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16. Abstract

This project entailed the design, development, testing, and evaluation of intersection decision support (IDS) systems to address straight crossing path (SCP) intersection crashes. This type of intersection crash is responsible for more than 100,000 crashes and thousands of fatalities each year. In developing these IDS systems for both signalized and stop-controlled intersections, a top-down systems approach was used that determined the necessary system functions and evaluated the capability of different technologies to perform those functions. Human factors tests were also conducted that evaluated the effectiveness of warning algorithms and infrastructure-based driver-infrastructure interfaces in eliciting a stopping response from drivers about to be involved in an SCP intersection crash. Results indicated that further technological development is needed for the sensing and intersection state IDS functions. Furthermore, infrastructure-based warning interfaces tested were greatly outperformed by previously-tested in-vehicle warnings. Thus, future research on IDS systems should focus on their infrastructure-cooperative configuration, where the system supports an in-vehicle warning.

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FINAL CONTRACT REPORT

INTERSECTION DECISION SUPPORT: EVALUATION OF A VIOLATION WARNING SYSTEM TO MITIGATE STRAIGHT CROSSING PATH COLLISIONS

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NOTICE

The project that is the subject of this report was done under contract for the Virginia Department of Transportation, Virginia Transportation Research Council. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

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LIST OF ACRONYMS AND ABBREVIATIONS

AASHTO – American Association of State and Highway Transportation Officials
BD – Braking Distance
BRD – Brake Reaction Distance
COF – Coefficient of Friction
CDS – Crashworthiness Data System
DFS – Distance-to-Full-Stop
DOT – Department of Transportation
FHWA – Federal Highway Administration
FS – Factor of Safety
GES – General Estimates System
HEL – Hardware Engineering Laboratory
IC – Infrastructure Consortium
ITS – Intelligent Transportation System
IDS – Intersection Decision Support
LTAP – Left Turn Across Path
LTAP/LD – Left Turn Across Path - Lateral Direction
LTAP/OD – Left Turn Across Path - Opposite Direction
LTIP – Left Turn Into Path
MOE – Measures of Effectiveness
NASS CDS – National Automotive Sampling System Crashworthiness Data System
NHTSA – National Highway Traffic Safety Administration
PCP – Perpendicular Crossing Path
POV – Principal Other Vehicle
PRT – Perception-Reaction Time
RT – Reaction Time
RTIP – Right Turn Into Path
SCP – Straight Crossing Path
SI/PCP – Signalized Intersection Perpendicular Crossing Path
SI/SCP – Signalized Intersection Straight Crossing Path
SSD – Stopping Sight Distance
SV – Subject Vehicle
TAR – Time-to-Accelerator-release
TB – Time-to-Brake
TFB – Time-to-Full-Brake
TFS – Time-to-Full-Stop
TIDA – Time-to-Initial-Driver-Action
TIP – Turn Into Path
TS – Time-to-Steering
TSAB – Transition-Time-from-Accelerator-to-Brake
TSAFB – Transition-Time-from-Accelerator-to-Full-Brake
TSBFB – Transition-Time-from-Brake-to-Full-Brake
TSS – Time-to-Severe-Steering
TTC – Time-to-Collision
TTI – Time-to-Intersection
UI/PCP – Unsignalized Intersection Perpendicular Crossing Path
UI/SCP – Unsignalized Intersection Straight Crossing Path
VTRC – Virginia Transportation Research Council
VTTI – Virginia Tech Transportation Institute

ABSTRACT

This project entailed the design, development, testing, and evaluation of Intersection Decision Support (IDS) systems to address Straight Crossing Path (SCP) intersection crashes. This type of intersection crash is responsible for over 100,000 crashes and thousands of fatalities each year. In developing these IDS systems for both signalized and stop-controlled intersections, a top-down systems approach was used that determined the necessary system functions and evaluated the capability of different technologies to perform those functions. Human factors tests were also conducted that evaluated the effectiveness of warning algorithms and infrastructure-based driver-infrastructure interfaces in eliciting a stopping response from drivers about to be involved in an SCP intersection crash.

Results indicate that further technological development is needed for the sensing and intersection state IDS functions. Furthermore, infrastructure-based warning interfaces tested were greatly outperformed by previously-tested in-vehicle warnings. Thus, future research on IDS systems should focus on their infrastructure-cooperative configuration in which the system supports an in-vehicle warning.

INTRODUCTION

Overview

This report describes the multi-year effort of the Virginia Tech Transportation Institute (VTTI) in the design, development, and testing of an Intersection Decision Support (IDS) system to reduce Straight Crossing Path (SCP) crashes at signalized and stop-sign-controlled intersections. In terms of the studies described in this report, an SCP crash occurs when a vehicle violates a signalized or stop-controlled intersection and strikes or is stuck by a vehicle on a perpendicular path through the intersection. In designing the system architecture, two distinct possibilities were considered and supported. The first was an Infrastructure-Only option that used infrastructure-based components to detect any violating vehicle that traversed through the intersection. In this case, specially-equipped vehicles would not be necessary since the infrastructure would detect all vehicles and determine whether any given vehicle would violate the intersection signal or sign. For this option, an infrastructure-based warning would be used to alert the violating vehicle. The second system architecture considered was an Infrastructure-Vehicle Cooperative option; this option used technology in both the vehicle and the infrastructure to warn the driver. In this scenario, the intersection infrastructure would provide signal phase and timing information via wireless communications to specially equipped vehicles. The vehicles would then use the signal phase and timing information to calculate, based on the driver's speed and distance from the intersection, whether the driver would likely violate the intersection control. The warning would be presented to the driver inside the vehicle. The emphasis of this effort was on the sensing, communications, and human-factors aspects of an IDS system and how these functions could be performed using infrastructure-based instrumentation while effectively supporting related in-vehicle components.

The project was performed as a series of subtasks (Figure 1), the results of which are described in this final report. First, a literature review was performed to quantify the magnitude of the SCP crash problem, examine past approaches to addressing similar problems, and examine past research on human capabilities and limitations in crash-avoidance situations. The results of this literature review are presented in the following section. This information was used in turn to drive the top-level system design that determined the necessary functions of an IDS system for SCP crashes; the information also allowed an initial technological scan of equipment that fulfilled these functions (see the section: Top-Level Requirements for an IDS System to Mitigate SCP Crashes). Once these steps were complete, detailed trade-off studies were conducted to evaluate these technologies for potential use in a near-term testbed vehicle and in potential field operational tests (FOTs) of IDS systems in the longer term (see the section: Trade-Off Analyses).

The trade-off studies were followed by the development of the testbed used to examine human factors issues related to IDS systems as well as the evaluation of performance specifications for sensing and communications equipment (see the section: Development of the Smart Road Intersection Testbed). Completion of the testbed allowed for human factors tests to be conducted (see the section: Human Factors Experiments). These tests examined, via a number of surrogate measures and using unique experimental approaches, the potential effectiveness of various Driver Infrastructure Interface (DII) and warning timing combinations in reducing the incidence of SCP intersection crashes for both signalized and stop-sign-controlled intersections.

These human factors tests also allowed the development and testing of various warning timing algorithms with potential to serve as means to provide effective warnings with low rates of nuisance and missed alarms. In developing these algorithms, important implications for the sensing equipment associated with an IDS system were also observed. These aspects of IDS system development are discussed in later sections.

In addition to allowing for the human factors tests, the testbed also allowed for the evaluation of various technologies based on their ability to perform the different functions that would be necessary for an IDS system. The results of these tests are presented in Human Factors Experiments section. In turn, these tests allowed for an overall assessment of the state of potential IDS technology in the light of a potential FOT and the development of performance specifications for an infrastructure-cooperative IDS system (see the section: Conclusions).

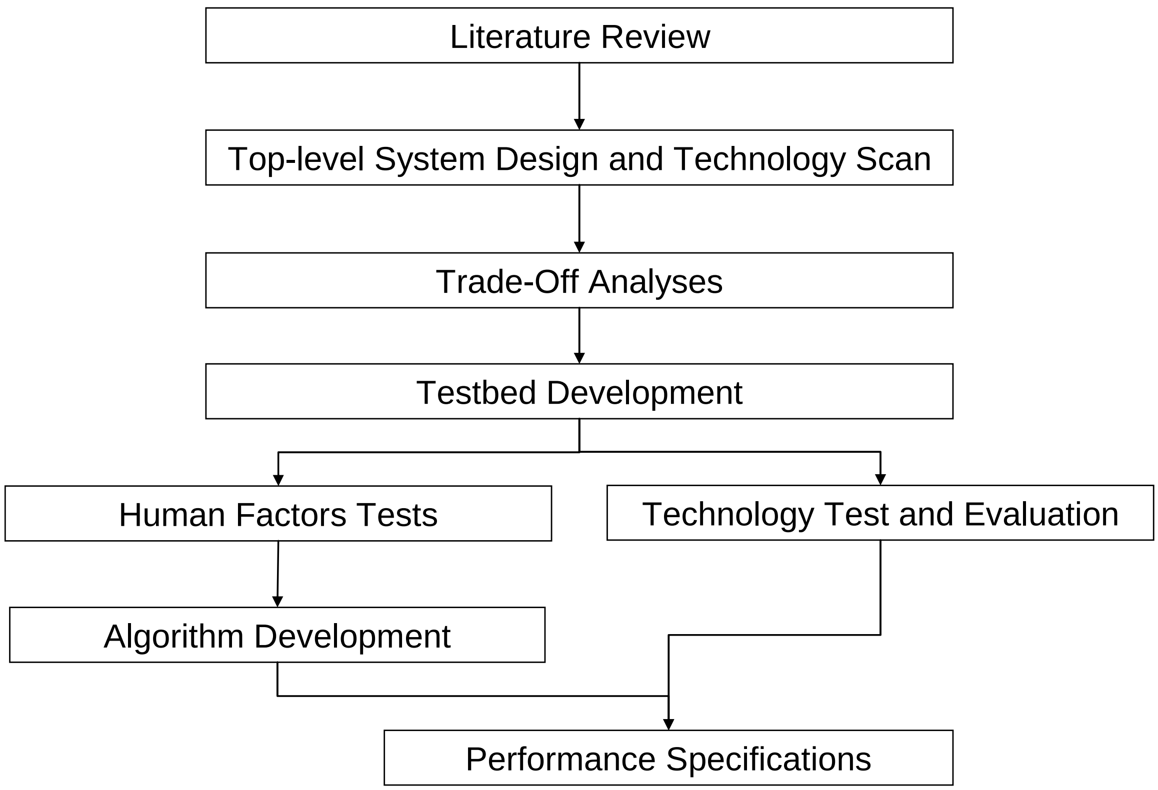

Figure 1. Flow of information amongst project tasks.

The authors would like to note that this project was conducted in close coordination Intersection Collision Avoidance – Violation (ICAV) project efforts, sponsored by the National Highway Traffic Safety Administration (NHTSA). The ICAV project considered in-vehicle warnings to reduce SCP crashes, and in the signalized intersection case, required the intersection to inform the vehicle about the intersection state, thus requiring a cooperative architecture. This information sharing eliminated duplicate tasks and allowed for further work than originally proposed to be performed as part of both projects. This report acknowledges the information gained from the ICAV project when appropriate.

Literature Review

The Intersection Crash Problem

Intersections are defined as areas where public roads cross, requiring vehicles to adjust their speed and path according to a signal or to the presence of other vehicles on adjacent roads. Since intersections require vehicles to cross one another's paths, they are prime areas for the occurrence of vehicle crashes. Of the 6.3 million police reported crashes in 2000, 2.7 million (43 percent) occurred at intersections or were intersection related (NHTSA, 2001). Of these intersection crashes, 8,490 were fatal (22.5 percent of all fatal crashes) and another 970,000 resulted in injury (48 percent of all injury crashes). Given that intersections represent a very small portion of all roadways, they inherently carry a substantially higher crash risk than for other street segments. Systems designed to prevent crashes at intersections could efficiently address a significant share of all traffic crashes. Bonneson (2001) reported that about 25 percent of all highway fatalities in 1999 occurred at intersections. Furthermore, Bonneson estimates that in 1999 about 50 percent of all non-fatal crashes involved intersections. Pierowicz et al. (2000) also estimated that intersection crossing path crashes make up 26 percent of all annual police-reported crashes. Thus, safety enhancements at such sites are an effective investment (Ragland and Zabyshny, 2003).

Taxonomies of Intersection Crashes

The incidence and severity of intersection related crashes varies with, among other factors, the relative positions and travel directions of the vehicles involved. It is difficult to re-create an intersection crash without understanding these crash characteristics. For this reason, various researchers have created different classification systems, or taxonomies, of intersection crashes. These taxonomies are based on the various combinations of vehicle collisions that can occur in a typical intersection. Use of these classification systems allows researchers to gather statistics, recreate, analyze, and experiment with particular intersection crash situations in a repeatable manner.

Each taxonomy considers the two different vehicles that must be present for an intersection crash to occur: the Subject Vehicle (SV) and the Principal Other Vehicle (POV). The vehicle of interest is the SV, whose travel path is intersected by the POV. The actions of the SV always initiate the crash sequence, since this is always a violating vehicle. The POV always has the right of way in these crash sequences. Note: the terms "Straight Crossing Path" (SCP) and "Perpendicular Crossing Path" (PCP) are frequently used interchangeably. For clarity, "Straight Crossing Path" will be used throughout this report. Using this terminology, three of these taxonomies are presented in Table 1. The figures that follow Table 1 (Figures 2 through 5) present the various intersection taxonomies in a graphical format.

Table 1. Summary of taxonomies for intersection crashes.

Characteristics used for classification	Reference	Classifications
SV and POV Positions Signalized vs. Unsignalized Intersections	Wang and Knipling (1994) Najm et al. (1995)	Signalized Intersection Perpendicular Crossing Path (SI/PCP): occur when the SV and POV approach an intersection with a traffic light from perpendicular paths (Figure 2). This is the same as an SCP crash in a signalized intersection. Unsignalized Intersection Perpendicular Crossing Path (UI/PCP): occur when the SV and POV approach an unsignalized intersection from perpendicular paths (Figure 3). The same as an SCP crash in an unsignalized intersection. Left Turn Across Path (LTAP): occur at signalized or unsignalized intersections when the SV makes a left turn across the path of a POV (Figure 4).
SV Turning Patterns	Ferlis (2001b)	SCP: The SV strikes, or is struck by, a POV while both vehicles are traveling through an intersection in straight paths perpendicular to each other (Figures 2 and 3). Left Turn Across Path - Lateral Direction (LTAP/LD): The SV strikes, or is struck by, a POV while the SV is making a turn (right hand situations in Figure 2 and Figure 3). In this category, the vehicles are traveling in opposite directions at the time of the collision, although both vehicles are initially traveling in perpendicular directions. Essentially, a subset of SCP. Left Turn Across Path - Opposite Direction (LTAP/OD): The SV attempts to turn left at an intersection and strikes, or is struck by, a POV traveling in the opposing traffic lanes. This category is equivalent to the LTAP classification (Figure 4). Right/Left Turn Into Path - Merge (RTIP or LTIP): The SV turns right or left into the path of a POV so that both vehicles are traveling in the same direction at the time of collision. Both vehicles are initially traveling in perpendicular directions (Figure 5).
SV and POV Positions Driver Behavior	Pierowicz et al. (2000)	Scenario 1: LTAP where the SV is required to yield but not stop (i.e., SV does not violate the traffic control), is stopped or slowing, and attempts a left turn across the path of the oncoming POV (Figure 4). The traffic control is either a green traffic signal or no signal at all. Scenario 2: SCP with No Violation of the traffic control. The SV stops at the intersection (i.e., obeys the traffic control) and then proceeds into the intersection, either traveling straight or left, crossing across the path of a POV (Figures 2 and 3). Scenario 3: SCP with Violation of traffic control. These are normally cases where both vehicles continue to travel in their straight, but crossing, paths. The traffic control might be a three-phase signal, a stop sign, or some other type of traffic control device. Scenario 4: Premature Intersection Entry. The SV initially stops at the intersection (i.e., obeys the traffic control), but then proceeds into the intersection while the light is still red because of inattentiveness (i.e., inadvertent violation of the traffic control).

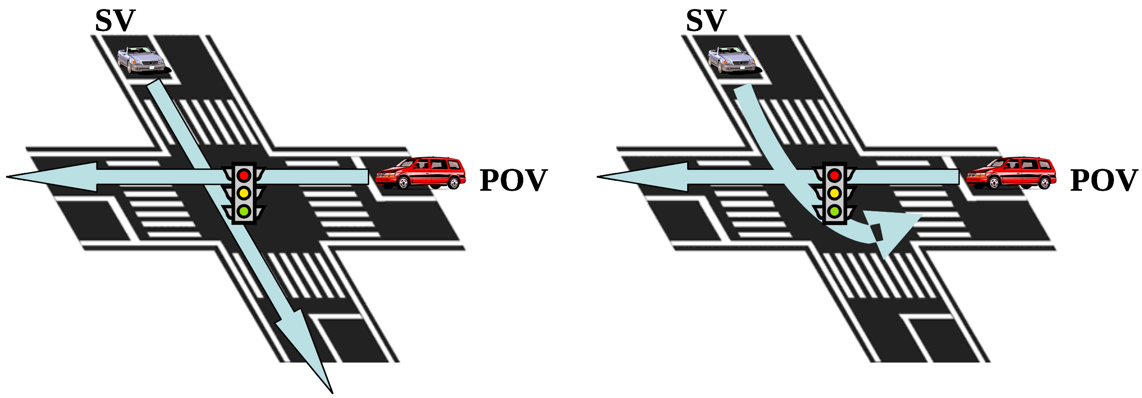

Figure 2. Signalized intersection straight crossing path (SI/SCP).

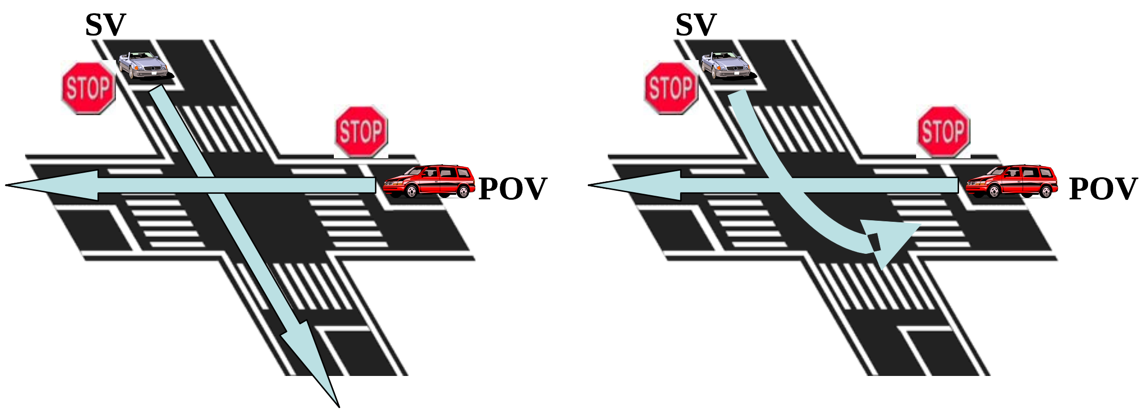

Figure 3. Stop-controlled (unsignalized) intersection straight crossing path (UI/SCP).

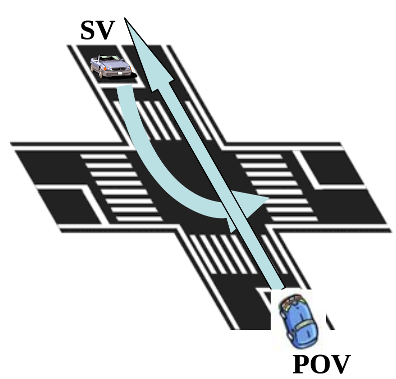

Figure 4. Left turn across path (LTAP).

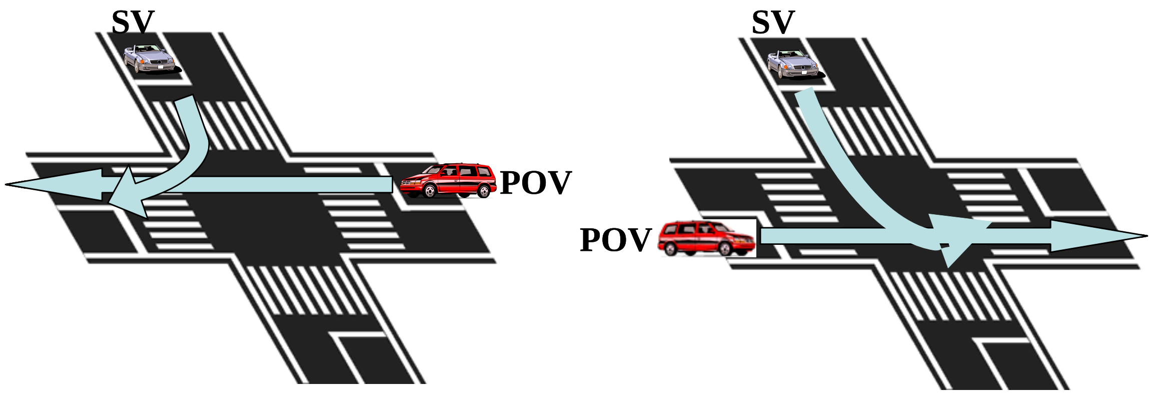

Figure 5. Turn into path – Merge conflict (TIP): a) Right – RTIP, b) Left – LTIP.

Crash incidence data segregated by intersection crash classification indicate that a large proportion (> 40 percent) of intersection crashes is classified as SCP (Ferlis, 1999). Using General Estimates System (GES) data from 1991, Wang and Knipling (1994) found that 14 percent of intersection crashes could be categorized under the SI/SCP scenario and 34 percent under the UI/SCP scenario. Najm et al. (1995) used 1993 GES data and found lower percentages for each of these scenarios (11 and 20 percent for SI/SCP and UI/SCP, respectively). The reason for these lower percentages is unclear from the data provided in the reports. However, given that the number of unclassified intersection crashes increased between the 1991 and the 1993 data, it is possible that crashes classified in 1991 as UI/SCP were not consistently classified in this same category in 1993. Similarly, GES data from 1998 listed 29.9 percent of intersection crashes as SCP (Smith and Najm, 1999). The second and third scenarios described by Pierowicz et al. (2000), which classify SCP accidents, accounted for 30.2 and 43.9 percent of the accidents, respectively, in their study based on data from the National Automotive Sampling System Crashworthiness Data System (NASS CDS).

Other studies suggest that the incidence of a particular crash type is a function of the type of road (Bellomo-McGee, Incorporated [BMI], 2001a). Based on police reports of crashes from specific intersections in California, Minnesota, and Virginia, BMI (2001a) reported that LTAP/LD crashes occur most frequently at urban intersections. SCP crashes, however, occur most frequently in rural intersections. In the intersections reviewed within the state of Virginia, for example, these authors reported that 537 (68.5 percent) intersection-related crashes out of 783 were crossing path crashes. In these 537 crashes, SCP crashes were the second most common intersection crash type classification.

