 in a graphical format.

Table 9. Frequency of Crossing-Path Crashes involving *Light* Vehicles by *Traffic Control Device,* 1999 GES data.

Crash Severity	**3-Color Signal**			**Stop Signs**	**Unknown TCD**	**Total CP**
	All Left Turns	**SCP**	**RTIP**			
Property Damage Only	159,000 14%	83,000 7%	18,000 2%	301,000 27%	11,000 1%	**604,000 54%**
Injury (all levels)	144,000 13%	86,000 8%	6,000 1%	204,000 18%	4,000 0%	**452,000 41%**
Unknown Severity	15,000 1%	11,000 1%	1,000 0%	20,000 2%	1,000 0%	**53,000 5%**
All Severities	**319,000 29%**	**179,000 16%**	**25,000 2%**	**525,000 47%**	**16,000 1%**	**1,109,000 100%**

Note: Due to space limitations, unknown crossing-path crash types for three-color signals are not included in this table. Altogether, there were 45,000 crashes of this type. There were also 544,000 crashes with no TCD or other types of TCDs, such as flashing lights.

Table 10. Frequency of Crossing-Path Crashes involving *Light* Vehicles by *Traffic Control Device,* 2000 GES data.

Crash Severity	3-Color Signal			Stop Signs	Unknown TCD	Total CP
	All Left Turns	SCP	RTIP			
Property Damage Only	161,000 16%	93,000 9%	16,000 2%	215,000 22%	19,000 2%	**536,000** **54%**
Injury (all levels)	149,000 15%	96,000 10%	4,000 0%	145,000 15%	9,000 1%	**412,000** **41%**
Unknown Severity	15,000 2%	10,000 1%	1,000 0%	14,000 1%	2,000 0%	**46,000** **5%**
All Severities	**325,000** **33%**	**199,000** **20%**	**21,000** **2%**	**374,000** **38%**	**30,000** **3%**	**994,000** **100%**

Note: Due to space limitations, unknown crossing-path crash types for three-color signals are not included in this table. Altogether, there were 45,000 crashes of this type. There were also 628,000 crashes with no TCD or other types of TCDs, such as flashing lights.

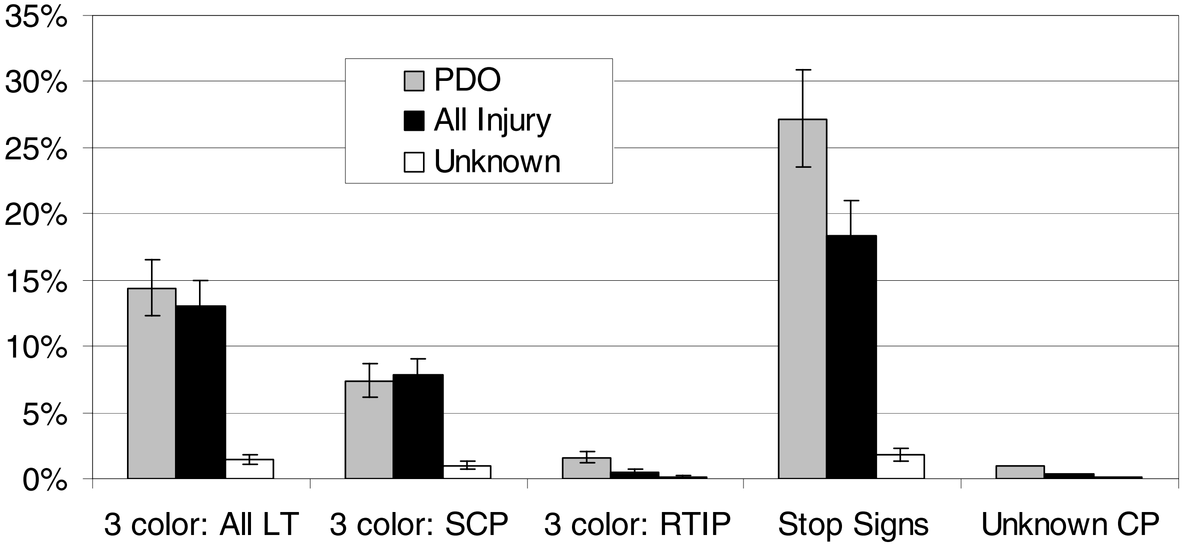

Figure 4. Percentage of CP Crashes by Type, TCD, and Severity Level, 1999 GES (bars represent 95% confidence interval).

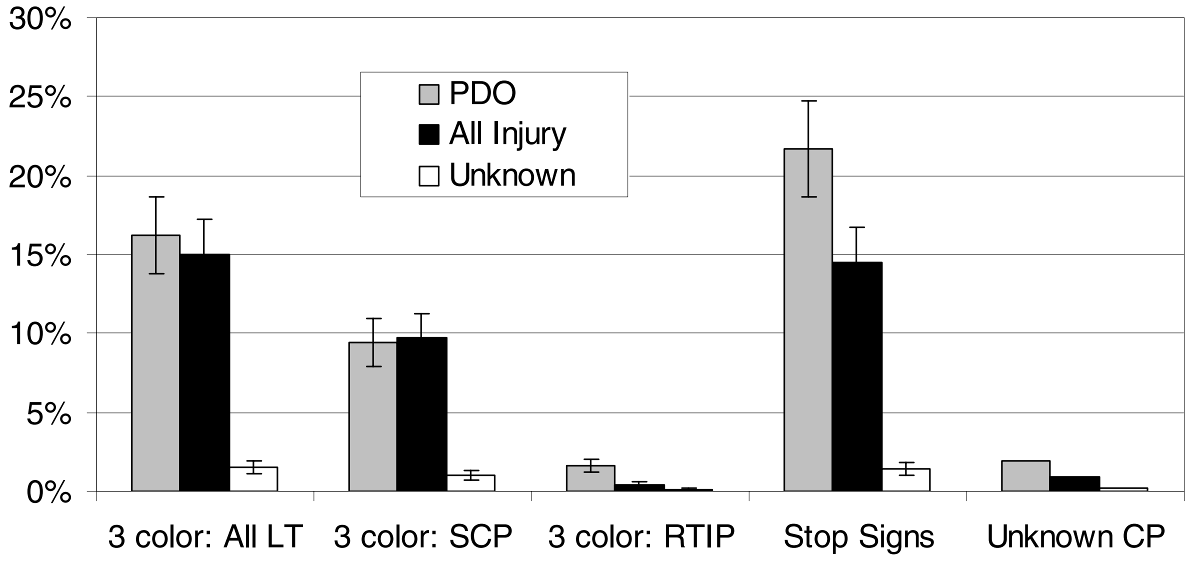

Figure 5. Percentage of CP Crashes by Type, TCD, and Severity Level, 2000 GES (bars represent 95% confidence interval).

As was the case for Subtask 1.1, an analysis similar to Tables 9 and 10 was performed by Najm et al. (2001; page D-1) for light vehicles involved in crashes at intersections and driveways. The Najm et al. results, which are based on 1998 GES in the older format, are presented in Table 11 for comparison to the 1999 and 2000 results. Again, the differences are minor and within expected variance given that different years were analyzed and that Najm et al. had access to the imputed and Hotdeck variables that are not available in the new databases (imputed and Hotdeck variables are variables for which the unknowns have been distributed into the known categories using various statistical methods). A comparison across the years of 1998 through 2000 is presented in Table 12.

Table 11. Frequency of Crossing-Path Crashes involving *Light* Vehicles by *Traffic Control Device*, 1998 GES data from Najm et al. (2001).

Location	**3-Color Signal**			**Stop Signs**	**Total CP**
	All Left Turns	**SCP**	**RTIP**		
Intersections	295,000 28.8%	181,000 17.6%	20,000 1.9%	487,000 47.5%	**983,000 95.8%**
Driveways	13,000 1.3%	1,000 0.1%	3,000 0.3%	26,000 2.5%	**43,000 4.2%**
All Locations	**308,000 30.1%**	**182,000 17.7%**	**23,000 2.2%**	**513,000 50.0%**	**1,026,000 100.0%**

Table 12. Comparison of 1999 and 2000 Crossing-Path Crash Type Frequencies and Percentages by TCD to Najm et al. (2001).

Year	3-Color Signal			Stop Signs	Total CP
	All LT	SCP	RTIP		
1998 (Najm et al., 2001)	308,000 30.1%	182,000 17.7%	23,000 2.2%	513,000 50.0%	**1,026,000** **100.0%**
1999 GES – this study	319,000 28.8%	179,000 16.2%	25,000 2.2%	525,000 47.4%	**1,093,000** **94.6%**
2000 GES – this study	325,000 32.7%	199,000 20.1%	21,000 2.1%	374,000 37.6%	**964,000** **92.5%**

Note: Unknown TCD is not included in this table, since it was not available for the Najm et al. data.

The Volpe Center's Noga, Smith, and Najm (2003) performed an analysis of the FARS database in a parallel fashion to the GES Subtask 1.2 analysis. As mentioned previously, their analyses do not precisely correspond because different variables were used in FARS and GES (the primary differences being that the Accident Type variable is not available in FARS and that all junction types were included in the GES analysis). These results are shown in Table 13.

Table 13. Frequency of Light Vehicle Fatal Crossing-Path Crash Scenarios by Traffic-Control Device for 1999 and 2000 (from Volpe FARS analysis).

Crash Severity	3-Color Signal			Stop Signs	Total CP
	All Left Turns	SCP	RTIP		
All severities (GES)	644,000	379,000	46,000	899,000	1,968,000
Fatal (FARS)	1,059	1,077	0	3,994	**6,130**

The following points were noted in interpreting the Subtask 1.2 results:

- Traffic-control devices were fairly evenly divided between 3-color signals and stop signs. There were very few unknown TCDs (1.5-3.0%).
- There were fewer stop-sign crashes for 2000 than for 1998 (Najm et al., 2001) or 1999. The analysis was double checked, but the cause for the discrepancy could not be found. However, Subtask 1.3 looked at stop-sign CP crashes in more detail, and the total numbers for 2000 look more realistic for this table. Since later subtasks derive from the numbers in Subtask 1.3, the discrepancy noted in Subtask 1.2 should not matter to the later analyses.
- In terms of crash severity, 3-color signal CP crashes were fairly evenly divided between PDO and injury crashes, while stop-sign CP crashes had more PDO crashes than injury crashes.
- In general, the findings from these analyses agreed with the findings of Najm et al. (2001) for TCDs.

SUBTASK 1.3 DISTRIBUTION OF STOP-SIGN CRASHES BY *TRAFFICWAY CONTROL*

The goal of Subtask 1.3 was to develop further insight into the stop-sign crashes identified in Subtask 1.2. The purpose of this subtask was to determine the number of vehicles with a stop sign at stop-signed intersection crashes and the number of vehicles with a thoroughfare (no stop sign) at stop-signed intersection crashes. Thus, for Subtask 1.3, the stop-sign crash data from Subtask 1.2 was subdivided according to whether one or both of the two crashing vehicles had a stop sign. Tables 14 and 15 provide the details of this analysis. As can be seen, in about 80% of the crashes, one vehicle had a stop sign, and one vehicle had no TCD. This 4:1 proportion holds true regardless of severity. Note that this analysis did not examine 2-way stop intersections vs. 4-way stop intersections. Rather, the crash could have occurred when two vehicles facing one another at a 2-way stop intersection came into the intersection together, with one turning across the path of the other. GES does not distinguish between these two types of intersections.

Note that for 1999, the total number of stop-sign crashes is somewhat less than the number identified in Subtask 1.2 (6.3% fewer crashes). This difference exists because the Subtask 1.2 analysis was performed at the Accident level, while Subtask 1.3 was performed at the Vehicle level to capture the TCDs associated with individual vehicles, and the results were then converted to the Accident level. Likewise, the numbers for 2000 are larger in Subtask 1.3 than in Subtask 1.2 by a significant amount (20.1% more crashes). The numbers in Table 15 are probably more representative of the true values since they are closer to the numbers for 1999 as well as to the Najm et al. values for 1998. Figures 6 and 7 show the proportion of stop-sign crashes for which either one or both vehicles had a stop sign. Note that a similar analysis was not performed by Najm et al. (2001) for this subtask because the 1998 GES did not report the traffic-control device variable at the Vehicle level. The new GES databases provided by NHTSA and used for this report include many variables at the Vehicle level that were previously only available at the Accident level, including TCD. For the same reason, Noga et al. (2003) did not perform a FARS analysis comparable to this subtask for fatal CP crashes.

Table 14. Frequency of Crossing-Path Crashes involving *Light* Vehicles at *Stop Signs* by *Trafficway Control*, 1999 GES data.

Crash Severity	Stop Signs		
	1 Vehicle with Sign	2 Vehicles with Sign	Total Stop Sign
Property Damage Only	225,000 46%	58,000 12%	**283,000 57%**
Injury	157,000 32%	34,000 7%	**191,000 39%**
Unknown Severity	11,000 2%	7,000 1%	**18,000 4%**
Total	**393,000 80%**	**99,000 20%**	**493,000 100%**

Table 15. Frequency of CrossingPath Crashes involving *Light* Vehicles at *Stop Signs* by *Trafficway Control,* 2000 GES data.

Crash Severity	Stop Signs		
	1 Vehicle with Sign	**2 Vehicles with Sign**	**Total Stop Sign**
Property Damage Only	217,000 48%	43,000 10%	**260,000** **58%**
Injury	148,000 33%	22,000 5%	**170,000** **38%**
Unknown Severity	16,000 4%	2,000 0%	**18,000** **4%**
Total	**381,000** **85%**	**68,000** **15%**	**449,000** **100%**

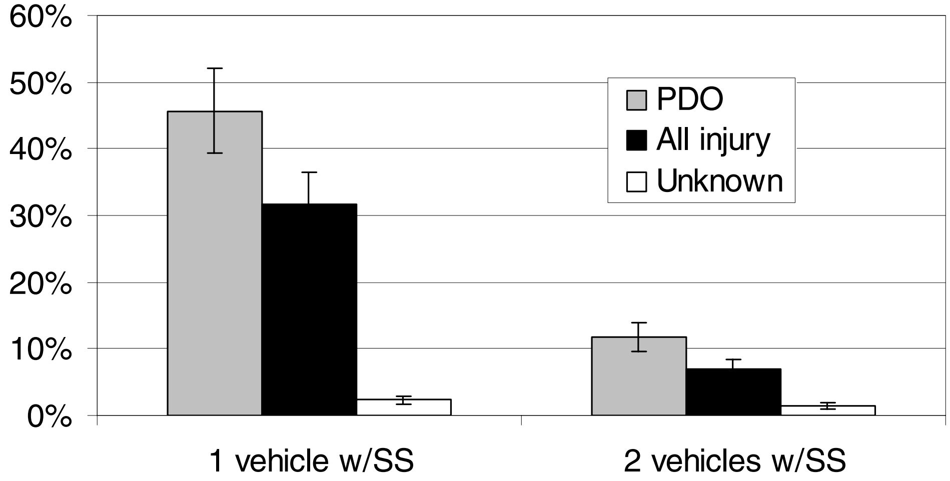

Figure 6. Percentage of Stop-Sign Crashes, one or both Vehicles with a Stop Sign, by Severity Level, 1999 GES (bars represent 95% confidence interval).

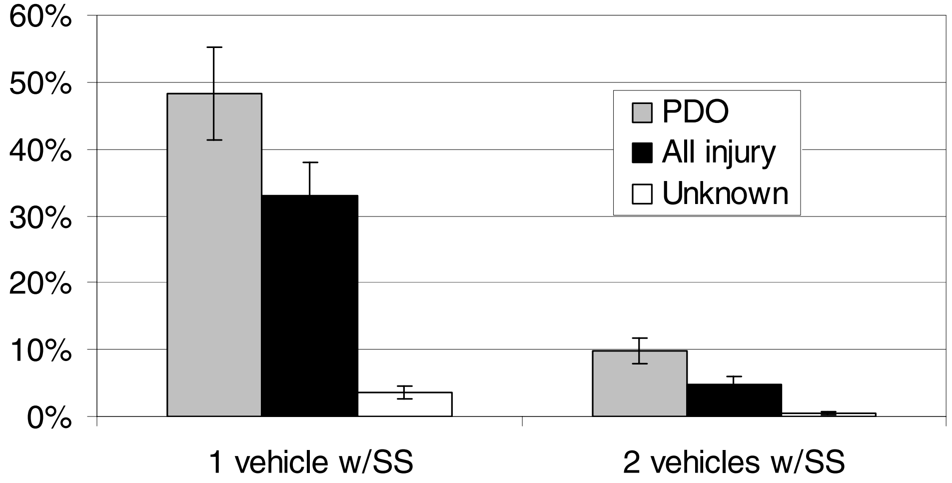

Figure 7. Percentage of Stop-Sign Crashes, one or both Vehicles with a Stop Sign, by Severity Level, 2000 GES (bars represent 95% confidence interval).

The following points were noted in interpreting the Subtask 1.3 results:

- Stop-sign CP crashes in which only one vehicle had a stop sign were 4 or 5 times more prevalent than crashes in which both vehicles had a stop sign.
- As noted in Subtask 2, there was a discrepancy in the number of stop-sign crashes for 2000, but this discrepancy largely disappeared in the Subtask 1.3 analysis.
- Although PDO crashes were more prevalent for all stop-sign crashes, the ratio of PDO to injury crashes was higher for crashes in which both vehicles had stop signs (a greater proportion of the two-stop-sign cases were property damage only crashes as compared to the one-stop- sign case).
- This subtask marked the point in the increasingly detailed analyses for which no comparison numbers from previous analyses could be found.

SUBTASK 1.4. DISTRIBUTION OF PRE-CRASH MANEUVERS BY LIGHT VEHICLES *CITED WITH VIOLATIONS*

Following the analyses performed in Subtasks 1.1 through 1.3, the next analysis (Subtask 1.4) identified the crash population of light vehicles cited with violations. At the same time, pre-crash maneuvers were also considered for the left-turn and right-turn CP crash types for three-color signals. The rationale for this approach is that the population of cited violations should contain nearly all of the preventable crashes (except perhaps for fatality crashes and extremely infrequent, uncited cases). Tables 16 and 17 were completed as the first step of the Subtask 1.4 analysis. In these tables, the signal crashes are sorted to the vehicle level by the type of maneuver with violation that the drivers were trying to complete. For example, a cited driver who was driving straight in a RTIP crash was classified differently than a cited driver who was making a right turn for the same crash type. Also, the columns under the stop-sign classification were derived from the analysis performed in Subtask 1.3, but were limited in this task to citations assigned to the vehicle with a single stop sign, or to citations charged to one of the two vehicles, where each had a stop sign. The unknown TCDs were dropped from the analyses for this and subsequent subtasks.

The analyses for this subtask and subsequent subtasks were performed at the Vehicle level and were then converted to the Accident level (necessary for the rare cases in which more then one vehicle was cited for a crash). In those rare cases, the violation charged to Vehicle 1 was used in the analysis (or the lowest vehicle number of those cited, for crashes with more than two vehicles and more than one citation).

The violations used in the analyses were those believed to most amenable to countermeasures of the type envisioned by the ICAV project. Therefore, the violations used were speeding, reckless driving, failure to yield right of way, running a traffic signal or stop sign, and unknown violations (since it was believed that for CP crashes, most of the unknowns would fall under one of the previous four categories). Figures 8 and 9 present the Subtask 1.4 findings in a graphical form.

The most notable item in Tables 16 and 17 is the high preponderance of straight pre-crash maneuvers. Assuming that both vehicles in an SCP crash have straight pre-crash maneuvers, 63% of all 3-color signal CP crashes with violations in 1999 involved a straight pre-crash maneuver by the violating vehicle. The percentage was a little lower in 2000, at 53%. Also, note that the frequency of citations varies according to the pre-crash maneuver for left and right crash types: *cited drivers were more likely to be making a turning pre-crash maneuver than a straight pre-crash maneuver*. For stop-sign crashes, *drivers with one stop sign were much more likely to receive one of the relevant citations than were drivers in crashes in which both vehicles had a stop sign*. Finally, *right-turn CP crashes were much less likely to be cited for the above types of violations, regardless of pre-crash maneuver*.

Table 16. Frequency of Pre-Crash Maneuvers Involving *Light* Vehicles Cited with *Violations* (1999 GES; grand total of 541,000 cited crashes).

Crash Severity	3-Color Signal					Stop Signs	
	All Left Turn		SCP	RTIP			
	Left Turn	Straight		Right Turn	Straight	1 S	2 S
PDO	42,000	29,000	45,000	6,000	3,000	139,000	6,000
Injury	46,000	32,000	55,000	1,000	1,000	119,000	7,000
Unknown	2,000	1,000	2,000	*	*	3,000	*
Total	**90,000**	**63,000**	**101,000**	**8,000**	**4,000**	**261,000**	**14,000**

Table 17. Frequency of Pre-Crash Maneuvers Involving *Light* Vehicles Cited with *Violations* (2000 GES; grand total of 393,000 cited crashes).

Crash Severity	3-Color Signal					Stop Signs	
	All Left Turn		SCP	RTIP			
	Left Turn	Straight		Right Turn	Straight	1 S	2 S
PDO	44,000	19,000	33,000	6,000	1,000	87,000	16,000
Injury	44,000	17,000	38,000	1,000	*	72,000	10,000
Unknown	1,000	1,000	1,000	*	*	2,000	*
Total	**89,000**	**37,000**	**72,000**	**7,000**	**1,000**	**162,000**	**26,000**

Note: In completing the above tables, VTTI used the following notes supplied by NHTSA in the SOW:

1. At a signal, at least one vehicle has to violate the red light in SCP, LTAP/LD, and LTIP crashes, but all crashes are not cited. This table shows only those cited.
2. At a signal, there may or may not be a red-light violation in LTAP/OD and RTIP crashes. This table shows only those cited.
3. With stop-sign crashes, a distinction has to be made between a vehicle "entering an intersection without stopping" and a vehicle "stopping first and then proceeding against traffic." Only the former entails a stop-sign violation. The pre-event vehicle-movement variable may be used to make that distinction. Unfortunately, the GES codes do not represent these maneuvers well. The violations-cited codes in the GES contain information on "running stop sign" and "failure to yield a right-of-way." The former indicates a stop-sign violation. (In some cases, the latter violation is also issued to drivers who did not stop.)
4. For each cell in the above table, determine the distribution of violation types as coded in the GES.

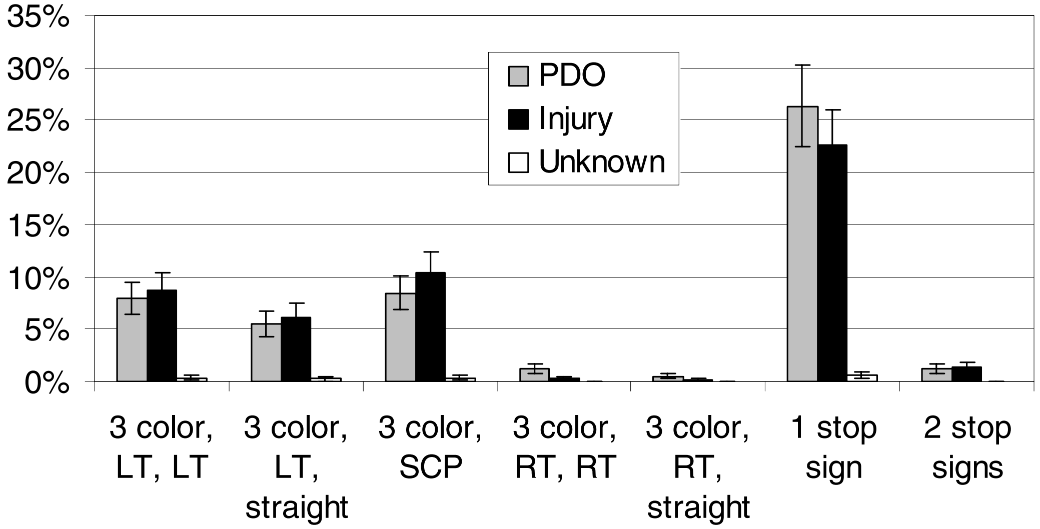

Figure 8. Percentage of Cited CP Crashes by TCD, Crash Type, Pre-Crash Maneuver, and Crash Severity, 1999 GES (bars represent 95% confidence interval).

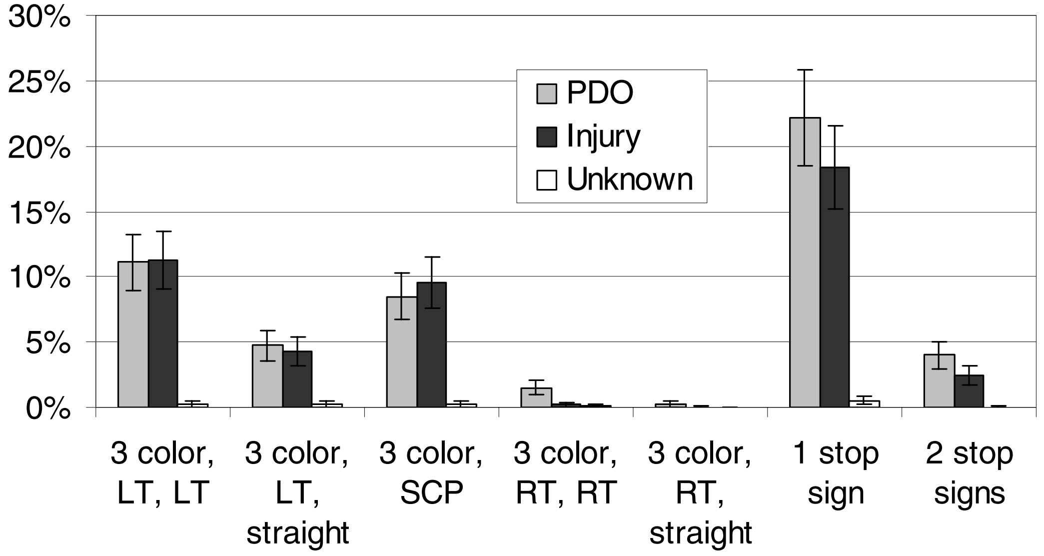

Figure 9. Percentage of Cited CP Crashes by TCD, Crash Type, Pre-Crash Maneuver, and Crash Severity, 2000 GES (bars represent 95% confidence interval).

At this point in the sequential analysis, the Noga et al. (2003) tables began to diverge so much from the tables presented here that no meaningful comparisons could be conducted. This fact was primarily due to the methods used given the available variables in FARS and GES. However, their report provides meaningful insight into the fatal crossing-path crash problem, and the reader is referred to this report should it be published by NHTSA in the future.

The next part of Subtask 1.4 required that each of the cells in Tables 16 and 17 be distributed by citation type. This resulted in seven tables for each year (a total of 14 tables) and one table for each column from Table 16 or 17. Summary Tables 18 and 19 are presented first and distribute the violation types across all crash types; these tables are accompanied by Figures 10 and 11 that present the same information graphically. These figures are followed by Tables 20 through 33, which present the violation distributions for each crash type.

Table 18. Violation Types across All CP Crash Types from Table 16, 1999 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	1,000	*	121,000	62,000	86,000	**270,000**
Injury	1,000	1,000	102,000	68,000	90,000	**262,000**
Unknown	*	*	3,000	2,000	4,000	**9,000**
Total	**2,000**	**2,000**	**225,000**	**133,000**	**180,000**	**541,000**

Table 19. Violation Types across All CP Crash Types from Table 17, 2000 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	2,000	1,000	104,000	47,000	51,000	**205,000**
Injury	2,000	1,000	82,000	51,000	46,000	**182,000**
Unknown	*	*	2,000	1,000	3,000	**6,000**
Total	**4,000**	**2,000**	**188,000**	**99,000**	**100,000**	**393,000**

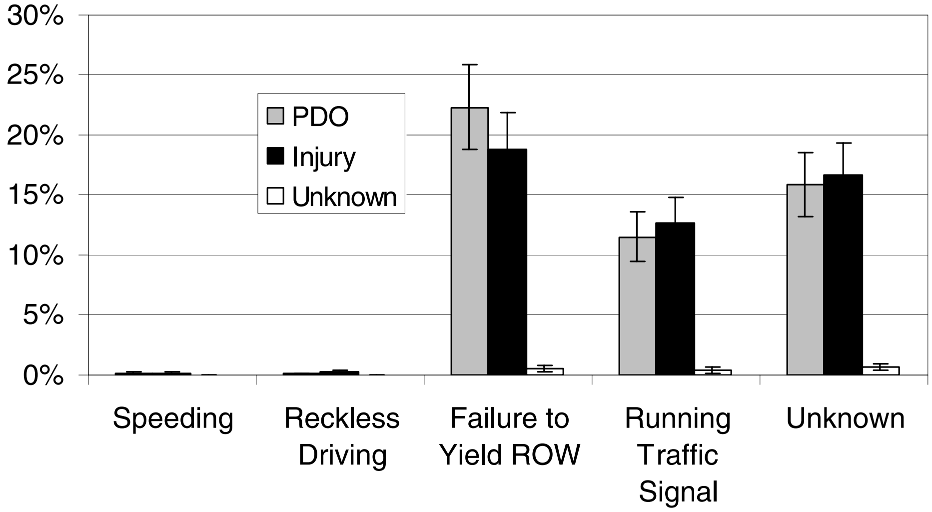

Figure 10. Percentage of Violation Types across All CP Crash Types, 1999 GES (bars represent 95% confidence interval).

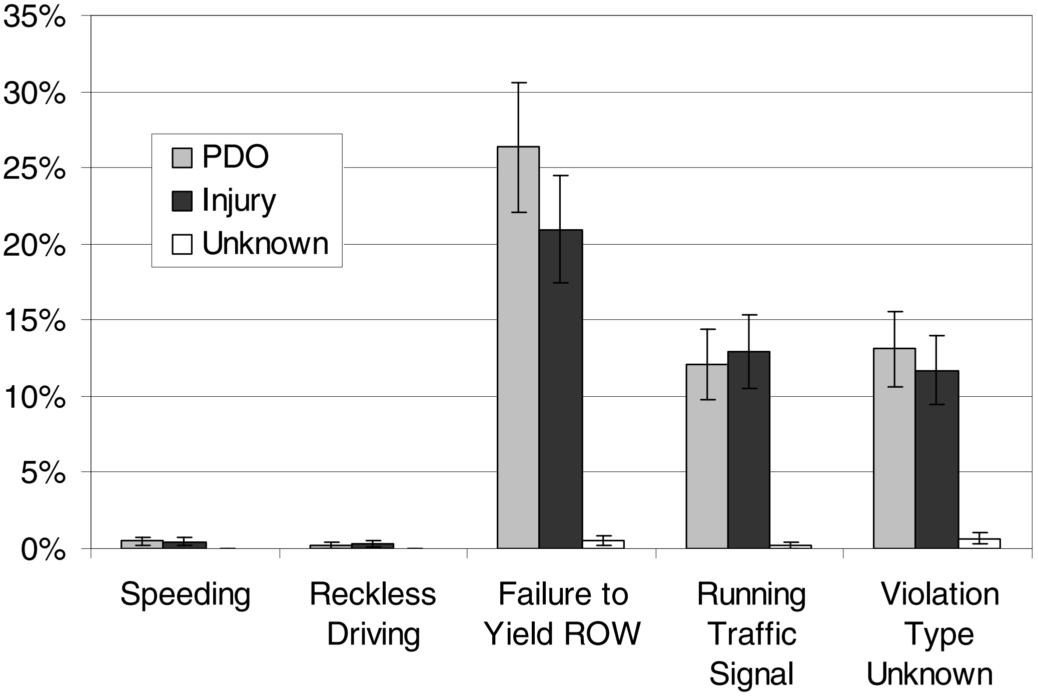

Figure 11. Percentage of Violation Types across All CP Crash Types, 2000 GES (bars represent 95% confidence interval).

Table 20. Violation Types for 3-Color Signal, left turn CP crash, and left turn pre-crash maneuver, 1999 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	*	*	25,000	3,000	14,000	**42,000**
Injury	*	*	25,000	2,000	19,000	**46,000**
Unknown	*	*	1,000	*	1,000	**2,000**
Total	*	*	**51,000**	**5,000**	**34,000**	**90,000**

Table 21. Violation Types for 3-Color Signal, left turn CP crash, and left turn pre-crash maneuver, 2000 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	*	*	31,000	2,000	11,000	**44,000**
Injury	*	*	31,000	2,000	12,000	**44,000**
Unknown	*	*	*	*	1,000	**1,000**
Total	*	*	**61,000**	**4,000**	**23,000**	**89,000**

Table 22. Violation Types for 3-Color Signal, left turn CP crash, and straight pre-crash maneuver, 1999 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	*	*	2,000	12,000	15,000	**29,000**
Injury	*	*	2,000	13,000	17,000	**32,000**
Unknown	*	*	*	*	1,000	**2,000**
Total	*	*	**5,000**	**25,000**	**33,000**	**63,000**

Table 23. Violation Types for 3-Color Signal, left turn CP crash, and straight pre-crash maneuver, 2000 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	1,000	*	1,000	11,000	5,000	**19,000**
Injury	1,000	*	*	10,000	6,000	**17,000**
Unknown	*	*	*	*	*	**1,000**
Total	**1,000**	**1,000**	**2,000**	**21,000**	**12,000**	**37,000**

Table 24. Violation Types for 3-Color Signal, straight CP crash, 1999 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	*	*	2,000	26,000	15,000	**45,000**
Injury	*	*	2,000	32,000	21,000	**55,000**
Unknown	*	*	1,000	1,000	*	**2,000**
Total	**1,000**	**1,000**	**5,000**	**59,000**	**37,000**	**101,000**

Table 25. Violation Types for 3-Color Signal, straight CP crash, 2000 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	*	*	3,000	21,000	8,000	**33,000**
Injury	*	*	2,000	25,000	11,000	**38,000**
Unknown	*	*	*	*	1,000	**1,000**
Total	**1,000**	*	**5,000**	**46,000**	**20,000**	**72,000**

Table 26. Violation Types for 3-Color Signal, right turn CP crash, and right turn pre-crash maneuver, 1999 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	*	*	3,000	1,000	2,000	**6,000**
Injury	*	*	1,000	1,000	*	**1,000**
Unknown	*	*	*	*	*	*
Total	*	*	**4,000**	**1,000**	**3,000**	**8,000**

Table 27. Violation Types for 3-Color Signal, right turn CP crash, and right turn pre-crash maneuver, 2000 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	*	*	3,000	*	2,000	**6,000**
Injury	*	*	*	*	*	**1,000**
Unknown	*	*	*	*	*	*
Total	*	*	**4,000**	**1,000**	**2,000**	**7,000**

Table 28. Violation Types for 3-Color Signal, right turn CP crash, and straight pre-crash maneuver, 1999 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	*	*	*	1,000	2,000	**3,000**
Injury	*	*	*	1,000	*	**1,000**
Unknown	*	*	*	*	*	*
Total	*	*	*	**1,000**	**2,000**	**4,000**

Table 29. Violation Types for 3-Color Signal, right turn CP crash, and straight pre-crash maneuver, 2000 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Traffic Signal	Violation Type Unknown	Total
PDO	*	*	*	1,000	*	**1,000**
Injury	*	*	*	*	*	*****
Unknown	*	*	*	*	*	*****
Total	*****	*****	*****	**1,000**	*****	**1,000**

Table 30. Violation Types for stop sign, where one vehicle had a stop sign, 1999 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Stop Sign	Violation Type Unknown	Total
PDO	*	*	85,000	19,000	34,000	**139,000**
Injury	*	1,000	70,000	20,000	29,000	**119,000**
Unknown	*	*	1,000	1,000	1,000	**3,000**
Total	**1,000**	**1,000**	**156,000**	**40,000**	**64,000**	**261,000**

Table 31. Violation Types for stop sign, where one vehicle had a stop sign, 2000 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Stop Sign	Violation Type Unknown	Total
PDO	1,000	*	58,000	9,000	20,000	**87,000**
Injury	1,000	*	45,000	11,000	15,000	**72,000**
Unknown	*	*	1,000	*	1,000	**2,000**
Total	**2,000**	**0**	**104,000**	**20,000**	**36,000**	**162,000**

Table 32. Violation Types for stop sign, where two vehicles had a stop sign, 1999 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Stop Sign	Violation Type Unknown	Total
PDO	*	*	2,000	1,000	3,000	**6,000**
Injury	*	*	2,000	1,000	4,000	**7,000**
Unknown	*	*	*	*	*	*****
Total	*****	*****	**5,000**	**2,000**	**7,000**	**14,000**

Table 33. Violation Types for stop sign, where two vehicles had a stop sign, 2000 GES.

Crash Severity	Speeding	Reckless Driving	Failure to Yield ROW	Running Stop Sign	Violation Type Unknown	Total
PDO	*	*	8,000	3,000	5,000	**16,000**
Injury	*	*	4,000	3,000	2,000	**10,000**
Unknown	*	*	*	*	*	*
Total	*	*	**12,000**	**6,000**	**7,000**	**26,000**

The following points were noted in interpreting the Subtask 1.4 results:

- For 1999, of the crash-involved drivers who were cited at 3-color controlled intersections: 63% were going straight, 34% were turning left, and 3% were turning right; for 2000, the percentages were 53% going straight, 43% turning left, and 3% turning right.
- In terms of the overall analysis, for left- and right-turn crash types, drivers making a turning pre-crash maneuver were more likely to be cited than drivers making a straight pre-crash maneuver, depending on the year, crash type, and pre-crash maneuver type.
- For stop-sign crashes overall, drivers in the one-stop-sign case were more likely to be cited than were drivers in the two-stop-sign case--to a degree that cannot be fully explained by the larger overall number of CP crashes in this category.
- In terms of overall violation type, there were a significant number of unknown violation types (25-30%). For those violations that were known, the most common overall violation was a failure to yield right-of-way, followed by running a traffic sign or signal.
- Speeding and reckless driving were rarely cited in CP crashes overall.
- The detailed analyses for each crash type showed the following most common violations:
  - For 3-color signal, LT with LT pre-crash maneuver crashes, 62% of the cited violations were for failure to yield right-of-way (ROW) (Tables 20 and 21).
  - For 3-color signal, LT with straight pre-crash maneuver crashes, 46% of the cited violations were for running a traffic signal (Tables 22 and 23).
  - For 3-color signal, SCP crashes, 61% of the cited violations were for running a traffic signal (Tables 24 and 25).
  - For 3-color signal, RT with RT pre-crash maneuver crashes, 52% of the cited violations were for failure to yield ROW (Tables 26 and 27).
  - For 3-color signal, RT with straight pre-crash maneuver crashes, 43% of the cited violations were for running a traffic signal (Tables 28 and 29).
  - For stop sign CP crashes in which one vehicle had a stop sign, 61% of the cited violations were for failure to yield ROW (Tables 30 and 31).
  - For stop sign CP crashes in which both vehicles had a stop sign, 44% of the cited violations were for failure to yield ROW (Tables 32 and 33).

SUBTASK 1.5 CRASH *CONTRIBUTING FACTORS* OF LIGHT VEHICLES CITED WITH VIOLATIONS

The next phase of analysis determined the contributing factors associated with light vehicles that violated the 3-color signal or the stop sign for each cell identified in Tables 16 and 17 of Subtask 1.4. The factor priority scheme method outlined by Najm, Koopmann, Boyle, and Smith (2001) was used. The factor priority scheme method uses a process of elimination in an attempt to capture the single-most important factor that could have caused or contributed to the crash. These factors may include items such as alcohol or drugs, drowsiness, inattention, vision obstruction (including vision obstruction due to road geometry), and speeding, among others. These factors are not all found under a single GES variable, so this subtask required an iterative analysis process that took a considerable amount of effort, time, and attention. For crashes that could not be connected to any of the factors identified in the course of competing the subtask, environmental and roadway factors were explored for crash contribution. Upon consideration of the SOW and previous research efforts, including Najm, Smith, and Smith (2001) and Najm, Koopmann, Boyle, and Smith (2001), the following factors were chosen, in order of consideration:

- Alcohol and drug (using the person-drug and person-alcohol variables).
- Driver's vision obscured (including due to roadway features).
- Driver impairment (including drowsiness).
- Driver distraction (including inattention).
- Speeding.

For any remaining crashes, the following environmental and roadway variables were explored, in order of consideration:

- Weather (not-clear).
- Roadway surface (not dry).
- Roadway alignment (not straight).

A little more detail is warranted for the factor priority scheme method. Once the order of factors was decided, as shown in the above lists, each factor was explored one at a time. For example, the alcohol and drug cases examined the alcohol and drug contributing factor, keeping in mind that an alcohol or drug citation was not issued for this crash (since these violation types were excluded in Subtask 1.4). So these values give an idea of the size of the drug and alcohol problem, even when no citation is issued. Once these numbers were derived for each crash type and injury level, all of the drug and alcohol cases were removed from the database so that the next factor, driver's vision obscured, could be considered. Again, these cases were then removed from the database before the next factor was considered.

Due to the repetitive nature of these tasks and the large number of tables generated (14 per-year analyzed) only the 2000 results are displayed in the report. The results are similar enough for the two years that additional information was not gained by examining the tables for both years. Since the following analyses and tables are based on the cells in Table 17, that table is repeated here as Table 34. Table 35 summarizes the contributing factors across all crash types and injury levels, while Tables 36 through 49 present one table per cell of Table 34. Each table is accompanied by a pie chart showing the distribution of crash-contributing factors for that crash type and injury level. For easy comparison between the table and accompanying pie chart, each set is presented on a single page.

Table 34. Reprise of Table 17: Frequency of Pre-Crash Maneuvers Involving *Light* Vehicles Cited with *Violations* (2000 GES; there were 387,000 cited crashes once unknown injury levels were removed).

Crash Severity	**3-Color Signal**					**Stop Signs**	
	All Left Turn		SCP	RTIP			
	Left Turn	Straight		Right Turn	Straight	1 S	2 S
PDO	44,000	19,000	33,000	6,000	1,000	87,000	**16,000**
Injury	44,000	17,000	38,000	1,000	*	72,000	**10,000**
Total	**88,000**	**36,000**	**71,000**	**7,000**	**1,000**	**159,000**	**25,000**

Table 35. Frequency and Percentage of *Primary Contributing Factors* for All CP Crash Types and Known Crash Severities (from Table 34) for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	8,000	2%
Driver's Vision Obscured	38,000	10%
Driver Impairment (including drowsiness)	3,000	1%
Driver Distraction or Inattention	143,000	37%
Speeding	8,000	2%
Total Primary Contributing Factors	**200,000**	**52%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	51,000	13%
Road Surface (not dry)	15,000	4%
Roadway Alignment (not straight)	6,000	2%
Total Environmental or Roadway Factors	**71,000**	**19%**
Total Contributing Factors	**271,000**	**71%**
Total Crashes from Table 34	**387,000**	**100%**

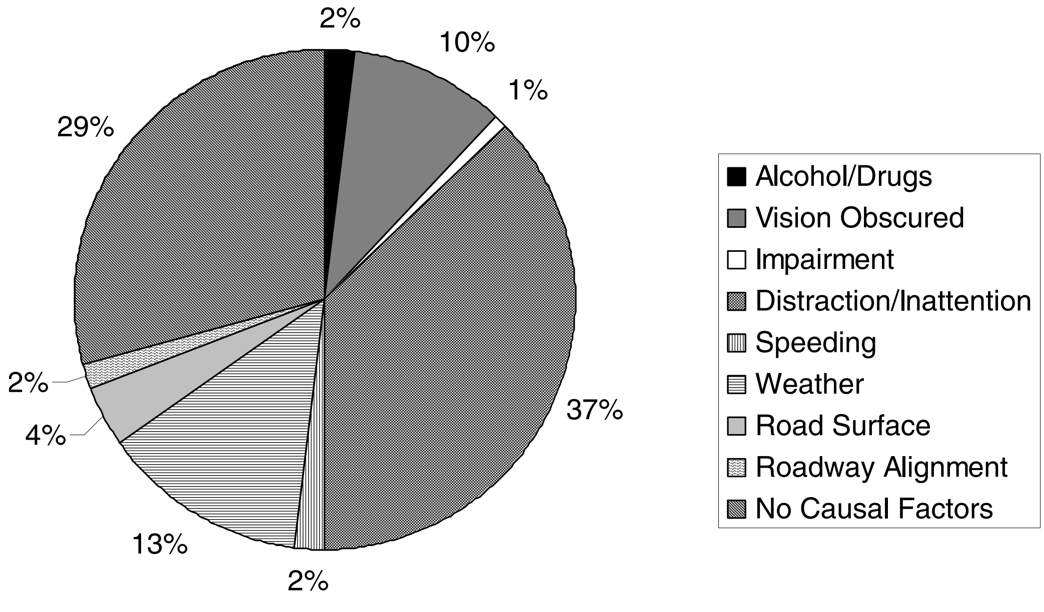

Figure 12. Percentage of *Primary Contributing Factors* for All CP Crash Types and Known Crash Severities for Light Vehicles Cited with Violations, 2000 GES data (all pie chart legends are presented clockwise starting at the top of the chart).