While less important than the relative position and behavior of the vehicles involved in an intersection crash, other incident characteristics should also be considered in the analysis of these crashes. For example, the majority of intersection crashes involve passenger vehicles (Wang and Knipling, 1994). The type of intersection infrastructure (signalized vs. stop-controlled) also influences the type and incidence of crashes. Pierowicz et al. (2000) reported that the SCP with no violation of the traffic control scenario occurs most frequently (95 percent of the time) at stop-controlled intersections. BMI (2001a) reported that while the LTAP/LD is the most frequent classification in signalized intersections, SCP crashes are the most frequent at stop-controlled intersections. In a study of driver errors in various types of road infrastructures, Wierwille et al. (2000) found that 68 out of 209 critical-incident events (33 percent) occurred at complex signalized intersections (i.e., those for which the setup is more complicated than the standard four-lane approach), 59 (28 percent) at stop-controlled intersections, and 25 (12 percent) at ordinary signalized intersections. Bonneson (2001) reported that intersection crashes in Texas were almost evenly split between signalized and stop-controlled intersections. When expressed as a percentage of total crashes, approximately 12 percent of crashes occur at signalized intersections and 9 percent at stop-controlled intersections. Ferlis (1999) reported that about 43 percent of crossing- and turning-path crashes at intersections occurred at signalized (3-phase) intersections, and 39 percent occurred at stop- (or flashing-light-) controlled intersections.

Weather and other environmental factors have been shown to be relatively unrelated to intersection crash risk. Tijerina et al. (1994) reported that SCP crashes at signalized intersections occur mainly on dry pavement, in good weather, and during daylight conditions. Similarly, Chovan et al. (1994) concluded that SCP crashes at stop-controlled intersections also take place mainly on dry pavement, in good weather, and during daylight conditions. These conclusions are supported by data from Wang and Knipling (1994). The intersection crossing-path crashes that these authors studied occurred largely during the daytime under no adverse weather conditions. While Stamatiadis et al. (1991) did report an effect of environmental conditions on accident rate; this effect was present only for a specific group of drivers. They found an increase in accident occurrence at stop-controlled intersections during snowy nighttime conditions for elderly female drivers. They hypothesize that this finding is due to vision deficiency and a slow reaction time for this group, and they note that further research is necessary to identify and evaluate countermeasures for this group.

More recently, analysis completed for the ICAV project (Lee et al., 2004) showed that in 1999 there were 1,698,000 crossing-path (CP) crashes, which comprised 27.1 percent of the 6,271,000 estimated crashes for that year. Similarly, in 2000, there were 1,667,000 CP crashes out of an estimated 6,389,000 crashes (26.1 percent). Analysis of the overall CP crash problem showed that, while left-turn crashes made up the majority (about 52 percent) of CP crashes, SCP crashes had the second highest level of prevalence, at about 30-35 percent, followed by right-turn crashes (about 6 percent) and unknown (7-11 percent).

These percentages translate to roughly 580,000 SCP crashes that occur at stop-controlled and signalized intersections every year. Most of these crashes (52 percent) are of the property-damage-only (PDO) type, but a large proportion (42 percent) result in injury and/or fatality. The severity of the remaining 6 percent of crashes is unknown.

The ICAV report also classified SCP crashes based on the intersection traffic control device (TCD). About 35 percent of SCP crashes occurred at 3-color signals, with about 64 percent at stop signs and a small number unknown. The report also conducted more detailed causal factor analysis for crashes at signalized intersections. This analysis identified signal violations and driver contributing factors (e.g., driver distraction) as important causal factors for SCP intersection crashes. Other commonly cited crash risk factors such as roadway environment and speed were not common causal factors for this type of crash.

In summary, previous research has shown large numbers of Americans are involved each year in intersection-related crashes. Categorization schemes for intersection crashes also have provided a framework for their study, and SCP crashes appear to be one of the primary mechanisms through which intersection crashes occur. The incidence of SCP crashes, however, appears to vary according to the intersection infrastructure (signalized vs. stop-controlled).

Based on the information reviewed, it appears that SCP intersection-related crashes represent a significant traffic concern worthy of further investigation. While these incidence data are helpful in understanding the extent of the problem, it is also helpful to examine past research on the contributing factors for SCP crashes. The following sections outline the results of a literature review to examine: 1) driver characteristics and their effects on intersection crash risk, 2) driver behaviors that result in intersection crashes, and 3) driver performance capabilities and limitations.

Driver Characteristics and their Effects on Intersection Crash Risk

Age

Driver age has been related in numerous research efforts to a driver's intersection performance and risk-taking behavior, with mixed results. Epidemiological studies have found that fatal multiple-vehicle crashes involving older drivers are more likely to occur in intersections than in any other type of traffic environment (Preusser et al., 1998). Specifically, crashes involving drivers in the 65- to 69-year age group occur in intersections at nearly twice the rate of crashes in other environments. This likelihood increases to nearly three times the normal rate for drivers 85 and older. Hakamies-Blomqvist and Henriksson (1999) reported a systematic increase in the rate of accident involvement in intersections as a function of age, although these increases are not constant from year to year of age. Hendricks et al. (1999) reported that in 43 percent of the crashes studied, drivers were more than 55 years old.

Overall intersection crash risks have also been shown to be high for both very young and older drivers, especially for SCP crashes (Chovan et al., 1994; Tijerina et al., 1994; Wang and Knipling, 1994). This pattern is also observable in fatality data (Alicandri, 2001). Preusser et al. (1998) found that the most prevalent crash situation for older drivers occurs at stop-controlled intersections when the driver is proceeding straight through or is just beginning to enter the intersection. For the oldest driver category in their study (age 75 and older), the causal factor of "running the traffic control" (i.e., failing to yield) at stop-controlled intersections accounted for more than half of the fatal crashes investigated. Rather than being a deliberate act, this situation appears to result from the inability of the driver to process changing information (i.e., status of cross traffic) before pulling into the intersection (Staplin et al., 1998a).

The causes for these epidemiological findings are not completely known, but some factors have been identified. In a simulator study, Sivak et al. (1989) determined that risk-taking behavior, as measured by the probability of successful crossings in a simulated driving task, was not affected by driver age. However, the probability of the driver attempting to make a crossing was greater for younger drivers; thus, the safety margins of the maneuvers were smaller for these drivers. Garber and Srinivasan (1991a) concluded that the risk of an older driver's involvement in an intersection accident is higher at rural intersections than urban intersections. Older drivers are also more likely to violate a traffic control when they are required to yield to opposing traffic (Garber and Srinivasan, 1991b; Wang and Knipling, 1994). Some driver workload measures have been shown to increase with age (e.g., response errors in brake/accelerator use, number of seconds from the intersection when the last pedal response was made, and heart rate activity, used as a surrogate of driver workload; Grubb, 1992). Other studies cite high numbers of older drivers watching the appropriate areas in intersections, but failing to observe the necessary signal or traffic pattern (Hendricks et al., 1999). Younger drivers, on the other hand, tended to use ineffective traffic scanning methods (i.e., failing to look at appropriate areas). In signalized intersections, however, this difference between older and younger drivers was not observable. The authors also found that for the causal factor "looked, did not see" at stop-controlled intersections, 43 percent of the drivers were more than 55 years old.

Reductions in driver capabilities that occur with age have also been shown to affect risk-taking behavior at intersections. According to Stamatiadis et al. (1991), left-turn maneuvers are troublesome for elderly drivers. Visual deterioration, such as scanning errors (Staplin et al., 1998a), seems to be a factor in many accidents involving these drivers. Furthermore, these authors conclude that the presence or absence of a traffic signal does not affect the accident involvement for older drivers. Some driver capabilities, however, appear to remain unchanged in older drivers. In a simulator study using simple evasive braking tasks outside of intersection environments, Lerner (1993) determined that perception-reaction time (PRT) did not vary between younger (20 to 40 years) and older (70+ years) drivers. PRT is defined as the total time required by a driver to respond to a driving-related emergency situation. However, since PRT is a function of both perception and reaction time, it is impossible to determine whether the lack of change in PRT is due to a tradeoff between these times. Factors such as driving experience or compensation for well-known degradation in psychomotor functions could be possible explanations for the results obtained by these researchers. Indeed, the considerable decline with age in some sensory capabilities (e.g., reduced visual capabilities) and an associated increase in time necessary to process sensory inputs and perform accordingly have been established in the past (Preusser et al., 1998). Factors common in intersection driving tasks, such as visual clutter and the requirement for divided attention tasks, exacerbate these sensory limitations. In addition, older drivers may have difficulty in turning their heads to view cross traffic (Smith and Sethi, 1975).

The propensity of older-driver involvement in intersection-related crashes has resulted in the development of infrastructure modifications to assist these drivers in their intersection-crossing decisions. These technologies include the provision of left turn phases and longer amber phases at traffic lights (Garber and Srinivasan, 1991a; Garber and Srinivasan, 1991b). Other researchers have proposed simplifying the need to detect and evaluate traffic at intersections through the use of traffic signals with left-turn arrows (at signalized intersections), four-way stop signs (at stop-controlled intersections), and one-way streets (Preusser et al., 1998). Based on comments obtained from older drivers, Staplin et al. (1998b) proposed that the median islands in the intersections should be reduced and rumble strips (textured pavement) should be used to warn of upcoming traffic signals.

Gender

Driver gender has been shown to have some impact on the incidence of intersection crashes, although research conclusions are mixed. While Sivak et al. (1989) determined that risk-taking behavior in a simulator was not affected by driver gender, the probability of the driver attempting to make a crossing was greater for males than females. Some driver workload measures (response errors in brake/accelerator use and heart-rate activity) have also been shown to be higher for female drivers (Grubb, 1992). However, data presented by Tijerina and colleagues (Chovan et al., 1994; Tijerina et al., 1994) indicate that gender is not generally indicative of the involvement in SI and UI/SCP crashes (60 and 58 percent of drivers in these crashes were male, respectively). Comparisons between crash rates and likelihood are also incongruent. Wang and Knipling (1994) showed that intersection SCP collision rates (per 100 million vehicle miles traveled) are higher for females than males, but the likelihood (involvements per 1000 registered drivers) is higher for males than for females. These authors also indicate the presence of an interaction between driver age, gender, and intersection type. At signalized intersections for drivers 24 years old and younger, involvement rate is only slightly higher for males than for females. However, for drivers 25 years and older, involvement rates for females are higher than for males. The likelihood rates are higher for males than for females for all age groups. At stop-controlled intersections, the age group is not a factor.

Males are also more likely to exhibit less cautious behaviors than females when crossing intersections. Caird and Hancock (1994) investigated driver perceptions of opposing vehicle arrival times at intersections and the effect on the timing of their own left-turn tasks. Men were generally more accurate in their estimations, and women tended to underestimate arrival time more often than men. The authors hypothesize that these results reflect the fact that men are more likely to turn into gaps between vehicles and to proceed through amber lights. Studies by Hankey and colleagues (Hankey, 1996; Hankey et al., 1996), based on driving simulator data, found that male drivers reacted in an appropriate manner (i.e., did not oversteer) to an unexpected intersection incursion more often than did female drivers (one-third vs. one-fifth of the respective male and female samples reacted appropriately). However, these researchers reported no significant difference in initial behavior reaction time due to gender.

Additional Driver-Related Factors

Driver-related factors are linked to as many as 93 percent of all crashes, with decision errors accounting for the largest percentage (47 percent) of these factors (Alicandri, 2001). Decision errors are made primarily with respect to maneuvers – for example, overestimation of the time remaining for a yellow signal. While their estimate of crash incidence is lower (75 percent versus 93 percent), Lloyd et al. (1999) divided crashes into driver inattention (28.7 percent), faulty perception (33.9 percent), and impaired/obstructed vision (11.1 percent). Hendricks et al. (1999) report that a driver behavioral error caused or contributed to 717 of the 723 crashes investigated (99 percent). A commonly reported error was driver inattention. Activities that led to inattention included focusing on internal thought processes (20 percent), looking for a street address (10 percent), hanging up cell phone (10 percent), and talking with a passenger (10 percent).

Given that the presence of a POV is common in intersection crashes, some researchers have tried to understand how the SV driver’s perception of the POV varies as the characteristics of the POV are varied (e.g., Hancock et al., 1991). Caird and Hancock (1994) reported that drivers tend to underestimate the arrival time of the opposing vehicle (i.e., predict that the vehicle will arrive at the intersection earlier than it actually does). As actual arrival time increases (i.e., the vehicle is farther away), underestimation also increases. However, this gap estimation issue is closely related to "gap acceptance," which refers to driver judgment about the minimum gap between cross traffic vehicles that would allow them to successfully cross an intersection (BMI, 2001c). Although driver judgment of gaps might be conservative, it is possible that gap acceptance levels are small enough to offset driver judgment benefits and make an intersection crossing risky.

Various studies indicate that other factors such as driver frustration (Wolf et al., 1988), age (Lerner, 1994), and driving environment (e.g., nighttime; Ward et al., 1996) can modify drivers' gap estimations and their minimum gap acceptance to allow for intersection crossing.

The size of the POV also affects estimates of its arrival time: the time estimates decrease as the size of the POV increases. The time afforded to the SV driver by the position of the POV also affects the SV driver's reaction time (Hankey, 1996; Hankey et al., 1996). Participants with shorter times to react demonstrated slower initial reactions than did participants who had longer to react. SV evasive behaviors were also better when the POV approached from the right rather than from the left of the SV.

Cultural factors have also been found to affect driver behavior in intersections. For example, in studies of crossing tasks, Sivak et al. (1989) found that West German participants attempted fewer crossing tasks, but had higher probability of success and greater safety margins than did participants from the United States and Spain. These differences are very likely related to the culturally acceptable levels of driving aggressiveness for each of these countries.

Crashes caused by driver aggressiveness and willfulness to violate a traffic signal have been investigated. The level of driver aggressiveness seems to be related to age, with younger drivers being more aggressive (Lloyd et al., 1999). These researchers, however, reported minimal correlation between aggressiveness and gender. An observational study of general aggressive behaviors over a variety of locations was performed by Shinar and Compton (2004). For this study 2177 aggressive maneuvers (honking, passing on shoulder, cutting across lane) were collected. Other studies point out the possibility of cultural differences in aggressiveness (Porter and England, 2000). For example, drivers who are unbuckled and non-Caucasian were found to be more likely to violate red lights. According to these researchers, driver age had no significant effect on the occurrence of this behavior.

In summary, driver characteristics and their effects on intersection crash risk, as well as other driver related factors, should be considered in conjunction with the environment in which the driver is placed. Different intersection types are distinguished primarily by their infrastructure characteristics, and these characteristics have some measurable effects on the likelihood of crashes. The end effect of these factors, however, can be characterized as an alteration in driver behavior for the intersection approach. Some of these driver behavior modifications are discussed within the next section.

Driver Behaviors that Result in Intersection Crashes

Intersection crashes are due to a variety of factors related to the SV, the POV, and the intersection infrastructure. An improperly designed intersection may fail to provide the SV with sufficient visibility of approaching traffic. Drivers often cite "did not see the oncoming vehicle" as a cause for "insufficient gap" crashes (the driver stops at the control but later proceeds into the intersection at an inappropriate time and, consequently, into the path of another vehicle [BMI, 2001a]). Some of these factors are discussed in this section.

BMI (2001a) identified a considerable number (366 out of 977) of crashes in which the primary cause was a traffic violation. Five different violation types were recorded: three-phase traffic signal (306), stop sign (24), yield sign (9), pedestrian crosswalk (8), and flashing traffic signal (4). Traffic violations represented the most prevalent causal factor. Factors leading to the violation were reported for a total of 139 out of the 306 three-phase traffic signal violations. Factors such as "did not see the signal or its phase" (40 percent), "tried to 'beat' the yellow phase" (25 percent), "mistaken phase" (believed that the light was green; 12 percent), and "intentional violation of the signal" (8 percent) were most commonly reported. These causes, however, are based on reports from involved parties and witnesses to the police. Thus, they are subject to a variety of biases, including misreporting.

The research by Hendricks et al. (1999) analyzed a sample of 723 driver-at-fault crashes from 1996-1997. The most frequent causal factors cited for SCP crashes were "looked, did not see," "driver inattention/traffic control device violation," and "crossed intersection with obstructed view." These authors provide typical infrastructure characteristics for each of these causal factors:

1. *Looked, did not see*
   - All cases occurred at 90-degree intersections with stop signs.
   - In 71 percent of the cases, the victim vehicle (POV) was struck from the passenger side.
2. *Driver inattention/traffic control device violation.* All crashes occurred at 90-degree intersections that typically use traffic signals.
3. *Crossed intersection with obstructed view*
   - All cases occurred at stop-controlled 90-degree intersections.
   - In 57 percent of the cases, the victim vehicle (POV) was struck from the passenger side.

Driver error rates are also dependent on infrastructure. In performing research on driver errors, Wierwille et al. (2000, 2001) considered the types of driver errors associated with both signalized and stop-controlled intersections. The data collection methodology consisted of video surveillance at selected sites (both intersection and non-intersection sites were used). The video surveillance was primarily conducted during high-traffic-volume times. Several types of analyses were then performed using the videotapes in conjunction with observer notes. The analysis of most interest to this research effort was a critical incident analysis, which resulted in the development of driver error probability taxonomies for complex signalized intersections, signalized ordinary intersections, and stop-controlled intersections.

Wierwille et al. (2000, 2001) also conducted a search of the Pennsylvania crash databases for the years 1995-96, which contained a total of 279,730 crashes involving 431,004 vehicles. Of all contributing factors (primary and secondary), 3.1 percent were "failure to respond to a traffic signal," 2.1 percent were "failure to respond to a stop sign," and 1 percent was "inattention to stop signs or traffic signals." When only the primary contributing factor was analyzed, 7.8 percent of the crashes were TCD-related.

The Pennsylvania crash database is a traditional crash database. North Carolina enhances their traditional database with a field containing a lengthy narrative description that can be searched by keyword. Wierwille et al. (2001) performed an analysis of the NC narrative database for 1994. Of 209,000 narratives, 1,008 were identified as being TCD-related. Of these, 172 were traffic signal violations (ran red or amber/red, or failure to yield) and 103 were stop-sign violations (ran the stop sign or failed to yield). The primary advantage of examining the narrative database as opposed to the conventional database is that the narrative has a potential to provide a further level of detail beyond "ran red or amber/red." For example, the above category provides some detail on the number of cases in which both drivers claimed green, how many drivers were distracted, how many were unsure of the color, and so forth. However, in 73 percent of cases, the "general" category was used, which does not provide much additional insight beyond that of a conventional database.

In conjunction with other observational studies, the Wierwille et al. (2000, 2001) studies show that red-light running and stop-sign running are common occurrences (up to 15 violations per hour (Institute of Transportation Engineers [ITE], 2003) have been reported). However, not every instance of TCD violation results in a crash. The crash database analyses showed that the crash rate was much lower than the violation rate, although there was not much insight into why the violations occurred. Of particular interest is the rate of intentional violation versus unintentional violation, as the countermeasures developed for these two cases could be quite different. The rest of this section explores previous research performed for signalized and stop-controlled intersection crashes related to infrastructure.

Certain intersection characteristics are related to the prevalence of intersection violations. The ITE (2003) summarized a review of violation related intersection characteristics performed by Bonneson et al. The review identified three exposure factors and five contributory factors that add to violation rates (Table 2).

There also appears to be an element of driver psychology involved in the action of signal violation. Relatively little is know about the influence of human emotions on intersection behavior, however, the likelihood of committing a violation varies from one person to another and within a single person from day to day (ITE, 2003). Violators appear to have a more combative attitude and do not want to be "taken advantage of" as opposed to compliant drivers who have a more courteous attitude. Motivations such as aggravation and being in a hurry to arrive at a destination appear to increase RLR (ITE, 2003).

Signalized Intersections

Crossing path collisions at signalized intersections normally involve a signal violation, and the causal factor is either unintentional (i.e., inattention-related) or intentional (i.e., trying to beat the change from amber to red, or knowingly running a red light). These two possibilities occur with similar frequencies (Dingus et al., 1998).

Table 2. Factors that lead to signalized intersection violations

Factor Type	Factor	Explanation
Exposure	Flow rate or volume	Every vehicle approaching the intersection at the onset of yellow is exposed to potential Red-Light Running (RLR).
	Number of signal cycles	The more times the amber is displayed the more potential for RLR.
	Phase termination by max-out	Actuated signals that extend green as long as approach is occupied may reach the max-out limit. The number of violations increases with increasing number of max out conditions.
Contributory	Actuated control and coordination	Violations in this case may be caused by a violation of driver expectancy. When driving in an area with coordinated and/or actuated control intersections drivers may expect the green to remain until they drive through. When system fails driver does not expect to be presented with the amber.
	Approach grade	Drivers on a downgrade are less likely to stop than drivers on even or uphill approaches.
	Amber duration	Amber durations that are too long may violate driver expectancy and do not “reward” a driver that stop with the red signal. Amber indications that are too short will result in more frequent dilemma zone problems as discussed previously.
	Headway	Drivers that follow too closely are more likely to run the red as the following vehicle is “drawn” into the intersection.
	Cross-street lanes	There is an increase probability for violation as the number of cross street lanes increases.

Tijerina et al. (1994) provided the characteristics of typical SCP crashes in signalized intersections (SCP/SI) based on CDS and GES data:

- The SV was unaware of or disregarded the traffic signal itself or its status, and entered the intersection inappropriately (i.e., without the right-of-way). The POV had the right-of-way, and thus obeyed the traffic signal when entering the intersection.
- The SV either struck or was struck by the POV.
- The velocity of the SV was close enough to the posted speed limit to indicate that the driver did not attempt to stop for the traffic signal.

Identified causal factors behind these crashes included “driver inattention” (36.4 percent), “failed to obey signal” (23.2 percent), and “tried to beat signal” (16.2 percent). The driver inattention category includes drivers who were not aware of an upcoming intersection or signal due to distractions inside or outside of the vehicle, or simply due to a "wandering mind." These drivers might benefit from an IDS system that would successfully draw their attention to the presence of an intersection and the status of the signal.

The previously described categorization of crashes by Pierowicz et al. (2000) is based upon driver behavior rather than on the type of intersection involved. However, Scenario 3 in that study is similar to the SI/SCP category described above. In this scenario, a driver violates a traffic control, proceeds into the intersection, and collides with another vehicle. Approximately half (53 percent) of Scenario 3 crashes occurred in signalized intersections. The most frequent causal factors for Scenario 3 crashes in signalized intersections include “driver inattention” (22.4 percent), “deliberate violation” (27.9 percent), and “tried to beat the signal” (3.2 percent).