Table 36. Frequency and Percentage of *Primary Contributing Factors* for PDO left turn CP crashes with left turn pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	1,000	2%
Driver's Vision Obscured	4,000	9%
Driver Impairment (including drowsiness)	*	*
Driver Distraction or Inattention	17,000	39%
Speeding	*	*
Total Primary Contributing Factors	**22,000**	**50%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	4,000	9%
Road Surface (not dry)	1,000	2%
Roadway Alignment (not straight)	*	*
Total Environmental or Roadway Factors	**5,000**	11%
Total crashes of this type from Table 34	**44,000**	**100%**

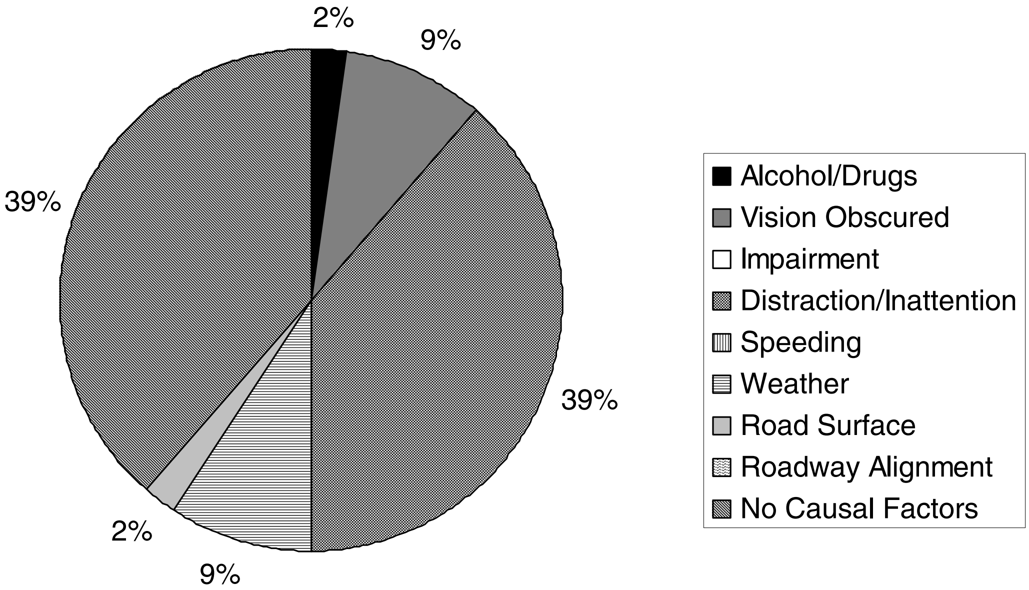

Figure 13. Percentage of *Primary Contributing Factors* for PDO left turn CP crashes with left turn pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Table 37. Frequency and Percentage of *Primary Contributing Factors* for Injury left turn CP crashes with left turn pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	2,000	5%
Driver's Vision Obscured	5,000	11%
Driver Impairment (including drowsiness)	*	*
Driver Distraction or Inattention	13,000	30%
Speeding	*	*
Total Primary Contributing Factors	**20,000**	**46%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	3,000	7%
Road Surface (not dry)	1,000	2%
Roadway Alignment (not straight)	1,000	2%
Total Environmental or Roadway Factors	**5,000**	**11%**
Total crashes of this type from Table 34	**44,000**	**100%**

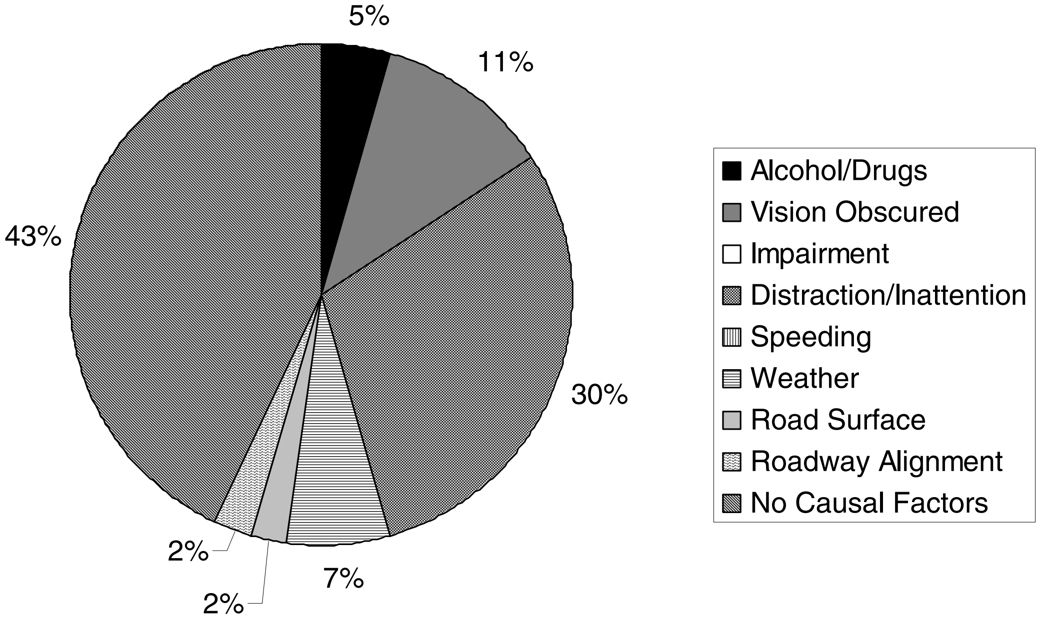

Figure 14. Percentage of *Primary Contributing Factors* for Injury left turn CP crashes with left turn pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Table 38. Frequency and Percentage of *Primary Contributing Factors* for PDO left turn CP crashes with straight pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	*	*
Driver's Vision Obscured	1,000	8%
Driver Impairment (including drowsiness)	*	*
Driver Distraction or Inattention	8,000	62%
Speeding	1,000	8%
Total Primary Contributing Factors	**10,000**	**77%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	2,000	15%
Road Surface (not dry)	1,000	8%
Roadway Alignment (not straight)	*	*
Total Environmental or Roadway Factors	**3,000**	**23%**
Total crashes of this type from Table 34	**13,000**	**100%**

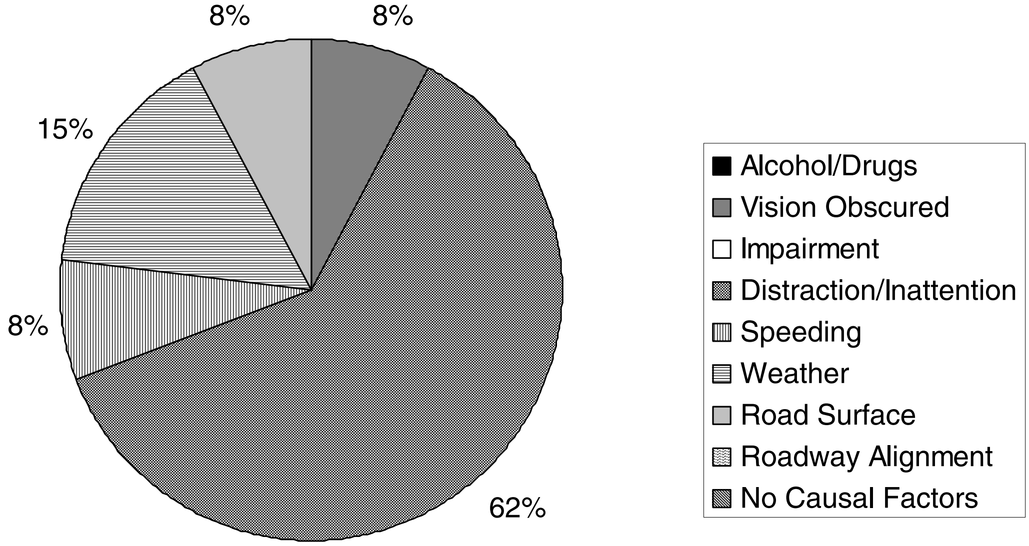

Figure 15. Percentage of *Primary Contributing Factors* for PDO left turn CP crashes with straight pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Table 39. Frequency and Percentage of *Primary Contributing Factors* for Injury left turn CP crashes with straight pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	*	*
Driver's Vision Obscured	2,000	12%
Driver Impairment (including drowsiness)	*	*
Driver Distraction or Inattention	5,000	29%
Speeding	1,000	6%
Total Primary Contributing Factors	**8,000**	**47%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	1,000	6%
Road Surface (not dry)	1,000	6%
Roadway Alignment (not straight)	*	*
Total Environmental or Roadway Factors	**2,000**	**12%**
Total crashes of this type from Table 34	**17,000**	**100%**

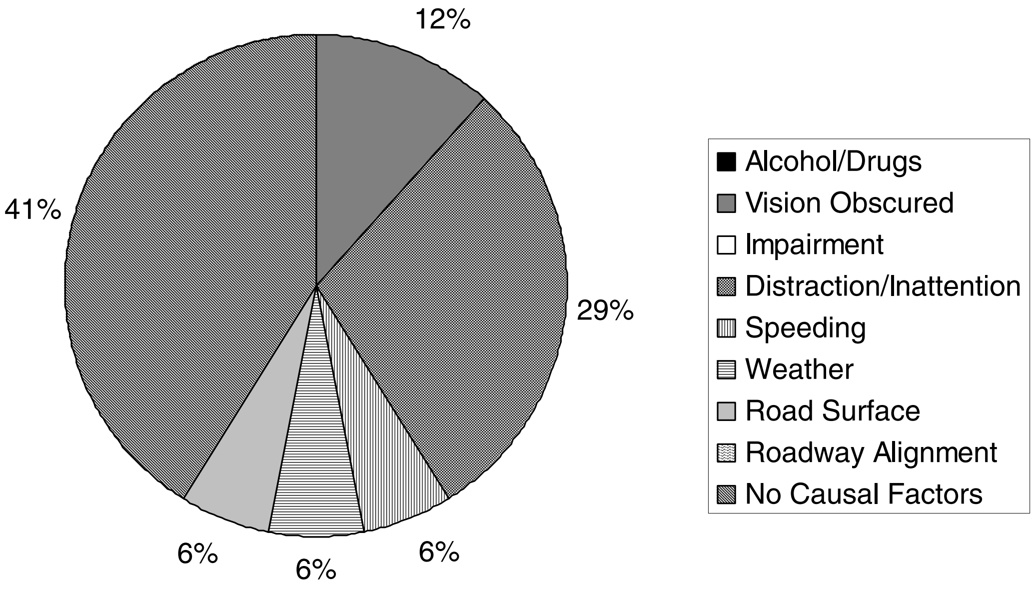

Figure 16. Percentage of *Primary Contributing Factors* for Injury left turn CP crashes with straight pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Table 40. Frequency and Percentage of *Primary Contributing Factors* for PDO Straight CP crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	1,000	3%
Driver's Vision Obscured	1,000	3%
Driver Impairment (including drowsiness)	1,000	3%
Driver Distraction or Inattention	20,000	61%
Speeding	2,000	6%
Total Primary Contributing Factors	**25,000**	**76%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	4,000	12%
Road Surface (not dry)	1,000	3%
Roadway Alignment (not straight)	*	*
Total Environmental or Roadway Factors	**5,000**	**15%**
Total crashes of this type from Table 34	**33,000**	**100%**

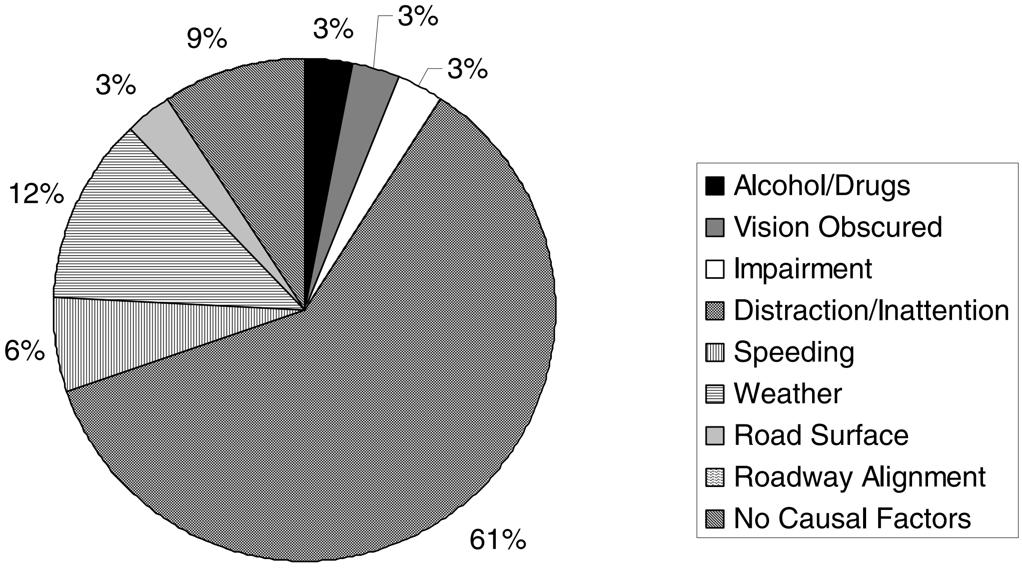

Figure 17. Percentage of *Primary Contributing Factors* for PDO Straight CP crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Table 41. Frequency and Percentage of *Primary Contributing Factors* for Injury Straight CP crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	1,000	3%
Driver's Vision Obscured	2,000	5%
Driver Impairment (including drowsiness)	1,000	3%
Driver Distraction or Inattention	17,000	45%
Speeding	1,000	3%
Total Primary Contributing Factors	**22,000**	**59%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	3,000	8%
Road Surface (not dry)	2,000	5%
Roadway Alignment (not straight)	*	*
Total Environmental or Roadway Factors	**5,000**	**13%**
Total crashes of this type from Table 34	**38,000**	**100%**

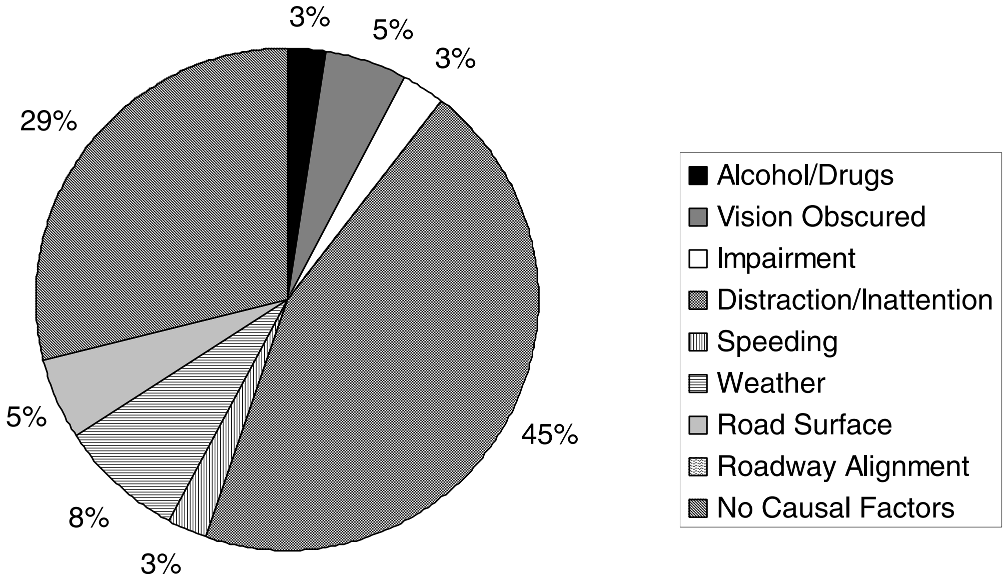

Figure 18. Percentage of *Primary Contributing Factors* for Injury Straight CP crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Table 42. Frequency and Percentage of *Primary Contributing Factors* for PDO right turn CP crashes with right turn pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	**Frequency**	**Percent**
Alcohol or Drugs	*	*
Driver's Vision Obscured	*	*
Driver Impairment (including drowsiness)	*	*
Driver Distraction or Inattention	2,000	33%
Speeding	*	*
Total Primary Contributing Factors	**2,000**	**33%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	*	*
Road Surface (not dry)	*	*
Roadway Alignment (not straight)	*	*
Total Environmental or Roadway Factors	*	*
Total crashes of this type from Table 34	**6,000**	**100%**

Due to the lack of significant values for Table 42, these data were not graphed.

Table 43. Frequency and Percentage of *Primary Contributing Factors* for Injury right turn CP crashes with right turn pre-crash maneuver, at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	**Frequency**	**Percent**
Alcohol or Drugs	*	*
Driver's Vision Obscured	*	*
Driver Impairment (including drowsiness)	*	*
Driver Distraction or Inattention	1,000	100%
Speeding	*	*
Total Primary Contributing Factors	**1,000**	**100%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	*	*
Road Surface (not dry)	*	*
Roadway Alignment (not straight)	*	*
Total Environmental or Roadway Factors	*****	*****
Total crashes of this type from Table 34	**1,000**	**100%**

Due to the lack of significant values for Table 43, these data were not graphed.

For PDO right turn CP crashes with straight pre-crash maneuver, at 3-color signal intersections, for light vehicles cited with violations, there were no significant table values (no values greater than 500). Likewise, for Injury right turn CP crashes with straight pre-crash maneuver, at 3-color signal intersections, for light vehicles cited with violations, there were no significant table values (no values greater than 500).

Table 44. Frequency and Percentage of *Primary Contributing Factors* for PDO Stop-Sign Crashes, where one vehicle had a stop sign, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	*	*
Driver's Vision Obscured	12,000	14%
Driver Impairment (including drowsiness)	1,000	1%
Driver Distraction or Inattention	29,000	33%
Speeding	1,000	1%
Total Primary Contributing Factors	**42,000**	**49%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	18,000	21%
Road Surface (not dry)	10,000	11%
Roadway Alignment (not straight)	1,000	1%
Total Environmental or Roadway Factors	**29,000**	**33%**
Total crashes of this type from Table 34	**87,000**	**100%**

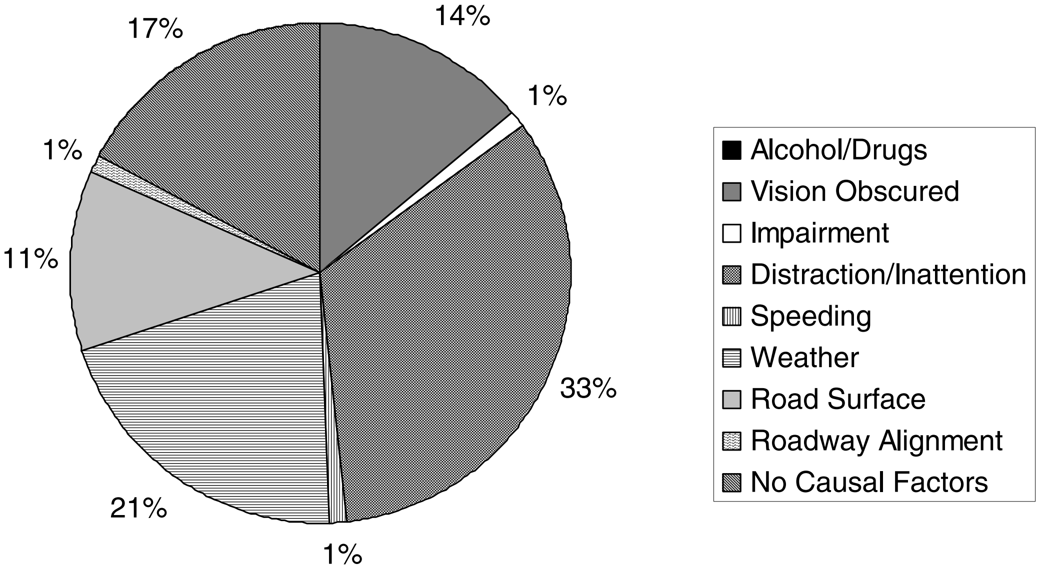

Figure 19. Percentage of *Primary Contributing Factors* for PDO Stop-Sign Crashes, where one vehicle had a stop sign, for Light Vehicles Cited with Violations, 2000 GES data.

Table 45. Frequency and Percentage of *Primary Contributing Factors* for Injury Stop-Sign Crashes, where one vehicle had a stop sign, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	2,000	3%
Driver's Vision Obscured	9,000	13%
Driver Impairment (including drowsiness)	*	*
Driver Distraction or Inattention	21,000	29%
Speeding	2,000	3%
Total Primary Contributing Factors	**33,000**	**47%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	10,000	14%
Road Surface (not dry)	5,000	7%
Roadway Alignment (not straight)	2,000	3%
Total Environmental or Roadway Factors	**17,000**	**24%**
Total crashes of this type from Table 34	**72,000**	**100%**

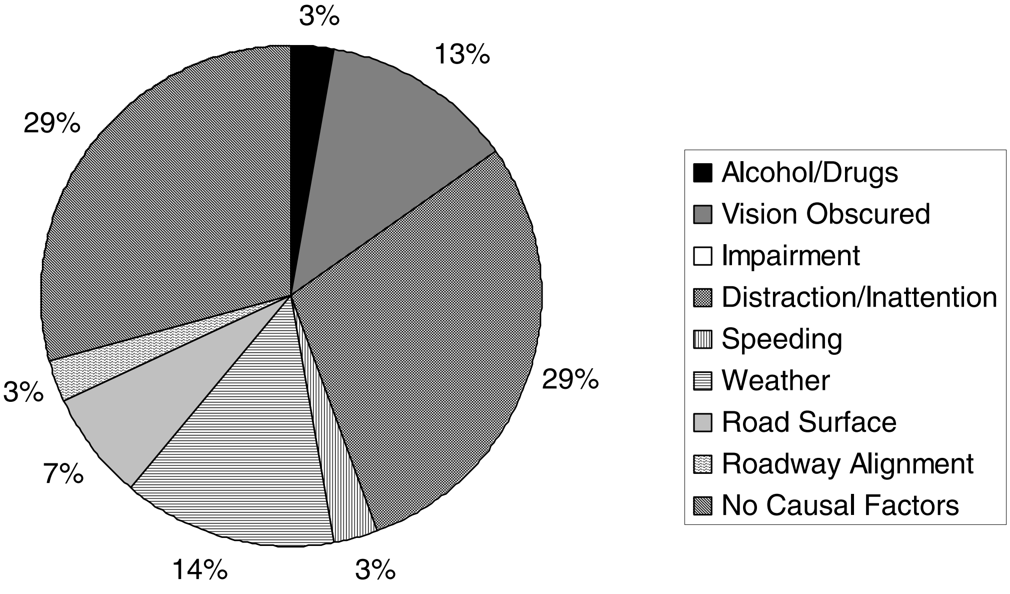

Figure 20. Percentage of *Primary Contributing Factors* for Injury Stop-Sign Crashes, where one vehicle had a stop sign, for Light Vehicles Cited with Violations, 2000 GES data.

Table 46. Frequency and Percentage of *Primary Contributing Factors* for PDO Stop-Sign Crashes, where both vehicles had a stop sign, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	Frequency	Percent
Alcohol or Drugs	*	*
Driver's Vision Obscured	2,000	13%
Driver Impairment (including drowsiness)	*	*
Driver Distraction or Inattention	7,000	44%
Speeding	*	*
Total Primary Contributing Factors	**8,000**	**50%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	4,000	25%
Road Surface (not dry)	3,000	19%
Roadway Alignment (not straight)	*	*
Total Environmental or Roadway Factors	**7,000**	**44%**
Total crashes of this type from Table 34	**16,000**	**100%**

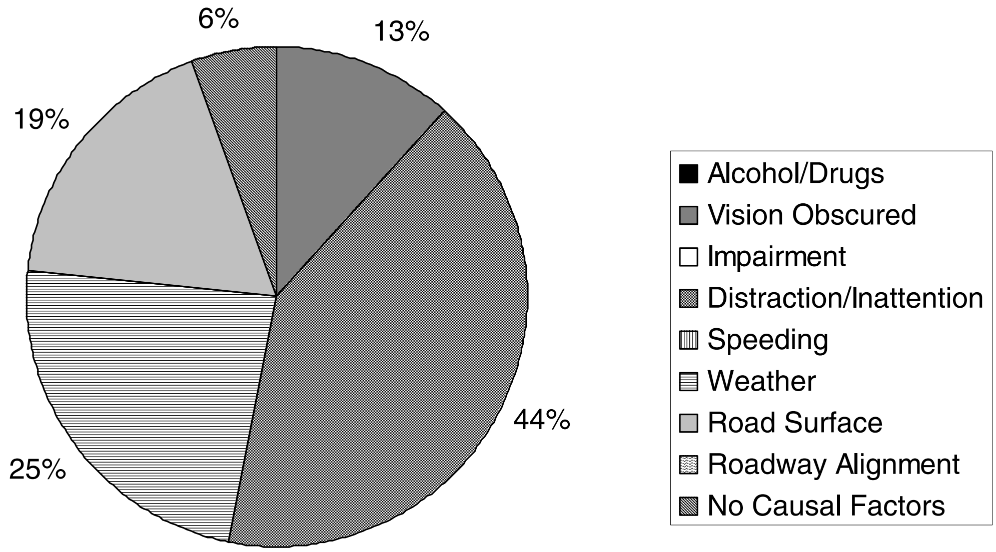

Figure 21. Percentage of *Primary Contributing Factors* for PDO Stop-Sign Crashes, where both vehicles had a stop sign, for Light Vehicles Cited with Violations, 2000 GES data.

Table 47. Frequency and Percentage of *Primary Contributing Factors* for Injury Stop-Sign Crashes, where both vehicles had a stop sign, for Light Vehicles Cited with Violations, 2000 GES data.

Primary Contributing Factor	**Frequency**	**Percent**
Alcohol or Drugs	*	*
Driver's Vision Obscured	1,000	10%
Driver Impairment (including drowsiness)	*	*
Driver Distraction or Inattention	4,000	40%
Speeding	*	*
Total Primary Contributing Factors	**5,000**	**50%**
Environmental or Roadway Factors	**Frequency**	**Percent**
Weather (not clear)	2,000	20%
Road Surface (not dry)	1,000	10%
Roadway Alignment (not straight)	*	*
Total Environmental or Roadway Factors	**2,000**	**30%**
Total crashes of this type from Table 34	**10,000**	**100%**

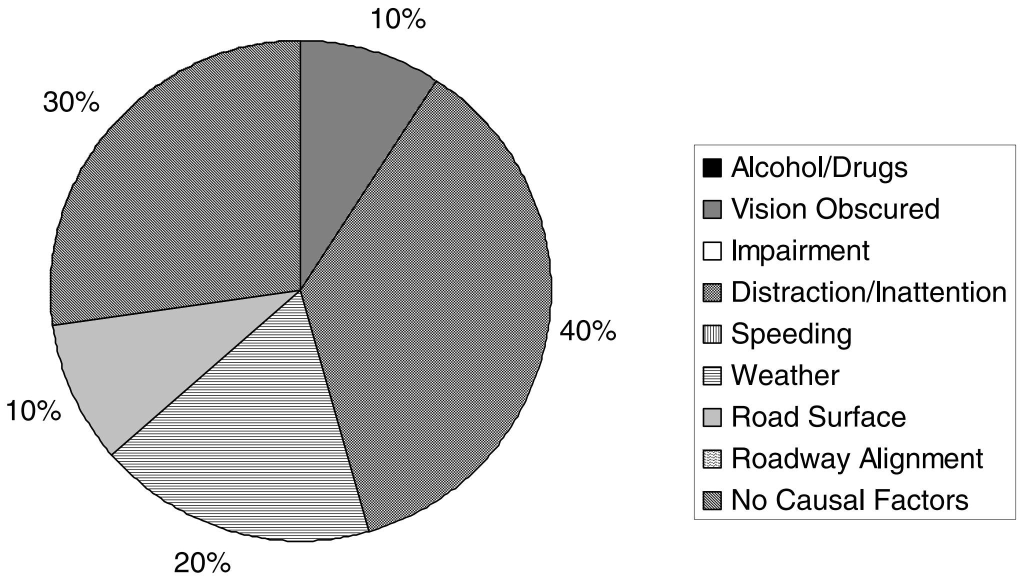

Figure 22. Percentage of *Primary Contributing Factors* for Injury Stop-Sign Crashes, where both vehicles had a stop sign, for Light Vehicles Cited with Violations, 2000 GES data.

The following points were noted in interpreting the Subtask 1.5 results:

- Over all crash types and injury levels, driver distraction and inattention was the largest primary contributing factor, at 37%. This finding validates some of the assumptions made in the early stages of the ICAV project, in that one of the primary purposes of the ICAV system is to capture the attention of the inattentive or distracted driver.
- Driver's vision obscured was the second largest category overall, at about 10%.
- For environmental and roadway factors, weather was the largest, at 13%, followed by road surface at 4%.
- Over all crash types and injury levels, 52% of crashes were able to be attributed to one of the primary contributing factors, while 18% were attributed to environmental or roadway factors. These results mean that 70% of crashes could be assigned to one of the eight factors.
- The percentage of crashes that could be attributed to one of the factors varied widely by crash type and crash severity, ranging from 8% to 98%, although the mean was closer to the 70% total mean.
- The maximum percentages for the contributing factors were as follows:
    - Alcohol or drugs – 3.9% of injury LT with LT pre-crash maneuver crashes.
    - Driver's vision obscured – 13.4% of PDO stop-sign crashes in which one vehicle had a stop sign.
    - Driver impairment – 1.8% of both PDO LT with LT pre-crash maneuver crashes *and* PDO SCP crashes.
    - Driver distraction or inattention – 68.6% of injury RT with RT pre-crash maneuver CP crashes.
    - Speeding – 8.1% of injury LT with straight pre-crash maneuver crashes.
    - Weather – 25.3% of PDO stop-sign crashes in which both vehicles had a stop sign.
    - Road surface – 16.6% of PDO stop-sign crashes in which both vehicles had a stop sign.
    - Roadway alignment – 2.8% of PDO stop-sign crashes in which both vehicles had a stop sign.
- Speeding was a greater factor for straight pre-crash maneuvers than for turning pre-crash maneuvers.
- There were so few right turn crash cases with violations that the estimates are probably not very accurate. For example, in the injury RT with straight pre-crash maneuver case, there were only 175 cases, and yet the analysis showed more than 200 cases in which weather was a factor.
- The tables prepared as part of this subtask provide a wealth of additional detail, depending on the research interests of the reader.

SUBTASK 1.6. *SPEED BEHAVIOR* IN CROSSING PATH CRASHES

The analyses performed in Subtask 1.6 characterized the speeding behavior of the violating, crashing drivers with various traffic-control devices. To this end, the distribution of the posted speed limits, the distribution of the traveling speed, and the speeding status (yes/no) were analyzed for each of the 14 cells in Table 17 (reproduced here as Table 48). Since this resulted in 42 tables for each year analyzed, only the 2000 results are presented here. Overall results showed that the posted speed limits were generally well known, while the traveling speeds were not generally known. In the majority of cases, the speeding status was listed as not speed related. Given the relatively low status of speeding as a contributing factor, this finding is not surprising. Tables 49 through 51 present the overall results, while Tables 52 through 93 present the results for each cell of Table 48. Graphs of posted speed distributions are provided for each of the cells, but given the large number of unknown traveling speeds, these were not graphed. Note that in some cases, contiguous tables representing the same population have different total numbers for crashes, due to rounding each of the table entries to the nearest 1,000 and then summing these rounded values.

Table 48. Reprise of Table 17: Frequency of Pre-Crash Maneuvers Involving *Light* Vehicles Cited with *Violations* (2000 GES; there were 387,000 cited crashes with known injury severity).

Crash Severity	**3-Color Signal**					**Stop Signs**	
	All Left Turn		SCP	RTIP			
	Left Turn	Straight		Right Turn	Straight	1 S	2 S
PDO	44,000	19,000	33,000	6,000	1,000	87,000	**16,000**
Injury	44,000	17,000	38,000	1,000	*	72,000	**10,000**
Total	**88,000**	**36,000**	**71,000**	**7,000**	**1,000**	**159,000**	**25,000**

Overall Results for Speed Behavior Analysis

Table 49. Frequency and Percentage of *Posted Speed Limits* for All CP Crash Types and Severity Levels for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	1,000	0%
60	*	*
55	14,000	4%
50	9,000	2%
45	46,000	12%
40	43,000	0
35	87,000	22%
30	58,000	15%
25	53,000	14%
20	3,000	1%
15	1,000	0%
10	*	*
5	*	*
Not Posted	6,000	1%
Unknown	65,000	17%
Total	**387,000**	**100%**

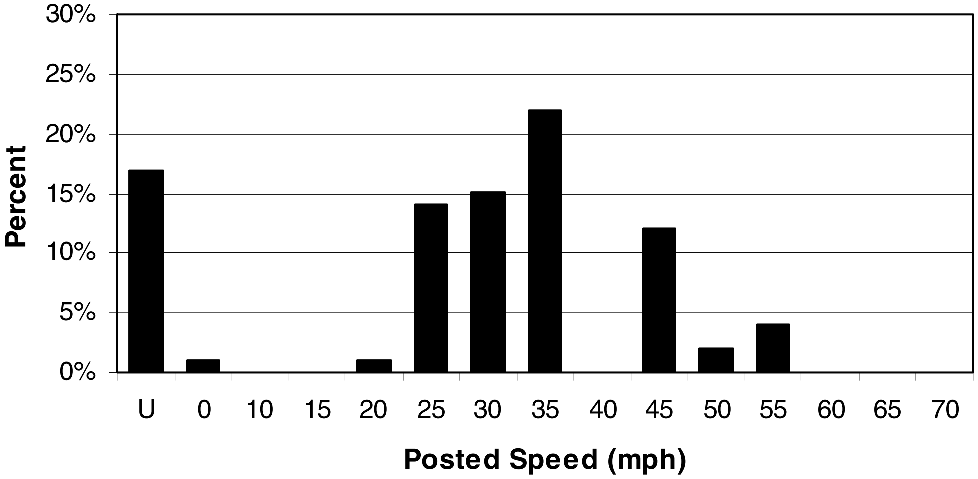

Figure 23. Percentage of Posted Speed Limits for All CP Crash Types and Severity Levels for Light Vehicles Cited with Violations, 2000 GES (a speed limit of 0 represents an unposted speed limit and U represents an unknown speed limit).

Table 50. Frequency and Percentage of *Traveling Speed* for All CP Crash Types and Severity Levels for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	1,000	0%
46-50	1,000	0%
41-45	6,000	2%
36-40	7,000	2%
31-35	12,000	3%
26-30	9,000	2%
21-25	12,000	3%
16-20	10,000	3%
11-15	20,000	5%
6-10	33,000	9%
1-5	26,000	7%
Stopped	1,000	0%
Unknown	247,000	64%
Total	**387,000**	**100%**

Table 51. Frequency and Percentage of *Speeding Status* for All CP Crash Types and Severity Levels for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	11,000	3%
No (not speeding)	361,000	93%
Unknown	16,000	4%
Total	**387,000**	**100%**

Specific Results for Speed Behavior Analysis

Table 52. Frequency and Percentage of *Posted Speed Limits* for LT, LT Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	1,000	3%
50	2,000	5%
45	6,000	14%
40	8,000	18%
35	13,000	29%
30	4,000	9%
25	4,000	9%
20	1,000	3%
15	*	*
10	*	*
Not Posted	*	*
Unknown	5,000	11%
Total	**44,000**	**100%**

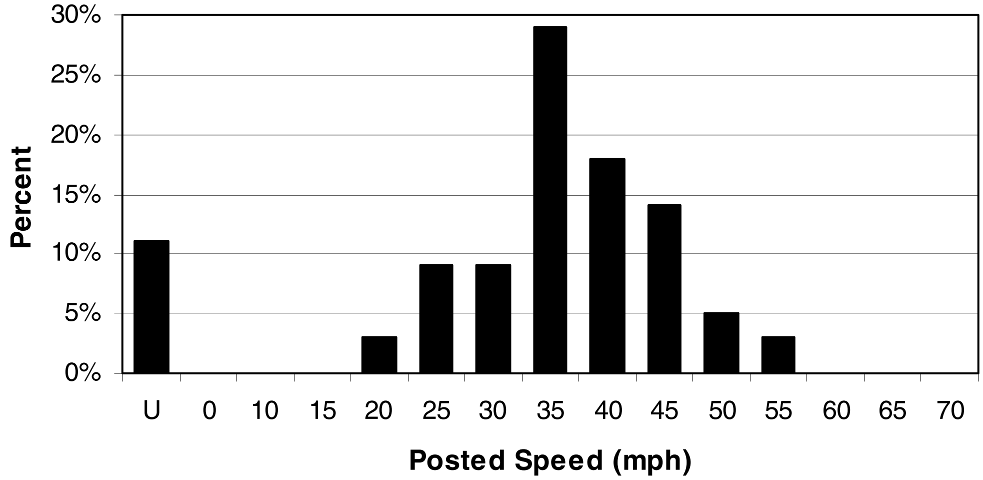

Figure 24. Percentage of Posted Speed Limits for LT, LT Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Table 53. Frequency and Percentage of *Traveling Speed* for LT, LT Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	*	*
36-40	*	*
31-35	1,000	1%
26-30	*	*
21-25	1,000	2%
16-20	2,000	4%
11-15	3,000	8%
6-10	6,000	14%
1-5	3,000	8%
Stopped	*	*
Unknown	27,000	63%
Total	**43,000**	**100%**

Table 54. Frequency and Percentage of *Speeding Status* for LT, LT Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	*	*
No (not speeding)	41,000	95%
Unknown	2,000	5%
Total	**43,000**	**100%**

Table 55. Frequency and Percentage of *Posted Speed Limits* for LT, LT Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	1,000	2%
50	1,000	3%
45	9,000	20%
40	9,000	20%
35	14,000	31%
30	4,000	9%
25	2,000	4%
20	*	*
15	*	*
10	*	*
Not Posted	*	*
Unknown	4,000	10%
Total	**44,000**	**100%**

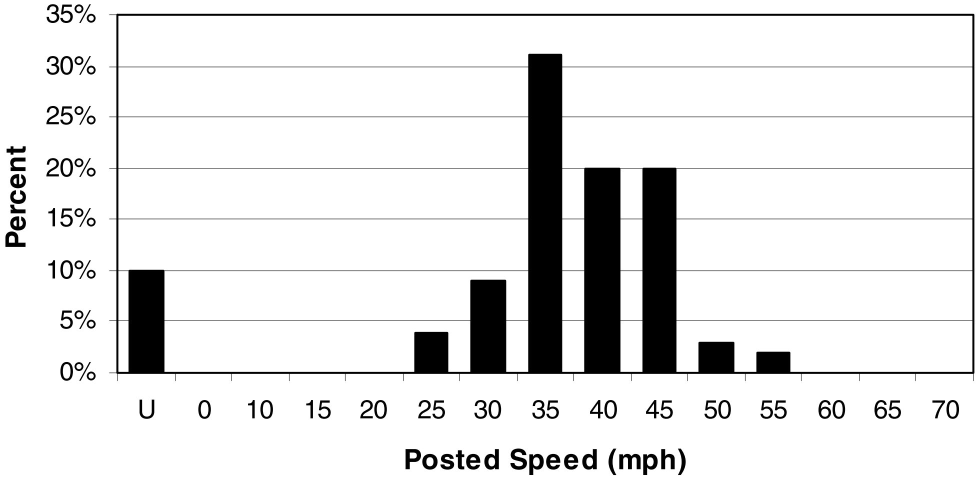

Figure 25. Percentage of Posted Speed Limits for LT, LT Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Table 56. Frequency and Percentage of *Traveling Speed* for LT, LT Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	*	*
36-40	*	*
31-35	1,000	1%
26-30	1,000	2%
21-25	2,000	5%
16-20	2,000	5%
11-15	4,000	9%
6-10	7,000	16%
1-5	3,000	7%
Stopped	*	*
Unknown	24,000	54%
Total	**44,000**	**100%**

Table 57. Frequency and Percentage of *Speeding Status* for LT, LT Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	*	*
No (not speeding)	42,000	95%
Unknown	2,000	4%
Total	**44,000**	**100%**

Table 58. Frequency and Percentage of *Posted Speed Limits* for LT, Straight Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	1,000	3%
50	1,000	4%
45	2,000	13%
40	4,000	21%
35	5,000	27%
30	2,000	11%
25	1,000	5%
20	*	*
15	*	*
10	*	*
Not Posted	*	*
Unknown	3,000	16%
Total	**19,000**	**100%**

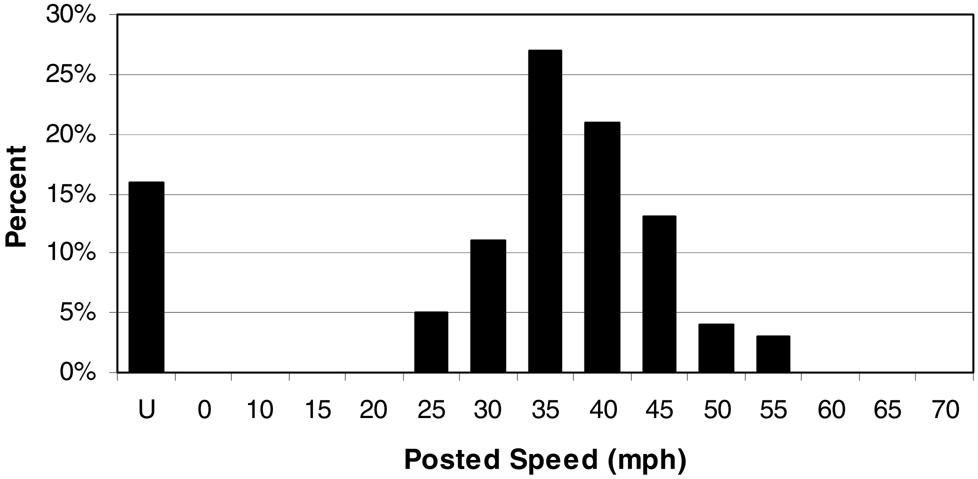

Figure 26. Percentage of Posted Speed Limits for LT, Straight Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Table 59. Frequency and Percentage of *Traveling Speed* for LT, Straight Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	1,000	6%
36-40	1,000	6%
31-35	2,000	12%
26-30	1,000	6%
21-25	1,000	6%
16-20	*	*
11-15	*	*
6-10	*	*
1-5	*	*
Stopped	*	*
Unknown	11,000	65%
Total	**17,000**	**100%**

Table 60. Frequency and Percentage of *Speeding Status* for LT, Straight Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	1,000	5%
No (not speeding)	17,000	90%
Unknown	1,000	5%
Total	**19,000**	**100%**

Table 61. Frequency and Percentage of *Posted Speed Limits* for LT, Straight Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	*	*
50	1,000	5%
45	3,000	20%
40	4,000	21%
35	6,000	33%
30	1,000	7%
25	*	*
20	*	*
15	*	*
10	*	*
Not Posted	*	*
Unknown	2,000	10%
Total	**17,000**	**100%**

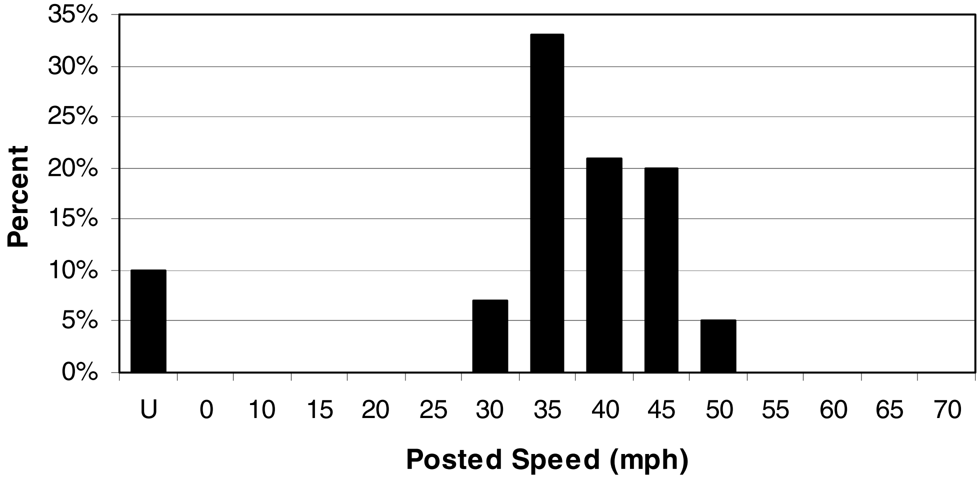

Figure 27. Percentage of Posted Speed Limits for LT, Straight Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Table 62. Frequency and Percentage of *Traveling Speed* for LT, Straight Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	1,000	8%
36-40	2,000	10%
31-35	2,000	11%
26-30	1,000	6%
21-25	1,000	3%
16-20	*	*
11-15	*	*
6-10	*	*
1-5	*	*
Stopped	*	*
Unknown	9,000	52%
Total	**16,000**	**100%**

Table 63. Frequency and Percentage of *Speeding Status* for LT, Straight Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	1,000	6%
No (not speeding)	15,000	94%
Unknown	*	*
Total	**16,000**	**100%**

Table 64. Frequency and Percentage of *Posted Speed Limits* for SCP, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	1,000	2%
50	1,000	2%
45	4,000	11%
40	4,000	12%
35	9,000	28%
30	5,000	15%
25	4,000	13%
20	*	*
15	*	*
10	*	*
Not Posted	*	*
Unknown	5,000	15%
Total	**33,000**	**100%**

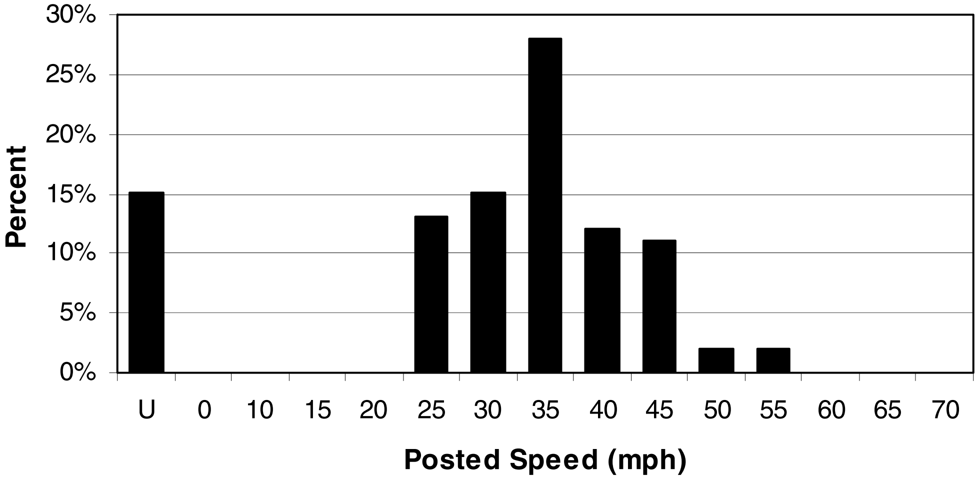

Figure 28. Percentage of Posted Speed Limits for SCP, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Table 65. Frequency and Percentage of *Traveling Speed* for SCP, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	1,000	3%
36-40	*	*
31-35	2,000	6%
26-30	1,000	3%
21-25	1,000	4%
16-20	1,000	2%
11-15	1,000	2%
6-10	1,000	2%
1-5	*	*
Stopped	*	*
Unknown	26,000	77%
Total	**34,000**	**100%**

Table 66. Frequency and Percentage of *Speeding Status* for SCP, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	1,000	4%
No (not speeding)	30,000	91%
Unknown	1,000	4%
Total	**32,000**	**100%**

Table 67. Frequency and Percentage of *Posted Speed Limits* for SCP, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	1,000	3%
50	1,000	2%
45	5,000	13%
40	4,000	11%
35	11,000	28%
30	6,000	15%
25	4,000	10%
20	*	*
15	*	*
10	*	*
Not Posted	*	*
Unknown	6,000	17%
Total	**38,000**	**100%**

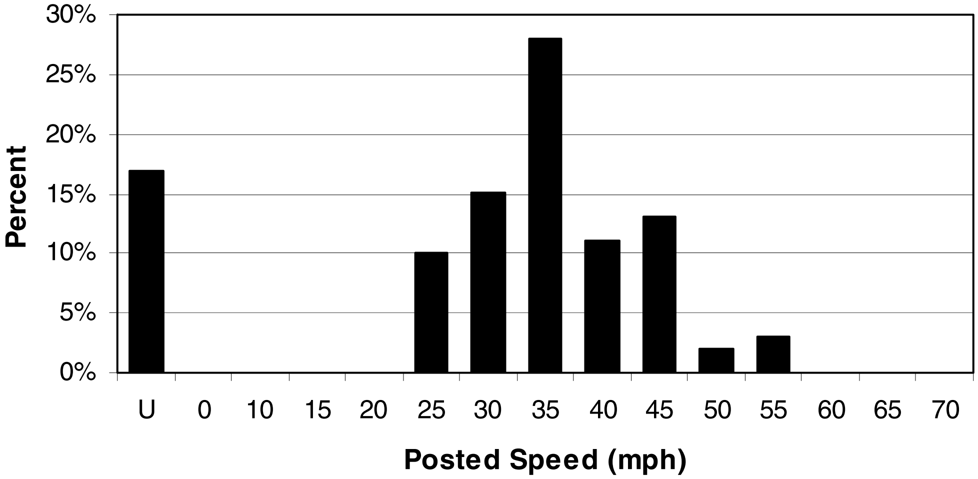

Figure 29. Percentage of Posted Speed Limits for SCP, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Table 68. Frequency and Percentage of *Traveling Speed* for SCP, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	1,000	4%
36-40	1,000	4%
31-35	3,000	9%
26-30	2,000	5%
21-25	2,000	5%
16-20	1,000	1%
11-15	*	*
6-10	*	*
1-5	*	*
Stopped	*	*
Unknown	25,000	68%
Total	**35,000**	**100%**

Table 69. Frequency and Percentage of *Speeding Status* for SCP, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	2,000	4%
No (not speeding)	34,000	90%
Unknown	2,000	5%
Total	**38,000**	**100%**

Table 70. Frequency and Percentage of *Posted Speed Limits* for RTIP, Right Turn Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	*	*
50	*	*
45	1,000	15%
40	1,000	18%
35	2,000	28%
30	1,000	18%
25	*	*
20	*	*
15	*	*
10	*	*
Not Posted	*	*
Unknown	1,000	17%
Total	**6,000**	**100%**

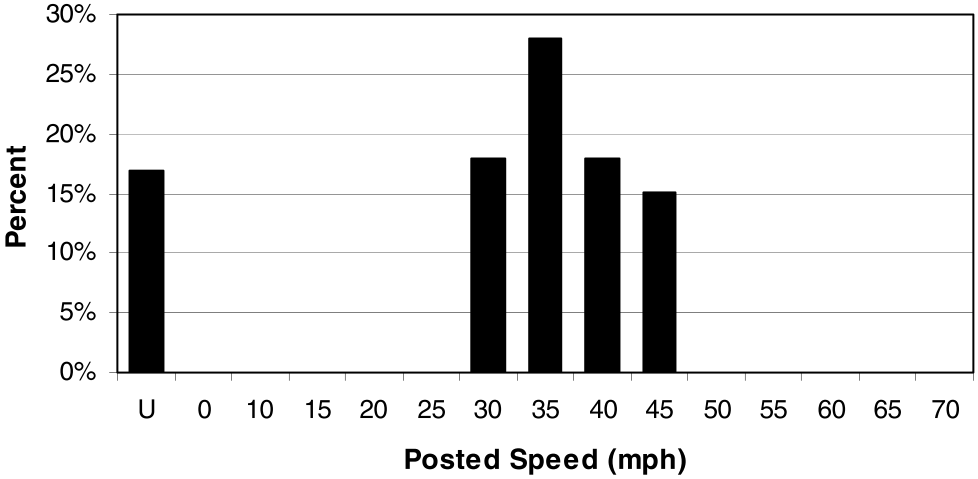

Figure 30. Percentage of Posted Speed Limits for RTIP, Right Turn Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Table 71. Frequency and Percentage of *Traveling Speed* for RTIP, Right Turn Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	*	*
36-40	*	*
31-35	*	*
26-30	*	*
21-25	*	*
16-20	*	*
11-15	*	*
6-10	1,000	17%
1-5	1,000	17%
Stopped	*	*
Unknown	4,000	66%
Total	**6,000**	**100%**

Table 72. Frequency and Percentage of *Speeding Status* for RTIP, Right Turn Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	*	*
No (not speeding)	5,000	100%
Unknown	*	*
Total	**5,000**	**100%**

For RTIP, right turn pre-crash maneuver, injury crashes at 3-color signal intersections, for light vehicles cited with violations, there were not enough significant data for meaningful tables or a graph (all values less than 500). The same was true for RTIP, straight pre-crash maneuver, PDO crashes at 3-color signal intersections, for light vehicles cited with violations. The same was true for RTIP, straight pre-crash maneuver, injury crashes at 3-color signal intersections, for light vehicles cited with violations.

Table 73. Frequency and Percentage of *Posted Speed Limits* for Stop-Sign PDO Crashes, where One Vehicle Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	4,000	5%
50	1,000	1%
45	7,000	8%
40	5,000	6%
35	11,000	13%
30	14,000	16%
25	21,000	24%
20	1,000	2%
15	*	*
10	*	*
5	*	*
Not Posted	3,000	4%
Unknown	19,000	22%
Total	**86,000**	**100%**

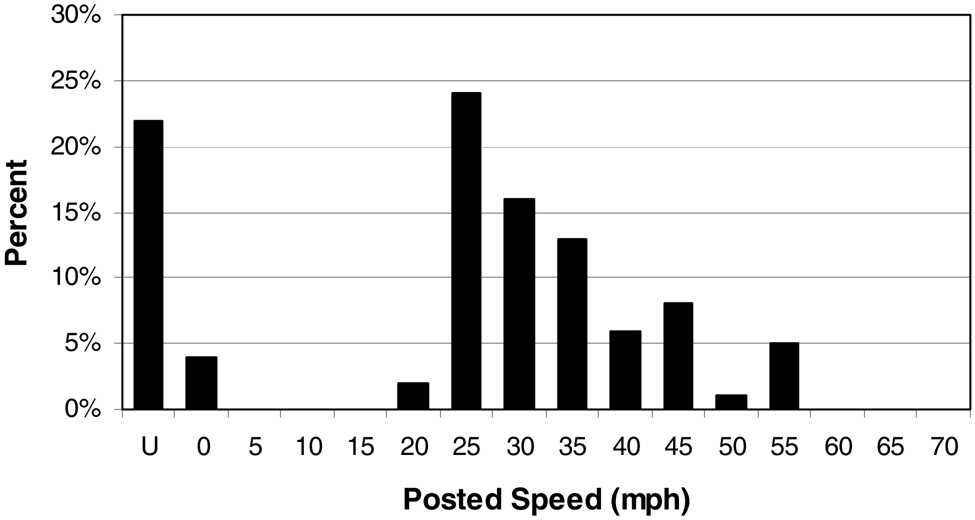

Figure 31. Percentage of Posted Speed Limits for Stop-Sign PDO Crashes, where One Vehicle Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Table 74. Frequency and Percentage of *Traveling Speed* for Stop-Sign PDO Crashes, where One Vehicle Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	1,000	1%
36-40	*	*
31-35	*	*
26-30	1,000	1%
21-25	1,000	2%
16-20	1,000	2%
11-15	5,000	6%
6-10	9,000	10%
1-5	8,000	9%
Stopped	*	*
Unknown	60,000	69%
Total	**86,000**	**100%**

Table 75. Frequency and Percentage of *Speeding Status* for Stop-Sign PDO Crashes, where One Vehicle Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	1,000	1%
No (not speeding)	84,000	97%
Unknown	2,000	2%
Total	**87,000**	**100%**

Table 76. Frequency and Percentage of *Posted Speed Limits* for Stop-Sign Injury Crashes, where One Vehicle Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	5,000	7%
50	1,000	2%
45	7,000	10%
40	3,000	4%
35	12,000	16%
30	15,000	21%
25	13,000	18%
20	1,000	1%
15	1,000	1%
10	*	*
5	*	*
Not Posted	1,000	2%
Unknown	12,000	17%
Total	**71,000**	**100%**

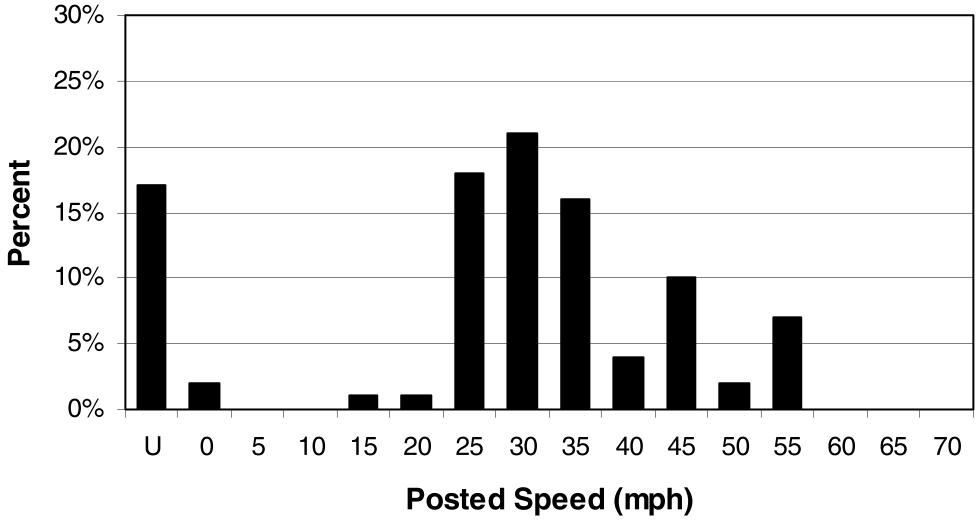

Figure 32. Percentage of Posted Speed Limits for Stop-Sign Injury Crashes, where One Vehicle Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Table 77. Frequency and Percentage of *Traveling Speed* for Stop-Sign Injury Crashes, where One Vehicle Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	*	*
36-40	1,000	2%
31-35	1,000	2%
26-30	1,000	2%
21-25	3,000	4%
16-20	3,000	4%
11-15	5,000	7%
6-10	8,000	12%
1-5	9,000	12%
Stopped	*	*
Unknown	40,000	55%
Total	**71,000**	**100%**

Table 78. Frequency and Percentage of *Speeding Status* for Stop-Sign Injury Crashes, where One Vehicle Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	3,000	4%
No (not speeding)	67,000	93%
Unknown	3,000	4%
Total	**73,000**	**100%**

Table 79. Frequency and Percentage of *Posted Speed Limits* for Stop-Sign PDO Crashes, where Both Vehicles Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	*	*
50	*	*
45	1,000	4%
40	1,000	6%
35	3,000	18%
30	3,000	17%
25	3,000	17%
20	*	*
15	*	*
10	*	*
Not Posted	1,000	4%
Unknown	5,000	30%
Total	**17,000**	**100%**

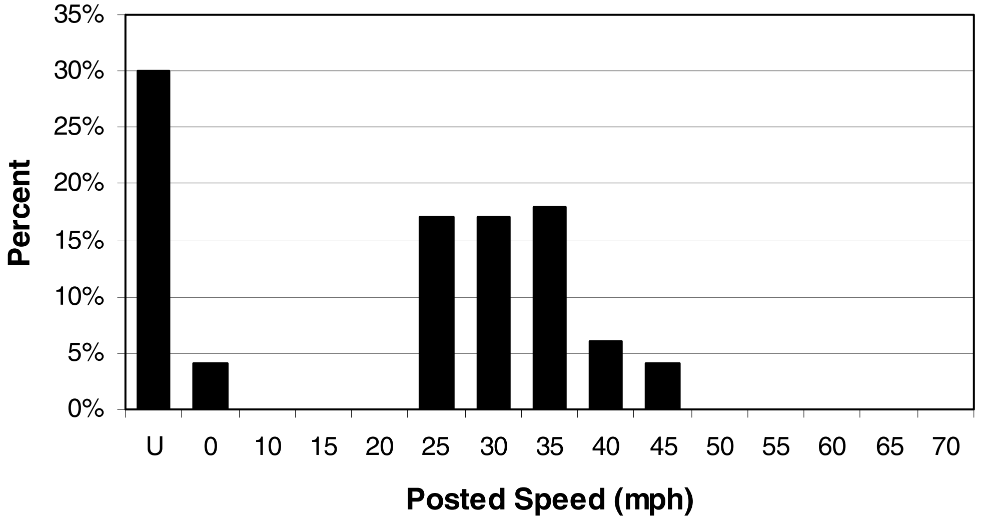

Figure 33. Percentage of Posted Speed Limits for Stop-Sign PDO Crashes, where Both Vehicles Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Table 80. Frequency and Percentage of *Traveling Speed* for Stop-Sign PDO Crashes, where Both Vehicles Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	*	*
36-40	*	*
31-35	*	*
26-30	*	*
21-25	*	*
16-20	*	*
11-15	*	*
6-10	1,000	7%
1-5	1,000	5%
Stopped	*	*
Unknown	13,000	81%
Total	**15,000**	**100%**

Table 81. Frequency and Percentage of *Speeding Status* for Stop-Sign PDO Crashes, where Both Vehicles Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	*	*
No (not speeding)	14,000	90%
Unknown	2,000	10%
Total	**16,000**	**100%**

Table 82. Frequency and Percentage of *Posted Speed Limits* for Stop-Sign Injury Crashes, where Both Vehicles Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Posted Speed Limit (mph)	Frequency	Percent
70	*	*
65	*	*
60	*	*
55	*	*
50	*	*
45	1,000	13%
40	1,000	13%
35	1,000	13%
30	2,000	25%
25	1,000	13%
20	*	*
15	*	*
10	*	*
Not Posted	*	*
Unknown	2,000	25%
Total	**8,000**	**100%**

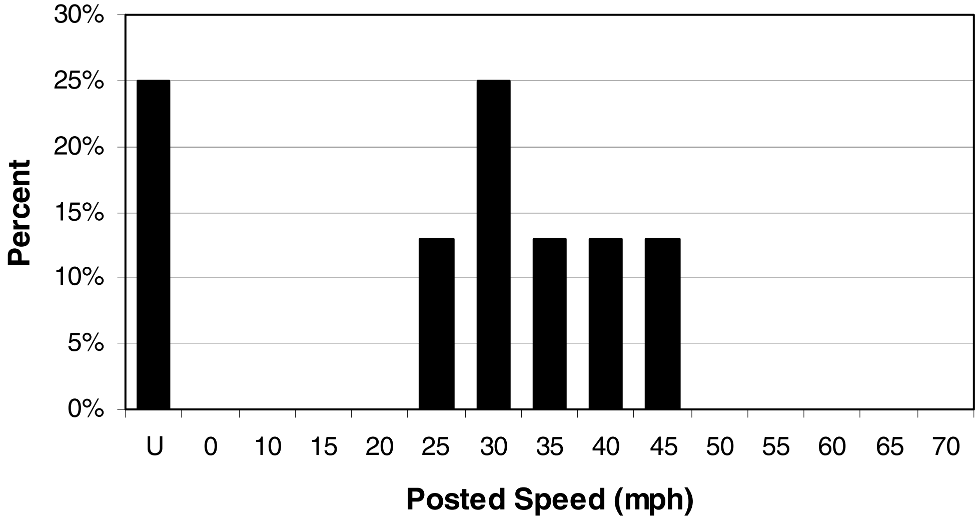

Figure 34. Percentage of Posted Speed Limits for Stop-Sign Injury Crashes, where Both Vehicles Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Table 83. Frequency and Percentage of *Traveling Speed* for Stop-Sign Injury Crashes, where Both Vehicles Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Traveling Speed (mph)	Frequency	Percent
66 and greater	*	*
61-65	*	*
56-60	*	*
51-55	*	*
46-50	*	*
41-45	*	*
36-40	*	*
31-35	*	*
26-30	*	*
21-25	1,000	6%
16-20	*	*
11-15	*	*
6-10	*	*
1-5	*	*
Stopped	*	*
Unknown	7,000	71%
Total	**8,000**	**100%**

Table 84. Frequency and Percentage of *Speeding Status* for Stop-Sign Injury Crashes, where Both Vehicles Had a Stop Sign, for Light Vehicles Cited with Violations, 2000 GES.

Speeding Status	Frequency	Percent
Yes (speeding)	*	*
No (not speeding)	8,000	89%
Unknown	1,000	11%
Total	**9,000**	**100%**

Findings from Subtask 1.6 include the following:

- Posted speed is well known in almost all cases (83% known).
- Traveling speed is not as well known (64% unknown).
- Most CP crashes with violations are not speed related (93% not speed related). This conclusion is a confirmation of the Subtask 1.5 findings regarding speed.
- Overall, speed does not seem to be an important factor in CP crashes with violations.

SUBTASK 1.7 *INFRASTRUCTURE CHARACTERISTICS* IN CROSSING-PATH CRASHES AT SIGNALIZED INTERSECTIONS

The final set of database analyses for Task 1 used GES to determine the number of travel lanes and the trafficway flow for the first harmful event in a CP crash with violation at a signalized intersection. This data could then be used along with other GES intersection infrastructure data to characterize the size and nature of the crash intersection infrastructure. This analysis will be completed for each signalized cell of the original Table 17, reproduced below as Table 85. This analysis is presented as Tables 86 through 92. In keeping with the format used in Subtasks 1.5 and 1.6, and for the sake of brevity, only the tables for the year 2000 are presented.

Table 85. Reprise of Table 17: Frequency of Pre-Crash Maneuvers Involving *Light* Vehicles Cited with *Violations* for Signalized Intersections with Known Injury Severity (2000 GES; there were 387,000 cited crashes).

Crash Severity	3-Color Signal				
	All Left Turn		SCP	RTIP	
	Left Turn	Straight		Right Turn	Straight
PDO	44,000	19,000	33,000	6,000	1,000
Injury	44,000	17,000	38,000	1,000	*
Total	**88,000**	**36,000**	**71,000**	**7,000**	**1,000**

Table 86. Percentage of *Infrastructure Types* for LT with LT Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations (out of 44,000 crashes of this type), 2000 GES.

Number of lanes	Undivided	Divided	One-Way	Unknown	Total
1	*	*	*	*	*****
2	12%	7%	*	*	**20%**
3	5%	15%	*	*	**20%**
4	15%	6%	*	*	**22%**
5	16%	*	*	*	**17%**
6	2%	*	*	*	**2%**
7	2%	*	*	*	**2%**
Unknown	2%	4%	*	11%	**17%**
Total	**54%**	**33%**	*****	**13%**	**100%**

Note: For divided highways, number of lanes represents number of lanes in direction where first harmful event occurred. For undivided highways, number of lanes represents number of lanes in both directions.

Table 87. Percentage of *Infrastructure Types* for LT with LT with LT Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations (out of 44,000 crashes of this type), 2000 GES.

Number of lanes	Undivided	Divided	One-Way	Unknown	Total
1	*	*	*	*	**2%**
2	8%	10%	*	*	**19%**
3	7%	15%	*	*	**22%**
4	11%	10%	*	*	**21%**
5	16%	2%	*	*	**18%**
6	3%	2%	*	*	**5%**
7	2%	*	*	*	**2%**
Unknown	3%	4%	*	6%	**12%**
Total	**50%**	**43%**	*	**6%**	**100%**

Table 88. Percentage of *Infrastructure Types* for LT with Straight Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations (out of 19,000 crashes of this type), 2000 GES.

Number of lanes	Undivided	Divided	One-Way	Unknown	Total
1	*	*	*	*	*
2	5%	10%	*	*	**16%**
3	4%	14%	*	*	**19%**
4	17%	5%	*	*	**24%**
5	15%	*	*	*	**17%**
6	*	3%	*	*	**3%**
7	5%	*	*	*	**5%**
Unknown	*	3%	*	9%	**14%**
Total	**49%**	**38%**	*	**12%**	**100%**

Table 89. Percentage of *Infrastructure Types* for LT with Straight Pre-Crash Maneuver, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations (out of 17,000 crashes of this type), 2000 GES.

Number of lanes	Undivided	Divided	One-Way	Unknown	Total
1	*	*	*	*	*
2	5%	17%	*	*	**22%**
3	4%	17%	*	*	**21%**
4	9%	9%	*	*	**18%**
5	13%	4%	*	*	**17%**
6	3%	*	*	*	**5%**
7	4%	*	*	*	**4%**
Unknown	4%	*	*	6%	**12%**
Total	**41%**	**52%**	*	**6%**	**100%**

Table 90. Percentage of *Infrastructure Types* for SCP, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations (out of 33,000 crashes of this type), 2000 GES.

Number of lanes	Undivided	Divided	One-Way	Unknown	Total
1	*	*	*	*	*
2	18%	9%	2%	*	**29%**
3	8%	12%	4%	2%	**25%**
4	12%	3%	*	2%	**17%**
5	8%	*	*	*	**9%**
6	2%	*	*	*	**3%**
7	*	*	*	*	*
Unknown	3%	3%	*	9%	**15%**
Total	**51%**	**28%**	**8%**	**13%**	**100%**

Table 91. Percentage of *Infrastructure Types* for SCP, Injury Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations (out of 38,000crashes of this type), 2000 GES.

Number of lanes	Undivided	Divided	One-Way	Unknown	Total
1	*	*	*	*	*
2	14%	10%	3%	*	**28%**
3	5%	9%	3%	*	**18%**
4	10%	5%	3%	*	**17%**
5	11%	*	*	*	**14%**
6	2%	*	*	*	**3%**
7	2%	*	*	*	**2%**
Unknown	5%	3%	*	9%	**18%**
Total	**49%**	**29%**	**10%**	**12%**	**100%**

Table 92. Percentage of *Infrastructure Types* for RT with RT Pre-Crash Maneuver, PDO Crashes at 3-Color Signal Intersections, for Light Vehicles Cited with Violations (out of 6,000 crashes of this type), 2000 GES.

Number of lanes	Undivided	Divided	One-Way	Unknown	Total
1	*	*	*	*	*
2	19%	10%	*	*	**33%**
3	10%	10%	*	*	**23%**
4	*	10%	*	*	**16%**
5	10%	*	*	*	**11%**
6	*	*	*	*	*
7	*	*	*	*	*
Unknown	*	*	*	14%	**14%**
Total	**47%**	**31%**	*	**17%**	**100%**

For RT with RT pre-crash maneuver, injury crashes at 3-color signal intersections, for light vehicles cited with violations, there were not enough significant data to fill a table (all values were less than 500). The same was true for RT with straight pre-crash maneuver, PDO crashes at 3-color signal intersections, for light vehicles cited with violations, as well as for RT with straight pre-crash maneuver, injury crashes at 3-color signal intersections, for light vehicles cited with violations.

Findings from Subtask 1.7 include:

- 45-50% of crashes occurred on undivided roadways.
- 35-40% of these crashes occurred on three and four lane roadways.

SUBTASK 1.8 ECONOMIC ANALYSIS AND CONSIDERATION OF ADDITIONAL DATA ANALYSES

Economic Analysis

NHTSA recently released its current estimates of the economic costs of motor-vehicle accidents, using 2000 data (Blincoe, Seay, Zaloshnja, Miller, Romano, Luchter, and Spicer, 2002). The timing of the report was ideal because it enabled the 2000 crash data to be used to estimate the costs of the CP crashes identified in this report (in year 2000 dollars). The Blincoe et al. (2002) report provides costs on a per-person basis and per-vehicle basis, depending on the category of cost. Since the numbers generated throughout the current analyses were on a per-crash basis, a preliminary per- person analysis was performed in GES in the same manner as for Subtask 1.1. The analysis was done at the KABCO level in order to account for various levels of injury. The resulting table is presented as Table 93.

Table 93. Person-level results of SAS analysis, 2000 GES.

Injury Severity	Frequency	Percent	Cumulative Frequency	Cumulative Percent
PDO	3,172,000	75%	3,172,000	75%
Possible Injury	592,000	14%	3,765,000	89%
Non-incapacitating Injury	273,000	7%	4,038,000	96%
Incapacitating Injury	110,000	3%	4,148,000	98%
Fatal	5,000	0.1%	4,153,000	98%
Unknown Injury	6,000	0.2%	4,159,000	98%
Unknown if Injured	71,000	2%	4,230,000	100%

The numbers generated for Table 93 were then run through a MAIS-KABCO translator to convert the KABCO numbers to the MAIS numbers necessary for the economic analysis. The results of the MAIS translator are shown in Table 94. Note that, for now, GES values are used for the fatalities. Future refinement of this model could include running a person-level analysis in FARS to generate more accurate fatality figures.

Table 94. MAIS totals after using MAIS-KABCO translator to convert the GES values from Table 93.

KABCO	A	B	C	K	O	ISU	Unknown	Total
GES Totals	**110,000**	**273,000**	**592,000**	**5,000**	**3,172,000**	**6,000**	**71,000**	**4,230,000**
MAIS 0	1,664	13,489	117,934	58	2,929,481	478	57,979	3,121,082
MAIS 1	53,974	216,406	424,685	75	235,426	4,486	11,365	946,417
MAIS 2	30,640	34,108	40,028	31	6,599	998	1,150	113,553
MAIS 3	18,341	8,218	8,935	6	920	276	555	37,252
MAIS 4	3,190	729	379	10	32	109	14	4,463
MAIS 5	1,933	189	107	0	0	8	32	2,269
Fatal	595	71	59	4,350	0	24	0	5,099
Total	**110,337**	**273,210**	**592,126**	**4,530**	**3,172,457**	**6,381**	**71,095**	**4,230,135**

The numbers from Table 94 were then converted to dollar values (in year 2000 dollars) using the unit values provided in Table 2 of Blincoe et al. (2002, page 9). The unit values include costs associated with medical expenses, emergency services, market productivity, household productivity, insurance administration, workplace cost, legal costs, travel delay, and property damage; however, they do not include pain and suffering or other intangible costs.

The results of this analysis are shown in Table 95 (in millions of dollars). Note that the PDO costs were calculated using a separate analysis of the 2000 GES data to estimate the number of PDO vehicles involved in the CP crashes identified in Subtask 1.1. The bottom line, \$47,024,745,295, represents the costs associated with the 1,667,000 CP crashes identified for the year 2000 in Subtask 1. Knowing both the number of crashes and the total cost allows the per-crash cost to be calculated. Thus, the estimated cost per CP crash from Subtask 1.1 is \$28,209. A series of pie charts are presented after Table 95 showing, first, the distribution of cost categories by MAIS levels and, second, the distribution of MAIS levels by cost category.

Table 95. Economic costs for crossing-path crashes involving light vehicles, in millions of dollars (year 2000 dollars), based on 2000 GES person and vehicle numbers and using the Blincoe et al. (2002) unit costs for 2000 data.

INJURY COMPONENTS	PDO	MAIS 0	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	Fatal	Total
Medical	$-	$3	$2,252	$1,774	$1,732	$586	$754	$113	**$7,215**
Emergency Services	$94	$69	$92	$24	$14	$4	$2	$4	**$302**
Market Productivity	$-	$-	$1,655	$2,841	$2,662	$475	$995	$3,036	**$11,664**
HH Productivity	$142	$103	$541	$831	$785	$125	$339	$977	**$3,843**
Insurance Admin.	$350	$250	$701	$785	$704	$144	$155	$189	**$3,278**
Workplace Cost	$154	$106	$238	$222	$159	$21	$19	$44	**$963**
Legal Costs	$-	$-	$142	$566	$589	$150	$181	$232	**$1,860**
INJURY COMPONENTS	**PDO**	**MAIS 0**	**MAIS 1**	**MAIS 2**	**MAIS 3**	**MAIS 4**	**MAIS 5**	**Fatal**	**Total**
Subtotal	**$740**	**$531**	**$5,623**	**$7,042**	**$6,644**	**$1,505**	**$2,445**	**$4,595**	**$29,125**
NON-INJURY COMPONENTS	**PDO**	**MAIS 0**	**MAIS 1**	**MAIS 2**	**MAIS 3**	**MAIS 4**	**MAIS 5**	**Fatal**	**Total**
Travel Delay	$2,426	$2,413	$735	$96	$35	$4	$21	$47	**$5,777**
Prop Damage	$4,484	$3,180	$3,638	$449	$253	$44	$21	$52	**$12,122**
Subtotal	**$6,910**	**$5,593**	**$4,373**	**$545**	**$288**	**$48**	**$42**	**$99**	**$17,899**
Total	**$7,650**	**$6,124**	**$9,996**	**$7,587**	**$6,933**	**$1,554**	**$2,487**	**$4,694**	**$47,025**

Note: Injury costs are based on the numbers of persons injured, while PDO costs are based on the numbers of damaged vehicles where there was no injury.

Modified Abbreviated Injury Scale (MAIS)

MAIS 0	uninjured
MAIS 1	minor injury
MAIS 2	moderate injury
MAIS 3	serious injury
MAIS 4	major/multiple
MAIS 5	unsurvivable

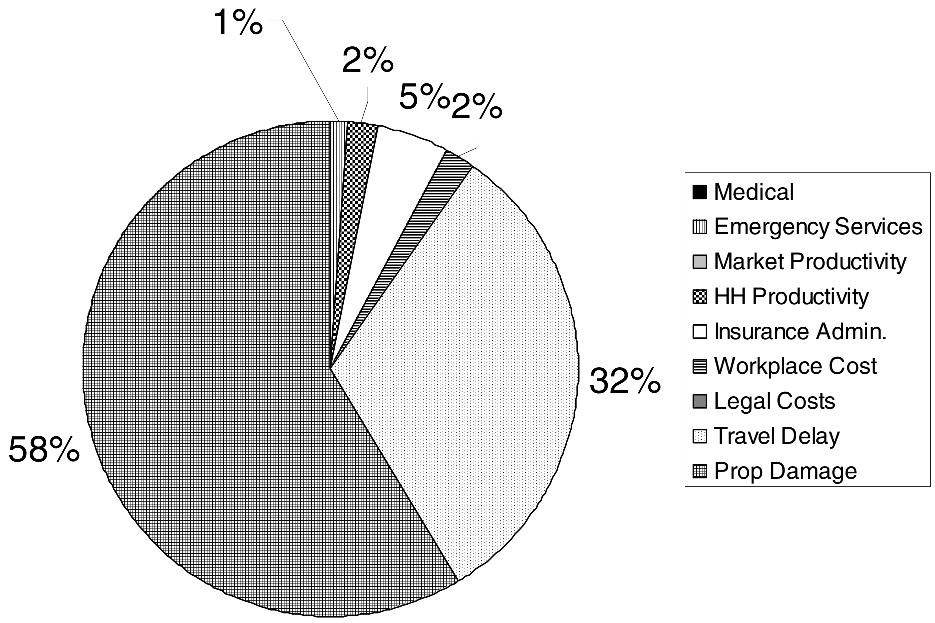

Figure 35. Distribution of costs for PDO accidents on a per-vehicle basis, 2000 GES.

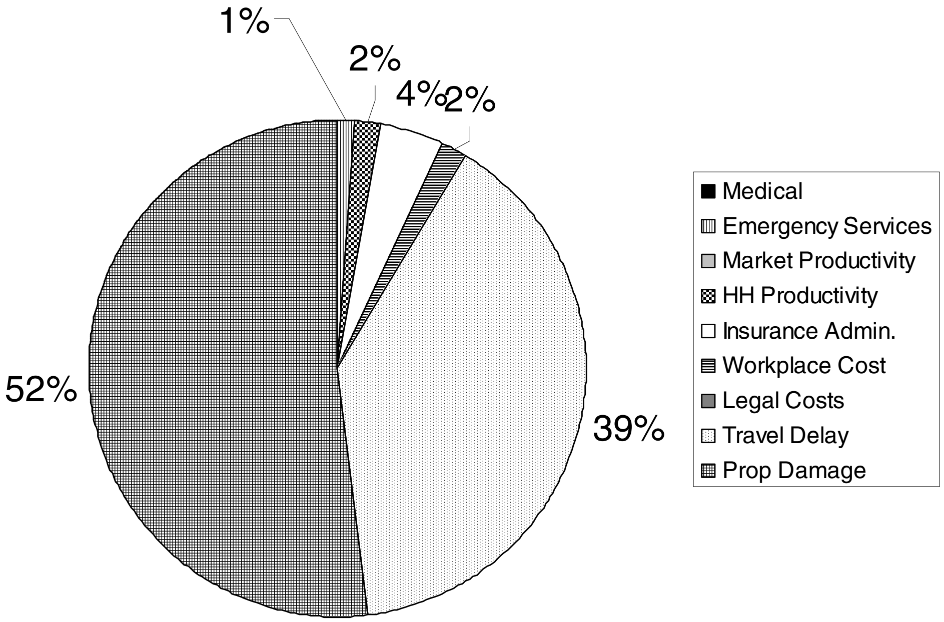

Figure 36. Distribution of costs for MAIS 0 injuries on a per-person basis, 2000 GES.

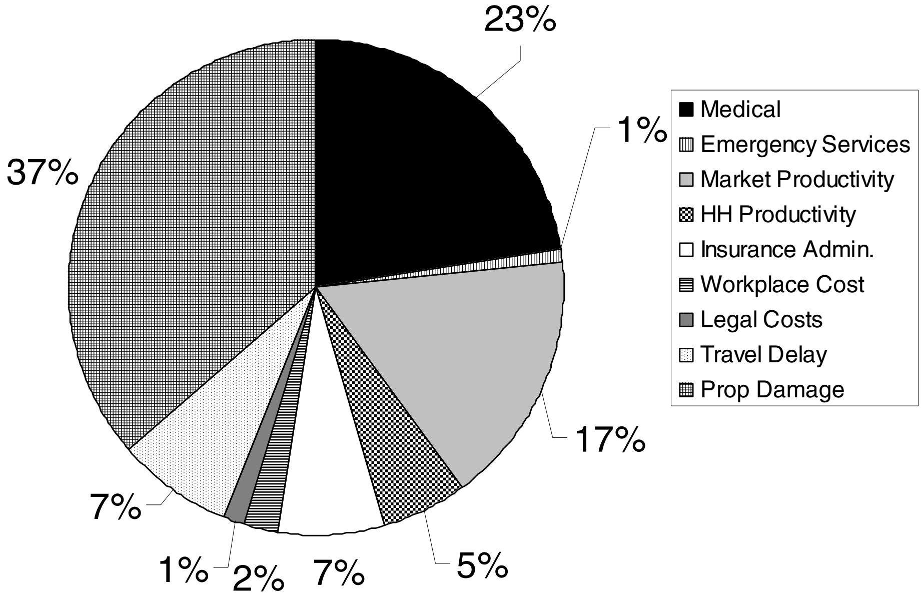

Figure 37. Distribution of costs for MAIS 1 injuries on a per-person basis, 2000 GES.

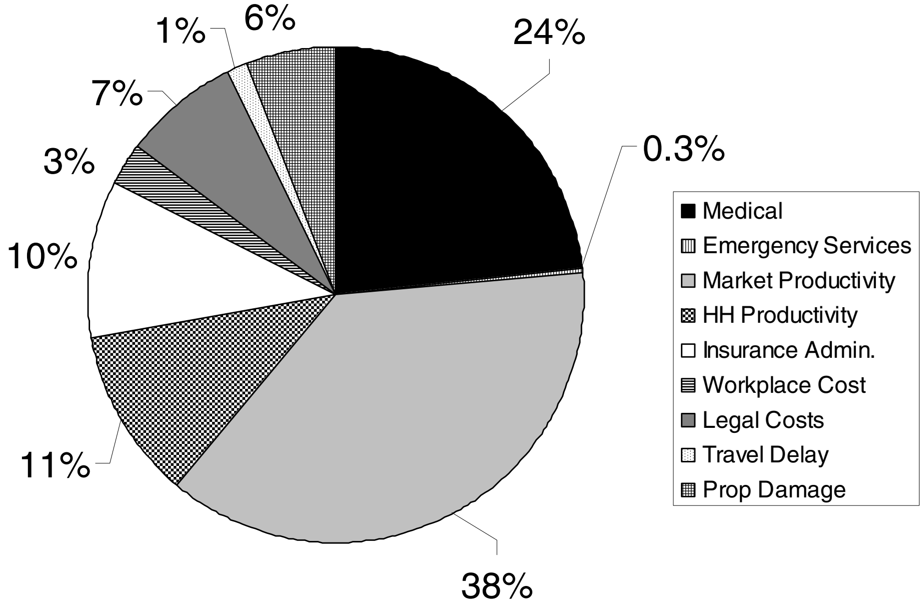

Figure 38. Distribution of costs for MAIS 2 injuries on a per-person basis, 2000 GES.

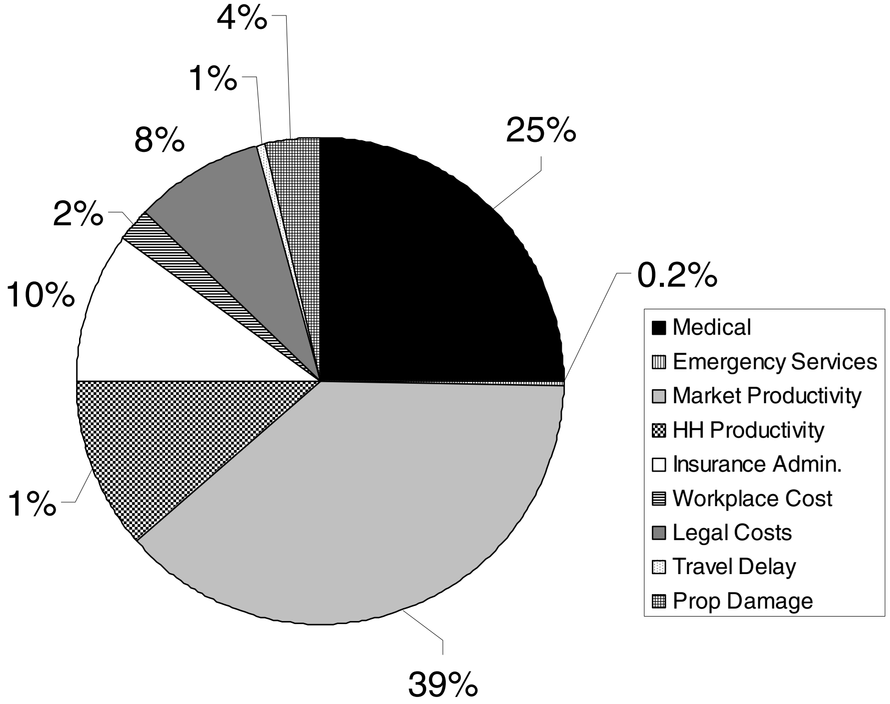

Figure 39. Distribution of costs for MAIS 3 injuries on a per-person basis, 2000 GES.

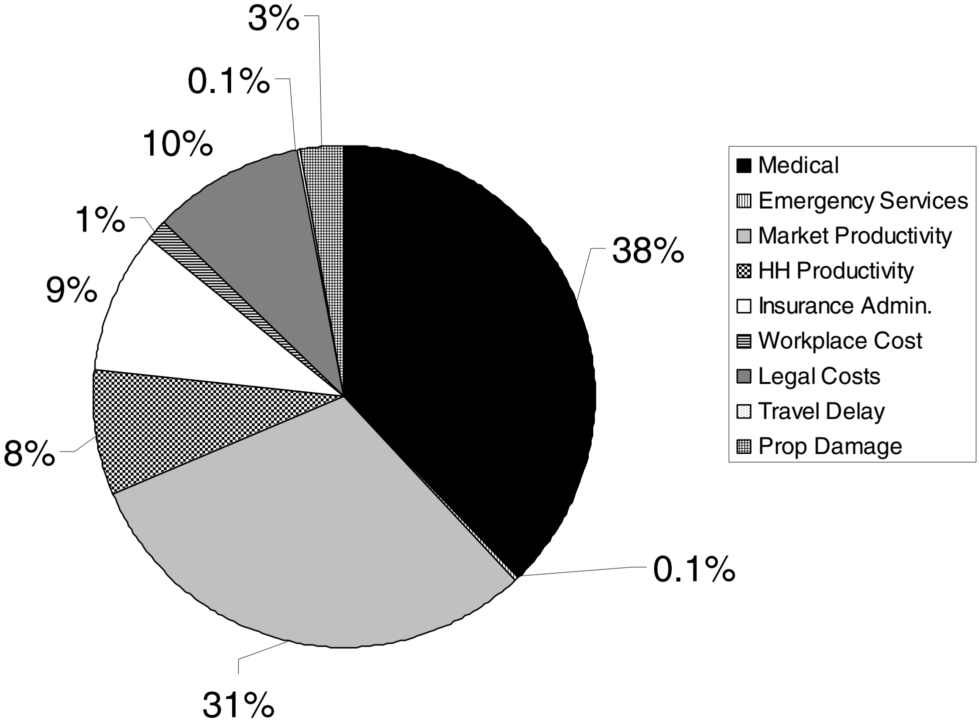

Figure 40. Distribution of costs for MAIS 4 injuries on a per-person basis, 2000 GES.

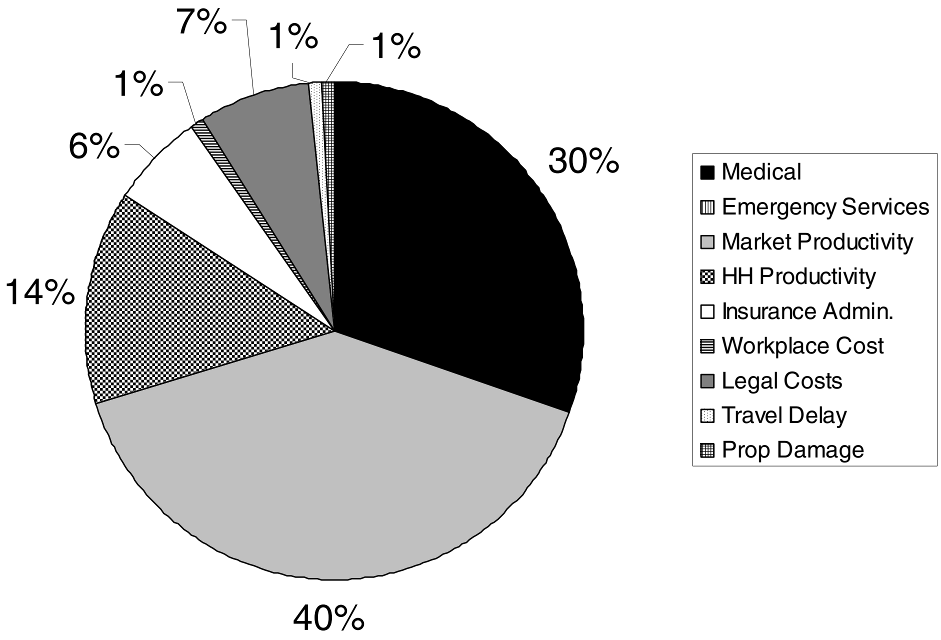

Figure 41. Distribution of costs for MAIS 5 injuries on a per-person basis, 2000 GES.