In their study of driver error in intersections, Wierwille et al. (2000, 2001) found a 3.3 percent overall probability of a driver error at complex signalized intersections (3.3 percent of all drivers entering the intersection made some sort of driver error). This probability can be broken down as follows: 1.5 percent occurred during left turns, 0.5 percent during right turns, 0.4 percent going forward, and 0.9 percent during other activities. The probability of proceeding on red (running the red light) was 41 per 10,000 vehicles for left turns, right turns, and going forward combined. Most of these RLR errors occurred during left turns (31 out of 10,000), followed by going forward (8 out of 10,000), and right turns (2 out of 10,000). These rates are similar to those reported by other researchers (for red light running [RLR] at all types of signalized intersections) of 41 per 10,000 vehicles (Brewer et al., 2002), 13 per 10,000 (Fakhry and Salaita, 2002), 16 per 10,000 (Retting et al., 1999b), and 38 per 10,000 (Retting et al., 1999a).

The overall driver error rate for ordinary (as opposed to complex) signalized intersections was 2.0 percent. Left turn maneuvers accounted for 1.5 percent of the total, going forward for 0.3 percent, right turns for 0.1 percent, and lane changes for 0.1 percent. However, none of the observed errors were RLR errors.

Both Pierowicz et al. (2000) and Tijerina et al. (1994) have presented causal factors that imply a deliberate disobedience of the traffic signal. The decision to run or attempt to beat a traffic signal is due to a belief that a collision can be avoided. This belief could be based upon: the failure to see cross traffic; misjudgment of the velocity, distance, or direction associated with perceived traffic; or the belief that other vehicles will yield to the violating vehicle. Presumably, the probability of an intentional attempt to run or beat the signal could be lessened by an IDS system if an indication was also provided of either the likelihood of a resulting upcoming crash or an indication that legal enforcement (e.g., fine) would ensue.

Stop-controlled Intersections

Chovan et al. (1994) presented an analysis of SCP crashes in stop-controlled intersections (UI/SCP) based on Crashworthiness Data System (CDS) and GES data from 1991. This study divided SCP/UI crashes into two types: Subtype 1 (42.3 percent) in which the SV ran the stop sign, and Subtype 2 (57.6 percent) in which the SV stopped but then proceeded across the intersection at an inappropriate time. There was no substantial difference between the percentages of crashes with vehicles approaching from the left versus the right for either Subtype. The SV struck the POV almost as often as the POV struck the SV in Subtype 1 crashes. However, the POV struck the SV in 74 percent of Subtype 2 crashes. Frequent causal factors for Subtype 1 included driver inattention (56.4 percent), obstructed vision (18.7 percent), and adverse environmental conditions (10.7 percent). Subtype 2 causal factors included faulty perception (81.7 percent) and obstructed vision (14.0 percent). Within the category of “faulty perception,” two patterns were noted: drivers who looked but did not see the other vehicle (62.1 percent) and drivers who looked but misjudged the other vehicle's distance or velocity (19.6 percent).

Wierwille et al. (2000, 2001) found that there was a 3.0 percent overall probability of a driver error of any type at stop-controlled intersections. Again, most occurred during left turns (1.5 percent), followed by going forward (0.7 percent), right turns (0.2 percent), and other scenarios (0.6 percent). The overall rate of running the stop sign was 19 out of 10,000 vehicles, while the rate for a rolling stop was similar, at 15 out of 10,000 vehicles, for a total stop-sign violation rate of 34 per 10,000 vehicles. Stop-sign violation rates reported by other researchers are much higher, ranging from 175 per 10,000 (Fakhry and Salaita, 2002) to 6,700 per 10,000 (Pietrucha et al., 1989). Most of these differences can probably be attributed to the definition of a rolling stop used in the various studies, the intersections selected for the studies, and the data collection methods used.

Pierowicz et al. (2000) indicated that common causal factors for UI/SCP crashes with a violation included driver inattention (22.4 percent) and deliberate violation (9.3 percent). Causal factors for UI/SCP crashes with no violation included looked, did not see (58.2 percent), driver inattention (22.4 percent), vision obstructed/impaired (13.2 percent), thought POV would stop (4.7 percent), and misjudged velocity/gap (1.6 percent). Thus, the critical driver error was usually either a lack of observance of the POV or a misjudgment of the POV distance, velocity, or actions.

The concept of "misjudged velocity/gap" is commonly discussed in the literature. This concept is related to the issue of gap acceptance, which depends on a driver judgment of a critical gap. Experimental measurements of critical gap generally agree that the measure normally ranges from 6 to 8 s for passenger vehicles (Kyte et al., 1996; Harwood et al., 2000).

Another causal factor of stop-controlled intersection crashes is willful violations of a traffic sign. Willful violations of stop signs are similar to the act of deliberately running a red light, discussed in the previous section. Similar to running a red light, running a stop sign is related to the belief that a collision can be avoided. IDS systems that provide either an indication of the likelihood of a crash or an indication that legal enforcement (e.g., fine) would ensue could decrease the probability of an intentional attempt to disobey the traffic sign.

Implications for the Development of an IDS System

Signalized Intersections

Information about causal factors in actual crashes provides a basis for developing IDS system countermeasures to reduce the occurrence of these factors. As mentioned previously, over half of all SCP crashes at signalized intersections are thought to be related to driver unawareness of a dangerous situation. IDS systems could address these factors by informing the unaware driver of a dangerous situation.

BMI (2001b) describes a number of potential measures to curb the violation of traffic controls at signalized intersections. Control alternatives include reactive measures (i.e., warning the driver) and proactive measures (i.e., addressing the causal factor). The most frequent causal factor for signalized intersections is "did not see the signal or its indication." A similar factor ("failure to see/observe") was also observed in Wierwille et al. (2000) in their analysis of specific signalized complex intersections. Specific intersection data (obtained, for instance, through police reports or video-recorded observation) would help in the determination of effective countermeasures for this factor, but some options include improving the visibility of the signal through design and location, and the provision of static "signal ahead" warning signs.

IDS systems could largely address this unawareness issue. Ideal driver behavior would consist of slowing down for preparation as the intersection is approached and then carrying through with appropriate actions based upon the status of the traffic signal. Thus, there are two distinct phases of the process where unawareness could be present. First, there is the possibility of unawareness about the presence of the intersection. Second, even when drivers are aware of the intersection, they could be unaware of the traffic signal itself, either in terms of the signal's presence or its status. The end result, however, is equivalent: the driver inappropriately attempts to cross the intersection.

Another frequently cited causal factor is "tried to beat the amber light." This factor is related to the timing of the driver's arrival to the intersection, especially for vehicles in the dilemma zone. The dilemma zone is the area near the intersection in which the vehicle can neither stop in time nor clear the intersection before the light turns red. Some possible countermeasures for this problem include a longer amber phase (although drivers might simply extend the zone within which they try to beat the light), intelligent "signal ahead" signs (when visibility is a problem), amber or red ball strobes (when inattention or visual clutter is a problem), and dilemma zone signaling (alteration of the phase change from green to amber depending on the presence of vehicles on the dilemma zone). Zhang (1995) describes the development of an Intersection Auxiliary Signal System (IAS) designed to assist drivers' judgments and actions related to the dilemma zone by relaying signal phasing, intersection geometry, speed limit data, and associated suggestions to the driver. In addition, the dilemma zone can be partly addressed via proper timing of the amber length (ITE, 1991). Theoretically these ITE equations should guarantee a simple go/stop decision for the majority of approaching drivers. Practically, however, the variability in driving styles, emotional states, perception-reaction time and traffic conditions frequently create a dilemma zone (Hicks et al., 2005).

The problem with the equations is their assumptions on certain driver parameters (e.g., typical travel speeds [85th percentile speed], deceleration [10 ft/s^2], and perception-reaction time [1 s]). Thus, the dilemma zone is calculated as though it is located at a fixed position relative to the intersection. Research has shown that the dilemma zone is not static as previously believed but instead depends on a variety of driver and environmental factors (Hicks et al., 2005). In particular, basing the dilemma zone on the 85th-percentile driver fails to consider the variation among both drivers and vehicle capabilities. Not all drivers can/will achieve the standard assumptions every time. This in-turn will underestimate the existence of a dilemma zone as well as their dynamic nature (Xiang and Tao, 2005). The dynamic nature of the dilemma zone may help explain intersection crashes. For instance, the high prevalence of rear-end collisions may be a result of two consecutive drivers experiencing dilemma zones at different locations. A driver that is not behaving in a typical manner (e.g., long PRT) is provided with an incompatible amber duration; thus, resulting in a signal violation.

Infrastructure-Only alerts and warnings should only be utilized at a point where the driver has time to properly react. Appropriate reactions might include maintenance of a constant velocity, discontinuance of acceleration, or braking. When driver processing and reaction are no longer feasible, options other than Infrastructure-Only should be considered, such as driver-vehicle intervention (partial or total control).

Tijerina et al. (1994) and Chovan et al. (1994) suggest functional distinctions between driver alerts and driver warnings, which are applicable to both Vehicle-Based and Infrastructure-Only implementations of IDS. The non-directive advisement of an upcoming intersection is called a driver alert, and the directive related to a potential collision is called a driver warning. The earliest form of alert in the intersection approach model would be an indication that an intersection is being approached. While a sign or signal some distance from the intersection might provide redundant information to some drivers, it would provide necessary information to an unaware driver. However, these systems have the potential to become nuisances to drivers and cause visual clutter.

If the simple "intersection ahead" alert does not or cannot relay sufficient urgency (e.g., if the light at the upcoming intersection turns amber or red), a warning would be presented to suggest that braking should begin. The actual message would depend upon various factors such as the signal phase (amber or red), distance to the intersection, and vehicle velocity. Tijerina et al. (1994) suggest a candidate procedure for this type of system:

- If the signal is green, no warning is provided.
- If the signal is amber
  - — and the SV will clear the intersection before the light turns red, no warning is provided.
  - — and the SV will not clear the intersection before the light turns red, a warning is provided.
- If the light is red, a warning is provided.

This system logic can also be altered to reflect more complex conditions using graded warnings. This concept alters the urgency level of the warning based upon sensed vehicle actions. Specifically, if the system indicates that a vehicle should stop, it checks for a prescribed value of normal vehicle deceleration at a given distance from the intersection. If this value is not acceptable, a warning would be issued. If the vehicle still does not heed the warning, a more urgent warning would be issued at some predetermined distance closer to the intersection. While this approach is more applicable to Vehicle-Based IDS systems, it also might be applicable in Infrastructure-Only systems, although it may create visual clutter issues.

Another alternative is a system that provides constant warning times to drivers approaching intersections. Based upon vehicle speed, deceleration, and distance from the intersection, a system can warn the driver of the need to stop at a consistent point prior to an event. For example, the system could be designed to always warn a vehicle to stop at a point 2 s before "normal" braking should occur.

Stop-Controlled Intersections

Based on the information about causal factors for stop-controlled-intersection crashes, IDS systems to reduce the effects or occurrence of these factors can be developed. One primary causal factor for stop-controlled-intersection crashes is driver inattention. An IDS system that provides a warning about an upcoming intersection could be an effective countermeasure for inattentive drivers. However, given that many stop-controlled-intersection crashes occur because of faulty driver perception of other vehicles, it may be beneficial to consider countermeasure systems that move beyond simple warnings of upcoming intersections and detect the presence of other vehicles and their distance from the SV. These systems might also be applicable to some crash types in signalized intersections (e.g., LTAP).

The earliest form of alert in the stop-controlled intersection approach model would be an indication that an intersection or stop sign is being approached. An alert should be provided at a distance from the intersection that would allow normal deceleration to the stopping point. However, as discussed for the case of signalized intersections, these systems should be designed so that they are not perceived as a nuisance. Although redundant information might be provided to some drivers, this information would be useful to unaware or distracted drivers. However, additional information about the presence of another vehicle in the intersection (not necessarily its velocity or distance from the intersection) would have to be provided for crashes in which a driver stops at the sign and then proceeds unsafely into the intersection.

Following unheeded alerts, countermeasure systems should offer warnings. Chovan et al. (1994) describe a warning that could be applied to stop-controlled intersections. This system checks for some prescribed value of normal vehicle deceleration (at the observed velocity) at a given distance from the intersection, and if the actual deceleration is not acceptable, a warning is issued. Graded warnings could also be implemented by sensing the vehicle characteristics (e.g., velocity and deceleration) and adjusting the urgency of the fixed warning accordingly.

The primary goal of an IDS system should be to assist the decision-making process by providing information and reducing confusion while avoiding complete dependence on the IDS system itself (BMI, 2001b). A model approach presented by these researchers to accomplish the primary information presentation goal and its enabling activities for the “failure to yield” action at a stop-controlled intersection is presented below:

1. Detect right-of-way vehicles.
   - Methodology
     - Presence
     - Speed
     - Acceleration
     - Path
   - Continuous versus incremental (technology for continuous detection has reliability limitations.)
2. Determine time required for desired vehicle movements (i.e., to reach the intersection).
   - Components
     - Acceleration
     - Road geometry
     - Inherent buffer time
     - Perception-reaction time
   - Use research and field studies to confirm.
3. Interpret and compare data.

4. Communicate interpretation (warning only) to violator vehicle through roadside display or signal.
   - Locate in sight line of critical approach.
   - May supplement with static warning sign that signifies purpose of the dynamic warning.
   - Perception-reaction time must be factored into the design of the warning presentation.

There are many other models to analyze UI/SCP crash scenarios (e.g., Chovan et al., 1994). Similar to signalized intersection models, the maximum time available for driver reaction and response to collision warnings in stop-controlled intersections is sensitive to the distance from the intersection. Thus, the IDS system should operate at the largest feasible distance from the intersection to allow maximum driver response time (Tijerina et al., 1994). However, careful consideration of intersection characteristics (e.g., curved vs. tangent approach, high vs. low speed) and human factors aspects should be undertaken, as some studies indicate negative effects of IDS systems in the context of signalized intersections (Pant and Huang, 1992). Previous modeling work has also been based upon the analysis of a fairly small sample of crash data taken under good environmental conditions; thus, further research would be necessary to provide more precise models (Chovan et al., 1994).

Driver Performance Capabilities and Limitations

Past studies of intersection collisions have defined several intersection areas that can be used to describe and control IDS system behavior. Tijerina et al. (1994) provide models to analyze SI/SCP crash scenarios; these models are based upon three vehicle zones. The clearance zone is the area in which the vehicle traveling at a constant velocity can clear the intersection before the signal turns red. The dilemma zone, as discussed previously, is the area in which the vehicle cannot stop in time or clear the intersection before the light turns red. The brake zone is the area in which the typical vehicle cannot stop before or at the stop line. The authors provide formulae to determine the points at which each area begins and ends, depending upon signal- and traffic-related variables. The techniques presented, however, are only a starting point for such work, and the formulae should be refined and expanded to reflect factors such as variations in typical velocity and deceleration patterns among different driving populations. These and other factors (e.g., distance from the stop line at the commencement of the amber light, the number of intersection approaches, the length of the amber light, and the volume of secondary versus main traffic flow) have been shown to influence individual decision-making about the dilemma zone (BMI, 2001c). Traffic volume also affects the willingness of drivers to proceed through an intersection (Hicks et al., 2005)

Brake reaction distance (BRD) is related to the dilemma zone, as this measurement can be used to assign a particular vehicle to a particular zone. BRD refers to the length of road traveled from stimulus introduction to the instant the brakes are applied. Two different factors directly affect BRD: vehicle speed and the driver's PRT, which will be referred to in this document as time-to-brake (TB). Formally, TB has been defined as the time it takes a driver to detect an object, recognize it as a hazard, decide on an action, and initiate that action (Fambro et al., 1998). This section will employ a more functional definition, in that TB will be considered as the time from initial stimulus appearance to placement of the foot over the brake pedal, as determined within the literature that is reviewed.

TB values have been determined and reported in the past due to the importance in determining Stopping Sight Distances (SSDs) and critical following gaps. SSD refers to a vehicle's change in location from the onset of a stimulus to the point at which the vehicle comes to a complete stop. In the case of a traffic signal, the length of roadway traveled between the moment in which the signal turns red (stimulus) and the moment when the vehicle stops moving is the SSD.

Reported TB values vary widely, probably because of differences between experimental protocols (Sohn and Stepleman, 1998; Green, 2000). For instance, Schweitzer et al. (1995) report a mean TB of 0.5 s, while Sivak et al. (1981) report a mean TB of 1.3 s. Other studies suggest even higher values for this measure. Carney (1996) reports estimates of driver reaction time to unexpected events in the range of 0.9 s to 1.6 s. In an application of this measure, the Japanese Advanced Cruise-Assist Highway Systems program assumes times of 2.65 and 1.0 s for driver response times to information and warnings, respectively.

Past research on TB has considered the effects of a variety of driver and road factors on this measure. Dingus et al. (1998) report that TB is not affected by speed, distance from the intersection when the light turns amber, or the driver's deceleration rate. Sohn and Stepleman (1998) carried out a meta-analysis of 26 studies. Using regression techniques, these researchers identified distance from stimulus, awareness level of the driver, the type of brake stimulus, and the country where the experiment took place as factors influencing TB.

Other researchers suggest that simple, all-purpose numbers for TB are impossible to derive (Green, 2000), an argument partially supported by the finding of geographical location as the most important TB determinant (Sohn and Stepleman, 1998). Green (2000) insists that the majority of published experimental results cannot be combined because of inter-study variations in experimental conditions. An alternative strategy, however, is to analyze the studies and determine expected TBs for specific situations. Unfortunately, the conditions under which the SSD will be utilized have not been empirically tested, and thus will very likely vary between different locations. However, some information from previous studies can be used to provide initial estimates of this measure for use in the SSD algorithm.

Green (2000) and Sohn and Stepleman (1998) suggest the following factors as significant determinants of TB:

- *Driver's Awareness Level:*
    - Expected – Driver knows the stimulus will occur and is prepared to initiate corresponding reaction. Stimulus usually has high spatial certainty.
    - Unexpected – Driver expects something unusual to happen but has no idea what or when. Drivers are typically prepared to react when the stimulus occurs.
    - Surprise – Driver has no previous knowledge of stimulus event or appropriate reaction.
- *Age:* Has shown mixed results across studies. In most cases it is not reported as a significant factor. However, age effects are probably heavily dependent on cognitive load and perceptual requirements and thus vary depending on study characteristics.
- *Urgency:* Results across urgency suggest a U-shaped function for TB. If the Time-to-Intersection (TTI) is long the driver will react slowly. As TTI decreases the driver will

react faster until TTI becomes short enough that alternative actions such as steering also have to be considered. Weighing these options increases the processing requirements and, consequently, the TB.

- *Cognitive Load:* Higher cognitive load slows the reaction time. Cognitive load can be introduced by the complexity of the driving environment or from the use of in-car devices.
- *Type of Stimulus:* Auditory stimuli tend to result in faster TB times then visual stimuli. In addition, stimuli that occur in expected locations result in faster TB.
- *Measurement Method:* Different methods can be employed to determine when a subject has initiated an action. Studies using pedal-mounted micro switches or speed detection devices (radar or laser) produce the most accurate results. Many studies use brake lamp voltage to mark response initiation. However, the inherent rise time required prior to brake-lamp illumination increases the TB reported in these studies.

Other researchers have studied more general braking behavior, rather than very specific components of the braking task. Landau (1996) summarizes a variety of investigations conducted to determine braking behavior of drivers when approaching stationary and moving vehicles. In general, this researcher reports that: 1) undistracted drivers are not prone to braking severely while approaching stationary vehicles; 2) predictably, deceleration patterns are more severe at higher velocities; 3) drivers maintain larger distances from the lead vehicle as both vehicle velocities increase; 4) drivers seek to minimize the severity of braking; and 5) single deceleration values and headway values should not be used to cover all warning modes.

Other past research has further expanded the use of behavioral approaches to model the intersection decision process as a system. Tijerina et al. (1994) and Chovan et al. (1994) present two alternatives for modeling driver behavior as related to crash avoidance driver alerts: a parallel system and a series system. If the modeled entity tends to be a series system, in which different forms of information are considered as separate entities (not processed concurrently), then the overall system reliability will be less than that of the driver alone. Occurrences of false alarms and other signal detection issues would yield an unreliable driver-countermeasure system (Parasuraman et al., 1997). Since behavior data for unaware drivers are lacking, the appropriate model is unknown and further research is needed. These authors suggest that the model for the effectiveness of intersection crash avoidance must consider reliability issues (e.g., driver reliability) in addition to kinematic analysis, and they present methods to determine reliability for various IDS systems. Assuming a series system, the probability of crash avoidance will be the product of the probabilities that the system functions properly, the driver detects the alert, the driver recognizes the particular hazard, and the driver reacts in the appropriate manner.

General models for driver behavior at signalized and stop-controlled intersections are also available in the literature. For example, Tijerina et al. (1994) summarize the decisions made by the ideal driver when approaching a signalized intersection:

- Detect the presence of an intersection and decelerate accordingly.
- Detect and properly process the signal status.
- If the light changes from green to amber, determine if it is safe to proceed through the intersection.
- Anticipate sudden deceleration of vehicle(s) that are being followed.

- Detect the presence of cross traffic and determine whether collisions are likely, based upon distance, velocity, and direction.
- Recognize and avoid visual obstacles.

Similarly, Chovan et al. (1994) summarized decisions made by an ideal driver at stop-controlled intersections:

- Detect the presence of an intersection and recognize the signage meaning.
- Anticipate sudden deceleration of vehicle(s) that are being followed.
- Detect the presence of cross traffic and determine whether collisions are likely, based upon distance, velocity, and direction.
- Be aware of any other traffic (or pedestrians) that might cause cross traffic to react suddenly and create further hazards.
- Recognize and avoid visual obstacles.
- Stop the vehicle.
- Estimate when it is safe to proceed through the intersection.

Some past behavioral research has focused on driver mental loads in signalized and stop-controlled intersections. Dingus et al. (1998) note that indications of right-of-way are provided for the driver at signalized intersections; however, in stop-controlled intersections this determination is based upon driver judgment and decision making. Alexander (1989) maintains that stop-controlled intersections present an extremely difficult task for the driver, as evidenced by the increase of TB at stop-controlled intersections. Traditionally, a maximum of 2.5 s has been used for SSD. Alexander (1989) argues, however, that this typical reaction time value does not include an allowance for a "search" task. This task represents a substantial mental load for drivers dealing with stop-controlled intersections due to the dynamic nature of the surroundings, the need to process this dynamic data, and the sheer physical requirements involved in scanning the area of concern. Alexander also indicates that visibility requirements for intersections should be empirically investigated, especially for skewed intersections (made up of roadways that are not all at right angles to one another), and traffic signalization instituted in those intersections where driver perception requirements are extensive. Other studies of intersection sight distances concur with these findings, and suggest the need to evaluate intersection sight distances differently for signalized and stop-controlled intersections (Harwood et al., 1996). Interestingly, some researchers have proposed that in some situations, limiting a driver's visibility at the intersection might be helpful by reducing approach speeds (Charlton, 2003).