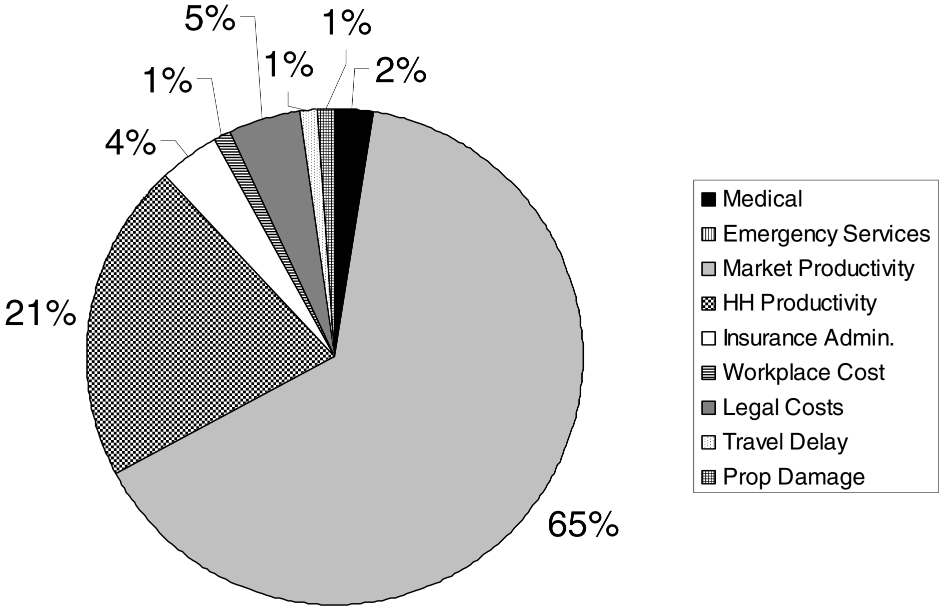

Figure 42. Distribution of costs for fatalities on a per-person basis, 2000 GES.

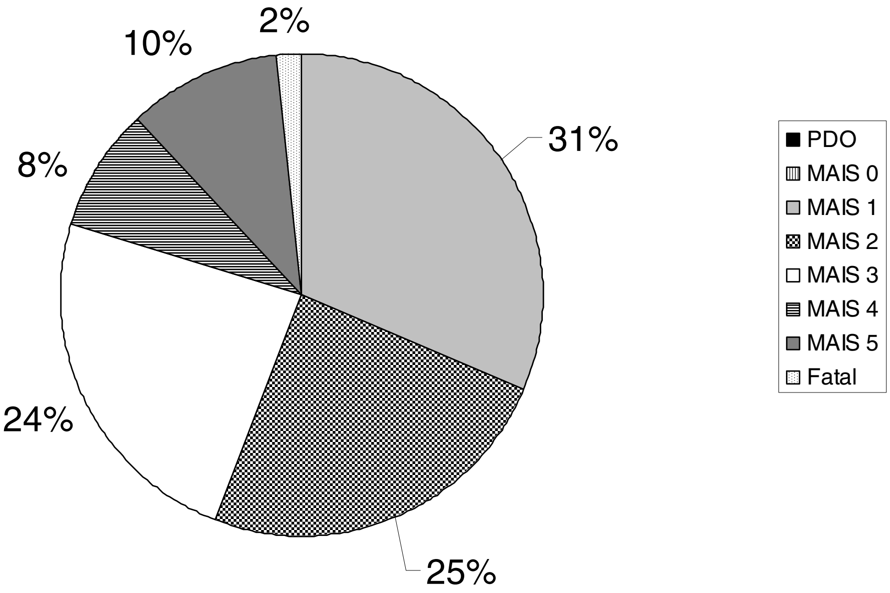

Figure 43. Distribution of medical costs, 2000 GES.

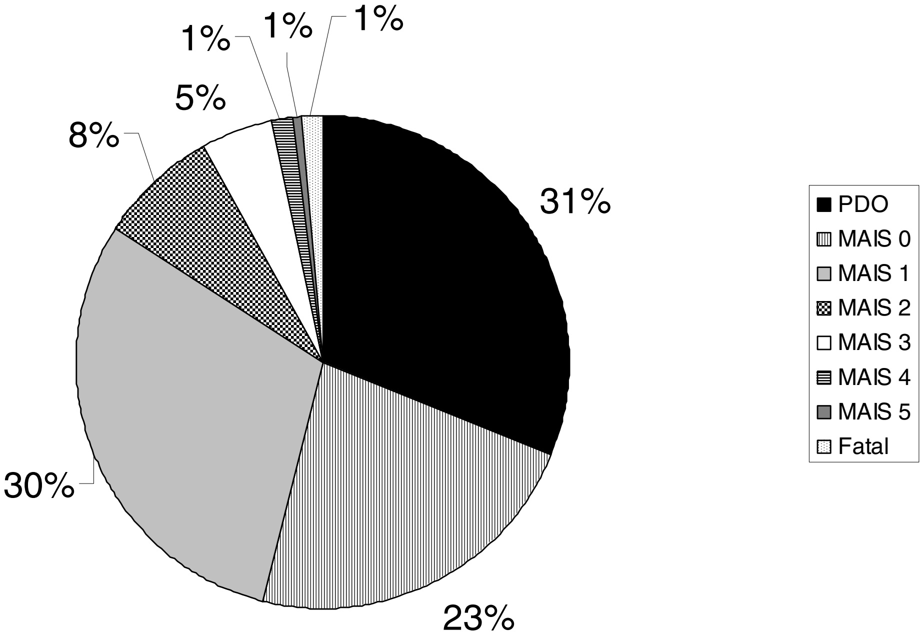

Figure 44. Distribution of emergency services costs, 2000 GES.

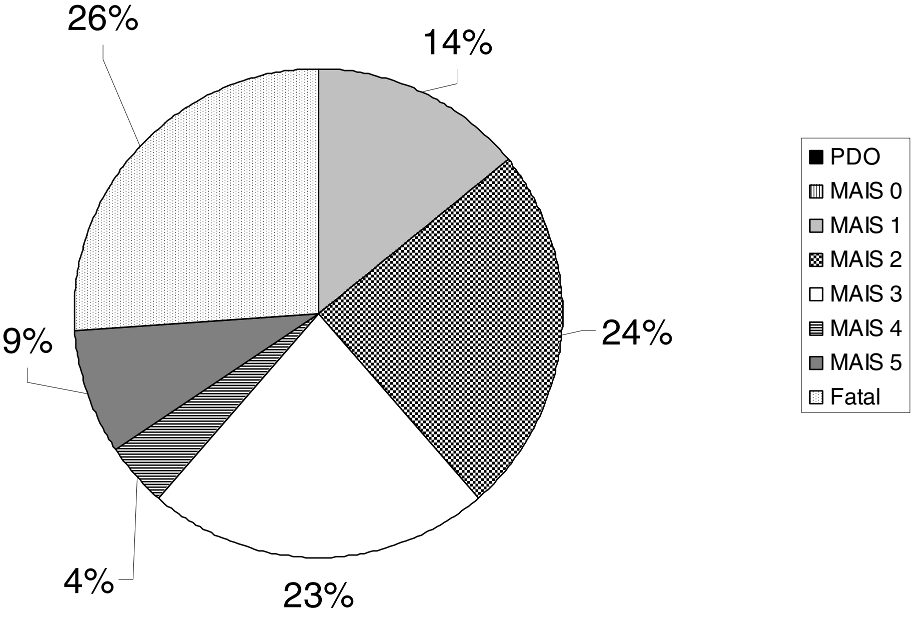

Figure 45. Distribution of market productivity costs, 2000 GES.

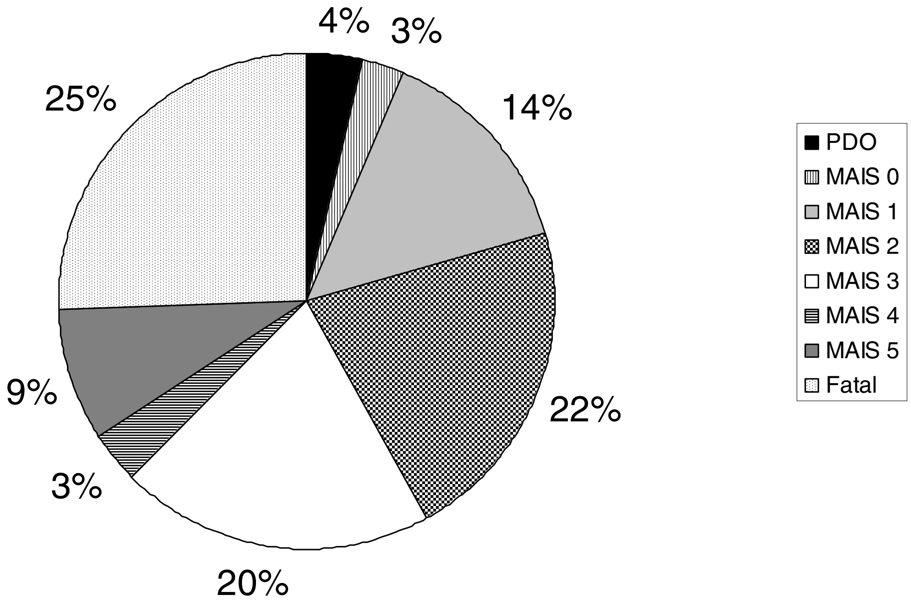

Figure 46. Distribution of household productivity costs, 2000 GES.

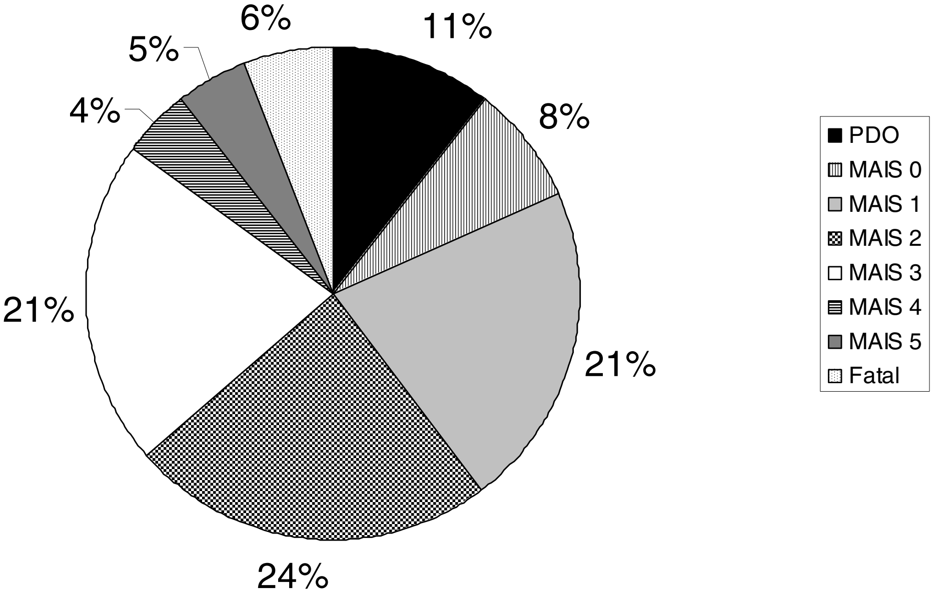

Figure 47. Distribution of insurance administration costs, 2000 GES.

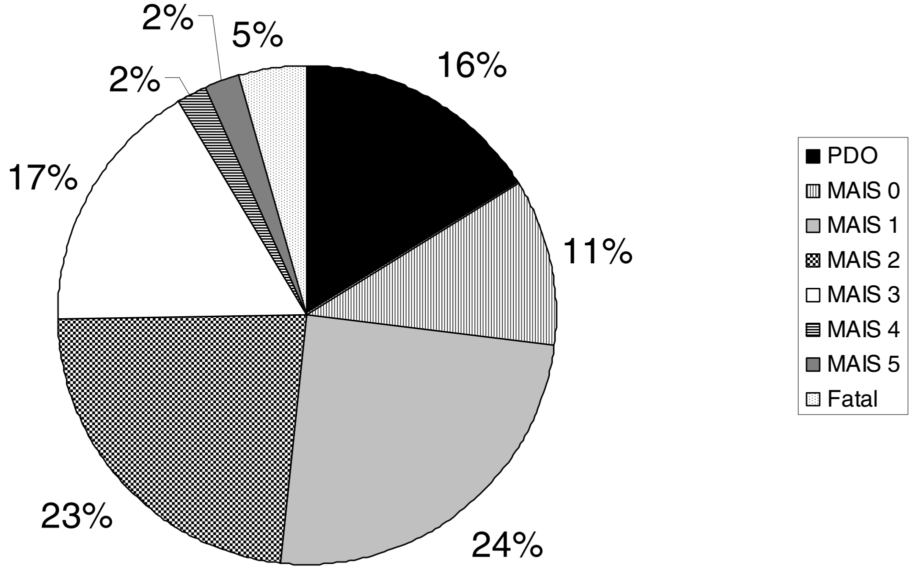

Figure 48. Distribution of workplace costs, 2000 GES.

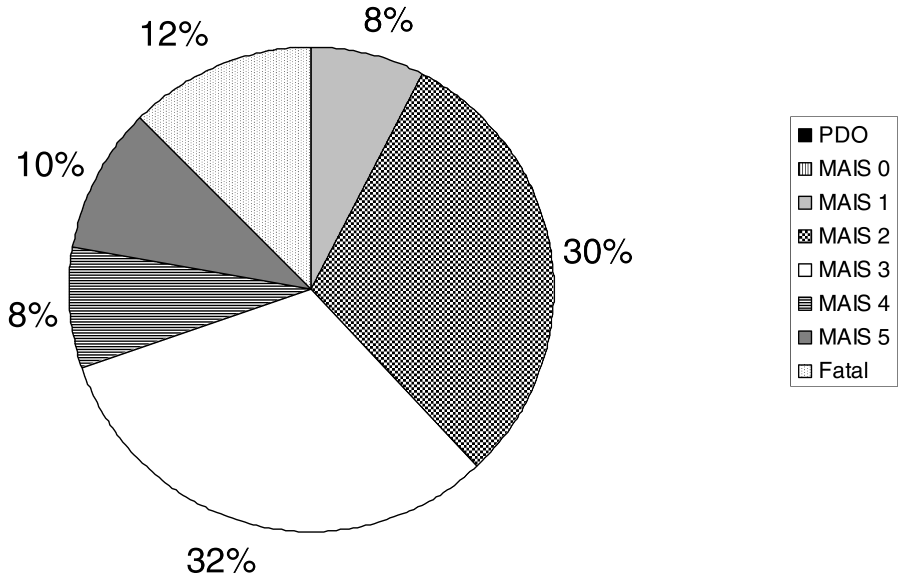

Figure 49. Distribution of legal costs, 2000 GES.

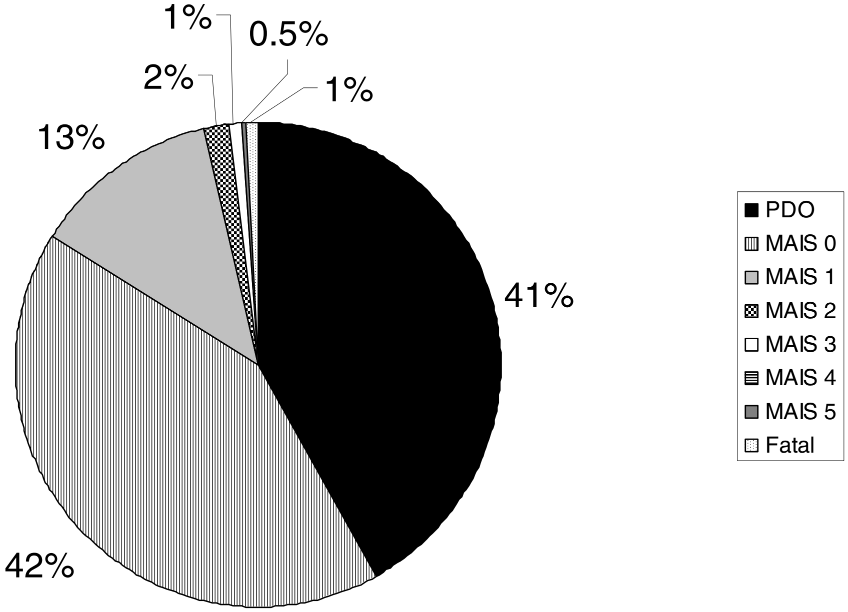

Figure 50. Distribution of travel delay costs, 2000 GES.

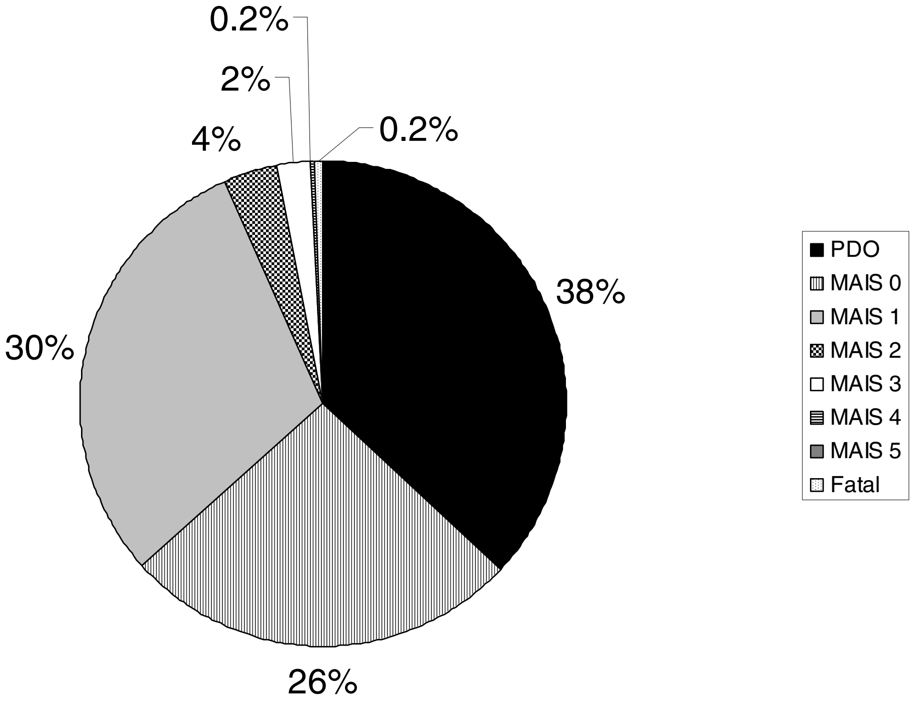

Figure 51. Distribution of property damage costs, 2000 GES.

Given the calculated per-cost crash rate of $28,209, it is also possible to begin to grasp the potential benefits of a system designed to prevent *intersection violations* by applying the per-crash cost to the number of *violation crashes* calculated as part of Subtask 1.4. This application results in the following costs for the 393,000 violation crashes in 2000 (note that the injury and PDO crashes are combined for this list since the per-crash cost is a combined figure):

- LT with LT pre-crash maneuver: 88,000 crashes for a total cost of $2.5 billion
- LT with straight pre-crash maneuver: 37,000 crashes for a total cost of $1.0 billion
- SCP: 72,000 crashes for a total cost of $2.0 billion
- RT with RT pre-crash maneuver: 7,000 crashes for a total cost of $0.2 billion
- RT with straight pre-crash maneuver: 1,000 crashes for a total cost of $28 million
- One vehicle with stop sign: 162,000 crashes for a total cost of $4.6 billion
- Two vehicles with stop sign: 26,000 crashes for a total cost of $0.7 billion

OTHER POTENTIAL ANALYSES

During the course of performing Tasks 1 and 2 of this project, the question of additional data analyses was explored, as required by the SOW. As a result, the following five areas were identified through the literature review, discussions with the contract sponsor, and discussions with other researchers pursuing similar research interests. Each area is briefly described below, along with the advantages or disadvantages of pursuing additional analyses. The final decision regarding additional data analyses will be made at a later date through consultation with the project sponsor.

- *SAVME database*. The SAVME database uses machine vision to track vehicles as they pass through a roadway. The kinematics of the vehicles can thus be studied. However, to this date, the SAVME database has limited intersection data available. Based on discussions with NHTSA personnel on project status, it appears that intersection analyses using the SAVME database will likely not be possible in the near future.
- *Naturalistic driving study*. VTTI is in the process of beginning a huge data-collection effort for 100 drivers over one year in the Washington, DC metro area. This database will be rich in intersection behavior and may provide some insight into parameters affecting intentional versus unintentional violations. However, there are two problems with using these data in the near future: 1) the data are just now beginning to be collected, and 2) the database will be so large that either GPS locations of selected intersections would have to be determined and searched, or a sample of the data would have to be manually searched. Thus, it is not thought to be a desirable alternative at present. Once the data are collected and analyzed, a sample of the critical incidents could be examined to see which incidents are intersection related and if there are enough incidents, whether these could be analyzed in depth to address ICAV issues.
- *Large-truck crash causation study*. The FMCSA is currently conducting a large-truck crash causation study, which could provide insight into the contributing factors for intersection crashes involving larger vehicles, as opposed to the light vehicles addressed in the current analysis. However, recent conversations with persons familiar with the progress of this study indicated that the results will not be available until sometime in 2004.
- *Case study of CDS data*. Previous researchers have analyzed CDS cases in some detail to try to determine the contributing factors in intersection crashes. This approach was used extensively by NHTSA during the mid-1990s in a series of research efforts described in the literature review performed as part of Task 2. There are limitations with using the CDS database, the primary one being that more severe crashes are over-represented. However, if there is agreement that such research would provide additional insight, this research avenue will be explored further.
- *In-depth analysis of the distraction/inattention cases found during Subtask 1.5*. The analyses conducted in Subtask 1.5 demonstrated that distraction and inattention play a significant role in intersection crashes with violations. Further analysis efforts could be devoted to looking at these cases in greater depth to categorize the specific sources of inattention and distraction. The examination would take the form of further analysis of the GES codes.

TASK 1 SUMMARY OF RESULTS

The Task 1 analyses were performed in a top-down fashion, beginning with defining the overall crash problem in Subtask 1.1 and then refining the analyses in later subtasks. Thus, the purpose of the first analysis was to determine the overall size of the crossing-path crash problem by scenario and maximum severity level. This goal was accomplished by considering the frequency of crossing-path crashes involving only light vehicles for 1999 and 2000. Subtask 1.1 showed that there were 1,698,000 CP crashes for 1999. Given that there were an estimated 6,271,000 crashes of all types in 1999, these CP crashes accounted for 27% of all crashes. In 2000, there were 1,667,000 CP crashes out of an estimated 6,389,000 crashes (26%).

Analysis of the overall CP crash problem in Subtask 1.1 showed the following:

- Left-turn crashes make up the majority of crossing-path crash types, at about 52% of CP crashes for the years 1998 (from Najm, Smith, and Smith, 2001) through 2000.
- The next most prevalent type is the straight crossing-path crash type, at about 30-35%, followed by unknown CP crashes at 7 to 11%.
- Right-turn crashes are the least common, at about 6% of all CP crashes for 1998-2000.
- In terms of maximum injury severity, property-damage-only (PDO) crashes made up the majority of CP crashes, at about 56%, followed by injury crashes (including fatality crashes), at about 39%. There were also a significant number of unknown severity levels, at about 5%.
- The CP crash type distributions for 1999 and 2000 were very much in agreement with previous studies (e.g., Najm, Smith, and Smith, 2001; Wang and Knipling, 1994).
- The KABCO distributions were also very much in agreement with these previous studies.
- The fatality estimates are known to be highly unreliable in GES. A comparison with a Fatality Analysis Reporting System (FARS) analysis performed by Volpe for similar crash types showed that GES overestimated the fatal CP crashes by a factor of approximately 1.8; however, differences in methodology and available variables could account for some of this difference.

In Subtask 1.2, the variable for traffic-control devices was introduced, with the following results:

- Traffic-control devices (TCDs) were fairly evenly divided between three-color signals and stop signs. There were very few unknown TCDs (1.5 to 3.0%).
- In terms of crash severity, three-color signal CP crashes were fairly evenly divided between PDO (50%) and injury crashes (46%); the remainder were unknown injury types, while stop-sign CP crashes had more PDO crashes (58%) than injury crashes (39%; the remainder were unknown injury types).
- In general, the findings from these analyses agreed with the findings from previous studies for TCDs (e.g., Najm, Smith, and Smith, 2001; Wang and Knipling, 1994).

Subtask 1.3 looked at stop-sign crashes in greater detail, with the following findings:

- Stop-sign CP crashes in which only one vehicle had a stop sign were 4 or 5 times more prevalent than crashes in which both vehicles had a stop sign.
- Although PDO crashes were more prevalent for all stop-sign crashes, the ratio of PDO to injury crashes was lower for crashes in which both vehicles had stop signs (i.e., a greater

proportion of the two-stop-sign cases were injury crashes as compared to the one-stop-sign case).
- This subtask marked the point in the increasingly detailed analyses for which no comparison numbers from previous analyses could be found.

Two new variables were introduced in Subtask 1.4: pre-crash maneuver for the signalized CP crashes, and violations and violation types for all CP crashes:
- Those citation types deemed to be most amenable to the ICAV countermeasures were speeding, reckless driving, failure to yield right-of-way, and running a stop sign or traffic signal; thus, these were the violation types explored for this subtask.
- For 1999, 63% of all three-color signal CP crashes with violations involved a straight pre-crash maneuver by the violating vehicle; for 2000, the percentage was 53%.
- In terms of the overall analysis, for the left- and right-turn crash types, more drivers were cited who made turning pre-crash maneuvers than straight pre-crash maneuvers.
- For stop-sign crashes overall, drivers in the one-stop-sign case were more likely to be cited than drivers in the two-stop-sign case, to a degree that cannot be fully explained by the larger overall number of CP crashes in this category.
- In terms of overall violation type, there were a significant number of unknown violation types (25 to 30%). For those violations that were known, the most common overall violation was failure to yield right-of-way, followed by running a traffic sign or signal.
- Speeding and reckless driving were rarely cited in CP crashes overall.

Subtask 1.5 attempted to understand the primary contributing factors for cited CP crashes, along with related environmental and roadway factors. A factor priority scheme was used to examine each variable in turn, disregarding those variables that had been previously examined.
- Among all crash types and injury levels, driver distraction and inattention was the largest primary contributing factor, at 37%. This finding validates some of the assumptions made in the early stages of the ICAV project, in that one of the primary purposes of the ICAV system is to capture the attention of the inattentive or distracted driver.
- Driver's vision obscured was the second largest category overall, at about 10%.
- For environmental and roadway factors, weather was the largest, at 13%, followed by road surface, at 4%.
- Among all crash types and injury levels, 52% of crashes were attributed to one of the primary causal factors, while 18% were attributed to environmental or roadway factors. Overall, 70% of crashes could be assigned to one of the eight factors.
- The percentage of crashes that could be attributed to one of the factors varied widely by crash type and crash severity, ranging from 8% to 98%.
- Speeding was a greater factor for straight pre-crash maneuvers than for turning pre-crash maneuvers.

Speeding behavior in cited CP crashes was examined in Subtask 1.6, including the distributions of posted speed limits, traveling speed, and whether or not the crash was speed related. Results included the following:
- Posted speed is well known in almost all cases (83% known).
- Traveling speed is not as well known (64% unknown).

- Most CP crashes with violations are specifically listed on the police accident report as "not speed related" (93%). This finding confirmed the Subtask 1.5 findings regarding speed.
- Based on law enforcement assessment using the Speed Related variable, speed does not seem to be an important factor in CP crashes with violations.

Subtask 1.7 explored the infrastructure characteristics for signalized, cited CP crashes, including number of lanes and trafficway flow, with the following results:

- 45 to 50% of signalized, cited CP crashes occurred on undivided roadways.
- 35 to 40% of signalized, cited CP crashes occurred on three- and four-lane roadways.

Subtask 1.8 consisted primarily of an economic analysis of the CP crashes identified for 2000. NHTSA recently released its estimates of the economic costs of motor-vehicle accidents, using 2000 data, and the timing of the report was ideal because it allowed the costs of the CP crashes identified to be estimated. The analysis showed costs of approximately $47,025,000,000 for the 1,667,000 CP crashes identified for the year 2000 in Subtask 1.1. Dividing the overall cost by the number of crashes resulted in an approximate estimated cost per CP crash of $28,209. Given the calculated per-cost crash rate of approximately $28,209, it is also possible to begin to grasp the potential benefits of a system designed to prevent intersection *violations* by applying the per crash cost to the number of *violation crashes* calculated as part of Subtask 1.4. The following list shows some of the more significant costs for the 393,000 cited CP-crash scenarios identified in 2000 (PDO, injury, and unknown injury crashes are combined for this list since the per-crash cost is a combined figure):

• LT with LT pre-crash maneuver:	89,000 crashes for a total cost of $2.5 billion
• LT with straight pre-crash maneuver:	37,000 crashes for a total cost of $1.0 billion
• SCP:	72,000 crashes for a total cost of $2.0 billion
• One vehicle with stop sign:	162,000 crashes for a total cost of $4.6 billion

The final aspect of Subtask 1.8 was to identify further areas of data analysis that could lead to an even greater understanding of driver behavior or vehicle kinematics in CP crashes or intersection violations. The following five areas have been identified as candidates for future analyses: the SAVME database, the naturalistic driving study database, the large truck crash causation study, case study using Crashworthiness Data System (CDS) data, and in-depth analysis of the distraction and inattention cases found during Subtask 1.5. Upon initial investigation, none of these approaches appears to be especially promising, but a final determination has yet to be made.

Conclusions from Task 1

Although an ICAV-target crash population could not be defined and determined with specificity in Task 1 based on GES variables, populations likely to be addressable by the countermeasure concept were identified as part of Subtask 1.4. An estimated 261,000 light vehicle crashes in 1999 and 162,000 in 2000 occurred at intersections where one of the two vehicles had a stop sign and was charged with a violation. There were an estimated 133,000 crashes in 1999 and 99,000 crashes in 2000 involving traffic signal violations. These crash populations could be target crashes for ICAV.

TASK 2. TOP-LEVEL SYSTEM AND HUMAN FACTORS REQUIREMENTS

LITERATURE REVIEW

Intersection (crossing-path) crashes account for approximately 25% of all police-reported crashes in the United States each year. They also account for 27% of all crash-caused delays and for over $47 billion in costs (see Task 1 results from this report). Given these numbers, the US Department of Transportation (USDOT) has expended considerable effort in developing methods to reduce the numbers and severity of intersection crashes. Within the USDOT, the Federal Highway Administration (FHWA) has approached the problem from the infrastructure perspective, while the National Highway Traffic Safety Administration (NHTSA) has taken the lead from the vehicle perspective.

This literature review represents one small subtask in a multi-pronged NHTSA initiative examining ways to reduce intersection crashes by integrating Intelligent Transportation System (ITS) components into vehicles. A major factor in solving the intersection crash problem is that many intersection crashes result from intersection violations of either a stop sign or traffic signal. One approach to the problem is to prevent violations from occurring, thus reducing the number of crashes; such an approach is taken in the current research effort. Other research efforts, such as crash-avoidance strategies, are focused on different aspects of the problem. This literature review supports this approach by outlining the problem-size description for intersection crashes, the general causal factors for the intersection crashes of interest, the approaches taken for this problem, and the components required to make such a system work.

INTERSECTION CRASH PROBLEM DESCRIPTION

Volpe/NHTSA Multi-Year Effort

The potential for effective countermeasure development aimed at reducing all crash types has commanded much attention and resources for research. In the mid 1990s, NHTSA's Office of Crash Avoidance Research (OCAR) joined with the Volpe National Transportation Systems Center (a subset of the Research and Special Programs Administration [RSPA]) to further investigate possibilities. These agencies undertook a three-year project to thoroughly outline the individual problems associated with nine common crash types. Extensive database analysis was used to develop ITS Collision-Avoidance System (CAS) concepts and algorithms for each type. The steps employed in these target crash analyses are as follows (Najm, Mironer, Koziol, Wang, & Knipling, 1995):

1. Baseline problem sizes and characteristics were described from the General Estimates System (GES) and the Fatality Analysis Reporting System (FARS).
2. Target subtypes and causal factors were identified via individual case investigation. This was done by clinical review of past case files; thus the findings from this type of analyses may not be generalizable to the full population of crossing-path crashes.
3. Countermeasure concepts and their subtype-dependent functional requirements were developed using causal factors.
4. Kinematic models for timing algorithm development were derived.

5. Sensitivity curves were developed from the models showing time/distance requirements for alarm activation.
6. Effectiveness estimates were made by matching countermeasure concepts with functional requirements.
7. Further research needs were identified.

Of the crash types targeted in these studies, three occur in intersections: Signalized Intersection, Straight Crossing Path (SI/SCP); Unsignalized Intersection, Straight Crossing Path (UI/SCP); and Intersection, Left Turn Across Path (LTAP). This report discusses in detail the findings for each of these relevant crash types. This approach results in a comprehensive description of each crash type, although it also results in a separation of topics to some degree (i.e., the topic of causation is initially discussed for each specific crash type rather than discussed in one location for intersection crashes in general).

Intersection Crossing Path Statistical Analysis

Wang and Knipling (1994) investigated all three (LTAP, UI/SCP, and SI/SCP) types of crossing-path (ICP) crashes and their relationships to one another. In 1991, there were 1,803,000 ICP crashes, amounting to 29.5% of all police-reported crashes. These crashes resulted in 1,082,000 injuries, 144,000 of which were either fatal or incapacitating to those involved. (A vehicle can be expected to be involved in 0.25 ICP crashes in its operational life.) An estimated 2,224,000 ICP crashes occurred that were not police-reported, causing an estimated 26.7% of all crash-caused delay to drivers of involved vehicles and to other drivers delayed by congestion resulting from the crash. Of the three ICP subtypes investigated, UI/SCP crashes accounted for the highest percentage (10.2%) in 1991, followed by LTAP crashes (6.8%), and SI/SCP crashes as the least common but still a significant portion of the total (4.2%). More than 3.5 million vehicles were involved in ICP crashes in 1991 (a collision between two cars is one crash, but two vehicles are involved), which accounts for around one-third of the vehicles involved in all crashes combined. Table 96 presents the number and percentages of ICP crashes for 1991.

Table 96. Incidence and percentage of intersection crossing-path crashes in 1991 based on GES data.

Crash Subtype	Incidence in 1991	Percentage of all in 1991
UI/PCP	621,000	10.2%
SI/PCP	260,000	4.2%
LTAP	413,000	6.8%
Other ICP	509,000	8.3%
Total ICP	1,803,000	29.5%
All Crashes	6,110,000	100%

Wang and Knipling (1994) found that almost all ICP crashes (98.8%) involved a passenger vehicle as at least one of the involved vehicles. The motorcycle crash-involvement rate per 100 million vehicle miles traveled (VMT) was about twice that of passenger vehicles (351.3 versus 173.8 for passenger vehicles per 100 million VMT). Crash involvement rates were highest for younger drivers (15 to 19 years of age), second highest for drivers aged 75 and over, and lowest for middle-aged drivers (roughly 25 to 64 years of age).

Twice as many ICP crashes occurred in the afternoon/evening traffic peak (15:31 to 18:30) than during the morning peak (6:31 to 9:30; Wang and Knipling, 1994). More crashes occurred on Friday, the least on Sunday, with other days very nearly equal. Weekends and weekdays differed slightly in time distribution due to the higher frequency of late-night and early-morning crashes on weekends.

In regard to roadway characteristics, Wang and Knipling (1994) found that slightly less than 75% of crashes occurred on non-divided highways, a little less than 25% on divided highways, and the remainder on one-way trafficways. Known values for travel lanes showed that almost half occurred on 1 or 2-lane roadways, about a third on 3 or 4-lane roadways, and almost 15% on roadways with 5 or more lanes. Most crashes occurred on straight and level roads. The majority of crashes occurred on dry roadways in daylight with no adverse weather conditions. Three different intersection types, signalized, stop-sign, and no control (such as driveway to road), had roughly equal crash frequencies. Most crashes occurred where posted speed limits were 35mph or less, which is consistent with the urban locations in which most crashes occur. Most crashes involved property damage only (64.9%), and very few involved alcohol (4.4%). Crashes were incapacitating 5.5% of the time and resulted in a fatality 0.3% of the time, which caused a substantial 144,000 fatal or incapacitating injuries.

Going straight was the most common pre-crash maneuver, at slightly more than 50%, with turning left the next frequent, and passing the least common (Wang and Knipling, 1994). The front of the vehicle was the most common point of initial impact, but the right side and the left side were also impacted with significant frequency (about 25% each). Only one-third of drivers were charged with violations, most commonly Failure to Yield, and only 1% was charged with alcohol/drug violations. Drivers 65 and older were charged with Failure to Yield twice as often as drivers aged 25 to 64, relative to their involvement.

Wang and Knipling (1994) reported that age and sex frequencies varied according to whether the number of vehicle-miles traveled (VMT, a variable called Crash Involvement Rate) or the number of licensed drivers (Crash Involvement Likelihood) was measured. For both sexes, the age group with the highest involvement rate was 15-19. The age group with the lowest rate for males was 55-64 and 25-54 for females. Female Crash Involvement Rates were higher than those of males in every age group, while the Crash Involvement Likelihood was higher for males than females across all age groups. This counterintuitive ratio can be explained by the fact that a given number of females drive fewer miles than the same number of men, but they become involved in a comparable number of crashes. (For example, if 10 females get involved in 2 crashes and 10 males get involved in 4 crashes, male likelihood would be higher, not taking into account how far each driver drove. However, if the 10 females drove a total of 1,000 miles with 2 crashes and the 10 males drove 10,000 miles with 4 crashes, the females would have more crashes per mile than the males. Their rate per mile would be higher, but their involvement per driver would be lower.) A comparison of involvement rates and involvement likelihoods by age and sex shows that older women have a low likelihood but a high rate, meaning that older women drive fewer miles but are disproportionately involved in crashes per mile.

Wang and Knipling (1994) defined a critical event as something that occurred to make the crash imminent (a causal event). Roughly the same percentage of causal events involved the subject vehicle (SV) entering the principal other vehicle's (POV) lane as involved the POV entering the SV's lane. No corrective action was attempted by a large majority (87.6%) of drivers, but of those who did, the most common action was braking or slowing (4.6% of total). Steering in either direction with or without braking was minimally represented. However, note that the GES tends to underestimate the "no corrective action" category.

Unsignalized Intersection/Straight Crossing Path

Chovan, Tijerina, Pierowicz, and Hendricks (1994) investigated stop-sign intersection-collision statistics for straight-crossing-path crashes. These are defined as crashes in which two vehicles, one with right-of-way and one without it, cross one another's paths perpendicularly in an intersection and collide. An analytic model of behavior at stop-sign intersections provides insight into possible driver-related contributing factors such as unawareness, unawareness related to visual obstruction, misunderstanding signs, failure to anticipate surprise braking by the lead vehicle, and failure to recognize hazards in cross traffic due to either inattention, misperception, or failure to recognize a threat.

Chovan, Tijerina, Pierowicz, et al. (1994) analyzed NHTSA's GES database from 1991. Six percent (375,000) of all police-reported crashes in 1991 were UI/SCP crashes. An estimated 436,000 were never reported, together causing upwards of 16 million hours of crash-caused delay (including delay to noninvolved vehicles caught in the resulting traffic congestion). The crash dynamics investigated in this report are very similar to the situation when two vehicles approach one another perpendicularly at an unsignalized intersection and one turns left across the path of the other. Including those crashes, this report applies to a total of 621,000 reported and 743,000 unreported crashes in 1991, strongly justifying countermeasure-development efforts.

While 74% of unsignalized-intersection crashes occurred on dry pavement (Chovan, Tijerina, Pierowicz, et al., 1994), a significant percentage (~25%) occurred on wet or snowy pavement (1% were not classified). Furthermore, since no estimate of exposure is easily obtainable for these distributions, it is impossible to determine the level of risk represented by these statistics. Thus, while initial algorithm development might focus on dry conditions, other pavement conditions should be considered in later iterations. Drivers involved in either struck or striking roles were usually younger than 55 years old. Most collisions occurred at posted speeds of 45mph or less since the majority took place in urban areas where speed limits tend to be 25 to 35mph.

The identification of contributing factors is simplified by a model of the steps ideally taken by the driver negotiating a stop at a stop-sign intersection. Chovan, Tijerina, Pierowicz, et al. (1994) define those steps as follows:

1. Detect the presence of the intersection.
2. Correctly identify signage.
3. Anticipate sudden deceleration of lead vehicle(s).
4. Detect the presence of cross traffic.
5. Recognize crash hazards posed by cross traffic, perhaps by estimating the speed, acceleration, and distance of the approaching vehicles.
6. Watch for and anticipate other traffic or pedestrians that may cause a cross-traffic vehicle to suddenly stop in the SV's path.

7. Identify visual obstructions and attempt to overcome them.
8. Stop the vehicle.
9. Estimate when it is safe to proceed through the intersection.

Chovan, Tijerina, Pierowicz, et al. (1994) applied this model to a detailed analysis of 100 well-documented crash records from the Crashworthiness Data System (CDS) and then applied severity weightings based on GES cases of the same crash type. Chovan, Tijerina, Pierowicz, et al. defined the SV as the vehicle without the right-of-way in any crash scenario and the POV as the vehicle with the right-of-way. Using these definitions, the 100 analyzed crashes fell into two categories. In subtype 1 the SV ran the stop sign, a behavior frequently caused by either inattention (56.4%) or obstructed vision (18.7%). In subtype 2 the SV stopped before proceeding across the intersection at an inopportune time, usually an occurrence involving faulty perception (81.7%) as well as obstructed vision (14%). In either subtype the POV is equally likely to be coming from the right or the left. These findings strongly suggest that driver unawareness of an upcoming hazard is a major factor in these crashes, which indicates that an alerting CAS could be highly beneficial. Whether to warn the SV, the POV, or both vehicles, however, remains an issue for discussion and investigation, and depends on the type of crash being studied and the specific characteristics of such a crash.

Signalized Intersection/Straight Crossing Path

According to Tijerina, Chovan, Pierowicz, and Hendricks (1994), SI/SCP crashes occur when the path of the SV without the right-of-way intersects perpendicularly with the path of the POV (which does have the right-of-way) in a signalized intersection. Possible sources of driver error are inattention to the presence of the intersection, inaccurate detection or interpretation of the signal status, time-estimation errors associated with signal status, lack of detection of cross traffic, and problematic visual obstructions.

Like Chovan, Tijerina, Pierowicz, et al. (1994), Tijerina et al. (1994) analyzed NHTSA’s GES data from 1991. Signalized intersection, straight-crossing-path (SI/SCP) crashes accounted for 3% (203,000) of the police-reported crashes in 1991. An additional estimated 200,000 crashes were never reported, together causing upwards of 18.1 million hours of crash-caused delay (4% of the total delay from all crashes in 1991), including delay to noninvolved vehicles caught in the resulting traffic congestion. The crash dynamics investigated in this report are very similar to crashes in which two vehicles approach one another perpendicularly at a signalized intersection and one turns left across the path of the other.

Initial algorithm development should assume good traction for braking models because 79% of these crashes occurred on dry pavement, 19% on wet pavement, and only 2% in snowy or icy conditions. Good weather and lighting conditions were the predominant environmental characteristics. Elderly drivers were proportionally over-represented; however, 81% of involved drivers were 54 years of age or younger. Vehicle travel velocity was unknown in 71% of the cases but was estimated to be 35mph or less for the majority of vehicles, which probably reflects roadway speed limits.

Tijerina et al. (1994) identified the steps ideally taken by the driver negotiating the crossing of a signalized intersection as follows:

1. Detect the presence of the intersection and slow down.
2. Detect and correctly identify the status of the signal.
3. If the light changes from green to amber, estimate if there is time to cross safely.
4. Anticipate sudden deceleration of lead vehicle(s).
5. Detect the presence of cross traffic.
6. Recognize crash hazards posed by cross traffic, perhaps by estimating the speed, acceleration, and distance of the approaching vehicles.
7. Identify visual obstructions and attempt to overcome them.
8. Watch for and anticipate other traffic or pedestrians that may cause a cross-traffic vehicle to suddenly stop in the SV's path.

Tijerina et al. (1994) performed a detailed analysis of 50 well-documented crash records, using 37 cases drawn from the 1992 CDS and 13 from 1991 GES data. All 50 crashes were similar in that the violating SV was unaware of or disregarded the signal and entered the intersection, resulting in a collision with the POV, which obeyed the signal and had the right-of-way. Although it never had the right-of-way, the SV could be the struck or striking vehicle, according to the specifics of the scenario. The SV speed tended to be close to the surrounding speed limit, suggesting that the driver did not attempt to stop.

Causal factors were difficult to glean from the data because they were after-the-fact crash reconstructions. Interviewed drivers, for example, might have been motivated to avoid admitting culpability. Based on these data, the authors reported that 39.4% of the SI/SCP crashes occurred because of deliberate violation of the signal; this finding was further broken down: 23.2% "failed to obey signal" and 16.2% "tried to beat signal." About 41% of the crashes were attributed to driver's lack of awareness, either inattention (36.4%) or vision obstruction (4.3%).

The different types of deliberate violation might be differentially influenced by an alerting CAS. Those who tried to beat the amber signal (16.2%) might not do so if they knew that there was not sufficient time to succeed. This behavior has been extensively studied with respect to the presence of dilemma zones in intersections, which are sections of the intersection approach where the driver can neither stop comfortably in time nor accelerate enough to clear the intersection (Gazis, Herman, and Maradudin, 1960). Drivers who tried to beat the amber signal were likely in this dilemma zone at the time of the amber-to-red signal change; an in-vehicle warning might improve dilemma-zone decision making by drivers. The drivers who directly ran the red light (23.2%) might not do so if they were aware of serious cross-traffic hazards not considered. Driver unawareness due to inattention or obstructed vision (40.7%) could be strongly influenced by a CAS alerting the driver to the hazards at hand or by making the driver aware of hazards he or she could not see. The remaining three factors, driver intoxication, vehicle defects, and other circumstances, are general in nature, so their solutions are not specific to the SI/SCP crash etiology.

Countermeasure models and algorithms are detailed by Tijerina et al. (1994) according to three zones in the approach to a signalized intersection: the Brake Zone, the Dilemma Zone, and the Clearance Zone. These models are further discussed in the algorithm section of this report.

Left Turn across Path

Chovan, Tijerina, Everson, Pierowicz, and Hendricks (1994) define LTAP crashes as collisions occurring in any type of intersection when the SV turns left into the path of the oncoming POV (proceeding in an opposite but parallel direction) and either strikes or is struck by it. Possible sources of driver error for this crash type include misjudging the speed of cross traffic, gap, or behavior, visual obstructions or other factors causing unawareness, and intentional signal violation.

Chovan, Tijerina, Everson, et al. (1994) analyzed GES data from 1991 and found that LTAP crashes accounted for 7% (413,000) of the police-reported crashes in 1991. An additional estimated 462,000 low-severity (property damage only) crashes were never reported, together causing upwards of 37 million hours of crash-caused delay (4% of the total delay from all crashes in 1991), including delay to noninvolved vehicles caught in the resulting traffic congestion. The proportion of LTAP crashes occurring at signalized versus unsignalized intersections was nearly equal (51.2% and 48.8% respectively). Like SI/SCP and UI/SCP crashes, the majority of LTAP crashes occurred in good weather, pavement, and lighting conditions and predominantly involved drivers under the age of 54, although elderly drivers were over-represented proportionally. Most of the SVs (59%) were traveling less than 10mph, likely due to the need to decelerate in order to turn safely.

Countermeasure design is facilitated by pairing driver tasks with possible driver errors that may be prevented while performing the task. Chovan, Tijerina, Everson, et al. (1994) identified the following tasks and corresponding errors, in chronological sequence:

1. Intersection Approach: driver may be unaware of intersection or its geometry.
2. Signal: driver may not activate turn signal.
3. Decelerate: driver may not slow down enough to process critical information accurately.
4. Perceive Traffic-Control Device (TCD): driver may be unaware of TCD entirely or may not know signal characteristics (i.e., phase timing).
5. Heed TCD: driver may not perceive TCD characteristics accurately.
6. Perceive signal color: driver may not know status (flashing/steady, color) of signal.
7. Respond appropriately to signal color: driver may not behave correctly according to the signal color.
8. Observe cross/oncoming traffic: driver may be unaware of approaching vehicles.
9. Judge oncoming traffic gap: driver may misjudge oncoming traffic gap.
10. Judge cross traffic gap: driver may misjudge cross traffic gap.
11. Edge into traffic to see around obstruction and confirm clearance: driver may not be aware of visual obstruction or may edge too much into traffic.
12. Check anticipated pathway of SV: driver may not check own pathway or may misperceive objects (people, vehicles) in it. Driver may not correctly anticipate the behavior of other traffic.
13. Adjust vehicle turning velocity: driver may turn too slowly or too quickly to clear the intersection safely.
14. Complete the left turn: driver may stop in the intersection without finishing the turn.

Chovan, Tijerina, Everson, et al. (1994) performed a detailed analysis of 154 well-documented crash records drawn from the 1992 CDS. The SV was the struck vehicle in a majority of signalized and unsignalized intersection collisions (76.3% and 81.1% respectively). The posted speed limit was 35mph or more in most cases. The SV slowed but did not stop before turning in 71.6% of cases, whereas it came to a complete stop before proceeding into the intersection for the remaining 28.4%. Drivers were unaware of the oncoming vehicle in 49% of these crashes, and 30% misjudged the velocity/gap of the oncoming traffic. Signal violation was a causal factor in 15.4% of LTAP crashes at signalized intersections. Other factors included trying to "beat" the other vehicle and driver intoxication. Altogether, faulty perception and obstruction of view were the two most common contributing factors, together accounting for nearly 78% of the LTAP crashes. Obstruction of view was primarily caused by intervening vehicles, so a traffic-hazard warning would be useful in this situation.

Summary of Volpe/NHTSA Multi-Year Effort

The studies performed by Tijerina et al. (1994), Chovan, Tijerina, Pierowicz, et al. (1994), Chovan, Tijerina, Everson, et al. (1994), and Wang and Knipling (1994) were summarized in a synthesis report by Najm, Mironer, Koziol, Wang, and Knipling (1995) that provided further insight into the general characteristics of intersection crashes. The Najm et al. synthesis report took the following statistical characteristics into account in crash-type analysis:

- Time of day.
- Lighting condition.
- Atmospheric condition.
- Roadway surface condition.
- Roadway alignment.
- Roadway profile.
- Speed limit – the higher-profile road of the intersection is coded.
- Relation to junction.
- Alcohol involvement.
- Maximum severity – police reported severity of worst-injured person.

Integrating results from each subsection's analyses of GES data, the synthesis study by Najm et al. (1995) found that backing crashes and rear-end crashes are the other crash types most associated with an intersection. All ICP crash types most likely occur between 9:31 a.m. and 3:30 p.m. (40.2%), followed by 3:31 p.m. to 6:30 p.m. (26.1%) and 6:31 p.m. to 11:59 p.m. (16.8%). Of all ICP crashes, 77.4% occur in daylight, 83.8% in good weather conditions, 76.2% on dry pavement, 98.8% with straight roadway alignment, and 79.5% on a level grade. Most result in property damage only (64.6%) while 0.2% cause a fatality. Alcohol is a factor in 3.2% of ICP crashes, compared to 6.4% of all crashes in the GES database. The speeds of these crashes vary considerably, with 1.9% at 20mph or less, the largest concentration at 35mph (29.5%), and 0% at 60 mph and above.

Najm et al. (1995) performed a comparison of factor analyses for all three ICP crash types. Causal factors are divided into five major categories: driving-task errors, driver physiological impairment, vehicle defects, low-friction roadway surface, and reduced visibility. Of the 11 specific ICP-related factors in those 5 categories, inattention played the largest role in SI/SCP crashes (36.4%) but barely affected the LTAP subtype (1.4%). Looked-Did-Not-See was a major factor in UI/SCP crashes (36.7%) and a significant factor in LTAP crashes (23.2%); however, this factor affected 0% of SI/SCP crashes. Obstructed Vision affected 24.4% of LTAP crashes and 14.3% of UI/SCP crashes but only 4.3% of SI/SCP crashes. The largest single factor in LTAP crashes was misjudged gap/velocity. Drunk drivers were involved in 12.6% of SI/SCP crashes but had minimal impact on the other two subtypes. Vehicle defects were a factor in only 1.6% of SI/SCP crashes but not at all in others. Bad roadway surface conditions were a factor in 7% of UI/SCP crashes but not others, and reduced visibility/glare also had minimal impact (UI/SCP 1.1%, LTAP 0.1%). Violation of signal/sign was a factor in 23.2% of SI/SCP crashes, 3.4% of UI/SCP crashes, and 7.4% of LTAP crashes.

Intentional violations complicate warning development. Deliberate violation occurs because the driver's motivations for traveling through the intersection outweigh the perceived risks or because the drivers think it unlikely that they will be involved in a crash. In the first case, a warning system is not likely to outweigh the motivations and, therefore, would be significantly less effective. In the second case, informing the driver of a hazardous situation may well change his or her course of action, according to Tijerina et al. (1994). This concludes information from NHTSA and Volpe's joint three-year project.

Other Problem Size Descriptions

A study done by Grubb (1992) examined driver characteristics in relation to driver behavior in the controlled setting of a lab-created roadway-intersection simulation. In this study, 72 participants (age 18-74) were measured on a battery of performance tests, administered questionnaires related to health and driving history, and exposed to a video display of approaching intersections as driver responses were measured. Each participant viewed 14 intersections that contained a variety of traffic-control devices. Each participant was assessed on six variables (chosen to reflect three response modes: pedal-response errors, speed of response, and heart-rate reactivity) during the driving simulation.

Grubb (1992) had several significant findings. In terms of pedal-response errors, the youngest group made fewer errors than either of the two older groups. Males made fewer pedal errors than females, while young males and females made fewer errors than females in the two older groups. Concerning speed of response, the youngest group responded earlier than the two older groups, and males responded earlier than females. Younger males and females responded earlier than females in the two older groups, while young males responded earlier than the oldest group of males. Analysis of heart-rate reactivity data showed that the youngest group had less reactivity than the two older groups, and males had less reactivity than females. Young males and females had less reactivity than females in the two older groups and males in the oldest group. Males in the middle group (40-52) showed less reactivity than females in the highest group (62-74).

There were also several significant results from regressions performed on the individual differences variables. Pedal-response error analysis revealed higher error rates for older drivers, females, and people scoring higher on anxiety trait and history of accident involvement. Age accounted for the largest amount of variance. Concerning speed of response, earlier final pedal responses were made by younger drivers and male drivers, while age accounted for the largest amount of variance. Analysis of heart-rate activity data found higher reactivity for older drivers and drivers with higher driving-anxiety ratings, poorer general health status, strong field dependency, and poorer depth perception. Age accounted for the largest amount of variance in this variable as well.

More recently, Najm, Smith, and Smith (2001) performed an analysis of crossing-path crashes, using the 1998 GES database. Several aspects of this report were used as guidelines for the crash database analyses conducted in Task 1, so some details of the analysis are included in that section of this report. Najm et al. estimated that there were 1.72 million police-reported crossing-path crashes. Of these, LTAP crashes accounted for the largest percentage, at 47.2%, followed by SCP crashes, at 29.9%. All other crossing-path crash types accounted for the remaining 22.9%. The great majority of these crossing-path crashes occurred in intersections (75.1%), followed by driveway/alley (21.0%). Overall, 41.6% of crashes occurred at signalized intersections, 36.3% at stop-signed intersections, and 22.1% at intersections with no controls or other types of controls. Finally, higher fatality rates were found for unsignalized-intersection crashes.

Red-Light and Stop-Sign Running Behavioral Characteristics

A study by Porter and Berry (2001) analyzed the findings of a telephone survey to determine self-reported tendencies in red-light running. A questionnaire was administered to a U.S. probability sample of 880 licensed drivers, addressing five issues:

1. The prevalence of violation and how driver characteristics can be used to predict it.
2. The effect of passengers on likelihood of violation.
3. The impact of frustration on violation behavior.
4. What role consequences play in decision making.
5. Ideas to reduce red-light running.

The survey results indicated that 1 of every 5 participants (19.4%) had run a red light in the last 10 intersections they had crossed. The only variable that significantly predicted violation behavior was age group, with the youngest group (18 to 25 years old) having the highest rate. Passengers had a significant impact on drivers' tendencies to run lights, in that 25.6% of drivers reported being likely to commit a violation while alone, while only 15.8% would be likely to commit a violation in the presence of an adult passenger. The presence of children in the car dropped the percentage of likely violators to only 4.8%. Frustration proved to increase the likelihood of other aggressive maneuvers, such as speeding and tailgating, but had little impact on red-light running. Regarding consequences, the participants believed on average that fewer than 2 of every 10 violators would be caught, and only 5.8% had actually been ticketed for the offense. Overall, 10.9% had been involved in a crash, and the majority believed red-light running to be dangerous (98.8%) and/or a problem (79.8%). The most commonly suggested solutions were increasing enforcement and intensifying public awareness. However, Porter and Berry (2001) raise doubts as to the effectiveness of education. For example, the participants themselves already believed such violations to be a serious concern, yet a significant number of them still ran red lights.

Porter and England (2000) conducted a study to provide data on the characteristics of red-light runners. The data were also used to develop safety programs tailored to modifying the behavior of drivers who run red lights. The study took place in three urban cities in Southeast Virginia and focused on six intersections. For this study, participants were defined as drivers who were the last to enter the intersections during observed light cycles: specifically, the last driver to cross the intersection bar prior to the onset of opposing traffic. Only drivers with straight crossing paths or making left turns were included (drivers making right turns were not included). Data collection took place only on weekdays for three out of the six intersections at a time (one from each city). Each intersection was observed for a two hour period between 3:00 p.m. and 6:00 p.m., and each intersection was observed every other weekday to account for changes in driving during the week. Driving conditions were observed in various weather conditions. A total of 5,112 participants were observed during the data-collection phase. Of those, 3,785 entered the intersection on yellow or red and were recorded in detail.

Of the 5,112 observed light cycles, 1,798 involved at least one red-light runner (35.2%). The last driver entered on yellow in 1,987 (38.9%) light cycles and 1,327 (26.0%) entered the intersections on green. This study also found that drivers who were not wearing seat-belts were 1.32 times more likely to run the red light than were seat-belt wearers, and non-Caucasians were 1.19 times more likely to run the red light than were Caucasians. No significant differences were found in the gender frequency of the driver.

Pietrucha, Opiela, Knoblauch, and Crigler (1990) performed a study of motorist compliance with TCDs, including stop signs and traffic signals. They performed surveys of driver attitude towards compliance with TCDs as well as observational studies of driver behavior. For a sample of 120 typical drivers, 38% reported having run a red light at some point in their driving careers, and 18% of these drivers reported doing so at least once a week. For stop signs, 38% reported running stop signs at some point, with 43% running a stop sign at least once a week. Pietrucha et al. also looked at chronic violators (those who had received a certain number of violation points). For 65 chronic violators, 60% reported running a stop sign at some point, with 30% of these doing so weekly. For red lights, 54% of the chronic violators reported running red lights at all, with 24% doing so on a weekly basis. When asked the reasons why they violated, drivers most frequently cited personal reasons (46%) for running red lights, while the most common reason for stop-sign running was that the respondents perceived no risk in running the stop signs (71%). Almost identical reasons were obtained for the chronic violators. The most common personal reason for running a red light for both groups was being “in a hurry.” For stop signs, the low-risk rationale for both groups was that “cross-street volume is low.”

Pietrucha et al. (1990) also performed observational studies at 906 sites scattered throughout the country. For red-light running, 156 sites were observed. During the observation periods, 79,055 vehicles were observed, resulting in 688 violations. Of the violations, the most common type (590) was entering on red without a conflict, while 65 were entering on red with a conflict, 24 were jumping the signal without a conflict, and 9 were jumping the signal with a conflict. For violations, the most common maneuver was straight crossing path (364), followed by turning left (210), and turning right (114).

For stop signs, 142 sites were observed, resulting in observations of 31,212 vehicles, of which 21,110 failed to come to a complete stop. The most common scenario for failure to stop was “did not stop completely, proceeded without conflict,” with 20,703 (this is the so-called “rolling stop”). There were 407 cases in which the vehicle did not stop completely and proceeded with a conflict present, and 327 cases in which the driver came to a full stop but proceeded with a conflict present. No driver characteristics were noted as part of the observational study; since this was an FHWA study, most of the focus was on infrastructure problems and countermeasures, rather than on the driver.

Stop Sign Crashes

Approximately one-third of the 700,000 police-reported crashes at stop signs every year involve injuries (Retting, Weinstein, and Solomon, 2002). In the year 2000, there were more fatal crashes at stop signs (3,424) than at signalized intersections (2,785). In an effort to better understand intersection-crash patterns in an urban environment, Retting, Weinstein, and Solomon analyzed 1,788 police-reported crashes at stop signs in four U.S. cities. They found that the most common crash type in all four cities involved sign violation, amounting to 70% of the total number of crashes. Drivers claimed to have stopped before entering the intersection in approximately two-thirds of violation-related crashes. Compared to these crashes, crashes in which drivers failed to stop were more than twice as likely to have occurred at night and were also more likely to involve injuries. Drivers were far more likely to run stop signs at cross-type intersections (19%) than at T-intersections (4%), but almost half of all crashes occurred at T-intersections. Disproportionate numbers of young drivers and older drivers were judged to be at fault in stop-sign crashes, and young drivers were particularly overrepresented (33%) in violation crashes in which the driver failed to stop.

Retting, Weinstein, and Solomon (2002) recommend that countermeasure designs take into account the fact that most stop-sign crashes occur after the driver has stopped and mistakenly identified a sufficiently large gap in conflicting traffic. Visual obstructions and failure to exercise appropriate caution are issues that also must be addressed.

INSIGHTS FROM PHOTO ENFORCEMENT RED-LIGHT RUNNING CAMERA STUDIES

An increasingly common solution to the problem of red-light running is to implement photo enforcement red-light- running cameras. However, studies on the effectiveness of these devices in preventing crashes have resulted in mixed findings. For the purposes of this literature review, these studies do provide some insight into the proportion of intentional versus unintentional red-lighting-running behavior, which will be helpful in determining the potential effectiveness of violation-warning systems.

McGhee (2002) summarized state-of-the-art research findings from a number of studies regarding the effect of red-light-running (RLR) cameras on crash occurrence and severity. Comparison of the disparate data reveals that there is no conclusive answer. Some studies show significant reductions, primarily in right-angle crashes, while many show no statistically significant effect. Several Australian studies show statistically significant increases in rear-end-collision crash rates when RLR cameras are introduced. While the literature consistently reports reductions in violations after the implementation of camera systems, this reduction does not consistently extend to crashes. The differing methodologies of the reviewed studies weaken the validity of result comparisons; McGhee et al. argue that no comprehensive and statistically rigorous design has provided a conclusive and reliable answer. Some critical issues to be addressed concern the factors that influence the efficacy of the RLR cameras, such as public awareness, intersection geometry, the time duration of the effects, the rate of spillover to other intersections, and the impact of the fine amount in curbing violations.

A study conducted by Retting and Williams (1996) observed and recorded driver characteristics as well as vehicle body style of red-light violators and compliers. This study took place in Arlington County, Virginia in 1994 on an eight-lane east/west roadway and a four-lane north/south street. In Virginia, drivers are supposed to stop for the yellow light unless deemed unsafe, but those who passed through the yellow light were not considered violators. For the cycles in which there was a violator, the last driver to violate the signal was recorded. For the cycles in which there was no violator, the first driver to comply or stop was recorded. The following criterion was used in the data collection: complying vehicles must have been within 250 to 375 ft of the marked zone of the intersection at the onset of the yellow light (the region often referred to as the dilemma zone). Those vehicles further than 375 ft from the marked zone were considered too far to pass through the intersection. Those vehicles closer than 250 ft to the marked zone were considered to be too close to stop. This implies that those vehicles within 250 to 375 ft were equally likely to either violate or comply with the signal, and those drivers who complied made a choice to obey the signal.

Retting and Williams (1996) recorded data concerning vehicle type, car make and color, driver sex, estimated age, and whether or not a shoulder belt was worn. These data were collected from a van parked unobtrusively near the intersection. Red-light cameras took pictures of vehicles that entered the intersection at least 0.5s after the onset of the red light. Data were collected from 9 a.m. to 5 p.m. on weekdays and when the pavement was dry.

Of the 1,373 observations made by Retting and Williams (1996), 462 were violators and 911 were compliers. The number of violators is not an accurate representation because of the possibility of having more than one violator per cycle. Violators were less likely to wear safety belts. They were also over three times more likely to have multiple speeding violations. Contrary to other studies, no gender difference was observed between violators and compliers. The violation times and percentage of violators is shown in Table 97.

Table 97. Percentage of violators who entered the intersection after varying times of red activation.

Time after signal turned red	**Percentage of drivers who entered the intersection**
0.5s – 0.9s	48%
1.0s – 1.4s	34%
1.5s – 1.9s	11%
2.0 s +	7%
Total	100%

Several other studies have observed the effects of red-light cameras on violation rates. One good example can be found in Retting, Williams, Farmer, and Feldman (1999), who studied these effects in Oxnard California. Fourteen sites were selected; nine camera sites and three non-camera sites were chosen in Oxnard, while two non-camera sites were chosen 40 miles outside of Oxnard for control purposes. The non-camera sites were chosen based on non-obtrusive cameraplacement capability. A violation was defined as a vehicle entering the intersection at a minimal driving speed of 15mph and more than 0.4s after the light had changed to red. Baseline data were collected prior to the warning of the red-light camera installment.

Upon analyzing three to four months of data after red-light camera installation, the researchers found a 40% reduction of violations at camera sites and a 50% reduction at non-camera sites in Oxnard. The baseline and after-installation data were analyzed using the same definition of a violation. There was a significant difference between the reduction rates at the Oxnard sites compared with the control sites (i.e., there was no significant change in violation rates at the control sites). The average violation rate in Oxnard was reduced by approximately 42%, which implies that a large percentage of violators were able to alter their behavior and not run the red light. This also implies that 58% of violations were either unintentional or were committed by drivers who were unwilling to change their behavior. Most people surveyed as part of this study favored the use of RLR cameras before and after installation. For those who did not favor the cameras, the main reason was privacy concerns. This issue promotes the idea of using in-vehicle violation countermeasures, with which privacy is not a concern.

Red-light cameras have been estimated in international research to reduce violations by 40% to 50%, but methodological flaws tend to distort results regarding the nature of crash effects. Retting, Ferguson, and Hakkert (2002) conducted an analytical review of the literature to determine underestimations and overestimations so the true nature of the results can be extracted from the whole.

Overestimations tended to involve a failure to adjust for regression to the mean (Retting, Ferguson, and Hakkert, 2002). If an intersection is chosen because the number of violations occurring there is unusually high for a period of time, some reduction in violation frequency can be expected to occur even without intervention. Underestimations tended to occur when nearby intersections without cameras were used as a comparison, disregarding the spill-over (or "halo") effect. This effect refers to the tendency for signal violations to decrease at uninstrumented intersections in close proximity to instrumented ones.

Crash-effect studies were categorized by Retting, Ferguson, and Hakkert (2002), depending on whether the methodology addressed regression to the mean, regression to the mean and the halo effect, or neither. Studies that addressed neither (group 1) tended to include intersections chosen based on a high incidence of crashes. They also used noncamera sites close to the target intersections for comparison, possibly resulting in distortion due to both overestimation and underestimation. Studies that addressed regression to the mean (group 2) did so by selecting comparable sites for the control group. However, because they failed to account for the halo effect, crash reductions were likely to be underestimated. The one study that considered both effects resulted in a crash ratio that was likely to be neither underestimated nor overestimated.

Considering these distortions, Retting, Ferguson, and Hakkert (2002) found that a large halo effect does occur. Reductions at noncamera sites were nearly as large as reductions at the target intersection. Regression to the mean was partially (but not fully) ruled out because similar sites in communities without camera enforcement experienced little change in their violation rates—

and occasionally even saw a slight increase. Total reductions were between 22% and 78% across studies.

The camera/noncamera crash ratios for each study were weighted (by the number of crashes they took into account) and averaged. The group of studies that addressed neither the halo effect nor regression to the mean showed a statistically significant 39% reduction in injury crashes. The group that took regression to the mean into account averaged a non-significant 10% reduction in injury crashes. Results for the study that considered both the halo effect and regression to the mean showed a statistically significant 29% reduction in injury crashes, which, as predicted, lies in between the overestimates of group 1 and the underestimates of group 2. Rear-end injury crashes were generally found to increase slightly across the studies, but the drastic reduction in right-angle injury crashes more than offset that effect. To reiterate a point made earlier in this section, the main point of trying to get at the true value of reduction for red-light-running cameras is to understand the percentage of red-light-running behavior that is intentional. Based on the Retting, Ferguson, and Hakkert (2002) analysis, one could assume that this value is around 30% (or at least that 30% of drivers change their behavior in the presence of these cameras). However, this estimate is based on a single, well-designed study. Further studies of the issue may result in a mean estimate that is higher or lower than the one reported by Retting et al.

ALGORITHM COMPONENTS

Signal Phase and Timing

Van der Horst (1988) determined through a literature review that increasing the interval of the yellow light at signalized intersections by 1 second would help reduce the amount of red-light violators. During this study, 23 signalized intersections (on one route) were changed from a 3-second yellow light to a 4-second yellow light, and data were collected for one year (the yellow light was changed from 4 to 5 seconds on a different route). After one year, the number of red-light violators was reduced by 50% (from 1.1 to 0.5% of the total number of vehicles and from 13.4% to 6.7% of the number of vehicles closely negotiating a signal change from yellow to red). Next, the probability of stopping at intersections with vehicle-actuated control (i.e., "triggered" lights) was compared with fixed-time control. Van der Horst found that vehicle-actuated controls reduce the number of red-light violators considerably compared with fixed-time controls. The reduction was attributed primarily to a reduction in exposure.

The goal of a study by Stimpson, Zador, and Tarnoff (1980) was to determine how intersection conflict frequency depended on yellow-signal time duration. This study used two different sites to collect data. At each site, approaching traffic was photographed from nearby buildings (cameras were kept out of view). Each site satisfied the following criteria:

1. Average approach speed near 30mph.
2. Current yellow duration relatively short (less than 5 seconds).
3. Signal should not be activated by through traffic on the main roadway.
4. Reasonably isolated relative to other signalized intersections.
5. No pedestrian signals visible to drivers on the main roadway.
6. Four-legged intersection with simple geometrics and good pavement surface.
7. Level approaches on main roadway.

Stimpson et al. (1980) collected data by developing a “catch zone” that included the dilemma zone at most approach speeds for each intersection. The upstream extremity of the catch zone was the point from which a car with an initial speed of 10mph in excess of the local average speed could come to a full stop at the traffic signal using a uniform deceleration. The downstream extremity was the point from which a vehicle traveling 10mph below the local average speed at yellow onset could just clear the cross street prior to red onset (site 1: 65 to 320 ft; site 2: 25 to 320 ft). The motion of all vehicles in the catch zone was recorded. Filming began at least two seconds prior to yellow-signal onset and continued until all vehicles initially in the catch zone stopped or cleared the intersection.

A “decision vehicle” was defined if the vehicle was either the first vehicle to stop or the last vehicle to cross the intersection. Data were obtained by Stimpson et al. (1980) for 150 decision vehicles at each site under each experimental condition. The next step was to extend the yellow-signal duration. For site 1, the duration was set equal to the maximum duration acceptable to the traffic engineer responsible for signal timing at that location. For site 2, the duration was chosen to produce a percentage increase of similar magnitude. Data collection began again two weeks after duration increase and continued for several months.

For site 1, the frequency of potential conflicts originally ranged from 12% to 19% with the initial yellow duration of 4.6 seconds. With the extended duration (6.0 seconds), potential conflicts were reduced to 0% to 2%. At site 2, the initial conflicts percentages ranged from 63% to 90% with a yellow duration of 4.3 seconds. With the extended duration (5.6 seconds), potential conflicts were reduced to 19% to 21%.

Altering the signal timing, however, addresses only crashes that are caused by the existence of a dilemma zone, which causes drivers to make improper decisions while trying to beat the amber light. While a significant number of intersection crashes are related to this factor, many others (e.g., distraction) would not be solved by an extension of the amber light. Thus, complementing this solution approach is necessary in a CAS that addresses most causal factors for intersection crashes.

Brake Reaction Time

The time required for a driver to brake is one of the principal determinants of precisely when an alert or warning should be activated. The total perception-reaction time (PRT) is composed of several components, as listed below (Green, 2000):

- Mental-processing time: Required to perceive a stimulus and choose an appropriate response. This is a complex process and involves the following subcomponents:
    - Sensation (detection)
    - Perception (identification / interpretation)
    - Response selection (decision) & programming (preparation to act)
- Movement time: Required for subject to physically move in response, as in the driver lifting a foot from the accelerator and pressing the brake pedal
- Device response time: Required for the system to complete a response, as in how long it takes a vehicle to come to a stop after the brake has been activated

Alexander (1989) proposed a critical change in the definition of perception-reaction time as used in CWS algorithm development. Alexander argued that crossing an unsignalized intersection requires the driver to perform a series of head and body movements that is more demanding, more complex, and more prone to error than any other information-gathering task performed while driving. Because the perception component of PRT cannot begin until the object is seen, a "search" element should be added to the formal definition of PRT used in current literature. Search should precede the elements of PRT used now. Neither search time nor basic PRT should be treated as constants in these calculations since they vary by needs to move only eyes or head and torso as well (search) and by the information processing load, decision complexity, and expectancy PRT. Search time calculation for design standards should take into account the subsets of the user population who must move or process information more slowly due to aging, etc. Skewed angles of intersections and visual obstructions further prolong necessary task time and increase vulnerability to error. The greater the angle, the less can be seen since the combination of head and torso turn as well as interior vehicle sight obstructions can make looking beyond a 90° angle physically difficult.

The PRT norms established by standards organizations (2.5 s in the United States and 2.0 s in Europe) have also been questioned by researchers investigating the variables involved. The principal variables examined are expectation, urgency, age, gender, and cognitive load. Green (2000) analyzed and critiqued the methodology of the many brake-time experiments in the literature in an attempt to determine typical brake reaction-time values for different driving conditions. Because terms are used inconsistently from study to study, Green referred to the entire "mental processing time" step as perception time. If a measurement includes the first two steps, mental processing time and movement time considered as one, it is referred to here as brake reaction time (BRT). A measurement is termed stopping time if it includes all three steps from initial detection until the system completes the response (ST).

Two information-processing strategies are available to the driver according to human cognitive dynamics (Green, 2000). The first strategy, called automatic response, is either biologically reflexive (an innate, immediate reaction) or is so well-learned that it is functionally reflexive (as if the processing skips response selection altogether to go directly from sensation to movement). An example of this learned automatic response is hitting the brake pedal immediately when the lead vehicle's brake lights flash. The second strategy is attentive or controlled processing and occurs whenever novel events require thought to understand or react appropriately. Attentive processing takes longer than automatic processing because it requires cognitive assessment and problem-solving synthesis. Drivers use both strategies not discretely but on a continuum dependent on the scenario; Alexander (1989) recommends that this fact be taken into account when computing RTs for the development of algorithms to be used in both complex and simple situations.

The wide disparity in response-time data found by different researchers may be principally caused by the various methodologies used. The methodology used in each of the studies reviewed by Green (2000) fell into one of three categories:

1. Simulator studies: Researchers used fixed-base simulators, either car mock-ups or cabins of actual vehicles, with computer graphics or video presentation of the visual environment.

2. Controlled road studies: Participants drove vehicles on roads (public, private, or closed-track) with a researcher in the passenger seat. Because of this, participants were not entirely unexpectant, although they were unaware of the exact nature of the research.
3. Naturalistic observation: Researchers set up recording equipment to observe response times of entirely unaware drivers, using measures such as the time of onset of the lead vehicle's brake lights until the onset of the driver's own brake lights.

Green (2000) noted that each of these paradigms lacked ecological validity in some way. Simulator studies lack non-visual and peripheral cues, require fewer eye movements due to the smaller field of view, and have decreased cognitive load. Simulators produce brake RTs that are on average 0.3 seconds faster than other paradigms. Drivers in controlled road studies are more alert than they would normally be, and both controlled and simulator studies suffer large practice effects since subjects are usually tested with many repetitions. These factors also result in an underestimation of BRTs. Fambro, Koppa, Picha, and Fitzpatrick (1998) found that BRTs were lower when subjects drove a provided car rather than their own vehicle, which causes more variation in the results of studies using different methodologies. While naturalistic observation has the highest ecological validity, this method is limited by the difficulty of testing independent variables, observing urgent or emergency situations, and ascertaining sufficient demographic information to guard against sample bias.

A wide range of signals introduces further variability in the BRT estimates produced by these studies (Green, 2000). The signal is most frequently visual, such as the brake lights or unannounced slowing of the lead vehicle, a traffic signal, or an object such as a vehicle or barrel entering the road from the side. BRTs are fastest when the signal is foveal rather than peripheral, as viewers are consistently much poorer at detecting motion in the periphery. Auditory cueing generally produced faster BRTs, possibly because auditory transduction is mechanical, whereas the biochemical processes of visual detection are relatively slow.

Another significant variable is the nature of the measurements recorded and the precise manner of their acquisition (Green, 2000). Studies may have recorded a single total BRT, split the time into perception and movement time separately, or examined movement time alone. Perception time is typically measured from the onset of the stimulus to the release of the accelerator, and movement time from release of the accelerator to application of the brake, but the qualifying degree of change varies from study to study. Rise-time variation makes brake-light actuation an inaccurate measure of brake application, and microswitches attached to pedals to report brake pressure require varied and typically unreported degrees of pressure to trigger. Most studies measure only initial brake response, but time to full depression of the brake has been shown to vary widely between individuals, so an individual with a faster BRT may require more room to stop anyway if his or her time to full depression is slower.

Sohn and Stepleman (1998) also performed a meta-analysis to investigate the sources of variation in the studies of total braking time (TBT). Their main concern was the PRT associated with reacting to an obstacle in a vehicle's safe path. The meta-analysis compared the mean and variance of total braking time. Key factors included:

- Speed of the vehicle.
- Distance away from the brake stimulus.

- Awareness level of the experiment.
- Type of obstacle.
- Country in which the study took place.

Sohn and Stepleman (1998) found that the data obtained in the United States have significantly larger variance of TBT than those for other countries. This finding appears to be due to spacious road facilities and a larger pool of drivers in the United States.

Because RT data are almost always skewed toward longer values but most studies only report means, most people actually have RTs shorter than those means would suggest (Green, 2000). Standard deviations are also misleading because slower responders vary widely, while fast responders vary far less, resulting in statistical data variance that suggests fewer slow responders than actually exist.

The most influential variable affecting BRT is expectancy, and the studies can be divided into driver-alerted and driver-unalerted categories. The first group investigates reactions under ideal conditions in order to establish an upper bound on reaction time, whereas studies using unexpected stimuli seek to describe more natural behavior. Different studies define the terms expected and unexpected in various ways, thus Green (2000) re-classified the studies into three categories: expected, unexpected, and surprise.

Studies that Green (2000) categorized as expected established the fastest possible reaction times by reducing uncertainty both temporally and spatially. The driver was told to brake at a stimulus, and usually the stimulus occurred at a consistent time and location in the visual field. Practice effects strongly biased findings in this paradigm since each driver was exposed to the driving/reaction task many times; reaction times have been shown in the literature to decrease significantly from the first to subsequent trials with the same driver. The most ecologically valid result for conditions of low uncertainty involve an intense foveally-viewed signal and no recent practice; results under these conditions show the best expected brake RT to be about 0.70 to 0.75 s, split into about 0.50 to 0.55 s perception time and 0.20 s movement time.

Events in studies categorized as unexpected by Green (2000) were, at most, temporally uncertain but were never truly unexpected. The drivers in controlled studies expected something out of the ordinary because of the researcher in the passenger seat, while drivers in the naturalistic paradigm are somewhat prepared for a traffic signal to change phase or for the brake lights of a lead vehicle to illuminate. The data vary, but taken together they suggest that common but uncertain signals produce a reaction time of between 1.20 and 1.35 s. Standard deviations also vary widely, but 0.60 s appears to be a good estimate. The American Association of State Highway and Transportation Officials (AASHTO) standardized a reaction time of 2.5 s as achievable by 90 to 95% of the general population. These studies show the standardized norm to be close to the true value if the alerted driver is responding to “normal” road events in good weather.

Surprise intrusion studies test truly unexpected, low-probability events, most often involving an object moving into the vehicle’s path from the side of the road. Each participant is given one trial so that there are no practice effects. Surprise incursions in the roadway produce slow brake

RTs, so much so that the data clearly show that the surprised driver will take longer to brake than a driver in the other conditions (Green, 2000). While a completely expected event requires only about 0.75 s to evoke a braking response, a surprise incursion causes the average driver to take roughly twice as long, 1.5 s or more, to respond. Surprise stimuli take twice as long because perception, response selection, and movement times all take longer. The perception is slower because an unusual event takes longer to interpret, and selection of a response takes longer because the driver must compare the merits of (or choose between) steering and braking. The movement times were found by most studies to be over 0.3 s, a 50% increase over the results from expected conditions, possibly due to uncertainty in the execution of the decision.

Green (2000) examined the following variables (other than the experimental paradigm): age of the driver, gender of the driver, urgency of the situation, and the driver's cognitive load at the time of stimulus presentation. Surprisingly, age was found to lack a robust effect, although there is a slight tendency to find increases in RT as participants get older. The lack of a clear effect may be due to sample bias since healthier older people are more likely to drive and, thus, to volunteer to participate in a study. Another possible explanation is that the extra experience an older driver has accumulated compensates for the slowing of perception or movement, which is likely since they also recognize dangerous situations more quickly than younger drivers do. Researchers using simulators tend to find greater differences than the other paradigms, supporting the theory of experiential compensation because the scenarios in a simulator would be less affected by a driver's previous experience on the road. Cognitive load may increase any age effects; while the exact degree of the effect is unknown, it likely grows with task complexity and increased information-processing demands.

Green (2000) reported that the research data on the effects of gender on BRT are mixed. While some studies found faster responses by men, others found no detectable difference. None found women to be faster, which may be a result of fewer vehicle miles traveled by women, thus resulting in less experience under which to develop faster responses.

Time-to-collision (TTC) was used to determine the level of urgency in all the studies reviewed by Green (2000). Although it seems that increasing urgency would consistently decrease RT, the literature shows that this trend reverses when TTC is very short and a crash seems imminent. When the scenario involves an intersection, this increased RT may be due to the fact that an incurring driver is more likely to attempt to cross the subject's path when the subject has a greater time-to-intersection (TTI), so the subject stays alert. When the subject comes quite close to the intersection, however, the likelihood of cross traffic pulling out in front of him or her is significantly lower, so the subject may have dismissed the possibility and shifted attentional resources to other tasks. The time difference could also be caused by the additional time necessary to determine the best reaction or by a reflexive tendency for a driver to release the accelerator in response to an emergency situation (Hankey, McGehee, Dingus, Mazzae, and Garrott, 1996). The resulting curve is U-shaped, as it decreases with increasing urgency but increases when the emergency situation forces a driver to mentally process the feasibility of alternative reactions, such as steering. This is the situation referred to as "deer in the headlights," when a driver seems temporarily paralyzed and unable to take any action.

Attention is a limited resource, so an increase in cognitive load would potentially decrease the availability of attention to detect a brake signal, resulting in slower RTs (Green, 2000). One method of increasing cognitive load experimentally is to complicate the driving path with turns and variations in the speed of the lead vehicle. In-car devices also increase cognitive load, an effect compounded by the driver's fixation on a near object, which forces him or her to monitor the forward view through peripheral vision. Cellular phones are one highly researched cause of this distraction effect, including hands-free and standard models. Both phone types have been shown to cause dramatic increases in accident likelihood, concurrently increasing RTs by about 0.5 s. Signals such as activation of the lead vehicle's brake lights are more likely to cut through attentional distraction (and so produce lower RTs) than are less discrete cues such as the unannounced deceleration of a lead vehicle (without brake lights) or the surprise incursion of an object from the side of the road.

A few studies reviewed by Green (2000) concerned steering RTs instead of braking RTs. Results show that initial steering RT is several tenths of a second (about 0.3 s) shorter than initial brake RT. This difference seems logical considering that the movement time from accelerator to brake is also roughly the same length of time, whereas the hands are usually already on the steering wheel.

Green (2000) concluded that no single RT estimate covers all situations, but literature findings do converge sufficiently to allow reasonable guesses for specific scenarios. The strongest determinant of RT is expectancy, and in methodology using high expectancy and little uncertainty, the shortest predictable driver response time is from 0.70 to 0.75 s, of which 0.20 s is composed of movement time. Normal and common signals, such as brake lights, produce reaction times of about 1.25 s, including 0.30 s of movement time. These mean values are about 0.10 s longer than the median values for the same studies. Urgency is an important variable that decreases RT until TTC becomes short enough to necessitate alternative assessment, at which point it again increases. The age of the driver is a questionable variable, but it seems probable that older people have RTs 0.1 to 0.3 s slower than younger drivers in many cases. There may also be a slight tendency for males to react faster than females, although gender effects are unclear. Cognitive load increases RT, although the exact degree of increase cannot be estimated because of the wide disparity of data. Because no experiment can adequately measure the complex human sensitivity to environmental variables, RT estimation is necessarily a combination of generalized trends, basic human factors, and anthropometric or psychophysical data.

Although Green (2000) performed a comprehensive review of previous studies of reaction time and brake reaction time, it is also worthwhile to review some of the same studies directly. The most relevant studies are briefly outlined below to provide a basis for brake reaction time inputs for the ICAV algorithm.

Extensive evaluations of driver braking performance, including braking decelerations and driver reaction times, were conducted in a forward collision warning (FCW) system study using a closed course test track under dry weather and road conditions (Kiefer et al., 1999; CAMP 1). Testing at speeds of 30 to 60 mph, baseline studies first looked at driver braking levels (decelerations) without benefit of a FCW system as exemplified in normal and hard braking in which the driver was tasked to wait until the "last second" before braking safely to a stop behind a stationary lead vehicle. (Moving lead vehicle tests were also performed, but the stationary case is considered the most applicable to an intersection approach scenario.) These tests compared the driver's actual stopping distance to the available/required stopping distance between the lead vehicle and the subject vehicle at braking onset. These distances were then used to compute the corresponding (assumed constant) "actual" and "required" decelerations. Both actual and required deceleration data varied directly with initial vehicle speed, V_{SV}. Linear regression fits, labeled as the CAMP Actual Deceleration Parameter (ADP) equation (Equation 1) and the Required Deceleration Parameter (RDP) equation (Equation 2), for the stationary lead vehicle case, are given by:

$$dec_{ACTUAL} = -0.260 - 0.002216V_{SV} \tag{1}$$

(CAMP ADP equation; results in g's with V_{SV} in ft/sec)

$$dec_{REQ} = -0.165 - 0.002673V_{SV} \tag{2}$$

(CAMP RDP equation; results in g's with V_{SV} in ft/sec)

The required deceleration value, dec_{REQ}, is then substituted into the Braking Onset Range (BOR) equation $\{BOR = -V_{SVP}^2/(2*dec_{REQ})\}$ to predict the braking alone distance for a specified vehicle speed at braking onset, V_{SVP}. (Conforming units would be dec_{REQ} in ft/sec^2 if V_{SVP} is expressed in ft/sec.)

In addition to the baseline evaluation of kinematic braking distance data, three human factors studies were conducted that looked at driver braking reaction time (Kiefer et al., 1999; CAMP 1). Various FCW warning types were issued to trained and naïve drivers in both alert and surprise/unexpected conditions while approaching a lead vehicle. For the alert condition tests, attentive drivers approaching a stopped lead vehicle had an average BRT following a FCW warning of 0.52 seconds. Surprise, or unexpected, conditions tests used a FCW issued for a moving lead vehicle, initially at 30 mph, which then braked hard continuously without brake light activation. Strategies employed to create inattentive drivers for the surprise tests ranged from natural conversation to asking the driver to locate a non-existent dashboard indicator light, but results varied little between these scenarios. Surprise conditions lengthened the drivers' reaction times to about 1.2 seconds and 1.5 seconds for 85th percentile and 95th percentile drivers, respectively. Researchers concluded that the acceptable FCW timing boundaries should be defined with "too early" and "too late" brake onset range cut-offs. The "too early" BOR cut-off is determined using a 1.52 second driver brake reaction time and the assumed driver-applied deceleration from the CAMP RDP equation. Similarly, the "too late" BOR cut-off results from a reaction time of 1.18 seconds and the braking deceleration computed in the CAMP ADP equation.

The purpose of a study by Lerner (1993) was to "measure realistic on-the-road braking PRTs for unsuspecting older and younger drivers, and to determine whether the currently assumed design value of 2.5 seconds is adequate for drivers of all ages." Lerner found that 87% of the drivers made some kind of maneuver in response to a barrel rolled in front of the vehicle. Of this 87%, 43% steered and braked, 36% only steered, and 8% only braked. The mean BRT was found to be 1.5 s (SD = 0.4 s). There were no significant main effects of age or gender.