Specific models on driver behavior for specific traffic signals have also been developed. Tijerina et al. (1994) discuss the meaning of the traffic signal phases in order to more fully investigate driver behavior at signalized intersections. Their model of intersection negotiation behavior includes decisions based upon the status of the traffic signal. A red or flashing red light indicates "stop." Some drivers do not stop, often due to anticipation that the light is getting ready to turn green. An amber light means "clear the intersection." Some drivers do not make it through the intersection before the light turns red, often due to miscalculations about the duration of the amber light, the distance across the intersection, or their own velocity. For a flashing amber light, drivers should evaluate the situation to determine whether they should stop before proceeding across the intersection. Misjudgments in this last case could result from misperceptions about the likelihood of cross traffic reaching the intersection in time to be considered a collision hazard. These misperceptions could be related to distance, velocity, direction (straight or turning), or even presence of cross traffic. A green light also provides the opportunity for driver reaction and decision making. Ideally, the driver should anticipate the possibility of the light turning amber and then red. Mistakes could occur if drivers do not adequately anticipate an upcoming slowing/stopping requirement, or if they do not think that there is sufficient stopping distance. All of these misjudgments are more likely to occur for hurried or impatient drivers.

The length of the amber light has been the focus of several studies (e.g., Van der Horst, 1988). Van der Horst observes that the driver's decision-making process is simpler at signalized (vs. stop-controlled) intersections. The principal decision in signalized intersections is whether to stop or proceed at the moment that the light changes from green to amber. An amber phase of appropriate length (defined in the van der Horst study as 4 s for a 30-mile-per-hour intersection and 5 s for a 48-mile-per-hour intersection) halves the frequency of red-light violations, at least before driver adaptation to the altered phase occurs. Other studies have produced similar findings (Retting and Greene, 1997). Another possible method to reduce RLR would be to implement controls that are actuated according to vehicle presence in a certain area (i.e., the green phase is extended as long as vehicles are detected within a defined area; Van der Horst, 1988), which would decrease vehicle exposures to the red-light phase.

Driver interactions with other vehicles are also important in the development of IDS technologies. Research on rear-end collisions, for example, has provided some baseline data on the timing of warnings for maximum effectiveness (Carney, 1996; Schreiner et al., 2001). Hankey (1996) found that drivers making decisions about crash-avoidance maneuvers note the size of the available gap and/or the required steering magnitude. Furthermore, drivers with the least available time for collision-avoidance action react significantly slower than other drivers and mainly utilize steering maneuvers to go around the front of the violator vehicle. Conversely, drivers with more time for collision-avoidance maneuvers often release the accelerator and brake before attempting to steer out of the collision. This researcher suggests that perhaps the transition time from pressing the accelerator to fully depressing the brake pedal is a function of the criticality of the situation, with a more critical situation resulting in a shorter time from accelerating to braking. Dingus et al. (1998) and McGehee et al. (1994) address similar issues.

More recently, the Crash Avoidance Metrics Partnership (CAMP) has generated data on the timing and warning modalities for collision-warning/avoidance systems, with a large emphasis on rear-end crash avoidance (Kiefer et al., 1999; GM, 2002). The problem posed by intersections is analogous in some areas to the problem that these rear-end collision-warning/avoidance technologies address, especially in the context of stationary lead vehicles. In this context, the stop line is equivalent to the rear bumper of the lead vehicle. Similarly, information on the violator vehicle's velocity and deceleration is needed for the collision avoidance technology to make a warning decision. Thus, many of the algorithms developed in rear-end collision avoidance efforts can be adapted to algorithms for IDS systems (Knipling et al., 1993).

Human factors issues that have been identified in the past for many other warning or alert technologies must also be considered in IDS system development. Some of these issues or considerations include visual acuity (dynamic and static), contrast sensitivity (age-related changes), color vision (nighttime deterioration), visual field (peripheral placement, effect of speed, age-related changes), and scan patterns (effects of workload, driver experience). Basic human factors design principles are also applicable to IDS system design, such as the issues of primacy and expectancy. Primacy ensures that the most important information is the most obvious; spreading information (reducing information clutter on a sign, for example) reduces the chance of information overload or inadequate processing time. Expectancy is related to designing according to stereotypical expectations of the driving population. Objectives of using these human factors design concepts include rapid and accurate perception of hazards, appropriate and timely driver reaction, minimal distraction from other driving-related tasks, and user acceptance of the system.

Several researchers have summarized previous research on these human factors principles and in-vehicle warning systems (e.g., Horowitz and Dingus, 1992; Landau, 1996; Hirst and Graham, 1997; Parasuraman et al., 1997; Campbell et al., 1998). While in-vehicle display research is out of the scope of this review, some principles and issues presented in these reports are also applicable to infrastructure-based IDS systems. In general, the design of IDS displays should consider factors such as: warning modality (e.g., visual, auditory, tactile, proprioceptive, and multi-modal); spatial location and temporal sequencing of warnings; driving changes as related to warning availability; warning or alert timing; minimization of false alarms; the use of graded warnings; and other design issues such as size of letters and background/foreground colors (Barker et al., 1998).

While these perceptual and behavioral factors are important considerations in IDS system design, the previously discussed kinematics factors have to be used as a starting point in the development of an infrastructure-based IDS system. Until these kinematics factors are accurately modeled, simulating specific human behaviors is of limited use in the presentation of appropriate warning signals in intersection-crossing tasks. These kinematics factors are addressed next.

Implications for Algorithm Development

Research on infrastructure-based systems for driver aid typically assumes an ideal driver reaction to stop signs and associated warnings. Drivers are assumed to respond uniformly to these signs by decelerating their vehicle. In reality, drivers might react differently depending upon the situation. For instance, an extended red light often results in anxious drivers who begin to creep into the intersection prematurely. Another tendency might be for drivers to speed through an amber light rather than slowing down if the upcoming red light is known to be of long duration (Zador et al., 1985). These tendencies, as well as other driver' behaviors and reactions, have to be quantified and modeled for the successful implementation of IDS systems. SSD is one driver behavior characteristics that is of special interest in the detection and avoidance of SCP intersection crashes.

SSD is often used during roadway development to determine variables such as sign location and signal phase. This measurement can potentially be useful in IDS if a minimum intersection-dependent value of SSD is determined that will provide most drivers with just enough time to stop. These SSD values are then used to define variables such as the "trigger point," which determines when the IDS system should be initiated, and the location of the IDS system stimulus with respect to the intersection. In the proposed algorithm, SSD is initially developed from theoretical constructs; the algorithm will then be modified as empirical data are collected after a prototype IDS system is created.

Algorithm Input Parameters

Prediction of SSD requires knowledge about the vehicle velocity and estimates of the BRD. Vehicle velocity is also an important component of BRD estimates. Since it is possible to measure velocity using available technology, the development of this algorithm assumes velocity as an input. Thus, all algorithm predictions are presented as a function of velocity. Estimates of TB, the non-velocity related component of BRD, are generated based on a series of assumptions and calculations which are described in this section.

Significant factors in an IDS scenario are the main determinants of criteria used in the selection of appropriate TB values. The main goal of an IDS system is to act as the final intervention prior to a collision. This intervention will be caused by a driver maliciously or inadvertently traveling at an inappropriate speed toward the intersection. If malicious, the driver will be aware of their inappropriate behavior and prepared to react. However, a distracted driver will likely be surprised by the intervention stimulus, both because of the stimulus content and its spatial location, which will result in longer reaction times. Thus, one could hypothesize that the IDS system should be designed for the inadvertent violator, as they will very likely show the longest reaction times. The IDS system must also accommodate drivers of various ages, presenting warnings that allow sufficient time for slower drivers to react. Urgency of the message must also be high, as the IDS system should not initiate warnings unless a collision is likely. While cognitive load is difficult to quantify accurately, the possibility of a distracter is high, and should be considered in the algorithm estimates. A series of studies fulfilling these constraints were considered in the generation of appropriate TB values (Table 3).

Table 3. Raw reaction time data from selected studies.

Study Details								Variable									
Study	Date	Experiment	Stimulus	Type	Paradigm	Condition	Speed	TAR	TS	TSS	TB	TFB	TSAB	TSAFB	TSBFB	TIDA	TFS
Hankey	1996	Subject vehicle approaches an I-sec when a incurring vehicle suddenly enters I-Sec (SCP)	Onset of incurring vehicle movement	Surprise	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*	.95*	.65*	.95*	
						TTI = 4.35	55	1.03*	2.63*	3.00*	1.2*	2.63*	.388*	1.59*	1.19*	.95*	
Carney	1996	Lead vehicle w/ relative speed to subject = 0, suddenly brakes heavily	Lead Vehicle deceleration coupled with brake lamps	Surprise	Simulator	TTC = 2.83	65	0.95			1.46						
Arbuthnott	1980	Car pulls out in front of subject	Onset of car motion	Surprise	Simulator	TTC = 3-4	27	0.904			1.27		0.313				
Barrett and Thornton	1968	Dummy from shed	Dummy	Surprise	Simulator	76.5ft	25				1.05						
Barett et al.	1968	Dummy from shed	Dummy	Surprise	Simulator	82.5ft	25				1.02						
Schreiner et al.	2001	Subject vehicle unexpectantly encounters stopped surrogate vehicle in lane.	Stationary Vehicle	Surprise	Track	TTC = 2.99	26		1.14		0.73		0.2		0.58	0.78	4.75
Shutko	2001	Subject Heavy Vehicle unrepentantly encounters stimulus with distracter task	Rolling Barrels	Surprise	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	Surprise	Track	200 ft	40				1.5						
Fambro et al.	1998	Object (fabric fence) suddenly rises from pavment	Fence	Surprise	Track	213 ft	55				0.928						
		Barrel rolls out of the back of a truck and into the road	Barrel motion	Surprise	Naturalistic	82 ft	44				1.1						

TTI = Time to Intersection
TTC = Time to Collision
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
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

* value interpreted from graph

TB is associated with other measures, some of which are of interest in the development of this algorithm. For instance, the values of Time-to-Accelerator-Release (TAR) or TranSition-time-from-Accelerator-to-Brake (TSAB) can provide information regarding the appropriate location of an IDS system. Definitions for each of these variables are presented below, accompanied by a graphical representation of their inter-relationships (Figure 6). Throughout the rest of this document, this set of variables will be referred to as reaction time (RT) variables:

- **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 0.2 g 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.

RT variables can also be described in the spatial domain (Figure 7). While steering behaviors are not shown, they are similar in structure to the braking behaviors. The TFS is of special interest, since it is equivalent to the SSD. When an IDS system is properly designed, this distance will be enough to provide most drivers with adequate time to stop before entering the intersection.

Another important parameter in the estimation of SSD, based on its relation with both SV speed and distance from the intersection, is the Time-to-Collision (TTC). TTC defines the time that will elapse prior to a collision if no changes in SV velocity occur. TTI has also been used as a parameter in past intersection research; TTI is more applicable than TTC to an IDS scenario. Less-frequently measured in past research than TTC, TTI defines the time that will elapse prior to the SV entrance to the intersection (measured from the stop line) if no changes in SV velocity occur. Indeed, for the scenario under consideration, the violating vehicle would optimally stop prior to entering the intersection rather than just before the crash. Once the violator enters the intersection, there is the possibility for a secondary collision from vehicles other than the POV. Increasing the physical distance between the SV and the POV also discourages the POV from performing an evasive maneuver that could result in a secondary collision. Unfortunately, few studies have measured TTI rather than TTC (Table 3).

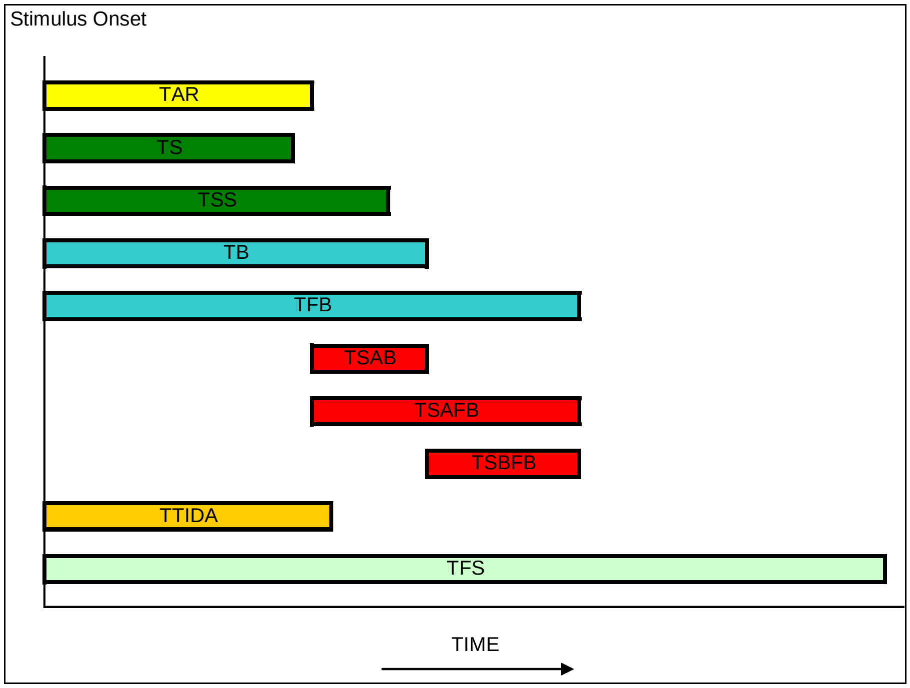

Figure 6. Temporal representation of RT variables. Different colors represent different reaction time classifications (yellow – accelerator release, green – steering, blue – braking, red – transition, orange – initial action, light green – full stop).

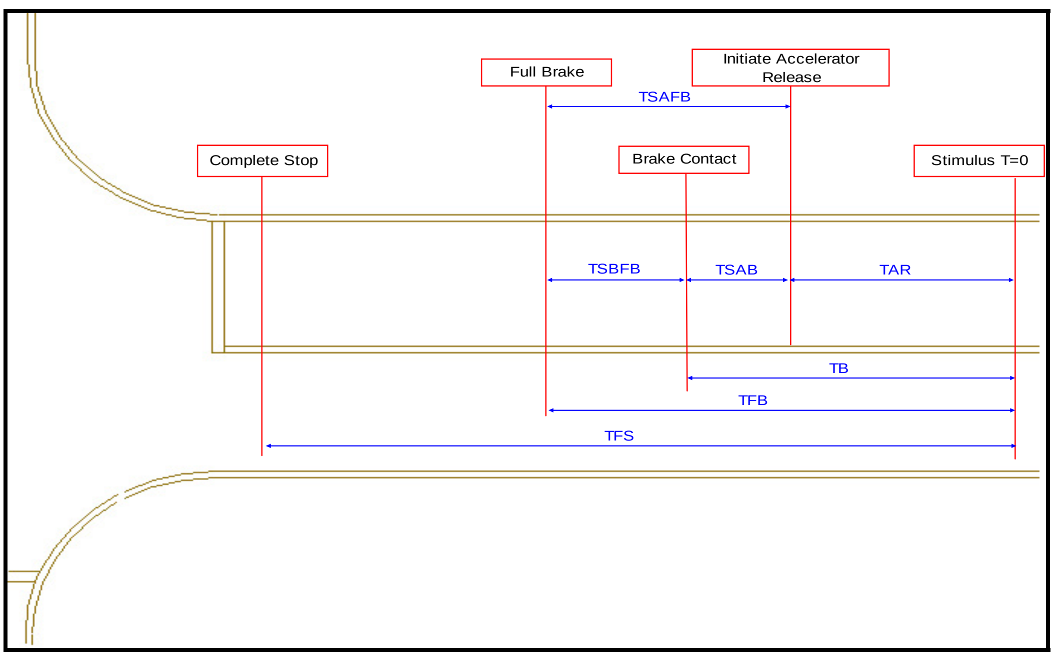

Figure 7. Spatial representation of RT variables.

For the current analysis, however, TTC values in the selected literature will be used as surrogates of TTI. This selection trades off additional time to stop before an accident involving the two primary vehicles (POV and SV) for a possible reduction in the sense of urgency and the associated longer RT values. However, reductions in the sense of urgency are unlikely to occur, for three main reasons. First, the violator is likely to use the stop line, rather than a moving car, as a frame of reference. Thus, the violator's sense of urgency is based on the location of the stop line, and TTI is equivalent to TTC. Second, in many cases the POV will not be visible to the violator, and no reference point for TTC is available to the violator. Third, the distance between TTC and TTI is typically reported to be near 12 ft, which may not be large enough to significantly alter urgency.

Once the decision to brake has been made and the driver's foot has made initial contact with the brake, the combination of driver's braking style, vehicle characteristics, and the road characteristics will influence the braking distance (BD). BD refers to the distance traveled after the driver has initiated the braking response, and includes both TSBFB and the time required by the brakes to bring ground speed to zero. TSBFB can be estimated by data from previous research (Table 3), but vehicle braking distance must be calculated considering a variety of vehicle and environmental factors.

The stopping ability of a vehicle in a roadway is dependent upon many factors, including the condition of its braking system; tire pressure, composition, tread pattern, and tread depth; the presence of moisture or ice on the road; and the ambient temperature. Simply considering manufacturer braking performance data to determine vehicle braking distance would neglect the road factors and any changes in vehicle characteristics (e.g., condition of tires) that might have occurred. Application of a classical equation of dynamics (Equation 1) provides a generalized braking distance value.

$$V_f^2 = V_o^2 + ad \qquad (1)$$

where:

V_f	=	Final velocity
Vo	=	Initial velocity
a	=	Acceleration rate
d	=	Distance traveled between initial and final velocities

In a braking scenario the final velocity is zero and the required distance can be described in terms of the initial velocity and the deceleration level (Equation 2).

$$d = -V_o^2/(2a) \qquad (2)$$

The deceleration of a vehicle depends on the coefficient of friction between the tire and the road and the grade of the road. These two factors can be combined to express the deceleration in terms of gravitational acceleration. Equation 3 illustrates the resulting equation.

$$d = V_o^2/(2g(f \pm G) \qquad (3)$$

where:

g	=	Gravitational acceleration constant
f	=	Coefficient of friction
G	=	Roadway grade percentage ÷ 100 (e.g., 2 percent → 0.02)

A manipulated version of this equation can also be found in the American Association of State Highway and Transportation Officials (AASHTO) "Green Book" (AASHTO, 1994) and is regularly applied to SSD situations. AASHTO also recommends a series of coefficients of friction based on vehicle speed. These coefficients are supported by a series of more than 2,000 measurements of forward skidding on 32 types of pavement in wet and dry conditions, at many speeds, and with several different tire compounds and vehicles (AASHTO, 1994). Published coefficients are intended to be all-inclusive rather than an average for most conditions. In addition, AASHTO only publishes the wet values since friction coefficients are lower for wet surfaces and, contrary to roadways with ice or snow, wet roadways do not necessarily result in slower vehicle speeds than dry roadways. Thus, SSD values obtained based on these formulas will be conservative for dry road conditions. Results from the use of these formulas are presented in the following section.

Stopping Sight Distance Analysis

The information presented in the previous section was used to perform a preliminary analysis of minimum SSD. After obtaining relevant RT values from the literature, means of these values were combined with the equation of motion (Equation 3) to generate an IDS triggering curve as a function of speed.

Mean values for each of the RT variables were calculated across selected studies (Table 3). These means were multiplied by a range of vehicle speeds, which produced a range of distances traveled by the vehicle during a particular driver RT. The same range of speeds was also input to Equation 3 to obtain the BD, using the AASHTO coefficients of friction and making the assumption of a level road. Since AASHTO does not provide coefficient of friction values for speeds less than 32.2 km/h (20 mph), the coefficient of friction value for 32.2 km/h (20 mph) was also used for 8.0, 16.1, and 24.1 km/h (5, 10, and 15 mph). This substitution produces conservative BD estimates, since the coefficient of friction increases as the speed decreases. The distances traveled during the TFB (one of the RTs considered) and the BD, once calculated, were added to obtain the Distance-to-Full-Stop (DFS) for each vehicle speed. Since the reported TFB is a mean, only some of the drivers will react within this time. Therefore, a factor of safety (FS) was used to systematically increase TFB values (and RTs in general). This manipulation was intended to result in DFSs that were sufficiently large for most drivers. An FS equal to one implies that the means for the RTs were used in the analysis, while an FS equal to two implies that the double of each RT was used in the analysis. Some assumptions about roadway geometry and conditions were used in the calculation of the BD (Table 4). IDS system triggering data and curves were calculated based on these assumptions (Tables 4, 5, and 6; and Figures 8, 9, and 10).