The results of a study by Landau (1996) on various approach speeds showed that a single deceleration value would be inappropriate for different closure speeds in the design of a timing algorithm for a CWS. A second study measured response time and severity of braking when cued by a warning light on the dash board, and it found that drivers preferred to brake at the lowest possible severity. The response time averaged 0.875 s from warning presentation, which agrees with the majority of studies investigating the reactions of alerted drivers who are anticipating a braking situation. This finding would not be applicable to the design of a system for distracted drivers. Landau described a two-stage warning hierarchy to address this issue. Findings from a third study by Landau showed that headway increased with relative vehicle speed, and drivers braked at longer distances from the lead vehicle as both vehicles' speeds increased. This finding implies that a single headway value for all warning modes would be inappropriate in the design of a timing algorithm. Because the drivers consistently chose to decelerate mildly, a caution warning stage to accommodate normal braking preferences was elected to supplement the emergency warning alarm.

A study by Hankey, McGehee, Dingus, Mazzae, and Garrott (1996) used a simulator to measure unalerted driver reaction times when the incurring vehicle came from different directions and at different temporal distances from an intersection. Findings showed that the initial reaction was more frequently to steer when the vehicle was coming from the right rather than from the left, possibly because drivers expected a left-incurring vehicle to stop prior to entering their lane. While there was no gender difference in initial reaction time, males tended to steer as a first response significantly more often. For the conditions with the two longest TTIs, the drivers generally slowed down to predict what the incurring vehicle would do. Drivers in the most critical situation reacted significantly more slowly than in conditions with longer TTIs; subjects in the 2.85 TTI condition performed their initial action 0.3 seconds slower than the other subjects.

A study by Schweitzer, Apter, Ben-David, Liebermann, and Parush (1995) monitored a group of 51 young male and female athletes during real driving conditions to determine total braking times. Individuals reacted to sudden brake applications for two following distances (6 and 12 m), two driving speeds (60 and 80 km/hr), and three awareness levels (naïve, partially aware, and fully aware of forthcoming maneuver). Effects were found for "distance" and "awareness stage." The "speed" factor did not achieve significance. A mean total braking time (TBT) of 0.678 s was found for trials in the naïve condition.

Fambro et al. (1998) examined adequate stopping-sight distances along highways. Stopping-sight distance is the sum of two components: brake reaction distance (distance traveled from the instant of object detection to the instant the brakes are applied) and braking distance (distance traveled from the instant the brakes are applied to when the vehicle is decelerated to a stop). The stopping-sight distances found in this study were used to support a new model for highway design.

Fambro et al. (1998) examined several other models and studies while developing this research, the most important of which is the Perception-Brake Reaction Time (PBRT) model. Perception-Brake Reaction Time "represents the total time it takes a driver to detect an object, recognize it as a hazard, decide on an action, and initiate that action." A study done by Johansson and Rumar (1971) established the 2.5s PBRT. AASHTO states that "for approximately 90 percent of the drivers, a reaction time of 2.5 seconds was adequate."

Fambro et al. (1998) used four different field studies to gather additional information on driver braking performance. The variables included vehicle-handling differences and driver capabilities associated with antilock braking systems (ABS), wet and dry pavement conditions, and the effects of roadway geometry. Studies 2 and 3 were split into three parts: Part A evaluated driver braking performance on an unexpected object; Part B evaluated driver braking performance on an expected object; and Part C tested the driver's baseline PBRT. Study 4 was an open-road study that measured driver braking performance to an unexpected object scenario. A PBRT of 1.98 s or less was found for 95% of the drivers. For Studies 2, 3 and 4, the mean PBRT for unexpected objects was approximately 2 s. The test subjects responded more quickly to the unexpected object when driving the unfamiliar vehicle than when driving their own vehicle. For Studies 2, 3, and 4, the mean PBRT for expected objects was 0.55 s.

A study by Johansson and Rumar (1971) investigated BRTs using both civilian drivers and an instrumented vehicle. The naturalistic measurements were made using 321 civilian drivers who braked as instructed in response to a klaxon horn at an unspecified location on a 10 km stretch of public road. The BRT was defined as the time from stimulus presentation to activation of brake lights. Results showed that median brake reaction time was 0.66 s, with times ranging from 0.3 to 2.0 s.

A second experiment by Johansson and Rumar (1971) compared reactions to a completely surprise signal with reactions to a somewhat anticipated signal. Five drivers were tested in an instrumented vehicle, 10 times per condition. The BRTs for the surprise condition were longer than the anticipated condition for every participant, but there was very little variation between subjects in median times of the same condition. The average individual median time for the anticipated signal was 0.54 s, and the average individual median time for the surprise signal was 0.73 s. By dividing the individual medians of the surprise condition by the individual medians of the anticipated condition, the correction factor of 1.35 was obtained. (A surprise signal causes a BRT 1.35 times as long as the BRT from a somewhat anticipated signal.) Applying this correction factor to the results of Experiment 1, the estimated brake time in 50% of all sudden accident situations was found to be 0.9 s or longer.

Liebermann, Ben-David, Schweitzer, Apter, and Parush (1995) performed a study exploring BRTs at two following distances (6 and 12 m) and two speeds (60 and 80 km/h). Two braking conditions were tested. In the "real" condition, actual braking was accompanied by normal activation of brake lights; in the second, the brake lights were activated, but the vehicle did not slow down (the "dummy" condition). The primary dependent variable of TBT was broken down into two parts: BRT and accelerator-to-brake movement time (MT). Results showed that drivers reacted and moved faster at the shorter following distance, similar to performance with real braking as compared to dummy braking. Almost all presentations of real braking produced braking responses (97%), whereas a smaller but still significant majority of dummy presentations resulted in braking behavior (83%). The authors concluded that brake-light onset may be enough to trigger a nearly reflexive (or "ballistic") braking response; the intensity of braking seems to be modulated according to changes in angular velocity during optic expansion of the decelerating lead vehicle.

A study by Hancock, Simmons, Hashemi, Howarth, and Ranney (1999) investigated the effects of cognitive and in-vehicle visual distraction on BRT and ST, which reflected intensity of braking. The stimulus presentation was temporally uncertain but not unexpected. Effects were tested for subject-vehicle speeds of 20 and 30 mph using a closed-circuit track with a traffic signal and an instrumented vehicle. Results showed that the presence of an in-vehicle distracter raised the average BRT from 0.61 to 0.93 s and that the average BRT at 30 mph (0.68 s) was faster than the average BRT at 20 mph (0.78 s). Women were shown to have a slightly higher BRT (0.95 s) than men (0.90 s), although the difference was not statistically significant. Mean time to full stop was shorter in the presence of a distracter (1.66 vs. 2.55 s). Subjects also braked harder at the higher speed (time to full stop of 2.07 vs. 2.14 s). Integrating these results with previous BRT research, Hancock et al. recommend a limit of two additional displays for tasks not concerning immediate vehicle control because more than two displays are likely to erode the margin of driver safety.

A study by Schreiner, Lee, and Dingus (2001) used a track, an instrumented test vehicle, and a lifelike surrogate vehicle to investigate driver responses to a subjectively critical situation. The driver of the test vehicle followed a lead vehicle several times around the track uneventfully before the lead vehicle changed lanes suddenly to reveal a stationary vehicle. The mean time to collision at stimulus presentation (as calculated using test vehicle velocity) was 2.99 s.

Schreiner et al. (2001) recorded many variables, including measures of the frequency and speed of steering responses as well as initial brake responses. The means of each of the following variables were calculated: time to initial driver action (TIDA = 0.78 s), transition time from accelerator to brake (TSAB = 0.2 s), time to brake (TB = 0.73 s), transition time from brake to full brake (TSBFB = 0.58 s), and time to full stop (TFS = 4.75 s). Those drivers whose first action was to steer instead of to brake had a mean time to steering (TS) of 1.14 s.

After the surprise presentation, Schreiner et al. (2001) asked participants whether some kind of warning alerting them to the presence of the stopped vehicle would have changed their reaction; all but one replied that it would have changed their reaction or that they would have responded sooner.

In an effort to synthesize the cumulative results from various methodologies, TBT distributions were estimated by Sohn and Stepleman (1998) as part of their meta-analysis of various braking time studies. Table 98 presents the 85th and 99th percentiles of brake reaction time for U.S. and non-U.S. studies.

Table 98. Example mean brake reaction time for studies in the U.S. and elsewhere.

	85th Percentile	99th Percentile
USA	1.92	2.52
Non-USA	1.69	2.26

The specific reaction-time studies referenced as part of this literature review have been summarized in two tables. Table 99 brings together results from many disparate conditions, originating in studies that investigated responses to either expected or somewhat anticipated events. Table 100 shows the results from prominent studies testing responses to complete surprise events. The variables and their definitions are as follows:

- **TAR** = Time to accelerator release: Time from initial stimulus appearance to beginning of accelerator release.
- **TS** = Time to steering: Time from initial stimulus appearance to initiation of steering input.
- **TSS** = Time to severe steering: Time from initial stimulus appearance and initiation of a severe steering input. While no set definition is available, lateral acceleration values over 0.2g caused by steering can be considered moderate.
- **TB** = Time to brake.
- **TFB** = Time to full brake: Time from the stimulus until the brake pedal was fully depressed.
- **TSAB** = Transition time from accelerator to brake: Time from the beginning of accelerator release to the point where the foot was positioned over the brake.
- **TSAFB** = Transition time from accelerator to full brake: Time from the beginning of accelerator release until the foot fully depresses the brake.
- **TSBFB** = Transition time from brake to full brake: Time from initiation of braking to full braking.
- **TIDA** = Time to initial driver action: Time between stimulus and first subject action performed.
- **TFS** = Time to full stop: Time to come to a full stop measured from initial stimulus appearance.

Table 99. Results from studies of responses to expected/somewhat anticipated events.

Study Details						Variables		
Study	Experiment	Stimulus	Paradigm	Condition	Speed	TAR	TB	TSAFB
Johansson and Rumar, 1971	Police stopped cars and asked drivers to participate; within 10 km a horn sounded	Horn on roadside	Naturalistic	Expected within 10km; one measurement/S	Unknown		0.66*	
	Driver using instrumented vehicle brakes to a buzzer	In-vehicle buzzer		Anticipated; 10 measurements/S			0.54*	
				Surprise; 10 measurements/S			0.73*	
Landau, 1996	Driver slowed at pre-determined deceleration rates (i.e., -0.1g) at stimulus presentation	Red light on dash	Track	Various deceleration rates	20, 30, 40, 50mph		0.875	
Liebermann et al., 1995	At two following distances and two speeds, lead vehicle braked either with or without brake lights	Lead vehicle's brake lights or slowing too	Track	Lights only, 6m behind LV	60 km/h	0.432	0.704	0.270
				Lights only, 6m behind LV	80 km/h	0.466	0.709	0.246
				Lights only, 12m behind LV	60 km/h	0.526	0.827	0.306
				Lights only, 12m behind LV	80 km/h	0.520	0.784	0.260
				Lights+slowing, 6m behind LV	60 km/h	0.380	0.608	0.229
				Lights+slowing, 6m behind LV	80 km/h	0.353	0.581	0.229
				Lights+slowing, 12m behind LV	60 km/h	0.436	0.683	0.252
				Lights+slowing, 12m behind LV	80 km/h	0.427	0.682	0.252
Study	Experiment	Stimulus	Paradigm	Condition	Speed	TAR	TB	TSAFB
Kiefer et al., 1999 (CAMP 1)	Test of FCW alerts for naïve and trained drivers, surprise and alerted conditions	FCW plus stopped lead vehicle	Track	Alerted	30 mph		0.52	

Study Details						Variables		
Hancock et al., 1999	Over 60 circuits of a closed-loop track, cognitive and visual distracters occasionally occurred simultaneously with traffic signals to stop	Stoplight signal from green to red	Track	Females, no distracter	20 and 30 mph		0.95	
				Males, no distracter	20 and 30 mph		0.90	
				M & F, no distracter	20 and 30 mph		0.61	
				M & F, distracter present	20 and 30 mph		0.93	
				M & F, distracter conditions combined	20 mph		0.78	
				M & F, distracter conditions combined	30 mph		0.68	

* Values reported for Johansson and Rumar, 1971 are medians and averages of medians; other values are means.

Table 100. Results from studies of responses to surprise events.

Study Details						Variable									
Study	Experiment	Stimulus	Paradigm	Condition	Speed	TAR	TS	TSS	TB	TFB	TSAB	TSAFB	TSBFB	TIDA	TFS
Hankey, 1996	SV approaches an intersection when an incurring vehicle suddenly enters intersection	Onset of incurring vehicle movement	Simulator	TTI = 2.85	55	1.55	1.44	1.88	1.79	2.19	.275	.68	.4	1.25	
				TTI = 3.60	55	1.1	2.13	3.38	1.43	2.125	.338	1.59	1.19	.95	
				TTI = 4.35	55	1.03	2.63	3.00	1.2	2.63	.388	1.59	1.19	.95	
Schreiner, et al., 2001	SV unexpectedly encounters stopped surrogate vehicle in lane	Stationary Vehicle	Track	TTC = 2.99	26		1.14		0.73		0.2		0.58	0.78	4.75
Kiefer et al., 1999 (CAMP 1)	Test of FCW alerts for naïve and trained drivers, surprise and alerted conditions	FCW & deceler-ating lead veh., no brake lights	Track	Self-chosen distance 85th %-ile	30				1.18						
				Self-chosen distance 95th %-ile	30				1.52						
Shutko, 2001	Heavy SV unexpectedly encounters stimulus with distracter task	Rolling barrels	Track	TTC = 1.5	20	0.5			0.92		0.42	1.74	0.81		3.95
Lerner, 1994	Trash barrel rolls into road	Trash barrel	Track	200 ft	40				1.5						
Fambro et al., 1998	Fabric fence suddenly rises from pavement	Fence	Track	213 ft	55				0.928						
	Barrel rolls out of the back of a truck and into the road	Barrel motion	Naturalistic	82 ft	44				1.1		xx				

xx values interpreted from graph.

Models

Among the considerable amount of collision-warning algorithm literature that exists, research into forward collision-warning algorithms was considered particularly relevant for the intersection case. As the technology to develop these systems has improved, so have the accuracy and, in some cases, complexity of the algorithms used to trigger a warning to the driver and/or an automatic vehicle response. Most of the algorithms that have been used are based on kinematic relationships, albeit some algorithms with a perceptual basis exist. In general, the algorithms can be classified according to their use of time-to-collision or stopping distance as their control variable. The relevant literature in the area is summarized in this section.

Janssen and Nilsson (1992) evaluated two different criteria to warn drivers: a TTC criterion and a "worst case" criterion. The TTC criterion warned drivers whenever the current TTC value was less than a preset amount; it was set at 4 s. The worst-case criterion warned drivers whenever there existed a configuration of vehicle speeds and distances in which a collision with more than a 10 km/h speed difference would follow if the leading vehicle were to suddenly brake with a 0.71g deceleration, considering a 1 s reaction time. Translated to the static vehicle case, this criterion would warn whenever a 0.71 g deceleration would be required to stop before the intersection. In general, results supported the use of the TTC criterion because the worst-case criterion warned drivers too late for them to avoid a collision.

Using vision technology, Roessle, Krueger, and Gengenbach (1993) created a driver's warning assistant that takes into account three different positions while approaching an intersection that are contingent on the driver's speed and braking parameters:

- Earliest warning position: point at which driver normally starts braking.
- Latest warning position: latest point at which a driver is able to stop in time.
- Latest action onset position: latest point at which movement must be initiated to stop in time.

While no method for the calculation of these positions is provided, these researchers present values for two conditions. At 30 km/h, the earliest warning position is set at 20 m, while the latest warning position is set at 13 m. Values of 40 and 30 m, respectively, would be used for a 50 km/h speed.

Simulation models have also been used in the development of these collision algorithms (Shinar Rotenberg, and Cohen, 1997). The algorithm created was used to develop a system that pre-activated the brake lights when possible hard braking was detected. Although the algorithm used is not applicable to the intersection problem, several inputs to the simulation are relevant to this review:

- For unalerted drivers, perception-reaction time (time from appearance of a stimulus to accelerator pedal release) averaged 0.7005 s (SD = 0.0239 s) and brake-movement time (time from initiation of accelerator-pedal release to initial depression of the brake pedal) averaged 0.3982 s (SD = 0.0185 s). For alerted drivers, average values for these times were 0.5182 s (SD = 0.0177 s) and 0.2238 s (SD = 0.0064 s), respectively.
- Brake lag time of the vehicles was assumed to average 0.11 s (SD = 0.0133 s).

Simulation was also used to test an algorithm developed by Farber and colleagues (Farber, 1994; Farber and Huang, 1995). Their algorithm is based on closing rate for two moving vehicles:

$$D_w = \frac{(FCS - LCS)^2}{2a_w} + (FCS - LCS)RT_w \tag{3}$$

where D_w is the warning distance, *FCS* is the following vehicle speed, *LCS* is the lead vehicle speed (zero in the intersection case), a_w is the deceleration of the following vehicle, and RT_w is the driver's response time. Initial estimates of a_w and RT_w were 0.31 g and 2.5 s respectively. Researchers indicate that the warning rates using these parameters might be too low to be sufficiently effective.

Knipling et al. (1993) used a similar approach in the development of rear-end collision algorithms. Their equations for the lead vehicle stationary situation are applicable to the intersection situation. Simulation results described by the authors indicated that systems using this algorithm would be effective, on average, in 79% of the crash situations studied if a sensor-dependent detection range of 300 ft was assumed. Assumptions made in the design of the algorithm included:

- Driver inattention was a principal cause of the crash.
- Driver's only response was to brake (i.e. no steering).
- Driver fully complied with the warning.
- The system had a 250 ms delay in issuing a warning.
- The driver reaction time was 1.50 s.
- The delay to maximum braking was 300 ms.
- The vehicle could brake at 0.6 g.

Krishnan, Gibb, Steinfeld, and Shladover (2001) used simulation techniques to design and test a collision-warning system for the lead vehicle not moving case. The system was designed to maximize its capability of preventing crashes, to minimize the severity of crashes, and to reduce the frequency of nuisance alarms. Their algorithm was based on several parameters obtained from the literature, including:

- Emergency braking distribution for new light-duty vehicles following a mean of -8.5 m/s^2 (0.87 g) with a standard deviation of 0.6 m/s^2 (0.06g). Note that these deceleration levels are particularly high and are typically only accomplished with professional drivers. This is a considerable limitation of this model.
- These values had to be derated to model vehicle wear and tear and unwillingness of actual drivers to brake at these elevated levels. The derated mean deceleration was -5.5 m/s^2 (0.56 g), maintaining the same standard deviation.
- The mean comfortable deceleration is speed dependent, as calculated with the following equation (A_{comf} in m/s^2, V_0 in m/s):

$$A_{comf} = -0.735 - (0.0859V_0) \tag{4}$$

- Response time distributions vary depending on driver state, alerted, surprised, and unalerted, with a distraction modifier. Surprised drivers have been reported to respond, on average, within 1.1 s (SD = 0.305 s) for objects stopped in the middle of the road. However, driver reaction time to moving vehicles is higher than this value.

- Sensor and brake delay times should be accounted for. For comfortable braking, a 200 ms delay should be added. Sensor delays are sensor dependent

Based on these assumptions, Krishnan et al. (2001) developed equations for two warning distances, stopping and comfortable. Stopping distances represent the distance from which the driver would have sufficient time to stop if they use emergency-braking deceleration. Comfortable distances represent the distance that would be traveled by a driver using comfortable deceleration levels. Equations for these distances follow:

$$R_d = -\frac{V_0^2}{2A_d} + (T_d + T_{sensor})V_0 \tag{5}$$

$$R_{comf} = -\frac{V_0^2}{2A_{comf}} + (T_d + T_{sensor} + T_{brake})V_0 \tag{6}$$

where R_d is the stopping distance and R_{comf} is the comfortable distance. A_d and A_{comf} represent braking capability and comfortable braking decelerations, respectively. T_d represents the driver response time, T_{sensor} and T_{brake} represent sensor and brake delay times, respectively. V_0 represents the vehicle speed.

The authors then determined probabilities of warning effectiveness and nuisance and used values within the limits set by R_d and R_{comf} as possible settings of the warning system. The end result is a possible warning design contour, but no detailed description of its parameters is available. The proposed warning design contour would warn a driver traveling at 55 mph when the distance to the intersection was smaller than ~400 ft.

Kinematic equations were also used by Hashimoto, Sasaki, and Kawai (1995) to describe driver braking behavior when approaching a stationary vehicle and, thus, determine an appropriate warning range:

$$\mathrm{X_{br}} = V_0 tau + \frac{1}{2}\frac{V_0^2}{a_0} \tag{7}$$

where $\mathrm{X_{br}}$ is the distance at which the driver senses a hazard and steps on the brake pedal, V_0 is the speed of the driver's vehicle, *tau* is an empirically determined constant indicating a reaction time, and a_0 is the mean acceleration with which the driver intends to stop.

The distance provided by this equation must be added to a free running distance caused by the driver's response delay. In empirical tests (five participants) to determine the value of some of these parameters, Hashimoto et al. (1995) found that *tau* ranged from 1.2 to 2.3 s, and a_0 ranged from 5.9 to 11.1 m/s^2. These acceleration values represented driver *intentions*; actual corresponding values were closer to 0.5-0.6 g, as expected for normal drivers. Large a_0 values simply represented situations in which the driver was either distracted too long or misjudged his/her braking capabilities. In these tests drivers were allowed to brake normally the moment they perceived that a target (which was stationary) would become a hazard if they did not brake.

These results were used in the development of an "automatic" braking system with a deceleration authority of eight m/s^2 and distinct warning and auto-braking zones.

Pierowicz, Jocoy, Lloyd, Bittner, and Pirson (2000) applied a kinematics-based algorithm to the intersection problem considering both SV and POV actions. Nominal velocity (40 mph) and acceleration (0.15 g) were assumed for the drivers' intentions. If any of the radars in the intersection (the system was designed to warn under a variety of crash scenarios) predicted a collision using these assumed parameters and basic logic, the system triggered a warning. This work is described in further detail in the review of Veridian's work presented later in this report.

Burgett, Carter, Miller, Najm, and Smith (1998) developed a commonly cited kinematics-based algorithm that uses range and range-rate to determine warning timing. Three main assumptions were made in the development of the algorithm:

- Constant deceleration after a warning would bring the vehicle to a stop at a distance of 6.67 ft behind a stopped vehicle.
- The deceleration of the vehicle is near 0.75 g
- There is a delay of 1.5 s between collision warning and brake activation.

The warning algorithm function used in this study follows:

$$\mathrm{WD} = \frac{V_F^2}{2d_F} + T_d V_F + R \qquad (8)$$

where WD is the distance at which the warning should be issued, V_F is the vehicle's absolute speed, d_F is the vehicle's deceleration, T_d is the warning time delay (assumed), and R is a confidence interval (assumed).

The researchers tested delay times of 1.0 and 1.5 s and concluded that the earlier warning produced faster reaction times and fewer, less severe, crashes (the study was simulator-based) than other conditions. The R parameter was set at 6.67 ft. A similar equation was developed by the Virginia Tech Transportation Institute (2000) to address the warning of following vehicles for minimizing the incidence of rear-end crashes. The Society of Automotive Engineers (1974) also employed a similar approach, assuming a braking capability of 90% of the maximum surface-friction coefficient. At 55 mph, their required range was ~150 ft. This system, however, was configured as an automatic braking device, thus, driver reaction time did not have to be considered.

Using a similar approach to Burgett et al. (1998), Lee, McGehee, Dingus, and Wilson (1997) used the following assumptions in determining their warning timing:

- Vehicle can decelerate at up to 0.75 g.
- Full brake reaction time is 2.15 s.
- Sensor processing delay is 300 ms.
- Display warning is 400 ms.
- Total reaction time equals 3.2 s.

Results using this warning approach indicated that the system could reduce the number and severity of crashes by reducing the collision speed and increasing headway. These outcomes, however, were achieved through a quicker time to accelerator release, rather than quicker brake applications.

Lee and colleagues (Lee, McGehee, and Brown 2000; Lee, McGehee, Brown, and Reyes, 2002a and 2002b) used the Burgett et al. (1998) algorithm in simulator tests of different conditions in which a warning would be required. "Early" warnings were more effective in reducing driver reaction times than "late" warnings (or no warning). This benefit was apparent in both distracted and undistracted drivers. In the early condition, the algorithm warned when a 0.40 g deceleration (d_F in Equation 8) would be required to stop in time, whereas the late condition required a 0.75 g deceleration. In a finding relevant to future research in the area, these researchers found that early accelerator release (produced by early warnings) was more important in crash avoidance than fast brake application. Thus, warning systems that can produce early accelerator releases will likely be more effective than those who leave it unaffected (or increase it).

More recently, Phamdo, Brunson, Preziotti, and Kyle (2002) expanded the Burgett et al. (1998) algorithm to include the possibility of driver sensitivity adjustments and to consider driver braking behavior. Their mathematical model (detailed in the paper) is based on the following physical model:

- Due to the presence of an obstacle, the driver decides to brake.
- The driver estimates his/her speed and the required stopping distance.
- The driver applies the brake in such a way so that he/she will come to a stop slightly before reaching the required stopping distance.
- It is not possible for the driver to brake harder than what the vehicle is physically capable of braking.
- Even under the same exact circumstances (speed and distance), the driver does not react the same way every time.
- Hard braking cannot occur instantaneously.

These researchers limit a vehicle's maximum braking capability to 0.8 g. In the model, a random component is added to the acceleration derived from physical parameters, and that acceleration level is filtered using a simple finite-impulse response low-pass filter to gradually increase the effective deceleration level once the brake is depressed.

Empirical evaluation of many of these algorithms has also been performed. In studying an automatic braking system, Fujita, Akuzawa, and Sato (1995) used empirical testing of avoidance maneuvers to develop a collision-avoidance system activation algorithm. Empirical results were used to generate this equation:

$$L_W = 2.2 \times DV + 6.2 \tag{9}$$

where L_W is the distance (in meters) at which the warning is given and DV is the difference in velocities (in meters per second) between a leading and a following vehicle (equal to the vehicle velocity for the intersection case). The equation produces distances in meters. These researchers do not describe any empirical testing of the equation using normal drivers.

Similarly, the Society of Automotive Engineers (1998) describes several efforts in algorithm development for an "automatic" collision-avoidance system, albeit without describing the specific parameters and equations used. While stressing that any algorithm should allow a certain level of driver customization, SAE summarizes three different algorithms:

- Mazda's algorithm: This algorithm employs a braking critical-distance definition derived using the vehicle velocity, relative velocity, maximum deceleration rate, delay times, and headway offsets. The warning is triggered when a critical headway distance (velocity dependent) is breached.
- Honda's algorithm: While the parameters used to generate the braking critical-distance definition remain the same, the critical distance obtained using this algorithm is more aggressive (i.e., smaller) than Mazda's.
- Proposed algorithm: Researchers in this paper propose a graduated light display that informs the driver on their following behavior. Parameters generating the light display can be adjusted to different drivers. Haptic warnings (in the form of applied braking) would be presented if a very conservative criterion is exceeded.

Simulation was used to test the proposed algorithm, but no information is provided on the actual parameters used to generate the warnings.

Empirical data on driver-deceleration levels has also been used by CAMP to generate collision-warning algorithms (Kiefer et al., 1999). The equation considers only closing speed in predicting an acceptable acceleration level that produces a suitably timed warning:

$$a_{REQ} = -0.165 - 0.00368 V_{SV} \qquad (10)$$

where a_{REQ} is an observable deceleration level (in g) and V_{SV} is the vehicle's velocity. This deceleration level is then input to a standard kinematics equation to produce the distance needed to bring the vehicle to a stop once the brakes have been applied, called the Brake Onset Range (*BOR*):

$$BOR = \frac{V_{SV}^2}{-2a_{REQ}} \qquad (11)$$

This *BOR* is added to an expected reaction time (nominally set at 1.18 s). An allowance for brake system delay time is provided (200 ms), and one for interface delay time is recommended, but no specific values are provided. The algorithm would allow a certain degree of adjustability in driver sensitivity by employing a more liberal a_{REQ} equation (i.e., one producing higher deceleration values).

Some kinematics-based approaches have been complemented by driver perception studies. Hirst and Graham (1997) created a collision-warning algorithm based on human perception. These researchers proposed a TTC based algorithm defined using the following equation:

$$R_W = TTC \times \frac{dR}{dt} + SP \times V_F \tag{12}$$

where R_W is the range at which the warning will occur, *TTC* is the time-to-collision (replaced by time-to-intersection in the case at hand), *dR/dt* the derivative of range with respect to time (same as speed in the case at hand), *SP* is a speed penalty factor and V_F is the vehicle's speed. The authors recommend setting the *TTC* and *SP* parameters at 3.0 s and 0.4905 m/km/h.

In an interesting evaluation of different approaches to the collision-warning problem, Brown, Lee, and McGehee (2001) tested a kinematics-based algorithm (Burgett et al., 1998) and a TTC algorithm (Hirst and Graham, 1997) using simulation. Results were empirically verified in a driving simulator. These algorithms have been previously described in this review. In general, the kinematics-based algorithm was more effective than the TTC algorithm, although both reduced the number and severity of accidents. Researchers suggest, however, that the original time-to-collision algorithm speed penalty (0.4905 m/km/h) be increased to a number between 0.8339 and 0.9811 m/km/h to allow higher reaction times. For the kinematics algorithm, reaction time was found to be more important on system performance than assumed deceleration levels, a finding supported by the need to impose an additional speed penalty in the TTC algorithm. Finally, in describing braking behavior, researchers found good agreement with a step-response (average r = 0.853, range = 0489-0.980). When low correlations were observed, they were due to driver modulations of the braking response.

Assumptions regarding drivers' braking behaviors are important for each of these algorithm approaches. Groeger (2000) described studies on drivers' braking behavior reacting to stationary targets. Empirical data from this study supports the idea that drivers use TTC and TTC change, to determine their braking behavior. This researcher cites the following sequence and timing of events:

- Stimulus to stop occurs.
- Driver begins to reduce pressure on the accelerator (500-600 ms, completed in ~400 ms).
- Movement of foot from accelerator to brake (100 ms).
- Braking pressure is applied.

In general, Groeger (2000) points out, braking pressure is not evenly applied. Minimum TTC is more or less coincident with the maximum brake pressure but increases much more rapidly than the reduction in brake pressure (has a steeper slope when graphed).

DRIVER VEHICLE INTERFACE CONSIDERATIONS

Past research has identified and examined a considerable diversity of driver-vehicle interfaces. The main distinguishing characteristic between these interfaces lies in their use of different warning modalities. Three warning modalities are feasible in the context of collision warning: visual, auditory, and haptic. Research on each of these modalities and their combinations has typically focused on designing to maximize warning effectiveness and to minimize harmful effects. While relevant research on driver-vehicle interface (DVI) development is summarized in this section, the reader is referred to Appendix A for a more comprehensive overview of the literature reviewed as part of this effort.

Visual DVIs have been evaluated by Horowitz and Dingus (1992) and McGehee, Dingus, and Horowitz (1992). These researchers advocated the use of graphical graded warnings. The timing and frequency of these warnings were considered important design considerations because these issues could affect driver attention to the warning and/or driver mental workload. While visual collision warnings typically take many forms, icons are a commonly researched format that has been proven to be an effective warning mechanism (Yoo, Hunter, and Green, 1996; Nakata, Campbell, and Richman, 2002; Richman, Campbell, and McCallum, 2002; Sayer, 2002). However, there is an important caveat with visual icons used independently of other modalities concerning older drivers: these drivers typically need higher warning luminance levels to detect a warning than do younger drivers (Davies and Rose, 1996).

Auditory warnings have also been the subject of numerous research efforts (Ben-Yaacov, Maltz, and Shinar, 2000; Hurwitz and Wheatley, 2001; National Transportation Safety Board, 2001; Ben-Yaacov, Maltz, and Shinar, 2002). This modality encompasses three distinct categories of warnings: speech, tone, and auditory icons. Speech warnings imply a recording or a synthesized voice that repeats a certain word or set of words (e.g., Warning!; Baldwin and Moore, 2002). Tone warnings use pure tones or combinations of tones to grab the drivers' attention. Auditory icons are also tone based, but the sound has an implicit meaning associated with it (e.g., sound of a tire screeching or sound of broken glass). Auditory icons have been proven to be very effective warning mechanisms, as long as the sounds are relevant to the situation (Graham, Hirst, and Carter, 1995; Graham, 1999). In general, however, speech is a less effective warning mechanism than pure tones or auditory icons (Tan and Lerner, 1995; Lerner, Steinberg, and Perel, 1997). Nevertheless, research is inconclusive as to the effects of loudness and frequency and perceived urgency. As with the visual modality, the effectiveness of auditory warnings is dependent on appropriate warning timing and frequency of occurrence (Lerner, Dekker, Steinberg, and Huey, 1996; Lerner et al., 1997), and older drivers require increased stimulus levels (Baldwin, 2002). Auditory warnings can be localized, however, which increases the usefulness of the modality in a variety of crash situations (Tan and Lerner, 1996; Lerner et al., 1997; Bliss and Acton, 2000).

Haptic warnings have taken the form of a brake pulse (Hashimoto et al., 1995), accelerator push-back (Bloomfield et al., 1998), steering-wheel vibration (Tijerina et al., 2000; Steele and Gillespie, 2001; Tijerina, 2001), and seat vibration (Zador, Krawchuck, and Voas, 2000). While effective in general, the use of these devices has been hindered by the need for special equipment that ties into the vehicle's control mechanism, raising safety and cost concerns, and the sometimes unexpected driver reactions, raising safety concerns. The effectiveness of each of the categories is similar, but Tijerina et al. and Tijerina suggest that steering-wheel vibration should only be used when a steering action should occur. Some of these systems have been developed as part of automatic braking devices with a limited braking authority.

The availability of these various modalities has motivated researchers to combine their use. Using this approach, some of the drawbacks of a particular modality can be overcome by the other modality(ies) that is(are) being used to warn. The possibility of combining these modalities has, in turn, prompted several researchers to develop design guidelines for the development of collision-warning systems.

One of the most comprehensive set of guidelines for visual and auditory modalities is provided by Green, Levinson, Paelke, and Serafin (1993; 1995). Basic visual-display guidelines include minimizing the information content of what the driver needs to read and placing displays near the line of sight. Other visual-display guidelines are provided in terms of legibility, understandability, organization, and content. Auditory-display guidelines are organized in terms of loudness, discriminability of warning sounds, and use of synthetic vs. recorded speech.

Another set of collision-warning display design guidelines was developed by Campbell, Carney, and Kantowitz (1997) and Campbell, Bittner, Pierowicz, and Lloyd (1998). These guidelines specify appropriate display types and formats for various information elements and vehicle states. These researchers also provide guidelines to estimate message complexity and priority. Head-Up displays receive particular emphasis in the document because these systems are becoming more prevalent.

Design guidelines applicable to a broader collection of displays were developed by Hanowski et al. (1999). In general, these researchers suggest that drivers benefit from the use of information devices; drivers can successfully transfer their attention between the road and the warning; older drivers tend to be more cautious in using the devices; older driver limitations in using the system might be addressed by improvements in system design, and auditory cues should be adjustable for intensity. Similar (in scope) guidelines are provided by Schumacher, Olney, Wragg, Landau, and Widmann (1995), Landau (1996), and Olney,Wragg, Schumacher, and Landau (1996). These researchers specify that warnings should draw the attention of the driver to the nature and direction of the hazard and that head-up displays are preferred over head-down displays. In addition, specific design principles are provided for visual, auditory, and haptic warnings. Lloyd, Bittner, and Pierowicz (1996), Lloyd, Barnes, Wilson, and Bittner (1999a), and Lloyd, Wilson, Nowak, and Bittner (1999b) also provide similar guidelines, albeit their focus is on the haptic modality. These researchers suggest the following criteria for the selection of a DVI warning modality:

- Benefit all drivers.
- Not require specific directional orientation.
- Be compatible with driver’s response.
- Have viable integration with other systems.

COMSIS (1996) developed specific guidelines based on the warning modality and the type of crash. While specific design principles are provided in this reference, some general guidelines include:

- Use multiple levels of warning, the more imminent the crash, the more intrusive the warning.
- Use unique imminent crash warning signals to minimize confusion and increase saliency.
- Imminent crash warnings should be of at least dual modality.
- Schemes for warning prioritization must be created.
- The warning must be compatible with expected driver behaviors (e.g. vibrating the accelerator might cause the driver to look down, an undesired and potentially harmful reaction).
- The content of the warning message is mostly device specific.

- The status of the device (i.e. operational or not operational) must be easily available to the driver so that no reliance is made on technologies that are not working.
- Nuisance warnings must be minimized.

Similarly, Dingus, Jahns, Horowitz, and Knipling (1998) suggest the following guidelines for in-vehicle warning systems, gathered from various literature sources:

- Provide redundancy in system design.
- Draw attention to the emergency situation.
- Prioritize visual displays by location.
- Avoid auditory signals for advisory warnings.
- Avoid speech displays for attentional warnings (use only for emergency).
- Provide unique warnings.
- Incorporate intelligence in warning presentation dynamics.
- Prioritize driver workload and warning (emergency warnings take precedence over anything else).
- Individualize warnings (e.g. novice vs. experienced).

Research on specific combinations of the various modalities is also abundant. Combining auditory and visual modalities, McGehee, Dingus, and Horowitz (1994) and Dingus et al. (1997) determined that the addition of auditory warnings to visual warnings served to improve driver reactions times. This reduction in driver reaction time has further been qualified as a reduction in the time to accelerator release (Lee et al., 1997; Lee et al., 2000; Brown, Lee, and Hoffman, 2001; Lee et al., 2002a and 2002b). Similar results were obtained by Belz (1997) and Belz et al. (1998, 1999) using auditory icons as the auditory display. Shirkey, Mayhew, and Casella (1996) determined that a multi-modal system using auditory and visual displays was more effective than each modality on its own, due to a decrease in the participant's ability to identify warnings that were offered using a single modality. A similar modality combination has also been shown to be effective in collision-warning systems for heavy trucks (Tomioka, Sugita, and Gonmori, 1995; Eaton VORAD Technologies, 2000). These benefits can be maximized by using graded and dynamic warnings (General Motors Corp. and Delphi-Delco Electronic Systems, 2002a, 2002b).

Combinations of auditory and haptic modalities have also received some attention, especially for their use in 'automatic' braking systems (Shefer and Klensch, 1973; Society of Automotive Engineers, 1974; Troll, 1974). Studies on this combination of modalities have shown that haptic warnings, in the form of a brake pulse, can reduce the number of collisions, likely because the vehicle is already braking while the warning is provided (Shutko, 1999). This researcher also determined that auditory warnings result in faster reaction times than do haptic warnings.

Combinations of the three warning modalities have also been studied. For studies of this nature, the determination of a 'best' modality has been attempted, but various researchers reach different conclusions. For example, Janssen and Nilsson (1992, 1993) determined that the haptic modality was the most effective in reducing headways while avoiding the development of other risky behaviors (e.g. increases in speed). Perhaps the most visible effort with respect to the design of tri-modal collision-warning devices, however, is being performed by the Crash Avoidance Metrics Partnership (CAMP 1: Kiefer et al., 1999; Kiefer, 2000). After considerable testing of numerous participants, this partnership developed a DVI consisting of a single-stage crash alert consisting of the non-speech tone combined with a flashing high head-down display of the visual icon with the word "WARNING." Recent reports by other groups, however, suggest that graded warnings, combined with head-up displays, are a better warning mechanism than this original alternative (General Motors Corp. and Delphi-Delco Electronic Systems, 2002a). A similar conclusion on graded warnings has also been reached by Pierowicz et al. (2000) (see also the review of Veridian's work, later in the report). Head-up displays were also effectively used by Zador, et al. (2000), especially when assisted by a haptic display. Zador et al. found that auditory warnings were generally considered the most annoying; however, they were very effective in attracting participants' attention.

Finally, the accelerated development of collision-warning systems, evidenced by the substantial amount of research available on them, has prompted the International Standards Organization (ISO) to develop a standard for the design of these systems (International Standards Organization, 2002). The main recommendations in the standard include:

- Inclusion of at least two separate (i.e., graded) warnings, preliminary collision warning and collision warning.
- Audible and/or tactile modalities should be the primary modalities; visual warnings may be used only in addition to one of these modalities.
- When a vehicle has more than one warning (e.g., rear and forward collision warning), each warning should be clearly distinguishable to the driver.

BEHAVIORAL ADAPTATION TO COUNTERMEASURES

Changes to the driving task or driving environment can result in long-term behavioral changes, which can be either positive or negative. A study by Ben-Yaacov et al. (2002) showed that safety interventions can have positive effects in the long term by educating drivers about safer driving strategies. They tested a forward collision-warning system using a laser headway detection device programmed to sound an auditory warning beep when temporal headway (the time until the subject vehicle reached the place of the lead vehicle) fell below a specified limit. The effects of reliability were investigated by testing subjects at system accuracies of 95, 80, or 60%. After a pre-exposure run with no system, each subject was exposed to one of the warning conditions. A last run with no system was performed immediately after these runs to test short-term learning effects, and six months later the subjects returned for another run with no system to test for long-term effects.

Findings showed that drivers are poor at estimating temporal headway, almost always thinking that there is more time available to stop than there actually is. The drivers' headway estimation can be greatly improved by a warning system such as the one investigated by Ben-Yaacov et al. (2002). The amount of time spent in the danger zone (defined as less than 1 second temporal headway to the lead vehicle) dropped significantly immediately after exposure to the system. Surprisingly, the time spent in the danger zone during the follow-up trial six months later did not differ significantly from the trial immediately after exposure. One implication of this result is that people can learn quickly to alter their behavior safely in response to valid feedback and that this learning can be incorporated into the driver's habitual strategies. The results unexpectedly revealed that no significant difference existed among the levels of reliability, so a system whose warnings are accurate only 60% of the time can be roughly as beneficial as a system with 95% accuracy.

Because drivers tend to overestimate the amount of time available to brake, a system that presents valid information about when safe braking should occur can effectively educate the driver to change habitual behavior. This effect can be so prominent that Ben-Yaacov et al. (2002) recommend that collision-warning systems of this sort be incorporated into driver training programs. Even short-term use, when combined with encouragement to continue the safer strategies, should lead to significant increases in safe driving behavior.

Other researchers have observed unintended changes in driver behavior with safety interventions designed to lessen crash risk. An analysis by Young, Frantz, and Rhoades (2002) summarizes and interprets findings regarding the nature and implications of behavioral adaptation. These changes in driving strategy tend to result in one of the following:

1) **Increased risk-taking**
   Safety interventions designed to influence driver decision-making tend to take the form of more robust environmental information, as seen in infrastructural changes such as paved shoulders, lane widening, and warning signs for curves. All three have been shown to result in higher vehicle speed, probably because the driver feels more secure and prepared to deal with the consequences of increased risk. The studies also showed that the interventions did produce some net increase in safety but less than was expected.

2) **No safety alteration, or less of a benefit than was expected**
   The same principle of more dangerous behavior negating more favorable conditions applies, but in this case the dangerous behavior results in a disbenefit strong enough to either significantly reduce or eliminate positive safety effects. For instance, researchers have long been concerned that the overall effect of more efficient brakes on road safety is actually detrimental. Studies evaluating ABS technology found that the risk of the vehicle being rear impacted increases due to drivers' tendencies to drive faster and with less headway.

3) **A net decrease in safety regarding the hazard primarily addressed by the intervention**
   Safety interventions occasionally magnify the exact hazard they were designed to reduce. A law mandating the wearing of helmets for motorcycle riders in Nigeria raised the frequency of fatalities from motorcycle crashes by more than 150%, again owing to the increased risk-taking of motorcyclists.

4) **A net decrease in safety regarding an associated but secondary and unaddressed hazard**
   Hazards not directly associated with the safety intervention may also be exaggerated by the negative repercussions of behavioral adaptation. If protective gear for one part of a machinist's body is made mandatory for safety purposes, the frequency of injuries to any part of the body may actually increase due to the machinist's increased sense of ease and control.

Young et al. (2002) suggest several methods of circumventing the adaptation itself in order to prevent unintended negative consequences:

- Keep the user unaware of the intervention entirely so no changes in driving strategy result from it.
- If keeping drivers ignorant of the intervention is not possible, minimize awareness of its safety-enhancing effect.
- If behavior is unaffected by safety concerns in the first place, behavioral adaptation will not be a factor in intervention.
- If behavior is tightly controlled from the start, people will likely not alter it in response to an intervention.

The complex nature of human behavior makes it difficult to predict how a product will affect driving strategy. Young et al. (2002) conclude that product exposure alone will reveal the full repercussions of many safety interventions. Consideration of possible long-term behavioral adaptation, either positive or negative, is a topic that will be kept in mind throughout the life of the ICAV project.

PREVIOUSLY TESTED VEHICLE-BASED COUNTERMEASURES FOR INTERSECTION CRASHES/VIOLATIONS

Perhaps the most comprehensive effort to date in creating and evaluating vehicle-based countermeasures for intersection violation was performed by Veridian (formerly Calspan) in the 1990's, sponsored by NHTSA. This effort is described in detail in a number of reports that Veridian submitted to NHTSA and is summarized in Pierowicz, Jocoy, Lloyd, Bittner, and Pirson (2000). Since these reports also contain information on other intersection-crash countermeasures not directly relevant to the intersection-violation scenario, this section summarizes the relevant data. Special emphasis will be placed on those sections of the report that describe the generation and verification of performance specifications for the various system components, as this is a primary goal of the current report.

Only a portion of Veridian's work was published; thus, it has been difficult to obtain some of the preliminary reports describing in detail the development of performance specifications. This section summarizes the reports that VTTI has been able to obtain to date. These reports include:

- Pierowicz*, et al.* (1994) - Task 1: Draft Interim Report, Volume 1: Technical Findings
- Pierowicz and Bollman (1995) - Task 2: Draft Interim Report, Volume 1: Technical Findings
- Pierowicz*, et al.* (1995) - Task 3: Draft Interim Report
- Calspan/SRL Corporation (1997a) - Task 5: Draft Interim Report, Design of Testbed System
- Calspan/SRL Corporation (1997b) - Task 5: Draft Interim Report, Driver-Vehicle Interface (DVI) Design Guidelines
- Calspan/SRL Corporation (1998) - Task 6: Draft Interim Report, Development and Refinement of Testbed Systems
- Pierowicz*, et al.* (2000) - Task 9: Final Report, Intersection Collision Avoidance System Performance Guidelines

To ease the process of referencing these reports, they will be referred to by the task and volume (if applicable) numbers throughout this section, rather than by the author list.

The various components of an ICAV system provide logical breakpoints for the discussion of Veridian's previous work. These components are GPS/GIS (mapping), algorithm & sensing, DVI, and communications with infrastructure. An additional section on Problem Definition has also been added to discuss Veridian's work on supporting the need for an intersection-violation prevention system.

Veridian's work extends beyond the realm of the SCP intersection-crash problem. Indeed, Veridian developed three different systems: the Driver Advisory System, the Defensive System, and the Communication System. The project was also divided in three phases. During Phase I, the three systems were conceptualized. Using sensors and vehicle-control systems, the Driver Advisory System would be able to detect a collision and to take control of the vehicle as needed to avoid the crash (the word "Advisory" seems to be a misnomer for this system, since it does take control of the vehicle). The Defensive System would leave control with the driver to alter the vehicle's state after being warned by the countermeasure. The Communication System would rely on communication between all vehicles on the road, but this system would require that all vehicles be outfitted with special equipment. Phase II of the project involved further design of the first two systems, the Driver Advisory and the Defensive System, while Phase III involved constructing and testing the Intersection Testbed System. However, only that portion of Veridian's work directly relevant to the SCP intersection violation scenario is summarized in this review.

Problem Definition and General System Requirements

The Veridian Task 1, Volume I report analyzes in detail the intersection-crash problem with the intention of identifying causal factors that define opportunities for intervention. The work first identifies intersection-crash configurations using FARS and GES data. The characteristics of intersection crashes identified in these databases were then analyzed to determine how the crashes occurred. A supplemental analysis of several NASS CDS cases was also undertaken to determine the causal factors behind intersection crashes. The end result of this process was an understanding of the types of crashes that occur at intersections and the scenarios and conditions that lead to these crashes.

The Task 2, Volume I report defines four different intersection-crash scenarios and suggests possible countermeasures for each. In addition, the functional goals of these countermeasures were defined. The SCP intersection-violation case is primarily encompassed in Scenario 3. A short description of each scenario follows:

- **Scenario 1**: Left Turn Across Path - no violation of traffic control, POV has right of way, SV is required to yield. Approximately 24% of intersection crashes fall under this scenario.
- **Scenario 2**: Perpendicular Paths - no violation of traffic control, POV has right of way, SV is required to stop, entry with inadequate gap. This scenario accounts for about 30% of all intersection crashes, mainly at stop signs. The critical driver error for Scenarios 1

and 2 is that drivers did not observe POV, and they misjudged the distance, velocity, or actions of the POV.

- **Scenario 3**: Perpendicular Paths - violation of traffic control, POV has right of way, SV is required to stop. This scenario accounts for the largest percentage, as approximately 44% of all intersection crashes fall under this category.
- **Scenario 4**: Premature Intersection Entry - violation of traffic control, POV has right of way, SV is required to stop. This scenario accounts for about 2% of all intersection crashes.

In Task 3, Veridian conceptualized possible countermeasures that could be used to prevent crashes due to each of the four different scenarios. This process was anchored in the development of driver models that described the logical flow of a driver's decision-making process. This process also resulted in the definition of initial conceptual definitions of the sensing technologies necessary to realize the various countermeasures. As part of this work, some initial outlining of requirements is provided. The system had to be adaptable, reliable, controllable, and integrated. The Task 5, Volume I report and the Task 6 report expand on some of these characteristics:

- System will become active upon activation of vehicle ignition system
- Possess indication visible to driver of system functional status
- Provide for built-in-test (BIT) of systems upon start-up of host vehicle
- Notify driver of acceptable passing of system BIT
- Provide driver means of deactivating system

In addition, this report provided some environmental requirements:

- System shall be sealed to allow operation in rain or snow conditions
- System shall operate in temperature range as prescribed in SAE J1211
- System shall operate in vibration/shock environment as described in SAE J1211

Positioning

The Task 3, Volume I report quantifies, based on results of simulation work, some initial requirements applicable to an SCP intersection-violation prevention system:

- Determine presence of an approaching intersection
- Determine traffic control device configuration
- Measure vehicle position to +/- 9 feet
- Measure vehicle heading to +/- 1°

Some of these requirements were refined as part of the Task 5, Volume I and Task 6 reports:

- Longitudinal position tolerance: +/- 3 ft
- Lateral position tolerance: +/- 3 ft
- Path bearing tolerance: +/- 2°
- Steering wheel angular movement tolerance: +/- 1°

The testbed GPS/GIS system is described in the Task 9 report. The system included a GPS system, a differential correction receiver, and an on-board map database. A modified map database, augmented from NavTech's original map, contained precise information on the location of intersections and the type of signal control at the intersection. The GPS/GIS data was updated every 100 msec (i.e., 10 Hz).

To determine the presence of an intersection, an algorithm was used that first determined what roadway node was being approached. Once this determination was made, the presence of an intersection at that node was queried. If the node was an intersection, the warning algorithm was executed to determine the adequacy of a warning. A library of NavTech software functions was used to query the map database.

Veridian produced, in the Task 9 report, a set of guidelines with respect to the positioning system. These guidelines suggest that:

- Position and roadway information update rate of 10 Hz adequate for ICAS – update rates of 1 Hz were tested and found inadequate.
- The time delays associated with accessing the map database were not sufficient to cause problems with the processing of countermeasure functions.
- Positional accuracy of ~3 meters were generally found to be adequate. However, in specific cases a greater positional accuracy was found to reduce false alarms in the threat-detection system. Thus, verification of this guideline appears necessary.
- The latency of the data is important in the ICAS and needs careful attention to detail. The main problem in this area occurred with a speed data delay of 1.5 sec, corrected via a lead filter.

The Task 9 report also specifies some of these guidelines further:

- Vehicle position accuracy – desired value: 3 m (same as currently available at the time)
- Intersection location accuracy: 1 m (3 m was currently available at the time)
- Vehicle position update rate: 10 Hz (same as currently available at the time)
- Accuracy of roadway data elements: >99.99% (same as currently available at the time)
- Accuracy of roadway shape characteristics: >99.99% (same as currently available at the time)
- Accuracy of traffic-control device inventory: >99.99% (same as currently available at the time for the study area)
- Data latency: <0.1 sec (only 0.3 sec considered necessary)

Algorithm & Sensing

The algorithm used by Veridian underwent various modifications as the project progressed. The Task 1, Volume I report describes a simple kinematic approach for determining the range at which a countermeasure would need to begin sensing vehicle behavior to perform effectively. This range is a function of distance from the center of the intersection to the stop line (D_i, in ft), time delays (T_D, in sec), vehicle velocity (V, ft/sec), and vehicle braking acceleration (a, in ft/sec^2) (Equation 13).

$$Range = D_i + T_D\frac{V^2}{2a} + 0.13V \tag{13}$$

A value of 16.1 ft/sec^2 (0.5 g) was assumed for a; the time delay was arbitrarily set at 2 seconds. A justification for the additional speed-dependent term (i.e., $0.13V$) is not provided. There are unit-consistency issues with this equation, and these are resolved in the Task 2, Volume 1 report. The revised equation follows (Equation 14). The speed-dependent term was not justified in this report, either.

$$Range = D_i + T_D V + \frac{V^2}{2a} + 0.13V \qquad (14)$$

In addition to the requirements described in the GPS/GIS section, the Task 3, Volume I report also quantifies several requirements for the determination of the vehicle's dynamic status:

- Measure vehicle velocity to +/- 1foot/sec
- Measure vehicle acceleration to +/- 0.1 ft/sec^2 (longitudinal)

The Task 5, Volume I report provides data on prediction methods for driver decision making using pedal and steering-wheel actuation, which can be used in the development of initial algorithm iterations. Additional algorithm-related data is provided as part of the Task 6 report, in which Veridian describes the results of an experiment to determine normal driver behavior when approaching stop-sign intersections. The results show that drivers released the throttle 9.3 sec (1.21 sec SD) before intersection entry, applied the brakes 7.27 (0.91) sec prior to intersection entry, and activated turn signals 6.6 (1.18) sec prior to intersection entry. Steering input did not occur until 0.8 (0.52) sec prior to intersection entry. The maximum longitudinal deceleration used was on average 0.20 (0.04) g. However, the sample size used was very small (19 drivers) to generalize over all driver behavior.

Based on this work, the Task 6 report describes the development of the a_P metric, which describes the acceleration that a driver must derive from the vehicle's braking system in order to prevent entry into the intersection. No equation for the calculation is provided in the report, but it is reasonable to assume that Equation 14 was solved for a. The Task 6 report indicates that five pieces of information are needed to calculate a_P: presence of the intersection (obtained through on-board maps), distance to the intersection (obtained through GPS), traffic control at intersection (obtained through on-board maps), vehicle velocity (obtained through the vehicle speedometer), and delay times (assumed at 2.0 sec, of which 1.5 sec are for the driver reaction time). The a_P metric is compared against a pre-selected threshold, and a warning decision is made. Veridian tested thresholds of 0.25 g and 0.4 g and identified distinct performance levels, but no threshold selection was made. Later Veridian work, briefly alluded to in the Task 9 report, suggested the use of 0.35 g as an appropriate threshold.

DVI

Veridian's Task 3, Volume I report contains some general requirements for warning presentation to drivers. These requirements, based on the crash analyses performed by Veridian, include the availability of multiple warning levels, prioritization of warnings, dual modality of warnings, unique imminent crash warning, and minimal nuisance/false alarms. Veridian suggests that information must be presented in two main areas: presence of the intersection and type of control device being approached. In addition, haptic displays require the actuation of vehicle controls, which can take a significant amount of time. Veridian suggests that brake controls react within

0.05 sec of command signal and throttle controls react within 0.2 sec of command signal. These requirements are refined in the Task 5, Volume I report to a minimum actuator response time of 0.1 sec, with a minimum rated actuator life of 100K cycles. This report also provides a detailed description of haptic braking and steering systems that comply with this requirement. The Task 9 report, however, describes a completely independent secondary braking system using hydraulic pressure and additional brake calipers. The reasons for the change in approach are not provided in any of the reports reviewed.

The Task 5, Volume I report also expands on the presentation methods for the visual modality. Veridian elected to use a Head-Up Display (HUD) as its initial visual warning indicator, and they prescribe a series of requirements for the system, expanded on the Task 5, Volume III report:

- The HUD displayed a graded warning, representing, through changes in color and the addition of other iconic elements, a more urgent warning
- 1.4:1 = Minimum daytime contrast, 2:1 = Minimum nighttime contrast
- Symbol luminance: daytime – 1,000 fL adjustable down to 10 fL; nighttime – 10 fL adjustable down to 0.01 fL
- Size of critical elements: 30 arcmin, minimum
- Symbol font must be clear and simple
- Any reasonably visible color may be used for symbols, except highly saturated blue
- Use icons instead of words whenever they have been verified as equally or more recognizable and require less display space
- Other HUD –specific requirements

The Veridian recommendation is to include a dual modality DVI with haptic and visual (HUD) components.

The Task 5, Volume I report and the Task 6 report also describe the different warning icons used by Veridian in their testbed. Of relevance to the current effort are the two that contain a signal and a stop sign within four corner lines arranged to represent an intersection. The Task 6 report also revises the minimum brightness of the HUD to 1500 fL.

The Task 9 report provides a set of guidelines for the design of an ICAS DVI. The system should inform the driver of intersection presence, traffic-control device presence, and system status. In addition, Veridian suggests two modes of information, advisory/alert and warning, depending on the imminence of the violation. In terms of modality, the Task 9 report suggests that a DVI modality should:

- Benefit all drivers
- Not require specific directional orientation
- Be compatible with driver's response
- Provide for a viable integration with other crash-avoidance systems and driver-assistance systems

These criteria were used to evaluate the auditory, visual, and haptic modalities, with the conclusion that all three modalities should be included because of the unique advantages inherent in each.

In addition to these guidelines, the Task 9 report presents several design goals for an ICAS DVI:

- Minimize the time required by the driver to accurately acquire and utilize salient information from the HWS (direct driver attention to emerging traffic situation)
- Minimize the requirements for learning to interpret the modal information elements as well as achieving a minimization of the time to acquire
- Provide the potential, where possible, for future expansion of supplementary modal information to accommodate the spectrum of CAS
- Maximize user acceptance of the ICAS DVI

These goals were used in concert with the results from experimental studies in the development of specifications for each of the modalities:

- Auditory: A 1000 Hz signal, 20 dB above the dynamic 1 kHz-center frequency level, should be temporally coupled with the pulsed braking signal.
- Visual: Use icons instead of words whenever they have been verified as equally or more recognizable and require less display space. The visual angle subtended by either the vertical or horizontal dimension or icons should be no less than 30 arcminutes.
- Haptic: Haptic warning or requirement to stop should be provided by a succession of braking pulses (three) of 100 ms with 100 to 200 ms separation periods and each braking pulse resulting in a -0.6 m/s velocity change.

Communications

The initial requirement provided by Veridian on communications is outlined in their Task 3, Volume I report, in which the communications range is required to be a 300 foot radius from the center of the intersection. The Task 5, Volume I report still maintains this requirement, but expands considerably upon the description of the communications system envisioned for application at intersections, in terms of coverage area. This communications system, however, was not implemented as part of their testbed (Task 9 report). Thus, the Veridian system could not warn about an impending signal violation since signal phase and timing information was not available on-board.

PRELIMINARY REQUIREMENTS AND SPECIFICATIONS FOR ICAV DEPLOYMENT, FOT, AND TESTBED SYSTEMS

Under the NHTSA program plan, the ICAV development process is expected to go through several stages, with the ultimate goal of a fully functional *deployment* system. The deployment system is still several years in the future, and in the meantime, there will need to be systems capable of testing the performance of the overall concept. These intermediate systems are the *field operational test (FOT)* system and the *testbed* system. A top-down systems engineering approach is being used, whereby the requirements of the deployment system, as they are now understood, are used to drive the development of requirements for the FOT and testbed systems. Existing knowledge gaps are identified and defined, and these knowledge gaps are then filled through tests conducted during the testbed and FOT phases. The knowledge gained during these tests is fed back into the system from the bottom up, so that the preliminary deployment system requirements and FOT system requirements are continuously refined as the project progresses and more information becomes available. By the end of the project, a more complete and unambiguous set of requirements and specifications for the FOT and deployment systems will have been developed, along with known constraints. The overall process and feedback loops for these three stages are depicted in Figure 52.

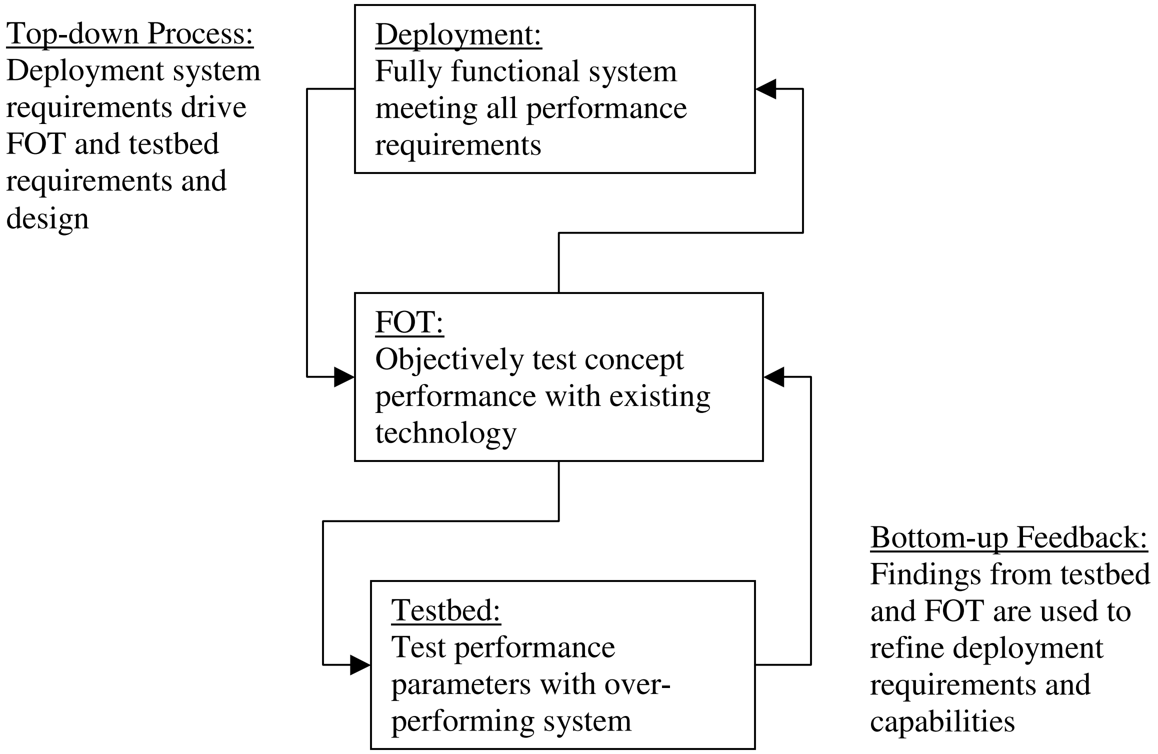

Figure 52. Depiction of ICAV development process and feedback loops.

A fully functional deployment system is the final goal of the NHTSA ICAV program. Most of the current and previous intersection violation avoidance system research has focused on deployment systems. However, a deployable system has not been fully designed or built, nor is one technically feasible at this time, so the requirements and specifications developed under these programs have not been fully tested. In some cases, they provide a range of specifications.

Given that the deployment of the ICAV system is a long-term goal (8-10 years), the requirements and specifications currently being developed for a deployment system should not be constrained by current technology, or by any particular set of components. Several different types of systems may be capable of meeting the requirements of the deployment system, using different types of technology. An analogy would be the adaptive cruise control (ACC) systems which are now being deployed. Manufacturers have developed systems that meet the overall requirements of ACC systems by using different types of technology (e.g., laser vs. radar technologies). Nevertheless, the ICAV deployment system is currently envisioned as being composed of certain functional components; preliminary requirements are presented for these envisioned components.

Before a system can be released for deployment, it must undergo field operational testing using an FOT system. One major purpose of FOT systems is to provide a platform for testing system performance before the system is fully specified for deployment. An FOT system is distinguished from a deployment system in that it is constrained by available technology. In other words, the FOT system is a system that meets the deployment system requirements to the degree possible, given the available technology. It is not necessary that a fully deployable system be used for the FOT. For example, if a deployment system has a requirement for a highly accurate and detailed positioning system covering the entire United States, an FOT system could be developed using a highly accurate and detailed positioning system for the geographic area where the FOT is being conducted. The local area positioning system should be sufficient for testing that aspect of the system prior to deployment.

A testbed system will be developed first and used to narrow down the range of parameter values for the ICAV components for subsequent systems. A testbed system provides a method for testing a range of system requirements and specifications to provide input into later FOT and deployment system requirements and specifications. In contrast to the FOT and deployments systems, a testbed system is a flexible system that allows varied (programmable) input for the parameters being tested. It contains all the components of an FOT or deployment system, but in a much more open-ended platform. It allows testing of varying degrees of accuracy, precision, system time lags, and errors. The end points for the range of values to be tested can be determined by examining findings from previous studies using the same types of components. Component-by-component testing will be conducted prior to subsystem integration in the testbed. The testbed system can be transformed into a demonstration platform at any point in the testing process by fixing variable parameters to the optimum settings determined by testing up to that point.

The deployment, FOT, and testbed systems are described more fully in this section, along with envisioned components, preliminary system requirements, knowledge gaps, and preliminary performance specifications for each type of system. The stop sign and signalized cases are addressed separately. It should be stressed that these are preliminary requirements and specifications, and one of the major goals of the current project is to continually evolve and update these requirements and specifications as new information and data become available. By the end of the project, a more complete and unambiguous set of requirements and specifications for FOT systems will have been developed, along with known constraints.

The following sections provide a framework to facilitate the ICAV development process. The stop sign ICAV framework is described first, followed by the signalized intersection framework. Within each type of system (stop sign or signalized intersection), the deployment system requirements, knowledge gaps, and preliminary specifications are presented first, followed by FOT system requirements, knowledge gaps, and preliminary specifications. Finally, the testbed implications of these deployment and FOT requirements, knowledge gaps, and preliminary specifications are presented. The most relevant references used for the development of these sections were: ARINC (2001), Burgett et al. (1998), Campbell at al. (1997), Campbell et al. (1998), COMSIS (1996), Dingus et al. (1998), GM (2002a and 2002b), ISO (2002), Kiefer (2000), Kiefer et al. (1999), Lloyd et al. (1996), and Pierowicz et al. (2000).

STOP SIGN DEPLOYMENT SYSTEM

Stop Sign Deployment System: Overview and Subsystems

The deployment ICAV stop sign system is envisioned as being composed of four functional subsystems: positioning, in-vehicle sensors, computations, and DVI. These subsystems are technology independent, in that NHTSA will not specify that any particular technology be used to meet the performance requirements. Table 101 describes the functions and interactions of these subsystems.

Table 101. Subsystems envisioned for ICAV deployment stop-sign system.

Subsystem	Purpose	Receives data from:	Sends data to:
Positioning	Accurate, timely knowledge of vehicle dynamic position with respect to upcoming stop signs	Not defined	Computations
In-vehicle sensors	Provide data stream to computations with respect to vehicle dynamic parameters	Not defined	Computations
Computations	Integrate input from the positioning & in-vehicle sensors; calculate vehicle dynamic position with respect to upcoming stop signs; decide whether violation will occur; provide feedback to the driver via a DVI	Positioning In-vehicle sensors	DVI
DVI	Provide information to driver with respect to imminent stop sign violations	Computations	Driver

Stop Sign Deployment System: Previously Reported Performance Requirements

The following performance requirements for a stop sign deployment ICAV system are based on previous and current research regarding similar systems. The requirements were then modified based on dialogue with the project sponsor.

- Positioning: The deployment system must be capable of determining whether the vehicle is subject to a “stop” for the intended path.

- Positioning: The deployment system must be able to distinguish what lane the vehicle is in, so that special situations (such as right-turn yield lanes) do not result in spurious alarms.
- In-vehicle sensors: For the deployment system, in-vehicle sensors must provide necessary in-vehicle information to the computational system. This information must be both timely and accurate.
- Computations and DVI: For the deployment system, the computations and DVI must not produce too many false alarms or too many misses.
- Computations and DVI: The deployment system must be capable of providing graded levels of warning to the driver (e.g., low level alert followed by high level warning if driver does not respond appropriately).
- Computations and DVI: The deployment system must be acceptable to drivers:
  - The deployment system must not warn too early or too late.
  - The deployment system must not produce too many nuisance alarms.
  - The deployment system DVI must not be annoying to drivers.
- DVI: The deployment system must provide a warning that reliably directs the driver's attention forward and elicits an appropriate driver response when a stop sign violation is about to occur.
- DVI: The deployment system must indicate to the driver its status (i.e., whether its components are fully operational or not).

Stop Sign Deployment System: Preliminary Performance Specifications and Knowledge Gaps

Previous and ongoing research projects have devoted much time to developing preliminary performance specifications for deployment systems. Because of this previous work, some of the specifications related to the deployment requirements are already known within a fairly tight range. For example, the large body of research into warning system DVIs (see Appendix A) provides very clear guidance as to what types of DVIs are preferred, and what the parameters of those DVIs should be. Values for other specifications are still to be determined, however. Table 102 outlines the specifications necessary to complete the requirements for the deployment system. Where values are generally well known and accepted, this is indicated, and where there are knowledge gaps, these are discussed.

Table 102. Preliminary Performance Specifications and Knowledge Gaps for Stop Sign Deployment System.

Specification Type	Performance Specification	Comments/Knowledge Gaps
		Positioning System
Lateral vehicle position accuracy	TBD	Other studies (CAMP EdMaps and Veridian) have used Circular Error Probable (CEP) accuracy specification. For a specification, the CEP should be broken down into its lateral and longitudinal components.
Longitudinal vehicle position accuracy	<0.3 m to <5 m	This range of values was uncovered during a search of the relevant literature (CAMP EdMaps and Veridian), and generally based on theory/calculation. Further testing over this range of values is required.

Specification Type		Performance Specification	Comments/Knowledge Gaps
Stopping location accuracy relative to stop bar		-2 m to 0 m	This range of values was uncovered during a search of the relevant literature (CAMP EdMaps and Veridian), and generally based on theory/calculation. Further testing over this range of values is required.
Vehicle offset		-1.8 m to -10 m	This parameter is a conservative correction factor which takes positioning errors into account and subtracts them from the required stop line position so the vehicle will not be warned too late (i.e., will not overshoot the stop bar, even with positioning errors). This range of values was uncovered during a search of the relevant literature (CAMP EdMaps), and generally based on theory/calculation. Further testing over this range of values is required.
Update rate		10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
Data latency		0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
In-Vehicle Sensors			
Speed	Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
	Accuracy	TBD	Knowledge gap; engineering judgment indicates testing in the range of ± 2 mph.
	Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
	False alarms and misses	TBD	Knowledge gap; engineering judgment indicates testing in the range of 1% to 5%.
Acceleration	Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
	Accuracy	TBD	Knowledge gap; engineering judgment indicates testing in the range of ± 0.05 g.
	Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
	False alarms and misses	TBD	Knowledge gap; engineering judgment indicates testing in the range of 1% to 5%.
Braking status	Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
	Accuracy	TBD	Knowledge gap; engineering judgment indicates testing in the range of ± 1% for on/off status (if percent pedal depression is used, ± 5%).
	Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
	False alarms and misses	TBD	Knowledge gap; engineering judgment indicates testing in the range of 1% to 5%.
Heading angle	Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
	Accuracy	TBD	Knowledge gap; Veridian indicated a specification of ± 2º.
	Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
	False alarms and misses	TBD	Knowledge gap; engineering judgment indicates testing in the range of 1% to 5%.
Computations			

Specification Type		Performance Specification	Comments/Knowledge Gaps
Computational speed (latency)		0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
False alarm rate		TBD	Knowledge gap; engineering judgment indicates testing in the range of 0% to 10% false alarms (false alarms are warnings given when they should not be, either because the algorithm requirements are not met, or because there is no stop sign or imminent red light).
Miss rate		TBD	Knowledge gap; engineering judgment indicates testing in the range of 0% to 10% misses.
Driver acceptance		TBD	Knowledge gap; engineering judgment indicates deployment system design must be rated as acceptable to 85% of drivers. Tested through usability techniques as design evolves.
Driver Vehicle Interface			
Levels of alert		Graded warnings with alert and warning modes	Recommended by several studies of in-vehicle warnings (see Appendix A).
Recommended Modality		Auditory, supplemented with visual display	Some studies indicate that this is the preferred DVI modality combination; other sources recommend haptic and auditory; knowledge gap for this application, so all three will be tested in two-way combinations.
Visual display	Warning type	Iconic indicator with the word WARNING below	General agreement that primary visual display should be an icon (less time to process than text). May need to test whether added word below has an impact on driver performance.
	Animation	Animated (multi-stage)	General agreement that animation captures the drivers attention more quickly than a static display; if animated, make sure display is always on (i.e., for blinking, driver glance during off interval may cause delayed reaction time).
	Color	Red-orange, amber, or yellow indicator	General agreement on warning colors. No further testing required.
	Icon type	Stop sign icon	Tested in one study of intersection violations (Veridian); further testing required.
	Size	Visual angle subtended ≥ 30 arcminutes	General agreement for DVI display size. No further testing required.
	Contrast ratio	1.4:1 Minimum for daytime 2:1 Minimum for nighttime	General agreement for visual display contrast ratio. No further testing required.
	Luminance (based on HUD)	Adjustable from 10 fL to 1,000 fL daytime; 0.01 fL to 10 fL nighttime	General agreement for visual display luminance. No further testing required for HUD displays.

Specification Type		Performance Specification	Comments/Knowledge Gaps
Auditory display	Type	Specific non-speech tone	General agreement with this specification, based on many studies and years of laboratory and theoretical research (tones easier to process than speech).
	Frequency	Mixed waveforms with 2500 & 2650 Hz peaks	General agreement with this specification, based on many studies and years of laboratory and theoretical research. Individual tones should be tested to assure they convey the correct level of urgency.
	Temporal	Intermittent or changing over time	General agreement for this specification, based on many studies and years of laboratory and theoretical research. No further testing required.
	Amplitude	At least 20 dB above the amplitude of the masked threshold	General agreement for this specification, based on many studies and years of laboratory and theoretical research. No further testing required.
	Integration	Well-separated from some existing auditory warnings, but similar to others, depending on required driver response	General agreement for this specification, based on many studies and years of laboratory and theoretical research. No further testing required. Overall integration being studied by other NHTSA projects.
Haptic display	Type	Soft braking	Tested during one study of intersection violations; generally agreed as appropriate method for situations in which driver should slow or stop.
	Duration-pulse separation	Duration-pulse separation of 50-100 ms; pulsing should be accompanied by auditory display	Tested during one study of intersection violations; further testing required over indicated ranges.
	Number and duration of pulses	Three pulses of 100 ms with 100 to 200 ms separation periods	Tested during one study of intersection violations; further testing required over indicated ranges.
	Velocity change	Each 100 ms pulse should result in a -0.6 m/s velocity change	Tested during one study of intersection violations; further testing required over range of -0.1 to -0.6 g.

STOP SIGN FOT SYSTEM

Stop Sign FOT System: Overview and Subsystems

The FOT ICAV stop sign system is also envisioned as being composed of four functional subsystems: positioning, in-vehicle sensors, computations, and DVI. However, given that the FOT could take place in a mid-term time frame (3 to 5 years), the technologies capable of meeting the performance specifications can be envisioned to a certain degree, given what is currently available and what is likely to become available in the next few years. The candidate technologies to be used for these subsystems are shown in Table 103.

Table 103. Subsystems envisioned for stop sign FOT system.

Subsystem	Purpose, Data Flow	Likely Technologies
Positioning	Accurate, timely knowledge of vehicle dynamic position wrt upcoming stop signs; sends data to computations	DGPS Detailed map database Inertial navigation system
In-vehicle sensors	Provide data stream to computations wrt vehicle dynamic parameters; sends data to computations	Data feed from in-vehicle network for speed, braking, longitudinal acceleration, etc.
Computations	Integrate input from the positioning & in-vehicle sensors; calculate vehicle dynamic position wrt upcoming stop signs; decide whether violation will occur; provide feedback to the driver via a DVI; receives data from positioning and in-vehicle sensors computations; sends data to DVI	Dedicated mini-computer with programmed algorithm
DVI	Provide information to driver wrt imminent stop sign violations receives data from computations	HUD or LCD for visual display Speaker(s) for auditory display Soft braking for haptic display

Stop Sign FOT System: Preliminary Recommended Performance Requirements

The FOT stop sign system should meet the requirements of the deployment system to the extent possible, given technological and economic constraints. The following list of FOT requirements is based on the earlier list of deployment requirements, but filtered through knowledge of existing and near-term technological constraints:

- <u>Positioning:</u> The FOT system must be capable of determining whether the vehicle is subject to a "stop" for the intended path.
- <u>In-vehicle sensors:</u> For the FOT system, in-vehicle sensors must provide necessary in-vehicle information to the computational system. This information must be both timely and accurate.
- <u>In-vehicle sensors:</u> For the FOT system, in-vehicle sensors must not produce too many false alarms or too many misses.
- <u>Computations and DVI:</u> The FOT system must be capable of providing graded levels of warning to the driver (e.g., low level alert followed by high level warning if driver does not respond appropriately).
- <u>Computations and DVI:</u> The FOT system must be acceptable to drivers:
    - The FOT system must not warn too early or too late.
    - The FOT system must not produce too many nuisance alarms.
    - The FOT system DVI must not be annoying to drivers.

- DVI: The FOT system must provide a warning that reliably directs the driver's attention forward and elicits an appropriate driver response when a stop sign violation is about to occur.
- DVI: The FOT system must indicate to the driver its status (i.e., whether its components are fully operational or not).

Stop-Sign FOT System: Preliminary Performance Specifications and Knowledge Gaps

As was the case for the knowledge gaps associated with the deployment system, most of the knowledge gaps for the FOT system lie in knowing what values to associate with the requirements. Again, VTTI can provide good engineering judgment values for some of these requirements based on previous work and knowledge of human performance, but the final values will not be known until after the testbed development and testing processes are complete. Some of the knowledge gaps are scheduled to be addressed by other groups working on similar projects (primarily the various CAMP projects and the Infrastructure Consortium). Where these knowledge gaps are to be addressed by other groups, this is noted. This method leaves a natural body of knowledge gaps that could potentially be addressed by an ICAV stop sign testbed system. The preliminary specifications for deployment systems and knowledge gaps for FOT systems provided the input for a set of preliminary FOT specifications (Table 104). Where these are different than the deployment specifications, this is noted.

Table 104. Preliminary Performance Specifications and Knowledge Gaps for Stop Sign FOT System.

Specification Type	Performance Specification	Comments/Knowledge Gaps
Positioning System		
Max. time loss for positioning data	10 sec	Knowledge gap – further testing required prior to FOT. Relevant for GPS systems if they are used in FOT.
Lateral vehicle position accuracy	TBD	Knowledge gap – further testing required prior to FOT. Some research to be conducted by CAMP EdMaps project.
Longitudinal vehicle position accuracy	<0.3 m to <5 m	Knowledge gap – further testing required prior to FOT. Some research to be conducted by CAMP EdMaps project.
Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
Vehicle offset	-1.8 m to -10 m	Knowledge gap – further testing required prior to FOT. Some research to be conducted by CAMP EdMaps project.
Stopping location accuracy	-2 m to 0 m	Knowledge gap – further testing required prior to FOT. Some research to be conducted by CAMP EdMaps project.
Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
In-Vehicle Sensors		

Specification Type		**Performance Specification**	**Comments/Knowledge Gaps**
Speed	Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
	Accuracy	TBD	Knowledge gap; engineering judgment indicates testing in the range of ± 2mph.
	Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
	False alarms and misses	TBD	Knowledge gap; engineering judgment indicates testing in the range of 1% to 5%.
Acceleration	Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
	Accuracy	TBD	Knowledge gap; engineering judgment indicates testing in the range of ± .05 g.
	Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
	False alarms and misses	TBD	Knowledge gap; engineering judgment indicates testing in the range of 1% to 5%.
Braking status	Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
	Accuracy	TBD	Knowledge gap; engineering judgment indicates testing in the range of ± 1% for on/off status (if percent pedal depression is used, ± 5%)..
	Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
	False alarms and misses	TBD	Knowledge gap; engineering judgment indicates testing in the range of 1% to 5%.
Heading angle	Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
	Accuracy	TBD	Knowledge gap; Veridian indicated a specification of ± 2º.
	Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
	False alarms and misses	TBD	Knowledge gap; engineering judgment indicates testing in the range of 1% to 5%.
Computations			
Computational speed (latency)		0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
False alarm rate		TBD	Knowledge gap –testing required prior to FOT.
Miss rate		TBD	Knowledge gap –testing required prior to FOT.
Driver acceptance		TBD	Knowledge gap –testing required prior to and during FOT.
Driver Vehicle Interface			
Levels of alert		Graded warnings with alert and warning modes	Will be set prior to FOT.

Specification Type		**Performance Specification**	**Comments/Knowledge Gaps**
Recommended Modality		Auditory, supplemented with visual display	Will be set prior to FOT.
Visual display	Warning type	Iconic indicator with the word WARNING below	Will be set prior to FOT if visual is included in FOT.
	Animation	Animated (multi-stage)	Will be set prior to FOT if visual is included in FOT.
	Color	Red-orange, amber, or yellow indicator	Will be set prior to FOT if visual is included in FOT.
	Icon type	Stop sign icon	Will be set prior to FOT if visual is included in FOT.
	Size	Visual angle subtended ≥ 30 arcminutes	No further testing required (if visual is included in FOT).
	Contrast ratio	1.4:1 Minimum for daytime 2:1 Minimum for nighttime	No further testing required (if visual is included in FOT).
	Luminance (based on HUD)	Adjustable from 10 fL to 1,000 fL daytime; 0.01 fL to 10 fL nighttime	No further testing required (if visual is included in FOT).
Auditory display	Type	Specific non-speech tone	Will be set prior to FOT.
	Frequency	Mixed waveforms with 2500 & 2650 Hz peaks	Will be set prior to FOT.
	Temporal	Intermittent or changing over time	No further testing required.
	Amplitude	At least 20 dB above the amplitude of the masked threshold	No further testing required.
	Integration	Well-separated from some existing auditory warnings, but similar to others, depending on required driver response	No further testing required.
Haptic display	Type	Soft braking	Will be set prior to FOT if haptic is included in FOT.
	Duration-pulse separation	Duration-pulse separation of 50-100 ms; pulsing should be accompanied by auditory display	Will be set prior to FOT if haptic is included in FOT.
	Number and duration of pulses	Three pulses of 100 ms with 100 to 200 ms separation periods	Will be set prior to FOT if haptic is included in FOT.
	Velocity change	Each 100 ms pulse should result in a -0.6 m/s velocity change	Will be set prior to FOT if haptic is included in FOT.

SIGNALIZED INTERSECTION DEPLOYMENT SYSTEM

Signalized Intersection Deployment System: Overview and Subsystems

The deployment ICAV signalized system is envisioned as being composed of five functional subsystems: communications, positioning, in-vehicle sensors, computations, and DVI. These subsystems are technology independent, in that NHTSA will not specify that any particular technology be used to meet the performance requirements. Table 105 describes the functions and interactions of these subsystems. Note that these subsystems are essentially the same as for the stop sign system, except that communications has been added.

Table 105. Subsystems envisioned for signalized intersection deployment system.

Subsystem	Purpose	Receives data from:	Sends data to:
Communications	Accurate, timely knowledge of signal phase, signal timing, signal location, and approach direction with respect to upcoming signalized intersections	Infrastructure	Computations
Positioning	Accurate, timely knowledge of vehicle dynamic position with respect to upcoming signalized intersections	Not defined	Computations
In-vehicle sensors	Provide data stream to computations with respect to vehicle dynamic parameters	Not defined	Computations
Computations	Integrate input from the positioning & in-vehicle sensors; calculate vehicle dynamic position with respect to upcoming signalized intersections; decide whether violation will occur; provide feedback to the driver via a DVI	Positioning In-vehicle sensors	DVI
DVI	Provide information to driver with respect to imminent signalized intersection violations	Computations	Driver

Signalized Intersection Deployment System: Previous Performance Requirements

The following performance requirements for a signalized intersection deployment ICAV system are based for the most part on previous and current research regarding similar systems. The requirements were then modified based on dialogue with the project sponsor.

- Communications: The deployment system must be capable of reliably receiving communications from all equipped signalized intersections (those with communication capability). Communications must be accurate and received in a timely manner.
- Communications and Positioning: The deployment system must be capable of determining whether the vehicle is subject to a “stop” for the intended path.
- Positioning: The deployment system must be able to distinguish what lane the vehicle is in, so that special situations (such as left-turn permissive and left-turn only lanes) do not result in spurious alarms.
- In-vehicle sensors: For the deployment system, in-vehicle sensors must provide necessary in-vehicle information to the computational system. This information must be both timely and accurate.
- In-vehicle sensors: For the deployment system, in-vehicle sensors must not produce too many false alarms or too many misses.

- Computations and DVI: The deployment system must be capable of providing graded levels of warning to the driver (e.g., low level alert followed by high level warning if driver does not respond appropriately).
- Computations and DVI: The deployment system must be acceptable to drivers:
  - The deployment system must not warn too early or too late.
  - The deployment system must not produce too many nuisance alarms.
  - The deployment system DVI must not be annoying to drivers.
- DVI: The deployment system must provide a warning that reliably directs the driver's attention forward and elicits an appropriate driver response when a stop sign violation is about to occur.
- DVI: The deployment system must indicate to the driver its status (i.e., whether its components are fully operational or not).

Signalized Intersection Deployment System: Preliminary Performance Specifications and Knowledge Gaps

Previous and ongoing research projects have devoted much time to developing preliminary performance specifications for deployment systems. For the most part, these were covered in the section on stop sign ICAV systems. However, the communications subsystem is unique to the signalized intersection case. The primary knowledge gap for the signalized intersection deployment system lies in knowing the requirements for the communications subsystem. Of all the component subsystems, this is the newest and least tested. So although it is known that there must be a communications system, whether any such system will perform reliably under real-world driving conditions is unknown at this time. The specifications for communications are presented below in Table 106 for the deployment system. Where values are generally well known and accepted, this is indicated, and where there are knowledge gaps, these are discussed.

Table 106. Preliminary Performance Specifications and Knowledge Gaps for Signalized Intersection Deployment System (communications only; others are the same as for stop sign case).

Specification Type	Performance Specification	Comments/Knowledge Gaps/Methodology
Communications Link with Infrastructure		
Communication path	Infrastructure-to-vehicle, one-way, point-to-multipoint	This path is generally accepted as the preferred method for communicating signal information from the infrastructure to vehicles to support violation warnings.
Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.

Specification Type	Performance Specification	Comments/Knowledge Gaps/Methodology
Range	215 - 300 m	Knowledge gap - this specification is theoretical; derived from prior Veridian work and CAMP Vehicle Safety Communications (VSC) project (concerning wireless communications for safety purposes, either vehicle-to-vehicle or infrastructure-to-vehicle) and should be tested over the indicated range of values.
Content of datastream	Traffic signal phase, timing, directionality, and location; weather conditions, road surface type	General agreement as to necessary and desired content of datastream from infrastructure.
Packet size	256 bytes	Knowledge gap - this specification is driven by the content specification, but should be as small as possible to impart the required data without causing a negative impact on other parameters (based on CAMP VSC and Veridian).

SIGNALIZED-INTERSECTION FOT SYSTEM

Signalized Intersection FOT System: Overview and Subsystems

The FOT ICAV signalized intersection system is also envisioned as being composed of five functional subsystems: communications, positioning, in-vehicle sensors, computations, and DVI. However, given that the FOT could take place in a mid-term time frame (3 to 5 years), the technologies capable of meeting the performance specifications can be envisioned to a certain degree, given what is currently available and what is likely to become available in the next few years. The candidate technologies to be used for these subsystems are shown in Table 107.

Table 107. Subsystems envisioned for signalized intersection FOT system.

Subsystem	Purpose, Data Flow	Likely Technologies
Communications	Accurate, timely knowledge of signal phase, signal timing, signal location, and approach direction wrt upcoming signalized intersections; receives data from infrastructure; sends data to computations	DSRC (dedicated short range communications at 5.9 GHz)
Positioning	Accurate, timely knowledge of vehicle dynamic position wrt upcoming signalized intersections; sends data to computations	DGPS Detailed map database Inertial navigation system
In-vehicle sensors	Provide data stream to computations wrt vehicle dynamic parameters; sends data to computations	Data feed from in-vehicle network for speed, braking, longitudinal acceleration, etc.
Computations	Integrate input from the positioning & in-vehicle sensors; calculate vehicle dynamic position wrt upcoming signalized intersections; decide whether violation will occur; provide feedback to the driver via a DVI; receives data from positioning and in-vehicle sensors computations; sends data to DVI	Dedicated mini-computer with programmed algorithm
DVI	Provide information to driver wrt imminent signalized intersection violations receives data from computations	HUD or LCD for visual display Speaker(s) for auditory display Soft braking for haptic display

Signalized Intersection FOT System: Preliminary Recommended Performance Requirements

The FOT signalized intersection system should meet the requirements of the deployment system to the extent possible, given technological and economic constraints. The following list of FOT requirements is based on the earlier list of deployment requirements, but filtered through knowledge of existing and near-term technological constraints:

- Communications: The FOT system must be capable of reliably receiving communications from all equipped signalized intersections (those with communication capability). Communications must be accurate and received in a timely manner.
- Communications and Positioning: The FOT system must be capable of determining whether the vehicle is subject to a "stop" for the intended path.
- In-vehicle sensors: For the FOT system, in-vehicle sensors must provide necessary in-vehicle information to the computational system. This information must be both timely and accurate.
- In-vehicle sensors: For the FOT system, in-vehicle sensors must not produce too many false alarms or too many misses.
- Computations and DVI: The FOT system must be capable of providing graded levels of warning to the driver (e.g., low level alert followed by high level warning if driver does not respond appropriately).
- Computations and DVI: The FOT system must be acceptable to drivers:
    - The FOT system must not warn too early or too late.
    - The FOT system must not produce too many nuisance alarms.
    - The FOT system DVI must not be annoying to drivers.
- DVI: The FOT system must provide a warning that reliably directs the driver's attention forward and elicits an appropriate driver response when a stop sign violation is about to occur.
- DVI: The FOT system must indicate to the driver its status (i.e., whether its components are fully operational or not).