Table 4. Example roadway geometry (COF = coefficient of friction, braking distances in feet). (1 mph = 1.6 km/h, 1 ft = 0.3 m)

	Vehicle Speed (MPH)											
Variable	5	10	15	20	25	30	35	40	45	50	55	60
Grade (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
COF - Wet	0.40	0.40	0.40	0.40	0.38	0.35	0.34	0.32	0.31	0.30	0.30	0.29
BD - Wet	0.97	3.88	8.73	15.53	25.54	39.93	55.95	77.64	101.43	129.40	156.57	192.76

Table 5. RTs (seconds) and distance to full stop (feet) for various vehicle speeds for FS = 1.0. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

		Distance Traveled (feet) at Each Vehicle Speed (MPH)											
State	**Time**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
TFB	2.32	16.98	33.95	50.93	67.91	84.88	101.86	118.84	135.81	152.79	169.77	186.74	203.72
TB	1.25	9.14	18.28	27.42	36.56	45.70	54.84	63.99	73.13	82.27	91.41	100.55	109.69
TAR	1.01	7.37	14.74	22.11	29.48	36.85	44.22	51.59	58.96	66.33	73.70	81.07	88.44
TSAFB	1.24	9.09	18.19	27.28	36.37	45.47	54.56	63.65	72.75	81.84	90.93	100.03	109.12
TSAB	0.32	2.36	4.73	7.09	9.46	11.82	14.18	16.55	18.91	21.27	23.64	26.00	28.37
TSBFB	0.73	5.32	10.65	15.97	21.30	26.62	31.94	37.27	42.59	47.92	53.24	58.56	63.89
DFS - Wet		18	38	60	83	110	142	175	213	254	299	343	396

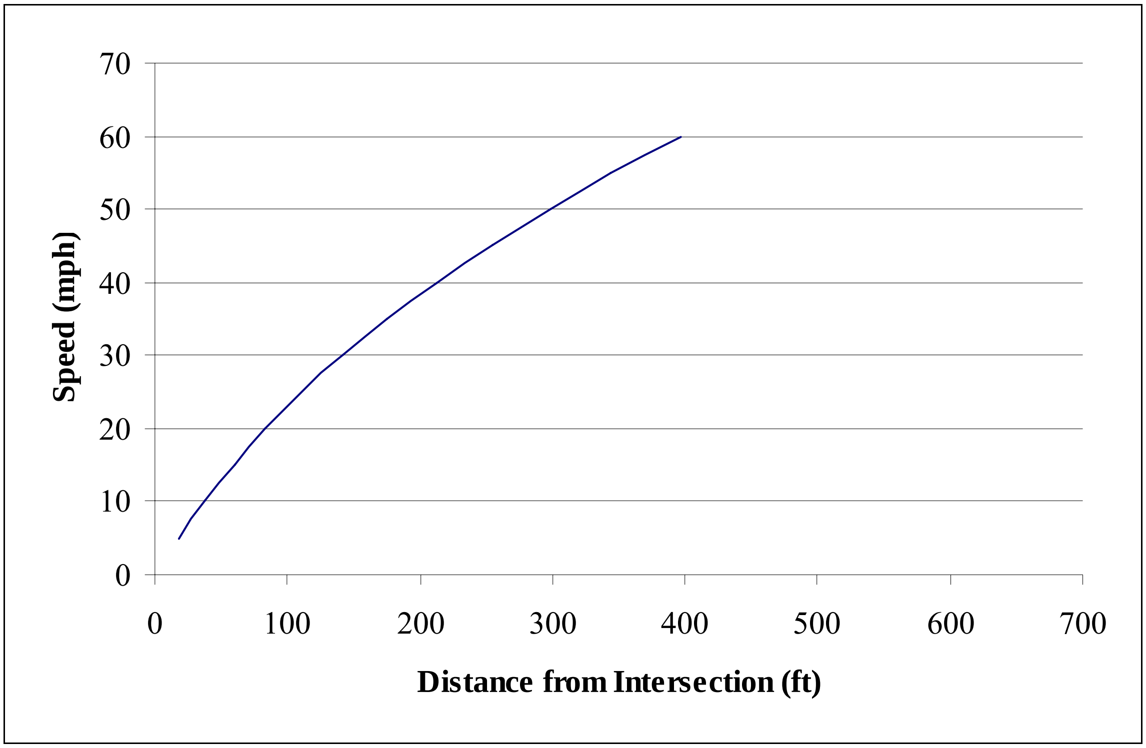

Figure 8. Triggering curve for FS = 1.0. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

Table 6. RT (seconds) and distance to full stop (feet) by vehicle speed for FS = 1.5. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

		Distance Traveled (feet) at Each Vehicle Speed (MPH)											
State	**Time**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
TFB	3.47	25.47	50.93	76.40	101.86	127.33	152.79	178.26	203.72	229.19	254.65	280.12	305.58
TB	1.87	13.71	27.42	41.13	54.84	68.56	82.27	95.98	109.69	123.40	137.11	150.82	164.53
TAR	1.51	11.06	22.11	33.17	44.22	55.28	66.33	77.39	88.44	99.50	110.55	121.61	132.66
TSAFB	1.86	13.64	27.28	40.92	54.56	68.20	81.84	95.48	109.12	122.76	136.40	150.04	163.68
TSAB	0.48	3.55	7.09	10.64	14.18	17.73	21.27	24.82	28.37	31.91	35.46	39.00	42.55
TSBFB	1.09	7.99	15.97	23.96	31.94	39.93	47.92	55.90	63.89	71.87	79.86	87.85	95.83
DFS - Wet		26	55	85	117	153	193	234	281	331	384	437	498

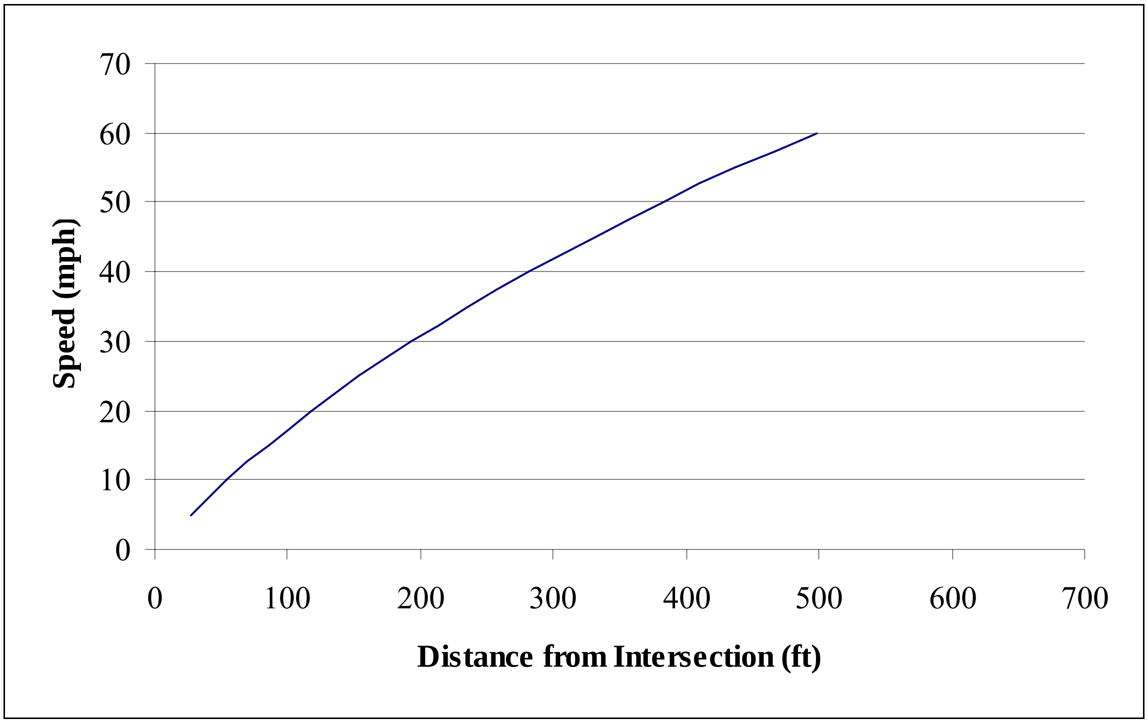

Figure 9. Triggering curve for FS = 1.5. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

Table 7. RT (seconds) and distance to full stop (feet) by vehicle speed for FS = 2.0. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

		Distance (feet) at Each Vehicle Speed (MPH)											
State	**Time**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
TFB	4.63	33.95	67.91	101.86	135.81	169.77	203.72	237.67	271.63	305.58	339.53	373.49	407.44
TB	2.49	18.28	36.56	54.84	73.13	91.41	109.69	127.97	146.25	164.53	182.82	201.10	219.38
TAR	2.01	14.74	29.48	44.22	58.96	73.70	88.44	103.18	117.92	132.66	147.40	162.14	176.88
TSAFB	2.48	18.19	36.37	54.56	72.75	90.93	109.12	127.31	145.49	163.68	181.87	200.05	218.24
TSAB	0.64	4.73	9.46	14.18	18.91	23.64	28.37	33.09	37.82	42.55	47.28	52.00	56.73
TSBFB	1.45	10.65	21.30	31.94	42.59	53.24	63.89	74.54	85.18	95.83	106.48	117.13	127.78
DFS - Wet		35	72	111	151	195	244	294	349	407	469	530	600

Figure 10. Triggering curve for FS = 2.0. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

These data were used in this project for initial triggering the IDS intervention. As explained in the next section, the IDS system monitored approaching traffic and produced a warning if a vehicle is observed traveling at a speed that, based on the triggering curve, would require stopping distances larger than the remaining distance to the intersection. Although calculations for three different FS values have been presented, FS = 1.5 was used during initial setup stages of the IDS system. This particular FS should provide sufficient stopping distance for 85 to 95 percent of drivers, based on the TB findings of Sohn and Stepleman (1998) and Fambro et al. (1998). These researchers reported an 85th percentile TB of 1.92 s and a 95th percentile TB of 1.98 s, respectively. In addition, this TB selection is also compatible with the conservative AASHTO-recommended 90th percentile value of 2.5 s (AASHTO, 1994).

The values presented in this section are intended as preliminary recommendations only. Given the unique characteristics of IDS systems, discrepancies in RT values from previously published data are likely. Some implicit assumptions about the linearity of these data have also been made by applying the concept of safety factors. This information was empirically and statistically verified through a series of road experiments conducted as part of this project and reported in later sections of this document.

Under the premise of IDS technology, information is relayed when a vehicle is determined to be a potential violator. The notification must be provided in a manner that will allow the driver to make a timely decision. Determination of the vehicle that should be presented with the IDS information depends on factors such as the actual time to relay the message to the target, driver recognition and response time, signal phase and timing, and time necessary to stop the vehicle once a decision is made. These factors will change depending upon variable data such as roadway conditions and other environmental factors. These influential factors could be monitored via actual roadway sensors (data collection equipment) or general information dissemination (such as local weather information systems). The next section describes a preliminary warning algorithm developed considering these issues.

This algorithm requires that special instrumentation providing (or receiving) the necessary inputs be installed within the infrastructure. A parallel algorithm development effort was undertaken by VTTI as part of its ICAV) project, which used in-vehicle systems to generate the necessary inputs and provide the warnings (Lee et al., 2005).

Warning Algorithm

Equations 1 through 3, presented in the previous section, described a minimum SSD value without providing for inherent human delays, typically referred to as RT. After obtaining relevant RT values from the literature as described in the previous section, means of these time values, multiplied by the initial velocity, were added to the braking distances determined by Equation 1 to generate an IDS triggering curve as a function of speed.

Considering RT in Equation 4 requires the addition of a term representing the distance traveled by the vehicle while the driver is detecting and reacting to the warning. In addition, a term is also added to represent the various sensing and DII lags inherent in any system. These delays are typically in the order of milliseconds (Knipling et al., 1993).

$$d = -V_o^2/a + (RT + L) * V_o \qquad (4)$$

where:

RT = Reaction Time

L = System lag times, net

Information gathered during the literature review suggested 2.5 s as a very conservative estimate of RT for a distracted driver. This value of RT was used in the generation of the preliminary algorithm used in the testbed, but was subject to scrutiny as experiments were conducted. System lag times are testbed-system specific.

Equation 1 requires the average acceleration used by a driver. This parameter and the RT are the only two elements of this equation that cannot be applied in real time for a particular driver. As such, they represent the only two elements that must be assumed. RT has already been assumed at 2.5 s for initial testbed testing, based on the literature review. The development of reasonable estimates for the deceleration level required a more complex design process.

Initial algorithm work (Neale et al., 2002) considered various constant deceleration magnitudes (Figure 11). However, the braking performance for a particular driver is dependent on many factors, including initial vehicle speed, road conditions, perceived urgency of the situation, and surrounding traffic. Given that initial algorithm testing occurred under controlled conditions, the work described in this section focuses on determining speed effects on the preferred deceleration rate, which was a principal area of interest in algorithm development.

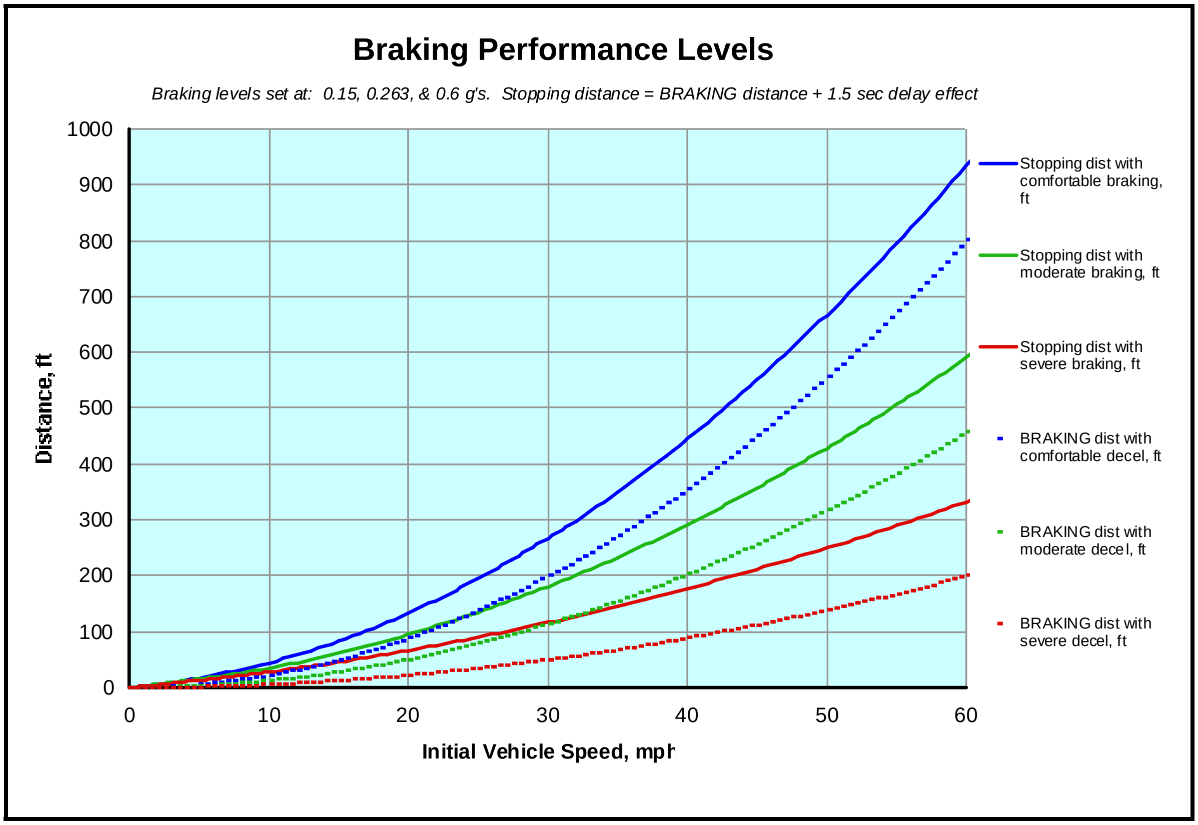

Figure 11. Stopping distances for various deceleration magnitudes. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

Recent estimates of deceleration are available from AASHTO (1994) and CAMP (Kiefer et al., 1999). Both organizations, using different assumptions and approaches, have generated guidelines for deceleration parameters. These approaches were combined in the development process for the initial testbed algorithm.

The AASHTO (1994) generated a series of recommended deceleration levels as a function of road design speed. These levels are based on obtaining safe stopping sight distances (i.e., providing drivers with sufficient distance to the intersection to stop comfortably once the intersection becomes visible) and tend to decrease with speed. A linear regression (Equation 5) was used to determine the best-fit line for the values cited in the AASHTO report, and is shown in Figure 12.

$$a = 0.4211 - 0.002126 V_0 \quad (5)$$

where:

a = Deceleration in g

V_0 = Vehicle speed in mph

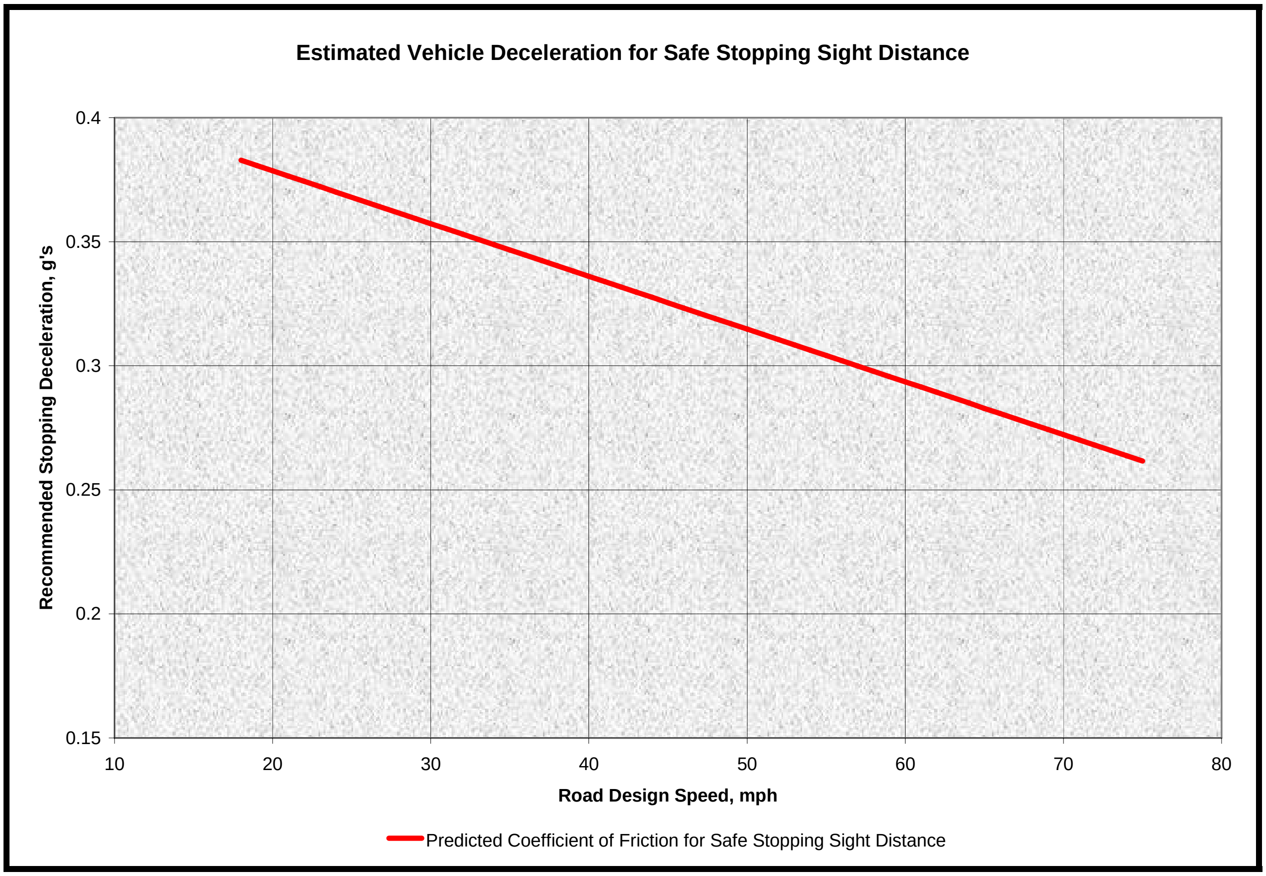

Figure 12. Regression fit of AASHTO vehicle decelerations as a function of speed. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

While the AASHTO values provide reasonable deceleration estimates for the intersection approach situation at low speeds, the decreasing trend with increasing speed results in unrealistically high stopping distances at upper highway speeds. AASHTO's data are based on gradual, comfortable, stops, suggesting that people stop comfortably at lower deceleration rates from higher speeds. However, development of an algorithm also required information regarding driver behavior during emergency stops at high speeds. These data were obtained through CAMP.

CAMP (Kiefer et al., 1999) reported, based on empirical tests of hard decelerations, a different relationship between deceleration levels and speed (Figure 13). Only three speeds were tested in these studies: 30, 45, and 60 mph. The "hard" braking test values were obtained while participants, presented with a stopped vehicle in their right-of-way, waited until the last possible second to brake. The "normal" braking values were obtained while participants, presented with the same stimuli, were allowed to react and brake as they normally would under a similar real-life stimulus. The hard values were deemed more applicable for intersection violation warning, given that people facing an intersection violation are unlikely to brake as they normally would. Based on the hard deceleration data, CAMP provided a linear equation for deceleration with vehicle speed (Equation 6).

$$a = 0.164 + 0.00368 V_0 \qquad (6)$$

where:

a = Deceleration in g

V_0 = Vehicle speed in mph

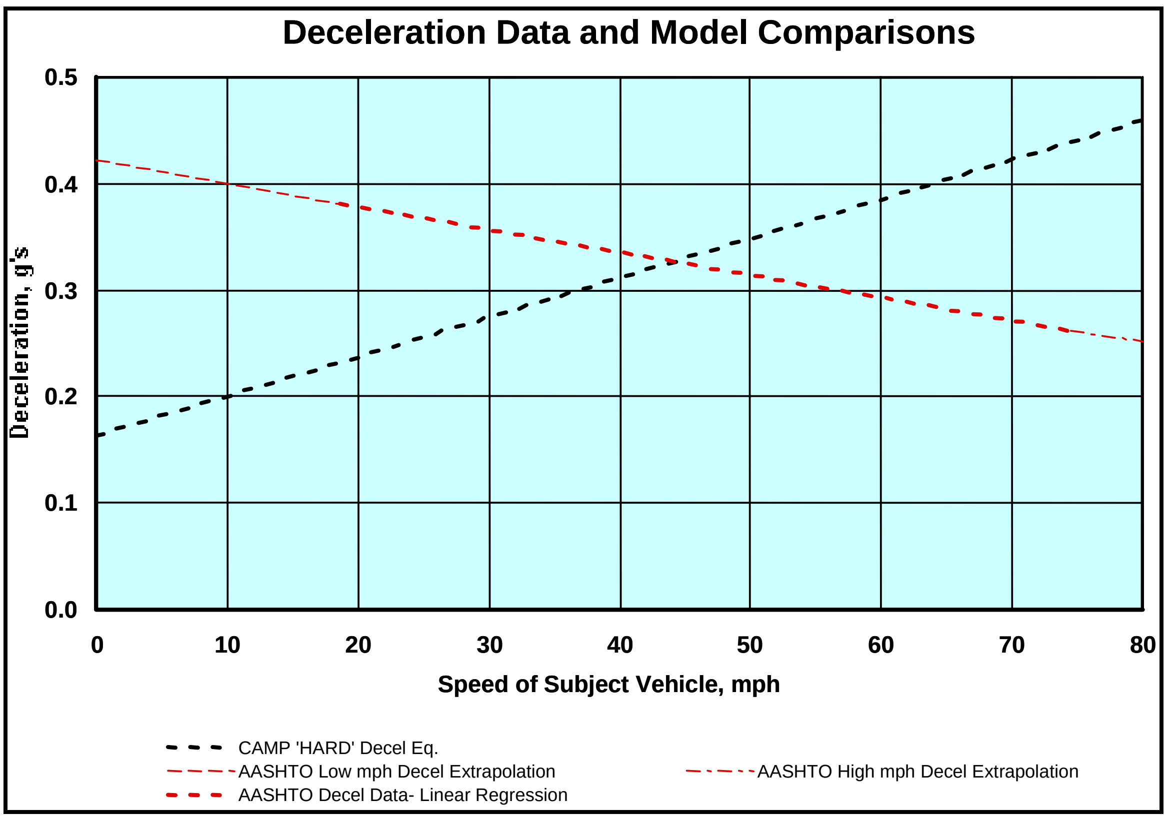

Figure 13. Comparison of regressions and extrapolations of CAMP's and AASHTO's approaches. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

Data from AASHTO and CAMP were then contrasted to determine their intersection and possible synergisms between the approaches (Figure 14). Given CAMP's use of high speeds in their tests, no data were available at speeds below 30 mph. AASHTO's approach, however, had some empirical data on deceleration values for lower speeds. Thus, both approaches were combined, with the AASHTO decelerations used for speeds below 44.3 mph and CAMP decelerations used for speeds above this value to generate a "merged" model as shown in Figure 14.

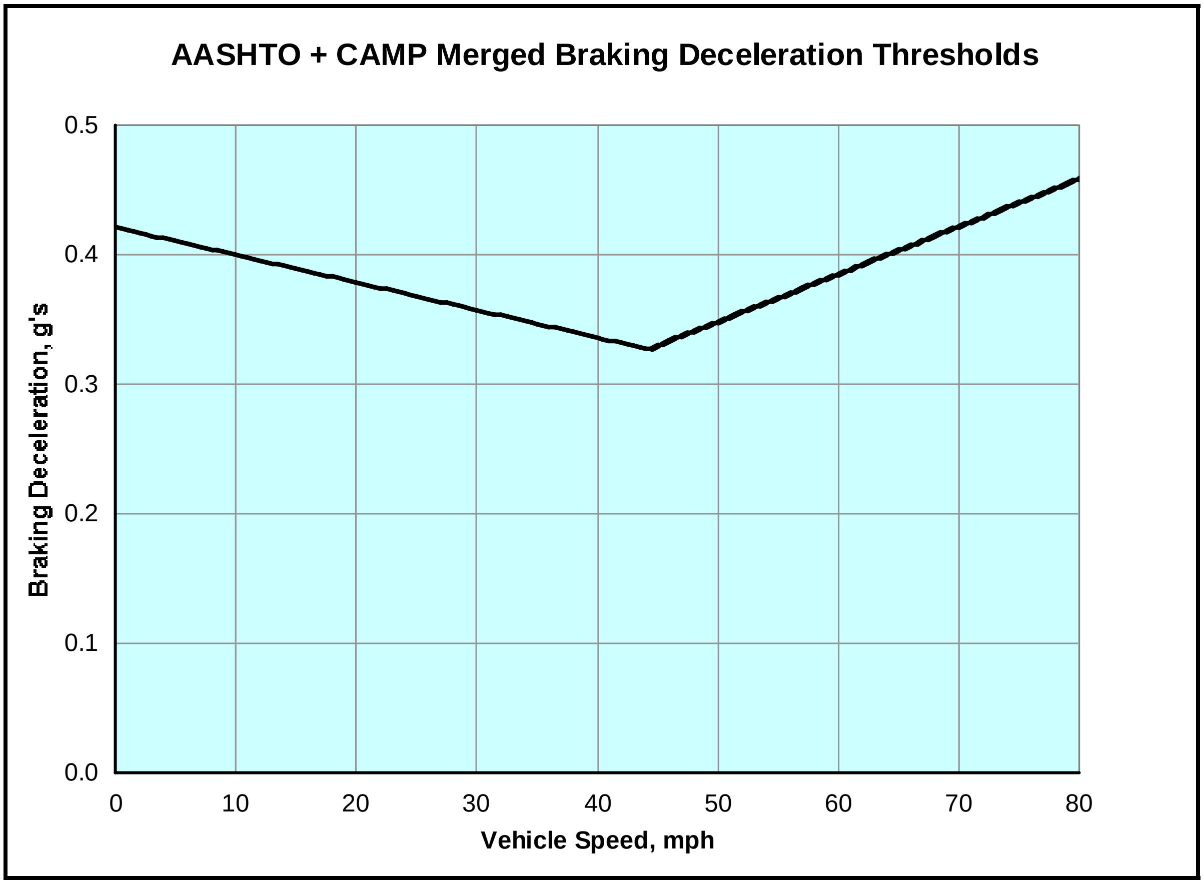

Figure 14. Merged model. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

The merged model was then used to generate warning distances. Assuming a 2.5-second RT, a warning threshold for a "non-braking" situation is also shown (Figure 15). Later experiments on the testbed were used to determine the utility and feasibility of detecting braking deceleration for approaching vehicles: if a driver was braking, the warning threshold could be relaxed back to the zero-reaction-time condition (lower curve), with a potential resulting decrease in nuisance alarms. Effective application of this technique will require accurate sensing of vehicle velocities at sufficiently high sample rates to determine a true braking condition well within the assumed reaction time. If a vehicle's deceleration cannot be determined within a small portion of the allowed RT, then the warning is more likely to be ineffective. Graded warnings may also be triggered by determining "escalation" thresholds if, for example, braking uncertainty exists.

Note that this approach can be used without modification for stop-controlled intersections. However, signal phase and timing must also be considered when a signal is present. When a red-light condition will persist beyond the projected vehicle intersection crossing time, that intersection approach becomes a stop-sign scenario and the algorithm can be implemented without modification. However, other signal conditions require additional algorithm development.

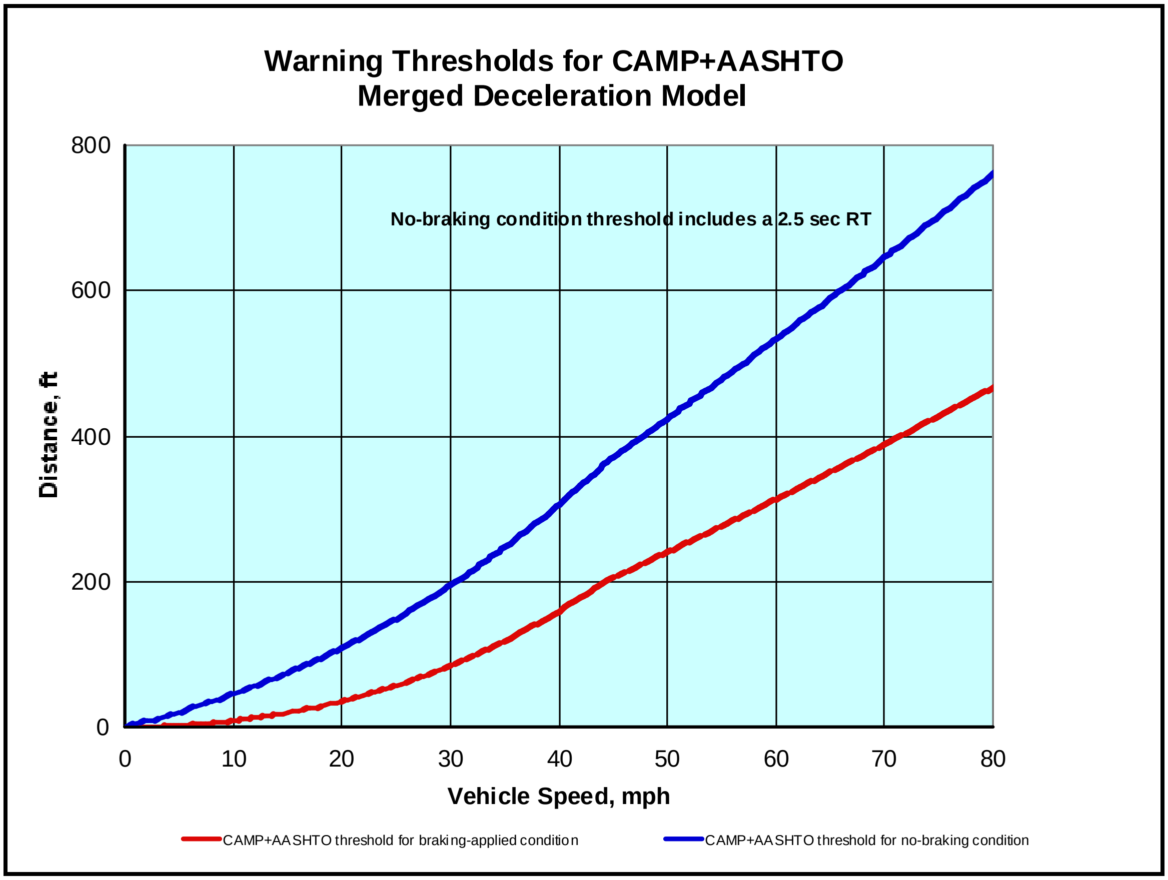

Figure 15. Distance vs. speed triggering curves for the merged model. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

One important phase and timing issue concerning the algorithm development in signalized intersections is whether to warn when the light is green and the driver has the right of way. Some infrastructure systems already perform this function with "Prepare to Stop when Flashing" signs, which have generally been shown to increase intersection speed after installation (Pant and Huang, 1992). These devices activate the warning after receiving a signal from the controller a certain amount of time prior to the green-to-amber phase change. The timing of this warning is based on road design speeds, and is commonly used to warn drivers when the line-of-sight distance may not allow sufficient amber phase warning to the prevailing traffic condition (e.g., road curvature and/or vehicle speeding). Newer, "smarter" controllers, however, may not be able to provide this functionality, as the decision to change to amber is often made only 1/10th of a second before the actual phase change. Furthermore, the effectiveness of these systems is debatable. While some studies demonstrate a reduction in the number of red-light violations, others indicate less success; a reduction in intersection conflicts and in some cases higher speeds have been observed (Pant et al., 1996).

Given the commonly cited ineffectiveness of warning drivers when the light is green, combined with the implementation issues with newer controller systems, amber-to-red signal timing was overlaid on the warning algorithm (Figures 16 and 17) to determine green-phase warning feasibility. Amber-phase lengths are primarily dictated by road design speed and traffic conditions, with most signal controllers providing an amber-phase time running from a minimum of 3 s to a maximum of 5 or 6 s with increasing design speed. Figure 16 illustrates potential effects of selected amber phase times as well as a likely amber phase design line. This figure shows that warning under a green phase may not be necessary if a RT significantly less than 2.5 s can be safely utilized.

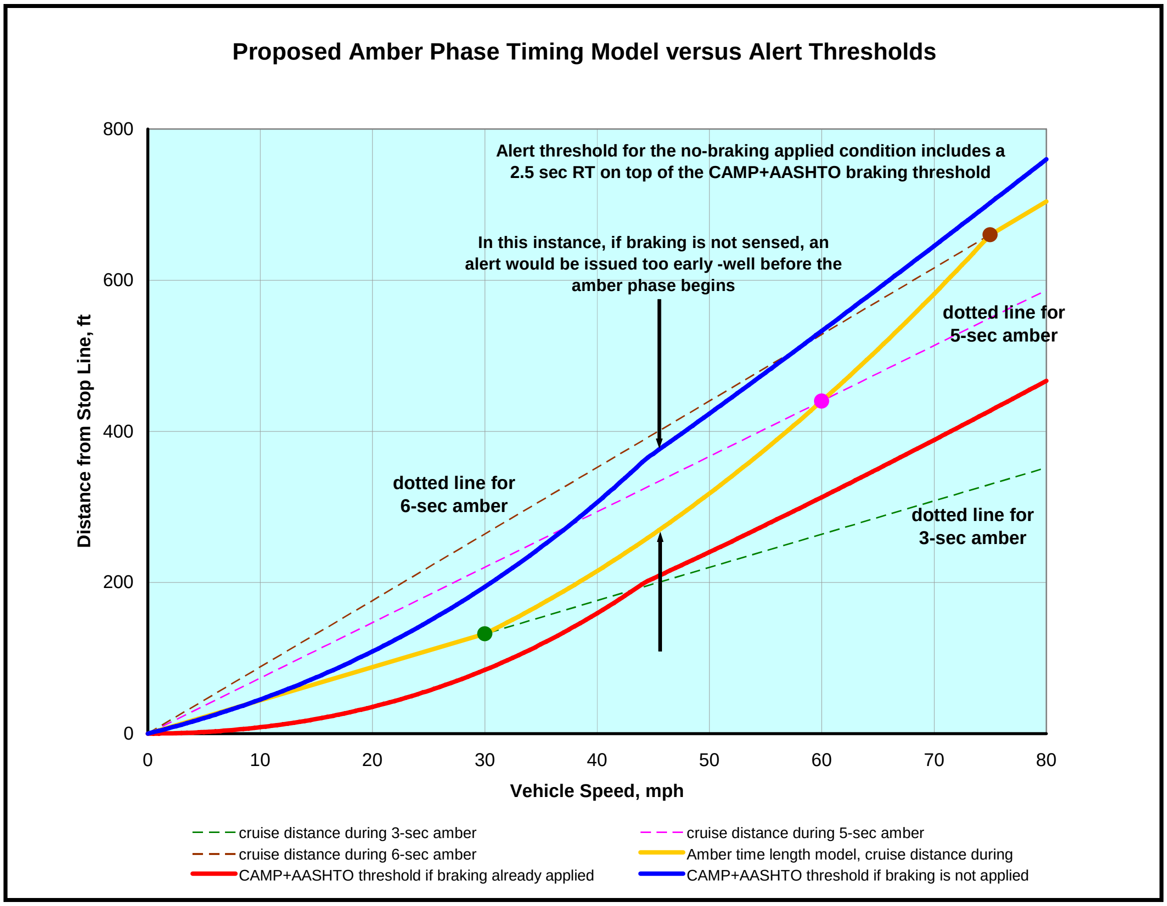

Figure 16. Consideration of various yellow-phase lengths. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

Existing IDS Driver-Infrastructure Interface (DII) Technologies

Previous research has proposed a variety of approaches to reduce the number of intersection crashes. These approaches vary from in-vehicle alert/warning systems to active intersection control systems that take partial or total control of the vehicle once it enters an intersection.

The process that any IDS technology must follow to perform its duties is the same. First, a potential violation must be sensed. Second, the driver of the vehicle identified as a potential violator must be alerted. (This second step is a primary concern of this review.) Third, a driver reaction occurs. Based on that reaction, the IDS technology might take further actions, the extent of which depend on the limits of the technology implemented in the IDS system. This approach is used to propose a preliminary IDS activation algorithm by White and Ferlis (2004).

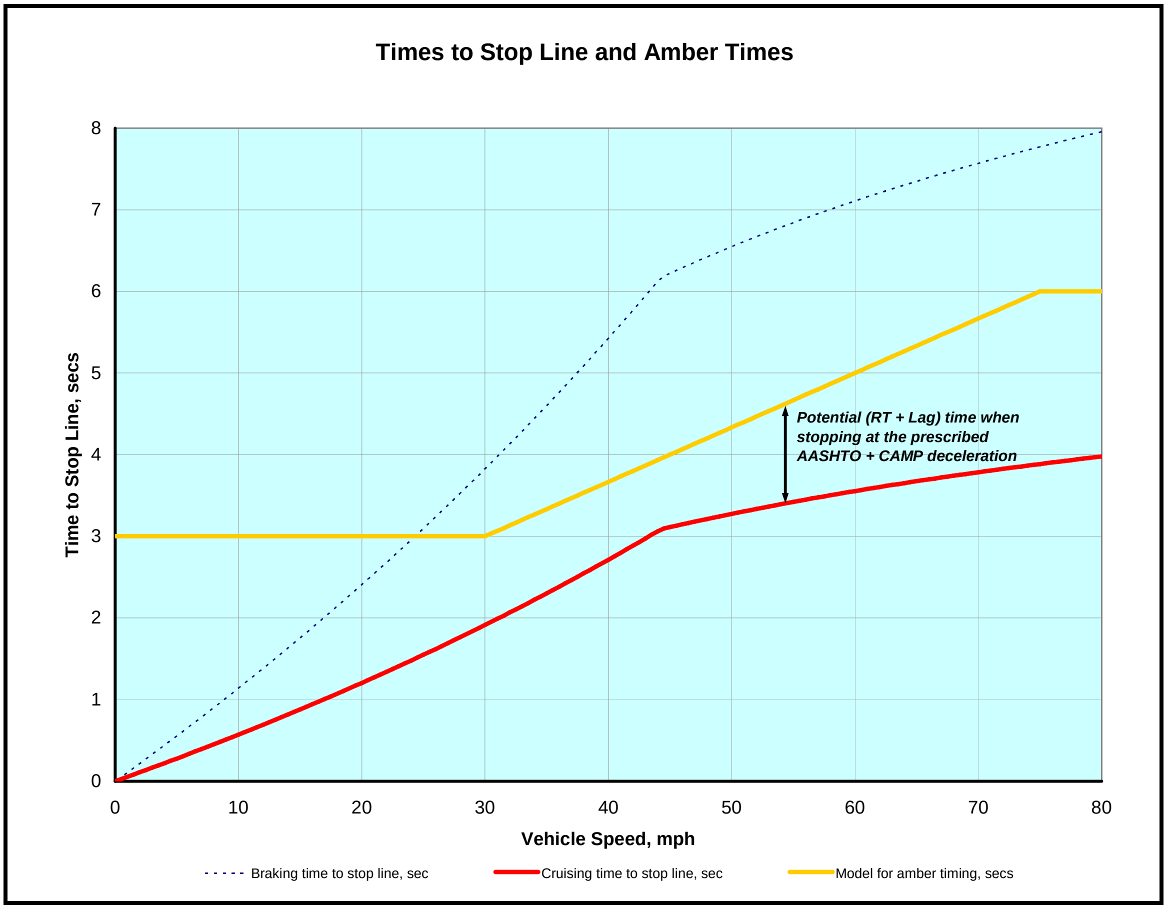

Figure 17. Proposed amber phase timing model versus alert threshold times. (1 mph = 1.6 km/h, 1 ft = 0.3 m)

Once a vehicle is targeted as a potential violator, information must be relayed to that vehicle. The notification must be provided at a reasonable location, or one that will allow the driver to make a timely decision. Only those drivers who are far enough away from the intersection under consideration (based on speed and possibly deceleration data), and who also have the ability to react in time to stop before entering the intersection, should be targeted. Determination of the vehicle that should be presented with the IDS information will depend upon factors such as the actual time to relay the message to the target, driver recognition and response time, and time necessary to stop the vehicle once a decision is made. These factors will change depending upon variable data such as roadway conditions and other environmental factors. These influential factors could be monitored via actual roadway sensors (data collection equipment) or via general information dissemination (such as local weather information systems).

Depending on the method of information relay, the classification of IDS systems includes Infrastructure-Only and Infrastructure-Cooperative systems. Information in the Infrastructure-Only systems is presented directly to drivers from devices on the actual roadway (e.g., traffic signals or signs), whereas Infrastructure-Cooperative systems provide information to the vehicle, which may react to that information and/or relay that information to the driver, depending on the technology used. Possible components for both of these system classifications include roadside sensors, processors, informational and warning devices, roadside-driver communication devices/interfaces, and traffic signals to provide driving assistance (Ferlis, 2001b). Some commonly available infrastructure components (e.g., roadway embedded loop detectors) have also been suggested as possible sensing technologies (Ferlis, 1999). Both of these system types are typically configured to offer information only to the violator SV, as some particular problems can occur when information is presented to both the SV and the victim vehicle (POV; Tijerina et al., 1994).

Warning the victim in an intersection crash is not necessarily helpful for a variety of reasons. First, the warning itself might cause undesirable reactions from the POV driver. For example, the POV might perform a severe steering maneuver and collide with a vehicle on an adjacent lane or run off-road. Similarly, the POV might brake severely and be involved in a rear-end crash. Second, since the warning must only occur when a crash is very likely, the SV must first be given an opportunity to respond appropriately before the warning is triggered. This reduces the available amount of time for the POV to respond, and increases the severity of the maneuvers that the POV must perform to avoid the crash. Finally, the POV driver might simply not be willing to perform the severe maneuver and would be involved in the crash anyway (Tijerina et al., 1994). More research on this aspect of IDS is needed before any systems warning both the SV and POV are implemented.

Ferlis (2001a) notes that even advanced technology, such as the processing of infrastructure-based cooperative systems, will require minimal and relatively inexpensive (when produced in volume) in-vehicle equipment. Researchers suggest that the required equipment will likely include a communications transceiver, an in-vehicle processor, and a driver interface. Vehicles already equipped with intelligent vehicle systems would require only the addition of a receiver, whereas those with no existing system would require all three types of equipment (receiver, processor, and interface). There is already equipment capable of translating emergency vehicle radar signals to message displays. It is possible that this equipment could be modified for use in IDS systems (Ferlis, 1999).

Infrastructure-Only Systems

Ferlis (2001b) notes that Infrastructure-Only systems that include roadside warning devices are feasible in terms of both time and cost/benefit factors. These inherent benefits increase the chances of public safety improvement, acceptance, and return on investment. Infrastructure-Only systems also provide a natural basis for future cooperative systems. Typically taking the form of warnings, these systems use information from one or more variables, including vehicle speed, acceleration, and distance. Human capabilities and limitations, such as the TB, should also be considered. For example, data from this set of variables can be combined to extend the red phase of cross-traffic lanes when an SV violates a red light.

Some of the principles discussed by Tijerina et al. (1994) regarding in-vehicle “driver warnings” (i.e., in-vehicle directives provided to the driver related to a likely upcoming collision) may also be applied to warnings located outside of the vehicle. The authors note that an important characteristic of collision warnings is the time allowed for the driver to process and react (and, if applicable, time for vehicular control to react). Intersection maneuvers are unique compared to general traffic maneuvers in that they do not generally involve sudden changes in vehicular movement related to crash occurrence. In other words, a vehicle might suddenly cut into the path of another during general traffic patterns, but upcoming traffic and possible crash scenarios at intersections are more easily predicted. Therefore, the idea of a constant warning time and thus constant time to react (depending upon kinematic conditions) is more easily attained for intersection traffic. Naturally, the most basic models would be based upon fairly ideal conditions (e.g., constant velocity and uniform deceleration), while complex driver behaviors would require more research and detailed modeling.

Once the sensing method and location are chosen, the point of information presentation must be determined. One possibility for presenting this information is the traffic light itself in a signal operated by an Advanced Traffic Controller (ATC). Initial versions of ATCs are being deployed, and will be commercially available in the future (Ferlis, 2001b). One possible function of such a traffic signal would be to provide collision avoidance measures by altering the signal timing for the violator vehicle. In other words, once a potential collision is registered, the traffic signal could alter its signal (e.g., extend the green light time) to avoid the predicted collision. One manufacturer has used machine vision sensors to perform this function (Ferlis, 1999). Naturally, this type of equipment could also allow changes to the light for the intersecting driver(s), or the victim(s) of a possible collision. Although warnings for the potential victim will not be addressed in this review, the possibility of changing the victim's light phase (i.e., from green to amber or red) if a potential collision situation is detected would be introduced with the ATC. The ATC also lends itself to further development as a component of the Infrastructure-Cooperative systems.