Signalized Intersection FOT System: Preliminary Performance Specifications and Knowledge Gaps

As was the case for the knowledge gaps associated with the deployment system, most of the knowledge gaps for the FOT system lie in knowing what values to associate with the requirements. Again, VTTI can provide good engineering judgment values for some of these requirements based on previous work and knowledge of human performance, but the final values will not be known until after the testbed development and testing processes are complete. The preliminary specifications for deployment systems and identified knowledge gaps for FOT systems provided the input for a set of preliminary FOT specifications. For the most part, these are the same as for the stop sign FOT system. Thus, only the communications specifications are shown in Table 108. Some of the knowledge gaps are scheduled to be addressed by other groups working on similar projects (primarily the CAMP VSC project). Where these knowledge gaps are to be addressed by other groups, this is noted. This method results in a set of knowledge gaps that could be addressed by a testbed system.

Table 108. Preliminary Performance Specifications and Knowledge Gaps for Signalized-Intersection FOT System (communications only; others are the same as for stop sign case).

Specification Type	Performance Specification	Comments/Knowledge Gaps/Methodology
Communications Link with Infrastructure		
Communication path	Infrastructure-to-vehicle, one-way, point-to-multipoint	No need for further testing prior to FOT.
Data latency	0.05 sec	This value is driven by the generally accepted update rate of 10 Hz for vehicle applications (1/2 the frequency). No further research required.
Update rate	10 Hz	This value is generally been accepted as a standard for update rate for vehicle applications. No further research required.
Range	215 - 300 m	Knowledge gap - further testing required prior to FOT. Some research to be conducted by CAMP VSC.
Content of datastream (packet content)	Traffic signal phase, timing, directionality, and location; weather conditions, road surface type	Will be set prior to FOT. Some research to be conducted by CAMP VSC.
Packet size	256 bytes	Knowledge gap - further testing required prior to FOT. Some research to be conducted by CAMP VSC.

IMPLICATIONS OF DEPLOYMENT AND FOT REQUIREMENTS AND SPECIFICATIONS FOR TESTBED DESIGN AND DEVELOPMENT

Task 3 of this project calls for testbed design and development. The preliminary requirements and specifications discussed in the preceding pages provide guidance on how this should be accomplished. Based on these requirements and specifications, Table 109 is a set of specifications requiring further testing and not definitively scheduled to be performed by any other group (such as CAMP or the Infrastructure Consortium).

Table 109. Potential Knowledge Gaps to be Addressed by ICAV Testbed System.

Specification Type	**Performance Specification**	**Comments/Knowledge Gaps/Methodology**
Communications Link with Infrastructure		
Range	215 - 300 m	Knowledge gap – potential testbed area of research, to be complemented by CAMP VSC research.
Packet size	256 bytes	Knowledge gap – potential testbed area of research, to be complemented by CAMP VSC research.
Positioning System		
Max. time loss for positioning data	10 sec	Knowledge gap – potential testbed area of research, to be complemented by CAMP EDMaps research (concerned with developing vehicle positioning and mapping concepts for future use). Relevant for GPS systems.

Specification Type		**Performance Specification**	**Comments/Knowledge Gaps/Methodology**
Longitudinal vehicle position accuracy		<0.3 m to <5 m	Knowledge gap – potential testbed area of research, to be complemented by CAMP EDMaps research. Relevant for GPS systems.
Vehicle offset		-1.8 m to -10 m	Knowledge gap – potential testbed area of research, to be complemented by CAMP EDMaps research. Relevant for GPS systems.
Stopping location accuracy		-2 m to 0 m	Knowledge gap – potential testbed area of research, to be complemented by CAMP EDMaps research. Relevant for GPS systems.
In-Vehicle Sensors			
Speed	Accuracy	TBD	Knowledge gap – potential testbed area of research; engineering judgment indicates testing in the range of ± 5 mph.
	False alarms and misses	TBD	Knowledge gap – potential testbed area of research; engineering judgment indicates testing in the range of 1% to 25%.
Acceleration	Accuracy	TBD	Knowledge gap – potential testbed area of research; engineering judgment indicates testing in the range of ± .05 g.
	False alarms and misses	TBD	Knowledge gap – potential testbed area of research; engineering judgment indicates testing in the range of 1% to 25%.
Braking	Accuracy	TBD	Knowledge gap – potential testbed area of research; engineering judgment indicates testing in the range of ± 5% (if percent pedal depression is used).
	False alarms and misses	TBD	Knowledge gap – potential testbed area of research; engineering judgment indicates testing in the range of 1% to 25%.
Heading angle	Accuracy	TBD	Knowledge gap – potential testbed area of research; Veridian indicated a specification of ± 2º.
	False alarms and misses	TBD	Knowledge gap – potential testbed area of research; engineering judgment indicates testing in the range of 1% to 25%.
Computations			
False alarm rate		TBD	Knowledge gap – potential testbed area of research.
Miss rate		TBD	Knowledge gap – potential testbed area of research.
Driver acceptance		TBD	Knowledge gap – potential testbed area of research.

Specification Type		Performance Specification	Comments/Knowledge Gaps/Methodology
Driver Vehicle Interface (DVI)			
Visual display	Warning type	Iconic indicator with the word WARNING below	Testbed fine-tuning required.
	Animation	Animated (multi-stage)	Testbed fine-tuning required.
	Icon type	Stop sign icon	Testbed fine-tuning required.
	Luminance (based on HUD)	Adjustable from 10 fL to 1,000 fL daytime; 0.01 fL to 10 fL nighttime	Knowledge gap – potential testbed area of research. Need to adapt HUD specification for high-head-up display.
Auditory display	Type	Specific non-speech tone	Testbed fine-tuning required.
	Frequency	Mixed waveforms with 2500 & 2650 Hz peaks	Testbed fine-tuning required.
	Temporal	Intermittent or changing over time	Testbed fine-tuning required.
	Amplitude	At least 20 dB above the amplitude of the masked threshold	Testbed fine-tuning required.
Haptic display	Duration-pulse separation	Duration-pulse separation of 50-100 ms; pulsing should be accompanied by auditory display	Knowledge gap – potential testbed area of research
	Number and duration of pulses	Three pulses of 100 ms with 100 to 200 ms separation periods	Knowledge gap – potential testbed area of research
	Velocity change	Each 100 ms pulse should result in a -0.6 m/s velocity change	Knowledge gap – potential testbed area of research

These testbed specification knowledge gaps will guide the next phase of this project (Task 3), especially the Task 3 Testplan and the Task 3 Testbed Design and Validation Plan. As can be seen from Table 109, a highly flexible and configurable (over-performing) testbed would allow for testing over a range of values for most of these knowledge gaps.

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APPENDIX A:
DVI REFERENCE LIST

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
RECAS	(McGehee, *et al.*, 1992)	X			Initial report of preliminary work in the development of a Forward Collision-warning System		Information should be provided to the driver with respect to headway and relative velocity. The researchers suggest presenting this information graphically.	
RECAS	(Horowitz and Dingus, 1992)	X			The article presents potential negative effects of warnings and suggestions for the design of these systems		Potential Human Factors Effects: • Circumstances requiring warnings will rarely occur, so false and nuisance alarms have to be avoided • Warnings may add to attention/information-processing load • Frequent warnings may be ignored Suggestions for Warning System Design: • Use a graded sequence of warnings • Change modality as the severity of the situation increases (e.g., warn first visually, the add auditory component as severity increases) • Individualize warnings (i.e., make some settings driver adjustable) • Present headway displays as initial status devices that expand to provide warnings as needed	
Icons	(Yoo, *et al.*, 1996)	X			Icons were compared against a text warning and no warning in a simulator-based collision-avoidance experiment	Icons resulted in fewer crashes than the other two alternatives, although differences were not statistically significant.	These researchers conclude that experiments of this type, where DVI alternatives are being evaluated, should use a large number of participants (> 50)	
Older Drivers	(Davies and Rose, 1996)	X			The authors varied location and movement of a warning stimulus for younger and older drivers. The study was performed in a low-fidelity simulator.	Older subjects consistently required higher luminance levels to detect the target. The 'costs' of spatial and temporal uncertainty were also much greater for the old than the young.		
Subjective Icon Evaluation	(Sayer, 2002)	X			Several icons were presented to drivers, who were asked to rank		The document presents a plausible testing scheme for various DVI icon options.	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					each based on their understanding of meaning.			
Subjective Icon Evaluation	(Nakata, *et al.*, 2002)	X			Compared general vs. situation specific icons in terms of their ability to convey the desired message (i.e. general vs. specific)		• General Icons should be used as long as they do not negatively impact driver acceptance or driver performance • For safety-related messages, specific icons will provide higher levels of driver acceptance than general icons.	
Subjective Icon Evaluation	(Richman*, et al.*, 2002)	X			Icons were presented to participants who were then asked to describe the warning represented by the icon and the situation in which it could occur		The document presents a plausible testing scheme for various DVI icon options.	
Auditory Icons	(Graham*, et al.*, 1995; Graham, 1999)		X		Describes an experiment that was carried out to compare the effects of conventional auditory collision warnings with auditory icon warnings in terms of reaction times and driver preferences. Two icons, the sounds of a car horn and of skidding tires, were compared with two conventional warnings, a simple tone and a voice saying 'ahead'. Simulator-based study	The auditory icons produced significantly faster reaction times than the conventional warnings but suffered from more inappropriate responses, where drivers reacted with a brake press to a non-collision situation.	Optimal warnings could be achieved by adjusting certain sound attributes of auditory icons as part of a structured, user-centered design and evaluation procedures.	
Multiple Attribute Evaluation	(Tan and Lerner, 1995; Lerner*, et al.*, 1997)		X		4 sources of warnings: 1) Existing auditory warnings and pre-recorded sounds (1-6) 2) Off-the-shelf warning devices (7-9) 3) New acoustic warnings developed to	The five most effective stimuli were 1, 4, 5, 8 and 10. 1 was also rated the most annoying. As a class, the voice sounds were somewhat		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					be compatible with recommendations in the COMSIS (1993) guidelines (10-14) 4) Voice warnings developed to be compatible with recommendations in the COMSIS (1993) guidelines. (14-26) 1) low-fuel warning, rapid wailing siren 2) take-off abort warning, slow, pulsed, whistle-like tone 3) Radio Shack (Pulse Mode), approximately 3500 Hz peak pulsed beep 4) Radio Shack #273-075 (Continuous Mode), high-pitched ambulance-like siren 5) Radio Shack #273-072, low-pitched ambulance-like siren 6) continuous tone high, narrow spectrum with peak centered at approximately 5200 Hz 7) continuous tone low, broader spectrum than stimulus 6 with more low frequency energy	less effective than the (non-voice) acoustic sounds. Generally, "Danger" had higher Multiple Attribute Evaluation ratings, but its ratings were related to loudness Effectiveness seemed related to the loudness of the warning		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					8) Pattern 1. 2500 & 7500 Hz broad pulse of 110 ms each repeated at 8 ms intervals, pause of 110 ms 9) Pattern 2, 5200 Hz, two paired bursts with a longer pause between a repeated set of paired bursts 10) Pattern 3, narrow 2600 & 7800 peaks, temporally similar to Pattern 1 11) 1500-2000 Hz, 75ms sweep time 12) 2000-2500 Hz, 75ms sweep time 13) car horn 14) DANGER, male, digitized 15) WARNING, male, digitized 16) HAZARD, male, digitized 7-5 17) DANGER, male, synthesized 18) WARNING, male, synthesized 19) HAZARD, male, synthesized 20) DANGER, female, digitized 21) WARNING, female, digitized 22) HAZARD, female, digitized 23) DANGER, female, synthesized 24) WARNING, female, synthesized 25) HAZARD, female,			

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					synthesized 26) tire skid 27) Stimulus 5 (+6 dB) 28) Stimulus 5 (-6 dB) (Paper included excerpts from COMSIS (1993) used to develop the stimuli)			
Inappropriate alarm rates	(Lerner, *et al.*, 1996; Lerner, *et al.*, 1997)		X		Inappropriate alarm rates and driver annoyance Participants were given 5 inappropriate alarms as follows: 1) four inappropriate alarms per hour of driving, one-week duration, tone stimulus; 2) one inappropriate alarm per hour of driving, one week duration, tone stimulus; 3) one inappropriate alarm per hour of driving, one week duration, voice stimulus; 4) one inappropriate alarm per four hours of driving, two week duration, tone stimulus; 5) one inappropriate alarm per eight hours of driving, three week duration, tone stimulus.	There was no statistically significant effect of the alarm condition on noticeability ratings for either daily or weekly analyses. Average annoyance ratings generally tended to increase as the frequency of inappropriate alarms increased. The acceptability of the 1 every 4 hours and 1 every 8 hours was significantly higher than the 4 per hour and 1 per hour voice warnings.		For independent, similar work, see (Wiese and Lee, 2001)
Localized Acoustic	(Tan and Lerner, 1996; Lerner, *et al.*, 1997)		X		12 speakers were placed throughout the vehicle, with 6 warning stimuli. Ambient noise speakers were located throughout the vehicle.	Both age groups responded at significantly different speeds for each sound, and Sound was significant at each level		Study needs to be widened to include such factors as • Vehicle interior: layout, materials and fabrics, seat/headrest configuration

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					They used voice warnings and acoustic warnings. Seven stimuli used are described below: 1. Low fuel warning 2. Off the shelf buzzer 3. Repeating Pattern 1 4. Repeating Pattern 2 5. Digitized male voice 6. Digitized female voice 7. Synthesized	of Age (Young- 20-45, Old- 65+) For the young age group- low fuel warning has a significantly faster response time The simple-effects of sounds were significant for 8 out of 16 speakers The best performing speakers were those that did not interact with sound Response time was fastest for the left and right speakers Similar result occurred for decision times Although the effects of sound, averaged across all speaker locations, were not particularly large, there was a significant sound-by-speaker interaction. Because of the sound-by-speaker location interaction, the effectiveness of various speaker locations must be considered for the particular sound.		• Noise conditions: road/traffic noise, stereo system, conversation, open windows • Occupancy conditions: other passengers or objects in the sound field • Driver-selected head locations within the three-dimensional field • Driver hearing abilities
Auditory	(Bliss and Acton, 2000)		X		While driving in the simulation, participants were required to react to intermittent alarms. The alarms originated	Drivers avoided collisions better using spatial alarms, yet their initial driving reactions were more appropriate		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					from either a center front console located behind the automobile cabin firewall or from various locations within the automobile cabin (rear, left rear, or right rear). The stimulus consisted of regular 1000 Hz. sine wave pulses at approximately 90 dB(A). After obtaining the digitized signal, personnel from AMCOM incorporated the alarms into the driving simulation at predetermined locations.	following console-generated alarms. One reason may be that driving reactions reflected the initial, reflexive reaction to the alarm. Results did not suggest that participants found spatial alarms to be more trustworthy than console-based alarms. However, alarm response rates suggested that the cry-wolf effect did occur.		
Auditory	(Hurwitz and Wheatley, 2001)		X		Researchers provided auditory warnings to drivers in a headway maintenance task	Drivers with an auditory headway warning were more likely to leave larger headways, even on trips with a secondary task.		(Ben-Yaacov, *et al.*, 2000; Ben-Yaacov, *et al.*, 2002) further suggest that headway estimation training can be assisted by these devices.
Army System	(National Transportation Safety Board, 2001)		X		Reports on a US Army study on collision-warning devices. Convoy vehicles were outfitted with these devices and their crash statistics collected	Crashes were significantly reduced for the convoy where the systems were used	Lessons learned indicate that: (1) drivers should always be in command and should be able to turn the system off and on when they think it is appropriate, and (2) human factors aspects are so significant that a CWS must be designed so that drivers understand the system and want to use it. In addition, the evaluation concluded that it was imperative for the drivers to be trained on the system because the system was not intuitive.	
Verbal Collision-warning System	(Baldwin and Moore, 2002)		X		4 signal words- Note, Caution, Warning, or Danger 6 CAS messages- Decrease Speed, Increase Speed, Close on Left, Close on Right, Vehicle	• Notice was rated as the least urgent, Danger was rated the most urgent • Perceived urgency increased as PL increased		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					Tailgating, Following Close 3 PL- 78dB S/N +10dB; 72 dB S/N +4dB; 66dB S/N -2dB			
Older Drivers	(Baldwin, 2002)		X		Literature review of older drivers sensory and cognitive degradation and changes that can be made in IVHS technologies to minimize the effect of these changes		These researchers suggest that: • The auditory channel should be used to presenting collision-avoidance warnings so that drivers do not have to take their eyes off the road. • Older drivers require auditory warning presentation levels 10 dB higher than their younger counterparts. • Auditory warnings should be at least +6 dB above background noise levels (+15 dB for drivers with hearing impairments) • Use standard signage and terminology when possible • Message length should be short • If speech is used, make sure it is digitized	
Brake Control	(Hashimoto, *et al.*, 1995)			X	The authors describe the development of a brake control device capable of automatic braking. The system initially provides a warning and then takes over vehicle control by braking (if the driver does not react).			
Accelerator push-back	(Bloomfield, *et al.*, 1998)			X	Developed a haptic system in which the accelerator pedal pushed upward against the driver's foot if a collision was imminent	Drivers controlled their speed and steering more precisely than control-group drivers when using the collision-warning device. However, the speed driving through fog also increased as drivers increased their trust in the system.		
Haptic	(Tijerina, *et*			X	Three studies were	The results indicated		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
Displays for Rear-end collisions & ACC	*al.*, 2000; Tijerina, 2001)				conducted using the Haptic display warning modality. The first study was conducted to determine the display parameter settings of a monopulse braking display. The second study examined the effects of active steering vibration amplitude, frequency, and duration on display detectability and appropriateness ratings. The third study sought to determine how drivers in a car-following situation would react to a mono-pulse braking display under two different simulated rear-end collision-avoidance warning scenarios. (True positive – lead vehicle was braking to a stop, and false positive- lead vehicle was not braking to a stop)	that, over the ranges of vibration frequency, torque amplitude, and duration used, all of the displays were essentially equivalent in terms of driver response. Active steering displays should be used only when a steering action should occur. Drivers tended to respond to the lead vehicle rather than the haptic display. In 1/3 of the FP cases, inappropriate brake responses were recorded.		
Haptic Steering Wheel	(Steele and Gillespie, 2001)			X	Created a haptic steering wheel to be used as a control interface for bi-directional information transfer (the human can simultaneously exert control and extract information from the machine). Experiments were simulator-based.	Visual load was reduced with the use of the device, but cognitive load was not.	None provided	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
Guidelines	(Green, *et al.*, 1993; Green, *et al.*, 1995)	X	X		General Guidelines for Visual and Auditory Displays		**Visual Display Guidelines** Basic: • Minimize what the driver needs to read • Place commonly used displays, or those that are critical, close to the line of sight Legibility: • Text should be 0.25 in high (64 mm) or higher • Use plain type face to minimize legibility • Use mixed case instead of all capital letters in messages in excess of two or three words • All lines and gaps between lines should be at least 0.6 mm (0.025 in) wide • In general use light characters on a dark background • Provide adequate display luminance and contrast • Use discriminable colors Understandability: • Use layman's terms and understandable graphics • Use international symbols to supplement words • When creating abbreviations, use consistent rules so that people can reconstruct them • Use common abbreviations Organization; • In general, left justify free text in fields and right justify numbers when they are alone • Use natural hierarchies to indicate priority and importance Content: • Information on in-vehicle displays about roads should agree with road signs drivers are likely to see at the same time. • On screens giving information about roads (especially traffic information	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
							text screens, but also in navigation displays), identify both the highway to which the information refers and the direction. Where numbered roads have names, both pieces of information should be given (e.g., Lodge Freeway - M-10 North). • On text screens, identify location ("from," "to," etc.) using formats with which people are familiar, including exit names, numbers, and mile markers (e.g., Plymouth Road, Exit 41). • Where route numbers are displayed, the appropriate shield (for Interstates, U.S. route, State roads, etc.) should surround it. • The update rate for distance displays must be set based on the driver's task. **Auditory Display Guidelines** Loudness: • Auditory tones should be about 15 dB above the masked threshold, but no more than 115 dB absolute level Discriminability of Warning Sounds: • Limit the number of different warning tones to three or four. • To create distinguishable sounds, vary two or more of the following parameters: (1) spectral content, (2) pulse duration, (3) pulse shape, and (4) temporal pattern. (6.4) Guideline 4 - The sound should be composed of 10 or more harmonically spaced components, at least 4 of which are prominent and in the range of 100 to 4000 Hz. • Most of the energy of lower-priority warning signals should be in the first 5 harmonics, whereas higher-priority signals should have relatively more energy in harmonics 6 through 10. • Urgency can be emphasized by incorporating a small number of additional, nonharmonically related,	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
							components or by introducing rapid glides in the fundamental frequency. • The duration of a signal burst should be between 100 and 150 ms. • Pulse shaping should be done by providing onsets of no greater that 1 dB that are linear or concave down. Offsets should match onsets. • Varying the temporal pattern (i.e., the timing and amplitude) of successive tone bursts substantially aids discriminability. Synthetic versus Recorded Speech: • Use nonspeech auditory messages (sounds) only for the purposes of alerting—either as a self-contained message or as a method of alerting the driver to an in-vehicle visual message or to a spoken message that follows. • Other auditory messages, including complex warnings, should be speech. • Computer-generated, on-line speech is recommended for situations that require substantial flexibility in generating spoken messages. • Where the choice of messages is relatively limited and known ahead of time, recorded human speech is preferred.	
RECAS	(McGehee, *et al.*, 1994; Dingus, *et al.*, 1997)	X	X		These researchers evaluated various information displays for headway maintenance and collision warning: • Visual perspective • Visual perspective with a pointer • Visual perspective combined with an auditory warning • Discrete visual warning	Auditory warnings are helpful in improving reaction times during deceleration events. Large numbers of false and nuisance alarms led to considerable system distrust.		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					- Discrete auditory warning			
Collision-warning System for Heavy Trucks	(Tomioka*, et al.*, 1995)	X	X		In the context of rear-end crash warnings, these researchers presented the driver with both audible alarms and lamp indicators.	Authors conclude, based on their results, that these systems are effective in preventing dangerous behavior from drivers. Subjective evaluations also indicated high system regard from drivers.		The paper focuses on effectiveness of the system rather than the effectiveness of specific warning modalities
Side-impact warnings	(Campbell*, et al.*, 1996)	X	X		- **Visual:** The experiment varied a number of visual display characteristics, including whether the warning was static or dynamic (static, flashing, moving, increasing in size) - **Auditory:** Some experimental conditions were accompanied by one of two distinct auditory alerts (different in their origin location) The study was simulator-based and designed to address side-impact warning.	Authors concluded that a caution alert under 'no intent to turn' situations and a hazard alert under 'intent to turn' situations would provide sufficient warning. Several iconic alternatives were deemed appropriate in the design of the warning. However, dynamic warnings were no better than static displays. Authors also recommended accompanying the visual warnings with an auditory tone.		
Subjective evaluation of icons and sounds	(Shirkey*, et al.*, 1996)	X	X		Subjective studies. Participants were asked to look at hazard pictograms and to verbalize their understanding and preferences regarding	A multimodal format was perceived as the most effective presentation method for a safety warning system, as concerns emerged whether		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					the following characteristics: color, flashing, tone, text message, and voice message.	participants could reliably identify a warning if it was provided in a single modality. The combination of color, audio tone, text, and a short voice message was preferred by participants.		
RECAS	(Lee, *et al.*, 1997; Lee, *et al.*, 2000; Brown, *et al.*, 2001; Lee, *et al.*, 2002)	X	X		Researchers used a high-fidelity driving simulator to examine driver response to imminent rear-end collision situations. Inferences were made in terms of warning activation algorithm and DVI sound level. In the 2001 paper, researchers explore the effect of warnings on on-going responses	Manipulating the urgency of the auditory warning by changing the volume of the warning tone had no systematic effects on driver response to the warning. In general, the studies also show that the system's safety benefits derive from their reduction of the time it took the driver to remove his/her foot from the accelerator. The warnings did not speed the driver's application of the brake, increase their maximum deceleration, or affect their mean deceleration. In the 2001 paper, the researchers found that warnings enhanced, rather than undermined, collision-avoidance performance in progress before the warning was provided.		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
Human Factors Guidelines	(Campbell, *et al.*, 1997; Campbell, *et al.*, 1998)	X	X		Tables from Guidelines are detailed below			
Auditory and Visual Warnings used in trucks for front-to-rear collision avoidance and side collision avoidance	(Belz, 1997; Belz, *et al.*, 1998; Belz, *et al.*, 1999)	X	X		Front-to-rear and side collisions were examined using the auditory warning. Auditory warnings were presented through loudspeakers located on either side of the driver's head rest. Visual warnings were also included. A visual warning with no auditory was allowed for side collision. • Front-to-rear display presentation mode-allowed no display, visual display only, auditory display only(sound of tire skidding), conventional auditory warning only, mixed-modality 1, or mixed-modality 2 • Side Collision dash-mounted iconic display, mirrors, auditory display (long horn honk), vehicle speed, and workload.	For front-to-rear, the brake reaction time was a measure of success of warning For side collision, the successfulness of the warning was measured by actions taken by participant (if they avoided a side collision, warning was effective)	• Auditory icon elicited significantly faster brake response times than conventional auditory warning or the no-display condition (may be due to less cognitive processing needed) • Performance was better when multiple modalities were utilized • Most participants guessed at meaning of auditory icon	• What would be an appropriate auditory icon for signal and stop sign? • A disadvantage of the auditory icons was that most participants did not think they sounded like 'serious' warning signals
Guidelines	(Hanowski, *et al.*, 1999)	X	X			Albeit not performed in the context of Collision Avoidance, some of the findings are relevant to this problem.		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
						Results showed that drivers benefited from the use of the information device, drivers could successfully transfer their attention between the road and the warning; older drivers tended to be more cautious in using the devices; older driver limitations in using the system might be addressed by improvements in system design, and auditory cues should be adjustable for intensity.		
Eaton VORAD	(Eaton VORAD Technologies, 2000)	X	X		High-Frequency radar system that transmits radar signals from the front and side of the truck. When it detects a potential hazard, a small display unit on the dash emits a combination of lights and audible tones at three, two, one, and half-second intervals to warn the driver to take evasive action. Graded warnings are used: • **Proximity Alarm:** Object detected within maximum range; a single yellow light illuminates, no auditory signal	The information is taken from a commercial brochure. Suggested benefits are quoted from existing literature for collision-warning systems in general, not for the Eaton VORAD system.	None provided.	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					- **Proximity Warning:** 1-3 second following, yellow and orange light illuminate, tones that increase in frequency as target closes. **Danger:** < 1 second following, slow moving, or stationary targets; yellow, orange, and red lights illuminate, tones presented at maximum frequency			
CAMP	(General Motors Corp. and Delphi-Delco Electronic Systems, 2002a; General Motors Corp. and Delphi-Delco Electronic Systems, 2002b)	X	X		Update on the original CAMP work. Introduces full use of HUDs and the development of animated ('multi-stage') icons, comparing these to 'single-stage' icons. Used both driver preferences and objective measurements in the evaluation of these alternatives	The data revealed that some multiple-stage icons facilitated Brake-Reaction-Times compared to single-stage alerts, especially those that increased in size as the warning became imminent. Driver preference of icons, however, was age dependent. Younger drivers liked 'single-stage' displays, but older driver preferred the more complex type.	Animation can be advantageous in designing DVIs, especially those that provide graded warnings.	
Radar Braking	(Shefer and Klensch, 1973; Society of Automotive Engineers, 1974; Troll, 1974)		X	X	Describe initial attempts of several companies to develop automatic braking systems supplemented by driver warnings. Describe a system in which, before automatic braking			

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					commenced in response to a possible collision, an audible warning signal was generated.			
Collision Warning in Trucks	(Shutko, 1999)		X	X	Test track experiment where a tractor-trailer had to avoid colliding with barrels that were suddenly released on the roadway. Warnings of auditory and haptic modalities were tested independently. • **Auditory:** auditory icon at 15dB above the ambient sound level; the sound of a tire skid was presented as the icon through two speakers located on the dashboard in front of the driver • **Haptic:** brake pulse at a rate of 0.3 g and lasting approximately 1 sec; full deceleration reached in 0.8 sec.	Both modalities reduced speed at collision, only haptic reduced the number of collisions (likely because it provided a certain amount of initial braking). The auditory warning also resulted in the fastest reaction times.	A methodology is provided for the determination of necessary sound levels for auditory warnings (by matching its perceived severity with the severity of the haptic warning). A problem with the haptic display used was uncovered. If drivers are not aware of the system's presence, they might be distracted trying to locate the reason for the deceleration (e.g. problem with vehicle) rather than attending to it. Thus, it seems that training is an integral part of successful haptic warning systems.	
Tri-modal systems	(Janssen and Nilsson, 1992; Janssen and Nilsson, 1993)	X	X	X	The information given to the driver was provided continuously via a visual indicator (at all times this indicator showed the distance required for the driver's vehicle to stop). In addition, three alerting signals were used that appeared only if the time-to-collision criterion was exceeded.	The haptic alert was the only alert of those they tested that produced a reduction in short headways without producing "counter-productive effects in overall speed, speed irregularity, or driving in the left lane." With the other warning systems, "the potential gain in safety obtained		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					The signal could be visual (the appearance of a red light on the dashboard), auditory (the sounding of a warning buzzer), or haptic (an abrupt 25-N [5.6-lbfJ force that was applied to the accelerator pedal).	by the reduction in short headways was more or less offset by an increase in other, more risky, behaviors."		
FOREWARN Collision-warning System (Forward Warning)	(Schumacher, *et al.*, 1995; Landau, 1996; Olney, *et al.*, 1996)	X	X	X	A rear collision-warning system is also described. Only forward collision-warning characteristics are described here. • **Auditory:** Graded warning; Omnidirectional chime was used for caution and voice (Brake!, Brake!, Brake!) was used for emergency • **Visual:** Graded warning; amber triangle on HUD used for caution and flashing red octagon on HUD used for emergency • **Haptic:** Single brake pulse (up to 0.3g command) was used for emergency	The emphasis on the study was on reaction times, not DVI design. The study, however, provides lists of general DVI design principles for the visual, auditory, and haptic modalities.	• Warnings should draw the attention of the driver to the nature and direction of the hazard • Head-Up Display preferred over Head Down Display • Visual warnings specified according to the following principles 1. icons should be simple, intuitive, and consistent with existing practices 2. standardized icons should be used if they exist 3. size, brightness, color, and shape of icons must guarantee legibility at a glance (30 arc minutes minimum) 4. population stereotypes for the meaning of color should be considered when allocating icon color 5. locate warning symbols within ±7° of vertical centerline and 6° below the horizon 6. contrast of warning and background of at least 2:1 7. color-blind individuals should be considered • Auditory warnings specified according to the following principles: 1. warning easily discriminable from other sounds in the car 2. sound must not startle drivers 3. sound must be instantly recognizable from others with little	• The HUD specifications are available in the Olney, et al. paper • Auditory specifications provided in the Landau (1996) paper

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
							training (<5 min) 4. sound should not be annoying (especially in the caution stage) 5. fundamental frequencies limited to 2000 Hz and below 6. other audio systems muted when warning is active 7. repetition rates should match those of visual warnings • Haptic warnings specified according to the following principles: 1. brake pulse should be felt at the same time or after the audio warning is heard 2. brake pulse should not startle the driver because of onset or intensity of deceleration 3. brake pulse should not interfere with the driver's ability to control the vehicle 4. duration of the brake pulse should be approximately 300 msec	
Brake Pulses / General Guidelines	(Lloyd, *et al.*, 1996; Lloyd, *et al.*, 1999a; Lloyd, *et al.*, 1999b)	X	X	X	These authors compared various types of warning modalities and created driver-vehicle interface design recommendations for use in intersection collision-avoidance technology. Guidelines for the design of haptic warnings in the form of brake pulses are provided.	Each of the following technologies was evaluated using the four criteria presented in the next column, with these findings: • **Auditory:** Tone feedback, compared with voice feedback, produced the best driving performance during critical traffic situations, but may not be appropriate if multiple driver assistance systems are involved. Voice feedback may create	In general, the following criteria are suggested for the selection of DVI warning modalities: • Benefit all drivers • Not require specific directional orientation • Be compatible with driver's response • Have viable integration with other CASs and DASs General recommendations based on the analysis of the various modalities prompted the authors to suggest that: • Intersection collision DVIs should include an in-vehicle HUD • A multimodality DVI interface is recommended to attempt to warn *every* driver, not only those that are attentive to the forward view. In essence, these authors suggest the use of visual warning via an HUD, haptic	The papers provide tables with more detailed advantages and disadvantages of employing each of the different technologies

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
						attention demands that overload the driver. - **Visual:** Non-head-up displays are appropriate when the driver can choose when to look at the display. Head-up displays located close to the forward view can benefit driving performance; these benefits are increased for older drivers - **Haptic:** haptic cues do not require a specific orientation of sensory receptors for detection and are perceived very quickly. Furthermore, their perception is not typically affected by common disabilities. However, haptic displays are intrusive. When used as an imminent warning, haptic warnings should supplement the main display.	warnings via brake pulsing, and an auditory tone. Specific design requirements for haptic warnings are also provided: - Minimize the time required for the driver to acquire and use the information available - Minimize learning and training requirements. - Provide expansion potential - Maximize user acceptance of the system - 100 ms-long brake pulses separated by 100 to 200ms, with each pulse resulting in a -0.6 m/sec velocity change	
Guidelines	(COMSIS, 1996)	X	X	X	The document proposes general (i.e. applicable to a variety of potential crashes) design guidelines for the various display		Specific (and comprehensive) guidelines are provided for each of the various display modalities within the document. The reader is referred to the document to read those guidelines. Some of the more general findings are summarized here:	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					modalities and specific ones for various crash-type warnings		• Use multiple levels of warning, the more imminent the crash, the more intrusive the warning • Use unique imminent crash warning signals to minimize confusion and increase saliency • Imminent crash warnings should be of at least dual modality • Schemes for warning prioritization must be created • The warning must be compatible with expected driver behaviors (e.g. vibrating the accelerator might cause the driver to look down, an undesired and potentially harmful reaction) • The content of the warning message is mostly device specific • The status of the device (i.e. operational or not operational) must be easily available to the driver, so that no reliance is made on technologies that are not working • Nuisance warnings must be minimized	
Driver Support System	(Mitsubishi Motors Corporation, 1998)	X	X	X	The system is meant to alert the driver to a variety of collision types, including side, rear, and forward. All three modalities are used as appropriate, but details of their design are not provided. • **Visual:** Icon is presented on the instrument panel. • **Auditory:** Audible warning is presented as necessary • **Haptic:** Steering wheel vibrates and/or a small	The information is taken from a commercial brochure, no information on benefits is provided.	None provided.	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					torque is applied to the steering wheel.			
Guidelines	(Dingus, *et al.*, 1998)				General guidelines for in-vehicle warning designs based on various literature sources		1. Provide redundancy in system design 2. Draw attention to the emergency situation 3. Prioritize visual displays by location 4. Avoid auditory signals for advisory warnings 5. Avoid speech displays for attentional warnings (use only for emergency) 6. Provide unique warnings 7. Incorporate intelligence in warning presentation dynamics 8. Prioritize driver workload and warning (emergency warnings take precedence over anything else) 9. Individualize warnings (e.g. novice vs. experienced)	
CAMP	(Kiefer, *et al.*, 1999; Kiefer, 2000)	X	X	X	In these interface studies, the driver was simultaneously presented (i.e., in a one-stage manner) crash alerts from two or more sensory modalities. The system crash alert types evaluated are listed below: • Head-Up Display + Non-Speech Tone • High Head-Down Display + Non-Speech Tone • High Head-Down Display + Speech message • High Head-Down Display + Brake Pulse • High Head-Down Display + Brake Pulse + Non-	A single stage crash alert consisting of the non-speech tone combined with a flashing High Head Down Display of the visual icon with the word "WARNING" added demonstrated good all-around performance in terms of objective data (e.g., faster driver brake reaction times) and subjective data (e.g., alert noticeability) during interface testing.	As a minimum, a single-stage alert consisting of a specific non-speech tone is required. A specific visual icon may be used to supplement this auditory alert if desired. Although optional, use of the visual icon is encouraged to improve alert noticeability for drivers who may not hear the tone, prompt drivers to look ahead in response to an alert, and to explain the non-speech tone to the driver. A single stage crash alert consisting of the non-speech tone combined with a flashing High Head Down Display of the visual icon with the word "WARNING" added is recommended. These findings also support replacing the High Head Down Display with a Head Up Display if desired. Overall, the speech alerts examined performed poorly in terms of both objective and subjective data. The brake pulse haptic alert is not currently recommended due to a number of unresolved implementation and driver behavior issues (e.g., activation on slippery surfaces, driver braking onset delays, observed foot / body movements).	See complete report for more detailed information.

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					Speech Tone - Flashing High Head-Down Display + Non-Speech Tone Both visual alerts were located centerline to the driver, with the amber High Head-Down Display (HHDD) located on the top of the dashboard near the cowl of the windshield and the blue-green Head-Up Display (HUD) positioned slightly above the front hood at a 1.2 m distance. An American National Standards Institute (ANSI) testing procedure was used to select the visual alert format. The auditory alerts included a non-speech tone and a speech message (the word "warning" repeated) played through the front car speakers. These sounds were selected based on drivers' subjective ratings of various alternative sounds on crash alert properties. The haptic alert evaluated was a brief brake pulse or "vehicle jerk" alert.		The single-stage rear-end crash alert recommendation is based on modeling how drivers actually perform this braking task. This supports the notion of a consistent driver "mental model" and simplifies driverr education while minimizing nuisance alerts. Specifications: Sound: mixed waveforms with 2500 & 2650 Hz peaks) Visual: Red-orange, amber, or yellow iconic indicator with the word WARNING below	
Tri-modal systems	(Pierowicz, *et al.*, 2000)	X	X	X	A HUD was used for the visual component, speakers for the	Among the visual modality icons, the stop sign was the most	The authors recommend a graded system consisting of (1) Advisory/Alert Mode, which provides information regarding the	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					auditory component (1000 Hz tone, 20dB above the ambient level at that frequency, and pulsed to couple with the haptic braking signal). The haptic modality was achieved by using a secondary, computer controlled brake system that provided three deceleration pulses when active. The three icons tested for the visual modality represented (1) the top view of an intersection, (2) a traffic light, and (3) a stop sign. Researchers also tested various haptic combinations of pulse duration and pulse separation.	meaningful. Among the haptic pulse duration-pulse separation alternatives 50-100 ms was rated as most appropriate. The pulsing should be accompanied by an auditory signal.	presence of an upcoming intersection, and (2) Warning Mode, which provides information regarding the need to stop to avoid violating a traffic control device. An evaluation of previously proposed guidelines suggested: • Auditory: multiple frequency with more than one frequency in the range of 250 Hz to 4000 Hz; intermittent or changing over time; at least 15 dB above the amplitude of the masked threshold; well-separated from existing auditory warnings. • Visual (HUD): use icons instead of words whenever they have been verified as equally or more recognizable and require less display space; visual angle subtended should be no less than 30 arcminutes • Haptic: pulses (three in this case) of 100 ms with 100 to 200 ms separation periods; each pulse should result in a -0.6 m/s velocity changes	
Evaluation of tri-modal systems	(Zador, *et al.*, 2000)	X	X	X	Initially, several sets of warnings: • set of visual alerts using pure icon-based symbology • set of visual alerts using visual text only • auditory alerts using digitized speech to present the visual alerts in the 2nd bullet, some with male voice and others with female • set of earcons and	• Subjects tend to prefer less annoying systems, even if they are less effective • Auditory warnings quickly attracted the participant's attention, but were considered the most annoying • HUD was very well received by participants • Tactile feel was good when combined with the	• Forward collision-warning simulation suggested the use of HUD with tactile feel and HUD with tactile feel and auditory alert as primary alternatives.	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					tones • set of purely visual alerts combining icons and text • set of alerts containing combinations of icon, text and auditory cues (including voice, tones and earcons) were evaluated using the following subjective criteria: • get attention • convey urgency • be annoying • be understandable • be effective at indicating where the collision is • be effective about what to do • overall utility. Later, a subset of these warnings (i.e. the best as determined based on the initial study) and a set of haptic warnings were evaluated in a simulator using forward and side collision scenarios	HUD • Participants showed concern that people would rely too much on these systems • False and nuisance alarms need to be eliminated or at least greatly diminished		
Subjective Evaluation of Various Systems	(Nicolas, *et al.*, 2002)	X	X	X	Five different devices or configurations were tested: • A sound, provided by two loudspeakers integrated in the driver backrest • Two flashing lights	Limited results are presented. A content analysis identified seven criteria that people use to evaluate the DVI: • Attraction capacity • Alert level • Representation of		

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
					down in the windscreen • Two flashing arrows in the instrument cluster • A vibrator in the steering wheel • Two vibrators in the driver seat	danger • Localization of the danger • Incitement to correct the drift • Comfort • "Distinguishability" from other vehicle signals No indication of 'best' alternatives is provided.		
ISO Standard	(International Standards Organization, 2002)	X	X	X	International standard for the development of forward collision-warning systems		• Forward vehicle collision-warning systems shall provide at least two separate warnings: a preliminary collision warning and a collision warning. The purpose of the preliminary collision warning is to inform the driver of the presence of a forward obstacle vehicle. In this case the driver should prepare to take the necessary action in order to avoid a collision • Warnings consist of independent or combined use of visual, audible and/or tactile sense. However in the case of a collision warning, audible and/or tactile means of warning shall be used and visual means may be used in addition to the aforementioned means • Preliminary collision warnings: **Visual**: Color, yellow or amber; Luminance: luminous enough in daylight, not glaring in the night; Interval: continuous or intermittent at long interval; **Auditory**: Pressure: sound pressure overriding background noise; Tone: not annoying tone; Interval: continuous or intermittent at long interval or single sound • Collision warning: **Visual**: Color, red; Position, main glance direction; Interval, intermittent at short interval; **Auditory**: Pressure, sound pressure	

System	Reference	V	A	H	Description	Results	DVI Design Principles/Guidelines	Notes
							should be the highest of those auditory warnings present in the vehicle conveying more urgency than other auditory warnings; Tone, pure tone should be avoided; Interval, intermittent at short interval is recommended. • Even when a vehicle is equipped with a forward vehicle collision-warning system along with other warning systems such as those for rear or side obstacles, the warning shall be clearly distinguishable to the driver.	

Human Factors Design Guidelines (Campbell, *et al.*, 1997):

Presentation of immediate hazard warning information

Information Element	Display Type	Trip Status	Display Format
Inform driver of incident/hazard	Auditory and Visual	Vehicle in Motion	Iconic or graphic representation with voice or text
Indication of the type of hazard	Auditory and Visual	Vehicle in Motion	Iconic or graphic representation
Distance to hazard	Auditory	Vehicle in Motion	Alerting tone and then speech
Status of hazard	Auditory	Vehicle in Motion	Alerting tone and then speech
Alternate route	Auditory	Vehicle in Stop	Iconic or graphic representation with or without text

Sensory modality for presenting ATIS/CVO messages

Information Characteristic	Sensory Modality
High Complexity	Visual
Low Complexity	Auditory
High Priority	Auditory
Low Priority	Visual
Intermittent Display	Auditory
Continuous Display	Visual
Requested Presentation	Auditory (Unless complex, then visual)
Automatic Presentation	Visual (Unless high priority, then auditory)

Heuristics for Assessing Complexity and Priority

High Complexity	Low Complexity
> 9 information units	3-5 information units
Processing time > 5 s	Processing time < 5 s
Examples: topographical representations of a route, or full route maps, or schedules for alternate modes of transportation	Examples: directions of turns, or estimates of travel costs

High Priority	Low Priority
Fast response needed (0-5 minutes)	No response needed (5 min +)
Serious consequences (death or injury)	No immediate consequences
Examples: notification of serious traffic conditions which may affect the safety of the driver, or mechanical problems which could impact the safety of the driver or the condition of the vehicle	Examples: vehicle maintenance schedules, or weather information

Design of Head-Up displays for ATIS

Design Element	Guideline
Image Viewing Distance	Locate the HUD image 2.35 to 2.80 meters from the design-eye-position of the HUD.
Image Distortion	No HUD element should vary from its intended size by more than +/- 10%.
	No point on the HUD display should be displaced by more than 5% of the total image width or height (horizontal or vertical FOV).
Luminance Adjustment Control	A luminance adjustment control for the HUD image should be provided.
	A continuous rotary knob, slide, or a thumbwheel should be the type of control provided for this adjustment
	Luminance values, as a function of control position, should be derived from a power function (see equation below)

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