One possibility for information presentation to the violator vehicle is available in roadside warning devices. The placement of these devices to allow the violator vehicle adequate time for avoidance measures is crucial. Much research will be necessary to adequately develop such products, but the following types are presented by Ferlis (2001b):

- Warning signs and/or lights that would be activated when a potential violator is identified (e.g., a combination of a sign and flashing lights warning of the stop ahead)
- Lights (such as strobe lights) incorporated into the traffic signal display
- Intelligent rumble strips, activated only when necessary and carefully placed to optimize driver reaction
- Variable message signs, designed to be easily and quickly understood

Similar research on roadside warning devices in the form of road sign evolution has also been proven beneficial. Hanscom (2001) describes an implementation of signs that graphically advised drivers of the presence and direction of other traffic in a public stop-controlled intersection. Results suggest significant reductions in speed for a month-long data collection period, but the permanence of these results was not measured.

Intelligent rumble strips are not commercially available, but technology does exist that would possibly be useful in the development of such a device. One technology that could be considered is the use of fluids with electrically-dependent viscosity. An imposed charge would effectively activate three to seven closely spaced rumble strips, providing a warning to the potential violator vehicle. These electronic rumble strips could also reduce run-off-road accidents (Stauffer and Lenz, 1996).

Ellison (2001) discusses some common avenues for reducing stop-sign violations, such as the installation of larger stop signs, additional warning signs, lights, and rumble strips. However, these authors note the need for additional research into driver behavior as related to stop-sign violation. Possible research areas include the effect of sign placement on driver behavior (particularly sight distance), visual cues for two-way vs. four-way stops, causes of driver inattention, the effect of speed, and the effectiveness of flashing beacons to warn of upcoming intersection activity.

Traffic control technology designed to aid emergency response vehicles could also be integrated into IDS systems (Roberts, 2001). Sensors mounted in traffic signals recognize approaching emergency vehicles (which are equipped with transmitters for this purpose), and the side street lights immediately turn red. This "all-red" option would be useful in preventing a POV from entering an intersection where an SV is predicted to enter inappropriately. Alternatively, some companies are marketing a device to be installed in private vehicles to alert drivers about the presence of nearby emergency vehicles.

The all-red clearance interval is a widely deployed engineering countermeasure. It provides a short buffer between the termination of yellow and the adjacent green presentation. The all-red is designed to provide enough time for a vehicle to clear the intersection once it enters the intersection at the instant the red is presented in Equation 7.

$$R = \frac{W + L}{V} \tag{7}$$

where:

R = Length of all-red clearance interval
W = Width of the intersection
L = Length of vehicle, recommended as 20 ft
V = Vehicular speed

Uncertainty surrounds the actual effectiveness of the all-red interval (Zimmerman and Bonneson, 2005). Some research cited indicated a 10 to 40 percent reduction in right-angle crashes after an all-red was added. However, research on the longer-term effects of all-red discredit these findings. While looking at intersection crash timing Zimmerman and Bonneson (2005) concluded that crashes occurring in the first few seconds of red are LTAP/OD, a situation in which the all-red has no impact. Right-angle crashes did not begin occurring until well after an all-red would have terminated. In a 4-year compressive before and after study of all-red clearances it was concluded that although all-red clearances do provide safety benefits initially, after a couple of years this safety benefit is extinguished (Souleyrette et al., 2004). Furthermore, the all-red interval reduces intersection capacity and increases delay, both of which can lead to a higher number of "avoidable" red-light violations (Souleyrette et al., 2004; Zimmerman and Bonneson, 2005).

Some Infrastructure-Only systems do not require advanced technology. For example, Retting and Van Houten (2000) report on the effects of moving the stop line back by 6 to 10 ft for the middle and left-most lanes of an intersection. The improvement in the visibility of oncoming traffic for drivers of vehicles in the right-most lane resulted in a reduction of right-turn-on-red conflicts with cross traffic, and also created more complete stops (behind the right-most stop line) for the vehicles turning right on red. Results from Retting and Van Houten (2000) also suggest that the increase in TTI (if a vehicle stops further back from the intersection) due to altered stop lines might decrease the chance of intersection collisions, and that these techniques could also be useful at stop-controlled intersections.

Most of these technologies also require some method that allows for “intelligent” autonomous operation. Gallego et al. (1996) describe a detailed mathematical method for the design of an optimal real-time signal control device that takes information such as color sequences for each signal (green-amber-red), clearing times between conflicting signals, and a maximum service delay for any user waiting in the intersection into account when making control decisions. Data are generally collected using inductive loops, and the optimal control structure was developed using Petri networks. Other control systems are also possible, but Petri networks are touted as harmonious to future types of intersection control systems that use traffic response mechanisms.

Management Information System for Traffic (MIST®) is an information management and control system (developed by PB Farradyne, Inc.) that communicates with and manages traffic signal controllers (Schintler and Farooque, 2001). The Partners in Motion program that is functioning in the Washington, DC metropolitan area utilizes MIST® as part of its traffic congestion reduction and general traffic information provision efforts. Some of the program's subsystems include variable message signs, improved intersection signalization, loop detectors, and surveillance cameras. The combination of these program elements leads to information that includes real-time graphics of vehicle operations at selected intersections. These elements, along with the Smart Traffic Signal System and other traveler information services, could provide the framework for the testing and implementation of many signalized IDS systems.

Other Infrastructure-Only systems are focused on enforcement. Drivers who are reckless enough to try to beat or deliberately violate traffic signals will probably not heed warnings provided by IDS systems (Tijerina et al., 1994). One increasingly common enforcement method for traffic signals is RLR photo enforcement (i.e., capturing signal violation on camera). While the focus of this report is not enforcement, it is mentioned because this system is becoming available in many areas, and has been shown to decrease the deliberate acts of violation (Insurance Institute for Highway Safety [IIHS], 2001, 2002). For instance, in Oxnard, CA (the site of the first scientific study of its kind), the frequency of front-into-side crashes at signalized intersections with RLR photo enforcement decreased by 32 percent. Automated RLR enforcement systems have resulted in significant crash risk reduction. A multi-jurisdictional investigation of 132 intersections showed that right-angle crashes were significantly reduced (Persaud et al., 2005). A study in Virginia that found a 44 percent decrease in violations after 1 year also noted a 34 percent reduction in violations at nearby sites that did not have automated RLR system (Retting et al., 1999a).

There are also problems associated with automated RLR systems. The decreases in right-angle crashes is at the cost of increased rear-end crash frequency (Council et al., 2005). Furthermore, issues associated with privacy and civil rights continue to slow the deployment of automated enforcement systems. Finally, these systems may do little for an inattentive driver which appears to represent a significant portion of the RLR crash problem.

Some Infrastructure-Only systems are summarized by BMI (2001c). These researchers describe 12 types of infrastructure-based IDS system concepts. Six of these 12 are related to SCP crashes and presented below:

- Dilemma Zone Control - Signalized Intersection
    - Dilemma zone is the distance before the intersection at the onset of a amber traffic signal within which the driver can decide to slow down to a stop or speed up to try to clear the intersection before the light turns red.
    - Control strives toward ensuring that the light phase changes from green to yellow when there are few cars approaching the intersection to minimize the number of vehicles caught in the dilemma zone.
    - Necessary equipment includes a signal controller and presence detectors in intersection lanes.
- RLR Photo Enforcement
- Red-Light Hold
    - Goal is to identify likely signal violators and to extend the opposing red-light phase to prevent cross traffic from entering the intersection.
    - Speed and distance information for vehicles in all lanes is collected by sensors and processed by a central processing unit, which then activates a signal controller accordingly.
    - The detection zone will depend upon the given road's design speed (the higher the design speed, the farther back from the intersection the detection zone will extend).
    - An additional method is the activation of strobe lights to warn the potential red-light runner to stop.
    - This concept is an alternative to the concept of all-red phased traffic signals.
- Minor Road Intersection Warning
    - Roadside warning alerts vehicle on minor road of presence of vehicle on major road.
    - Designed for two-way, stop-controlled intersections.
    - A detector on the major road (based on speed or presence) activates an active warning sign on the minor road (placement and timing dependent upon type of major road detector).
    - Detector could also be placed on minor road such that warning is activated only when a vehicle is on the minor road.
- Major Road Intersection Warning
    - Roadside warning alerts vehicle on major road of presence of vehicle on minor road.
- Active Advanced Warning Sign (variations of the Passive Symbolic Signal Ahead [PSSA] sign, which indicates that a signal is upcoming)
    - Prepare To Stop When Flashing (PTSWF) sign: a PSSA sign with strobe lights that are activated when the upcoming intersection signal is about to change from green to yellow.
    - Flashing Symbolic Signal Ahead (FSSA) sign: a PTSWF sign that uses a picture of a traffic signal, rather than wording.

— Continuous Flashing Symbolic Signal Ahead sign: identical to the FSSA, except with a continuous flashing strobe light that is independent of the actual traffic signal phase.

Some of these systems could also be developed into Infrastructure-Cooperative systems if the warning was provided through in-vehicle technology. Each of these system types is described in more detail in BMI (2001c), which also provide details of their actual implementation. For example, one of these systems was implemented at a rural, two-way, stop-controlled, limited sight-distance intersection in Prince William County, VA. While detailed descriptions and evaluations of the system are available elsewhere (Raytheon, 1999; Hanscom, 2001), a brief overview is presented here.

The main component of the system is a warning (a flashing car symbol) provided to the vehicle with the right-of-way on a major road when a vehicle without the right-of-way (from a minor stop-controlled road) is preparing to enter the intersection. Another system element is a "crossing traffic" alert (an animated car symbol) provided to the vehicle on the minor road when traffic is approaching from either direction on the major road. The overall system utilizes sensors embedded in the roadway to detect vehicle presence and speed on the major and minor roads, and a computer that processes the resulting data and activates the warning signs accordingly. The system uses advance warning times of 3.0 and 4.6 s (based on estimates of times required to slow and completely stop a vehicle, respectively). Various measures of effectiveness for this system were used: sign response speed; intersection arrival speed; first, second, and overall speed reduction; and projected TTC. Results indicate that this system is more influential on driver behavior for approaching lanes with shorter sight distances, and that collision-related behavior is generally decreased. However, the long-term permanence of this effect was not measured.

Infrastructure-Cooperative Systems

Although the focus of this review is mainly infrastructure-based displays, some of the research performed in the Infrastructure-Cooperative context is relevant to the development of Infrastructure-Only devices. Thus, this section describes relevant reports of Infrastructure-Cooperative systems, with an emphasis on their sensing requirements and warning presentation modalities, rather than on the in-vehicle displays. For some of these prototype systems, the driver is even partially removed from the loop, as the system assumes partial or total control of the vehicle.

Components of a program called Prometheus (Program for a European Traffic with Highest Efficiency and Unprecedented Safety) are presented by Roessle et al. (1993), and Ulmer (1994). These studies describe anti-collision technology that uses combinations of equipment such as radar, cameras, and beacons to provide driver information under various conditions. One of the Prometheus systems is called "Stopping at Stop Signs," and uses a message that is relayed from a beacon at a stop-controlled intersection to an approaching vehicle's receiver (De Saint Blancard, 1992). This message includes distance information for the stop sign, and will apply automatic braking if the vehicle does not appear to be responding appropriately. Anti-collision control is the main goal of most of the Prometheus systems, but other related functions such as autonomous intelligent cruise control were also considered (Ulmer, 1994).

A variety of countermeasure system concepts are presented in Najm et al. (1995). These concepts include headway detection, proximity detection, lane-position monitoring, in-vehicle signing, and gap-acceptance aid. Each of these concepts is discussed with respect to its applicability of each to various crash scenarios.

A collision warning system called FOREWARN is described in Landau (1996). This particular system uses object detection sensors, along with existing vehicle electronic systems, to provide forward- and rear-driving collision warning. This system was tested in a variety of applications, including highway-rail grade crossings (Polk, 2001).

Parasuraman et al. (1997) evaluated various driver-centered collision warning systems. These authors state that other studies have found that the alternative automated systems, in which autonomous vehicular control is used (and the driver is left out of critical control loops) have resulted in various problems. However, problems also exist with systems that require drivers to perceive, process, and react to information during the driving task. Tradeoffs of both options must be carefully considered in designing efficient IDS systems.

Lloyd et al. (1999) describe an in-vehicle collision avoidance system using haptic, auditory, and visual (via a head-up display) advisories. The system was evaluated for stop-controlled intersections. User comments were generally positive, although the authors believe that the timing of the tested advisory system (8 s prior to intersection entry) should be longer to allow proper driver reaction.

Ferlis (1999) mentions various possible Infrastructure-Cooperative systems. One possible method is facilitated through the use of an autonomous vehicle intersection collision avoidance system which uses a Global Positioning System (GPS)/in-vehicle map database along with radar sensors. This in-vehicle system would recognize and advise the driver (via an in-vehicle display) of an upcoming traffic control (signal or stop), and, if necessary, provide a warning of the upcoming control and any potential collision. This type of system has been researched by NHTSA through Veridian (formerly Calspan). Other current systems that utilize sensors and data processing equipment in vehicles are the Eaton-VORAD collision avoidance system (to detect collision situations by using radar to detect vehicles in blind spots) and the Mercedes-Benz Stability Enhancement System (to control the stability of the vehicle in a collision avoidance situation; Pierowicz et al., 2000).

Pierowicz et al. (2000) also describe various phases of the Intersection Collision Avoidance Using Intelligent Transportation Systems (ITS) Countermeasures Program. Phase I of this research studied the intersection collision problem, common features of such crashes, and three countermeasure concepts. These countermeasures are called the Driver Advisory System, the Defensive System, and the Communication System. The Driver Advisory System included vehicles equipped with sensors to identify problems, and a vehicle control system to provide suggestions on problem resolution. The Defensive System included only the sensors to identify problems without any vehicular control equipment. The Communication System included transponders on all vehicles. These transponders were used to communicate with an intersection controller. This final system was discontinued during the early stages due to the inherent difficulties of equipping all associated vehicles with the necessary devices. Unfortunately, without technologies similar to the Communication System, there is no opportunity to effectively warn against collisions resulting from driver violation of red traffic signals.

Phase II of Pierowicz et al. (2000) investigated technology (e.g., processors, sensors, actuators, and driver-vehicle interfaces) to implement the countermeasures discussed in Phase I, and defined a test-bed for the evaluation of these countermeasures. Only systems that did not require installation of infrastructure equipment were proposed for evaluation in Phase III of the work. The IDS system used in Phase III was made up of four subsystems, including the Threat Detection System (consisting of three discrete radar systems), the Geographical Information System (GIS)/Differential Global Position System (DGPS), the Driver-Vehicle Interface, and the Vehicle Support System. Results for this IDS system are generally described as favorable.

The primary application of an IDS system would be to assist in decreasing intersection collisions, described in Pierowicz et al. (2000) as Scenarios 1, 2, and stop-controlled Scenario 3. Based on the descriptions for each of these scenarios, this system was primarily useful for intersection collisions in which there is no need to account for a traffic signal phase. This IDS system would apply only to SCP crashes in stop-controlled intersections in which the driver did not stop at all, or did stop but then proceeded into the intersection at an inopportune time. The IDS system conveyed information to the driver through in-vehicle technology.

An extension of the in-vehicle display system can be achieved by including partial control assistance (e.g., through some level of automatic braking). The Infrastructure-Only system must rely on driver processing and reaction to the provided warning. Infrastructure-Cooperative systems, through the use of in-vehicle displays, improve the probability of fast and effective driver reaction to the information. However, the idea of partial or fully automated control of the vehicle through an advanced system might provide fast and flawless responses to emergency situations by eliminating the time or error associated with driver reaction and response. Design of basic technologies for these types of systems is underway, but a vast amount of research is needed before these systems can be deployed.

PURPOSE AND SCOPE

This project was intended to design, develop, and evaluate the different aspects of an IDS technology to prevent a subset of intersection crashes. Overall, it is estimated that over one million crashes per year are intersection related causing 8,760 fatalities (NHTSA, 2004). A substantial proportion (approximately 30 percent) of these crashes occurs in an SCP configuration, mostly due to an intersection violation. Thus, the IDS technology developed as part of this effort was intended to address SCP intersection crashes that were due to a signal or stop-sign violation.

Previous research has pointed to a variety of reasons for these intersection crashes, including driver distraction and errors in judgment. Thus, the IDS system concept discussed in this report was designed with these factors in mind. In developing the system, it was necessary to consider both human factors and technology issues.

The technology issues considered included the ability of existing vehicle sensing technology, wireless communication, and intersection control devices to assist and complement the IDS function. The human factors issues explored included a detailed description of normal intersection approaches, development of nuisance alarm thresholds, and an exploration of the effectiveness of various interface mechanisms to allow for informing the driver about the possible conflict.

All of these tests and experiments were then used in a system development effort to produce performance specifications for IDS systems. Throughout this process, the main goal remained the reduction in the number of SCP intersection crashes due to signal or stop-sign violation. The process to obtain the results employed a combination of laboratory and test-track experiments, which yielded a working IDS system at our test facility. While the system is limited to test purposes, this document lays some of the foundation for future tests of IDS technology in real-world environments.

TOP-LEVEL REQUIREMENTS FOR AN IDS SYSTEM TO MITIGATE SCP CRASHES

The literature review provided information about the extent of the SCP crash problem, possible causal factors, and the results obtained from past efforts to counteract SCP crashes. With this information available, the next step was to characterize the required functionality for an IDS system designed to prevent SCP crashes. The four steps used to accomplish this characterization included:

1. Perform a functional analysis.
2. Perform a task analysis.
3. Perform a technology survey.
4. Delineate top-level requirements.

Detailed results for these steps are provided in the Task B report (Perez et al., 2002). However, a brief summary is provided in this section.

Functional Analysis

The functional flow analysis provided a top-level description of the various tasks that an IDS system, which at this stage was non-existent, would have to perform in order to serve its purpose. This analysis not only considered the functions necessary, but the expected inputs and outputs. The analysis identified seven top-level functions, as shown in Figure 18: system startup, traffic monitoring, driver-intersection interface (DII) system status determination, driver response, communication with in-vehicle systems, and systems shutdown. Six of these seven functions (all but System Shutdown, who was considered a single-step function) were broken down into sub-functions (Figure 19), allowing for system components to be envisioned.

These system components for an IDS system included sensing technologies, communications, decision algorithm, DII, system integration hardware, and human behavior. Once established, these components allowed for the distribution of project resources into investigating all these areas. The technical aspects were evaluated from a functionality and technological capability perspective, whereas the human behavior was evaluated using human factors approaches.

The following two sections indicate the initial steps taken to research these different components, with the goal of obtaining enough information on each to allow for the generation of the top-level requirements. The human behavior aspect was researched via a task analysis, whereas the technical aspects were researched via a general survey of technologies to perform the diverse IDS functions. These initial steps were complemented by much more detailed analyses, tests, and experiments, which are discussed in subsequent sections.

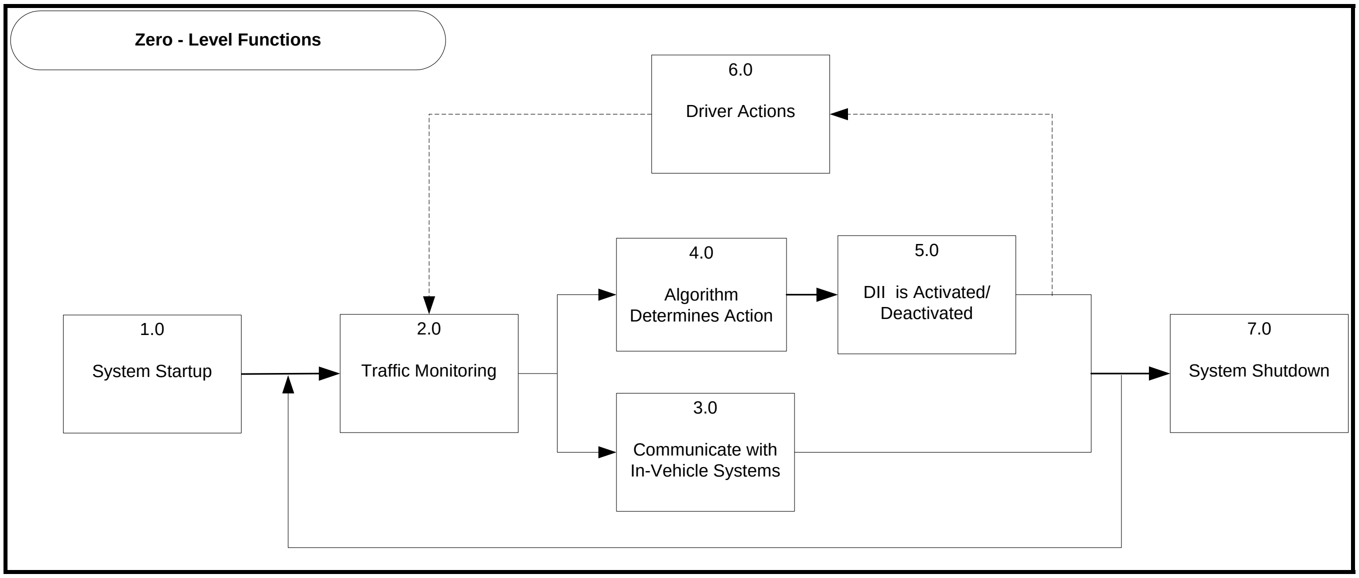

Figure 18. Top-level functions for an IDS system.

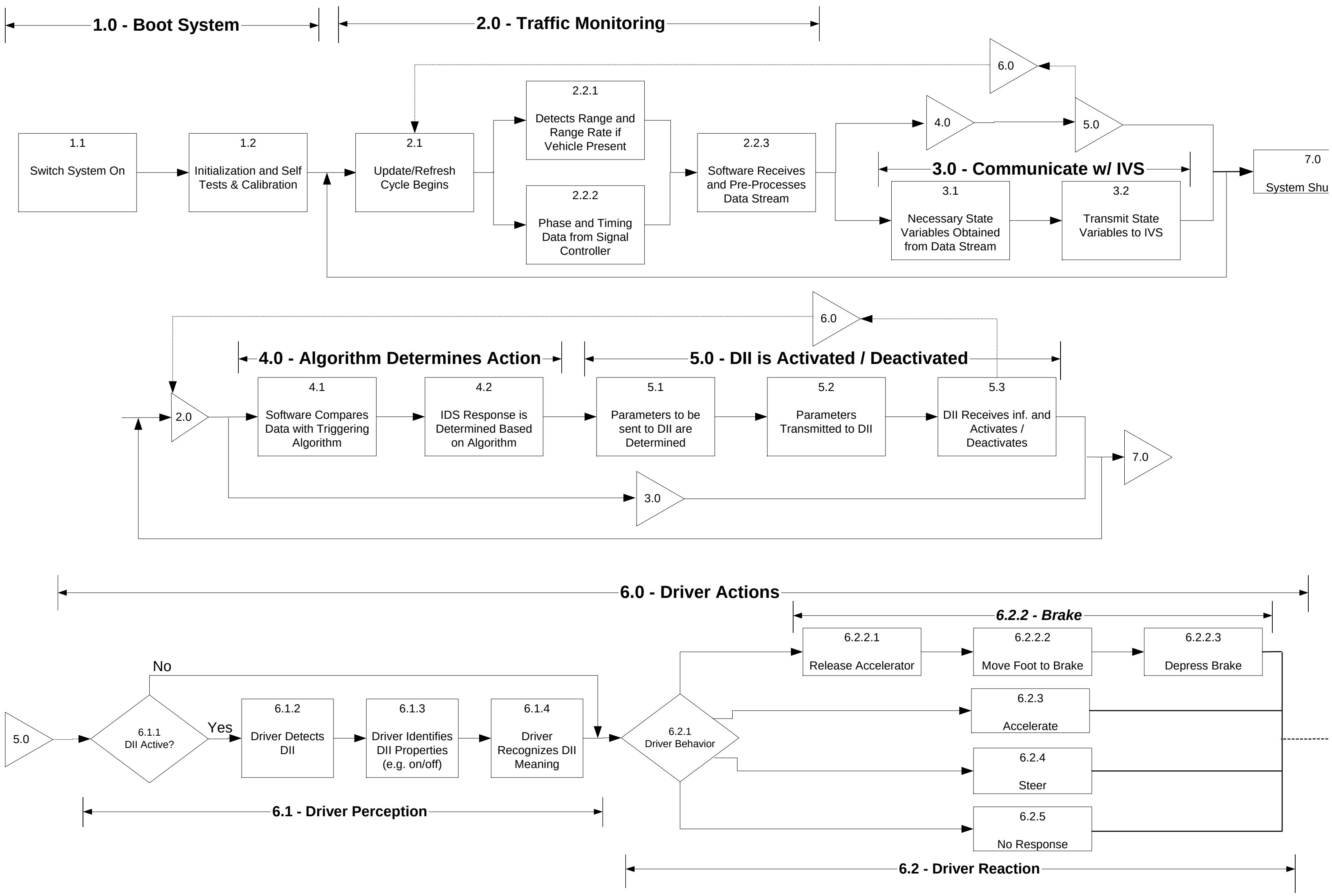

Figure 19. Top-level function decomposition for an IDS system

Task Analysis

The task analysis helped inform the top-level requirements related to human behavior aspects of an IDS system. During this process, the project team made the assumption of one basic behavioral goal: the driver intends to cross the intersection as quickly as possible without being involved in a crash. Note, however, that in spite of this goal, allowances for distracted drivers were made in the task analysis process, as discussed below.

It was initially determined that signalized and stop-controlled intersections should be considered separately. While these two intersections cases are somewhat similar, driver behavior while approaching them was considered distinct. For example, while the driver might not need to stop for the signalized intersection if there is a green indication, the driver will always have to stop (or at least reduce speed considerably) for a stop-controlled intersection.

Once it was determined that signalized and stop-controlled intersections would be considered separately, the task analysis began with a decomposition of the intersection approach into its basic tasks.

For the signalized intersection, these tasks were:

1. Detect the presence of an intersection and decelerate accordingly.
2. Detect and properly process the signal status, determining preliminary response to signal.
3. Iterate response to signal status based on situation updates.

For the stop-controlled intersection, these tasks were:

1. Detect the presence of an intersection and decelerate accordingly.
2. Detect traffic surrounding the intersection and predict its behavior. React to stop sign, modifying actions according to approaching traffic.
3. Iterate response to stop sign based on situation updates.

The task analysis then continued by defining the steps needed to accomplish each of these tasks. For each step, descriptions of the information available to the driver, any necessary driver evaluation or decision, and any expected driver actions were generated.

Throughout this analysis, an important goal was to determine performance differences between attentive and inattentive drivers. Interestingly, in performing the task analysis, it became clear that the required intersection approach tasks did not change. Rather, inattention affected only the timing at which the tasks occurred. For example, while an attentive driver might have ample time to detect the presence of an intersection and its signal status, the distracted driver might have less time to make these observations and thus less time to respond to them.

The final result of this process was included in the Task B report (Perez et al., 2002) and is not reproduced here. In general, the task analysis process aided the IDS effort by:

- Identifying the behaviors that could be expected in an intersection approach.

- Indicating which of these behaviors may be problematic for inattentive drivers, who miss some of the cues that generally allow for a normal approach.
- Guiding the structure of on-road tests and DII selection to maximize the probability of reacquiring a driver's attention at key points during the intersection approach.
- Highlighting the need to quantify the sequence and duration of the intersection approach tasks with baseline timing data.

As will be apparent in the discussion of human factors experiments, these task analysis results defined the order in which the on-road studies were performed and the types of studies completed. Initial studies collected baseline intersection approach behavior data. Later studies focused on driver distraction at key points in the intersection approach, followed by IDS warnings intended to direct the driver's attention back to the intersection and convey enough urgency and information to elicit a stopping behavior.

Summary of Existing IDS Technology

While the task analysis aided in the analysis of the human behavior component of an IDS system, the technical components required a different approach. It is important to realize that testing of every technological possibility to achieve the different technical functions required by IDS would have been impossible. Thus, it was necessary to trim any technology alternatives to those that showed a substantial level of promise and had the potential to be commercially available, even on a limited scale, in the near future.

For the purpose of developing top-level requirements, however, it was only necessary to perform a general survey of technological alternatives, and this was performed by obtaining information about each technology. In general, this information was acquired from vendors, State Department of Transportation (DOT) personnel, and published evaluation studies. Recall that there were five different technical components: sensing technologies, communications, decision algorithm, DII, and system integration hardware. Tables 8 through 10 describe the technologies initially surveyed for sensing, communications, and DII. The decision algorithm did not depend on any particular technology and was thus considered separately. Detailed discussion about this aspect of an IDS system is presented in a later section of this report. The system integration hardware was also not considered in this survey, as the functions required of the system are basic enough to be achievable using relatively basic, widely available, microprocessors.

While the Task B report (Perez et al., 2002) provides a description for each of these technologies, it is omitted here to avoid overlap with later discussion. After the top-level requirements were generated, it was necessary to select some of these technologies for further testing, an involved process that is described on the Trade-Off Analyses section. Thus, a more detailed description for each of these technologies is delayed until that section.

With the task analysis and survey of existing technologies complete, the next step was to develop top-level requirements for each of the technical components of an IDS system. These top-level requirements are discussed in the next section.

Table 8. Sensing technologies surveyed.

Technology
Radar
Doppler
Frequency Modulated
Acoustic
High-frequency pulsed Doppler
Passive
Infrared
Active
Passive
Magnetic
Active
Passive
Laser
Single-Beam
Multi-Beam
Piezoelectric
Fiber-optic
Video
Imaging Alone
Image Detection
Loop Detectors
Single
Multiple, in-series

Table 9. Communication technologies of interest.

Technology
Communication
DSRC
Other 5.9 GHz Protocols
Networking
802.11 a
802.11 b

Table 10. DII technologies surveyed.

Technology
Visual
Variable message signs
LED with static sign
Strobe lights
In-pavement lighting
Static sign on dynamic post
Haptic
Dynamic rumble strip
Auditory
Auditory alarm
Combination (visual and haptic)
Retractable pylons

Top-Level Requirements and Trade-Off Studies

Information gathered from the previous subtasks was used to develop a set of top-level requirements, or criteria, that should be adhered to by the different IDS system components integrated to address SCP crashes. The functional analysis provided an indication of the basic functions that the system should perform, which in turn determined the functions required from each of the system's subcomponents. Using a safety perspective, the task analysis detailed the various behaviors and decisions made by an individual approaching an intersection, and uncovered areas in which decision-making assistance could be provided. Finally, the examination of existing technologies determined the capabilities and limitations of available DII and sensing alternatives, which were used to guide (but not constrain) the requirements development. Throughout this process, consultation with experienced Virginia Department of Transportation (VDOT) traffic engineers and Federal Highway Administration (FHWA) officials was used to maintain requirements within realistic limits.

Top-level requirements were generated separately for each of the technical IDS system components (Tables 11 and 12). Sensing technologies, communications, decision algorithm, and system integration hardware were separated from DII technology, as the latter could be defined more specifically than the other components. Not all of these requirements could be quantitatively defined at this early project stage. Instances of insufficient specification are accompanied by the stage of the project in which this specification would most logically occur. Furthermore, these requirements were meant to prescribe a minimum performance goal without excessively limiting the candidate technologies to be considered for testing.

These requirements are presented here as an initial description of the functionality needed for an IDS system. However, evolution of these requirements was considered inevitable as the project progressed and initial assumptions about the systems' functions and properties were confirmed or modified. These requirements, however, were essential in determining the initial technologies that were bench-tested and/or employed in the VTTI experimental testbed. This selection process is the focus of the next section.

Table 11. Top-level requirements for sensing technologies, communications, decision algorithm, and system integration hardware.

System Component	Requirement	Specification
Sensing technologies	Minimum detection range	Must be determined based on the expected behavior of drivers and analysis of situations in which a warning should occur. These determinations will be made during the early stages of algorithm development. Preliminary estimates suggest a distance of 750 ft from the intersection. In addition, the accuracy of sensing devices is often dependent on the target's range. Preliminary estimates suggest that maximum accuracy should be available within at least 600 ft from the intersection.
	Update rate	Technologies must periodically update their readings as new conditions warrant. Initial algorithm development suggests a minimum rate of 10 Hz, but this number will be tested and likely modified during testbed development.
	Available data / error	The technologies must be able to, at a minimum, discriminate between vehicles, indicate vehicle presence, distance to vehicle, speed of the vehicle, and vehicle acceleration. Error rates should fall within acceptable limits, which will be determined as part of the detailed requirements and will be influenced by the precision needed for the algorithm.
	Operational characteristics	Sensing devices must operate within the range of temperatures normally encountered on a roadway throughout the year. Devices must also operate in a variety of weather conditions.
	Power	*Signalized intersections:* The sensing device's power requirements shall be fulfilled by the intersection's power infrastructure. *Stop-controlled intersections:* The sensing device shall consume a minimal amount of power, little enough to be potentially powered by a solar cell system.
	Size	Sensing devices must not significantly interfere with driver's line of sight when they are operating.
	Cost	Given that a prototype system is being developed, cost considerations are secondary. Costs are partly based on the volume of product, and any technology that is selected for inclusion in a final system would become less expensive due to economies of scale. Thus, while no set requirement is provided here for cost, it is expected that the costs of installing one of these systems will not exceed a reasonable percentage (TBD based on benefits obtained from the system) of the present installation costs for each intersection type. Signalized intersections typically cost $175,000 to install and $5,000/yr to maintain. Stop-controlled intersections typically cost $500 to install. These costs are averages for the state of Virginia; costs for other states might differ considerably from these estimates.

System Component	Requirement	Specification
	Installation and Maintenance	The device's installation and maintenance shall occur with minimal effects on the intersection traffic. Lane closures shall be minimized to the extent possible for both installation and maintenance. The need for training of qualified installers and level of intersection-specific design effort shall be minimized.
	Durability	TBD
	Availability	Device components should be COTS by the end of the project's performance period.
Communications	Update rate	Update rate should match vehicle or IDS system algorithm requirements.
	Range	Must be determined based on the expected behavior of drivers and analysis of situations in which a warning should occur. These determinations will be made during the early stages of algorithm development. Preliminary estimates suggest a distance of 750 ft from the intersection.
	Bandwidth	Undetermined at this point, but must be sufficient to transmit the required information at the necessary update rate
	Operational characteristics	Communications devices must operate within the range of temperatures normally encountered on a roadway throughout the year. Devices must also operate in a variety of weather conditions. The devices must also be upgradeable as changes in the technology occur. Initial testbed system will use 802.11a equipment.
	Power	*Signalized intersections:* The communications device's power requirements shall be fulfilled by the intersection's power infrastructure. *Stop-controlled intersections:* The communications device shall consume a minimal amount of power, little enough to be potentially powered by a solar cell system.
	Size	Communications devices (including antennas) must not significantly interfere with driver's line of sight when they are operating. Components that must reside within the signal controller must fit inside a NEMA cabinet.
	Cost	Given that a prototype system is being developed, cost considerations are secondary. Costs are partly based on the volume of product, and any technology that is selected for inclusion in a final system would become less expensive due to economies of scale. Thus, while no set requirement is provided here for cost, it is expected that the costs of installing one of these systems will not exceed a reasonable percentage (TBD based on benefits obtained from the system) of the present installation costs for each intersection type. • Signalized intersections typically cost $175,000 to install and $5,000/yr to maintain. • Stop-controlled intersections typically cost $500 to install. • These costs are averages for the state of Virginia; costs for other states might differ considerably from these estimates.

System Component	Requirement	Specification
	Installation and Maintenance	The device's installation and maintenance shall occur with minimal effects on the intersection traffic. Lane closures shall be minimized to the extent possible for both installation and maintenance.
	Durability	TBD
	Availability	Communications hardware should be commercial-off-the-shelf (COTS) by the end of the project's performance period.
Decision Algorithm	Update rate	At this point, a 10 Hz minimum update rate is suggested, but this number will be tested and likely modified during testbed development. Computer processing power available for the algorithm shall be sufficient to allow the warning decision to be updated every cycle (i.e., every 1/10th s based on a 10 Hz update rate)
	Operational characteristics	Given the probability of conflicting algorithm warning decisions near the activation threshold (i.e., first cycle – no warning, second cycle – warning, third cycle – no warning), memory shall be allocated to maintain a moving window of algorithm warning decisions. The data in this moving window shall be used by the algorithm in deciding warning presentation to induce stability in stimulus presentation. In essence, no change in warning presentation status would occur until the algorithm has made a preset consecutive number of equivalent warning decisions.
	Hardware	At this point, the decision algorithm and the system integration software share the same computer processor. See the system integration section for more details.
	Inputs & Outputs	The algorithm shall make decisions based on inputs consisting of signal phase and timing, vehicle data (e.g., range, velocity, and presence), environmental data (possibly), and hard-coded (static) information on human capabilities. Based on these inputs, the algorithm will control the display presented in the warning device. Some limited information might be transmitted to the signal controller if modifying the signal (e.g., holding the red-phase for the POV) becomes necessary. The feasibility of this approach will be tested as part of the testbed development.
System Integration	Interface	The interface shall allow control of the various system parameters, as well as initialization and shut-down procedures.
	Adaptability	The system shall allow for easy and quick hardware and software updates.
	Maintainability	Maintenance activities shall be easy, quick, and required at considerably long intervals.
	Safeguards/System Isolation	Malfunctions of the system shall not affect in any way the functioning of a traffic signal in a signalized intersection. In a stop-controlled intersection, a malfunction of the system shall not leave the intersection without any traffic control device (i.e., at least a visible static sign shall remain).

System Component	Requirement	Specification
	Hardware	At this point, will be shared with the hardware used by the decision algorithm. Minimum specifications are: • Pentium class processor (266 MHz minimum) • Compact Flash hard drive • Large number of interface options • Rugged exterior case that fits in any NEMA cabinet along with existing equipment

Table 12. Top-level requirements for the driver-infrastructure interface (DII).

General Category	Requirement	Specification
Interface Features	Conspicuity	The defining characteristics of the technology should be salient enough to attract the driver's attention under most driving conditions and situations. At a minimum, the device should be perceptible during both nighttime and daytime and in various weather conditions, including rain, snow, and fog (within reasonable limits). Included in this aspect are issues of size, loudness, brightness, color, and location, to name a few. In addition, the device shall be visible to the driver at a minimum distance that provides for sufficient driver reaction time.
	Flexibility	At this project stage, the content and characteristics of the warning message are not clear. Thus, technologies that are capable of presenting different information levels and types are needed to avoid unnecessarily constraining design alternatives. At a minimum, technologies should be able to present different warning levels (i.e., warnings of different perceived urgency).
	Addressability	The technology should allow warning presentation to only a certain portion of the drivers approaching an intersection. At a minimum, the technology should be able to address drivers in each leg of the intersection independently, without influencing the actions of drivers on other intersection legs.
	Update rate	To assist with specificity issues and changing activation algorithm decisions, the device should be refreshable at a minimum 1 Hz rate. Thus, on/off status transitions or information updates should occur in a maximum of 1 s.
	Effects on 3 rd parties	The device shall not be annoying to pedestrians or cyclists using the intersection and/or to people living around the vicinity of the intersection. While annoyance is a subjective term, engineering judgment will be used in determining what constitutes annoyance. Furthermore, the device shall not cause any harm to pedestrians or cyclists near the intersection.
Installation and Operation	Power	*Signalized intersections:* The DII's power requirements shall be fulfilled by the intersection's power infrastructure. *Stop-controlled intersections:* The DII shall consume a minimal amount of power, little enough to be potentially powered by a solar cell system.
	Operating temperature range	DII's must operate within the range of temperatures normally encountered on a roadway throughout the year.
	Operability in various weather conditions	DII's must operate in a variety of weather conditions.
	Durability	TBD
	Installation and Maintenance	The device's installation and maintenance shall occur with minimal effects on the intersection traffic. Lane closures shall be minimized to the extent possible for both installation and maintenance.
	Reliability	Self-test mechanisms are not required, but might be used to differentiate between similar technologies. In any event reliability should be high, with high Mean Time Between Failures (MTBF) values.

General Category	Requirement	Specification
Costs and Availability	Purchase and installation costs	Given that a prototype system is being developed, cost considerations are secondary. Costs are partly based on the volume of product, and any technology that is selected for inclusion in a final system would become less expensive due to economies of scale. Thus, while no set requirement is provided here for cost, it is expected that the costs of installing one of these systems will not exceed a reasonable percentage (TBD based on benefits obtained from the system) of the present installation costs for each intersection type. • Signalized intersections typically cost $175,000 to install and $5,000/yr to maintain • Stop-controlled intersections typically cost $500 to install These costs are averages for the state of Virginia; costs for other states might differ considerably from these estimates.
	Operating/maintenance costs	See above
	Commercial availability	Components of the DII device shall be commercially available by the end of the project's performance period.

TRADE-OFF ANALYSES

The top-level requirements presented in the previous section had the main goal of aiding the selection of technologies for an IDS system. Technologies had to be evaluated based on two different goals: first, whether the technology could have been useful in the testbed by supporting the human factors tests and second, whether the technology had potential for use in near-term IDS systems to address SCP crashes.

The first step in the trade-off analyses was to perform a top-level study on the sensing and DII technologies to be included in the initial testbed (Tables 13 and 14). These two categories were selected for this analysis given the large array of options that were available at first glance. The goal of this effort was to limit the number of technologies that had to be considered in the more detailed trade-off studies. In the following two tables, the columns are based on the top-level requirements presented in the previous section. Cells indicate the compliance of each technology with the minimum requirement.

The rest of this section considers how these trade-off studies aided in the evaluation of existing technologies and ultimately yielded technology recommendations to fulfill the two original goals: support of human factors tests and support a near-term IDS deployment.

Sensing

Results of the top-level analysis for sensing technologies were not as useful as expected. At a top level, all of the sensing technologies complied with most of the requirements. Furthermore, none of the technologies stood out as justifiably better than all the other technologies. This prompted two actions. First, a detailed trade-off study was conducted on all of the sensing technologies in Table 13 and several additions. These additions were complemented by consideration of sensing alternatives based in the vehicle. While these in-vehicle technologies would not be useful in supporting near-term IDS, they were considered for their utility in supporting the human factors tests. Tables showing the results of these detailed analyses are presented in Appendix A.

Table 15 shows the technologies selected for the testbed, either in support of human factors tests or for formal tests of the effectiveness of the technology for future application in IDS systems. Note that some technologies, while found to be suitable for IDS, were not tested. Given project constraints, only those technologies that showed the most promise were selected for testing. These untested technologies might be considered in more detail in future efforts, if required by the limitations of other sensing technologies.

Furthermore, factors such as ease of installation, ease of maintenance, durability, and cost were not explicitly considered in this selection, since the importance of these factors will need to be determined when and if IDS systems are deployed or tested in the real-world, which was not a goal of this project. Furthermore, the sensing trade-off studies made no distinction between signalized and stop-controlled intersections, since the extent of the variability in the requirements for these two situations was unknown when these studies were conducted. Thus, these recommendations should be revisited prior to an IDS deployment effort, once the unique sensing requirements for signalized and stop-controlled intersections have been formally established.

Table 13. Top-level trade study: sensing. An "X" indicates compliance with the minimum requirement.

Technology	Minimum detection range	Update rate	Available data / error	Operational chars.	Power	Size	Cost (indicates cost is within budget limits)	Installation/ Maintenance (initial evaluations)	Durability	Availability
Doppler radar	All are below minimum, frequency-modulated radar would provide the largest range without requiring multiple installations and/or devices. Other devices would likely require more than one installation.	X		X	All devices should comply with the requirements, but these assumptions have not been tested.	All devices will likely comply with the requirements	All are within budgetary limits, but budget would not allow purchase of all the different technologies. Furthermore, technologies that require multiple installations to comply with minimum detection range would require a larger investment	X	While known for some devices, this requirement needs to be determined through empirical testing	All device components are commercially available within the specified timeframe
Frequency-mod. radar		X	X	X				X		
High-frequency pulsed Doppler acoustic		X						X		
Passive acoustic		X		X						
Active infrared		X	X					X		
Passive infrared		X						X		
Active magnetic		X		X						
Passive magnetic		X		X						
Single-beam laser		X	X							
Multi-beam laser		X								
Piezoelectric		X		X						
Fiber-optic		X		X				X		
Imaging video		X								
Image detection		X	X							
Single loop detector		X		X						
Multiple, in-series, loop detectors		X	X	X						

Table 14. Top-level trade study – DII. Xs indicate compliance with the minimum requirement.

	Interface Features					Installation and Operation					Costs and availability	
Technology	**Conspicuity**	**Flexibility**	**Addressability**	**Update Rate**	**Effects on 3rd parties**	**Power**	**Temperature/ Weather**	**Durability**	**Installation/ Maintenance**	**Reliability**	**Cost (Installation/ Maintenance)**	**Availability**
Variable Message Signs	All devices appear capable of complying with minimum conspicuity req. However, detailed evaluation of this compliance is device specific and still pending	X	X	X	X	All devices should comply with the requireme nts, but these assumptio ns have not been tested.	All of these devices appear to comply with the requirement to varying degrees. Detailed evaluation of this compliance is device specific and still pending	Evaluation of this requirement is device specific and still pending.	X	Detailed evaluation of this compliance is device specific and still pending	All, with the possible exception of variable message signs, are within budgetary limits. Detailed evaluation will require the consideration of specific devices.	X
LED with Static Sign		X	X	X	X				X			X
Strobe lights		X	X	X	X				X			X
In-pavement lighting		X	X	X	X							Not for this application, in-house development
Static sign on dynamic post			X		X				X			
Dynamic rumble strip			X	X	X							
Auditory alarm		X		X					X			X
Retractable pylons			X	X	X							Not for this application , in-house development

Table 15. Summary of trade-off study results for vehicle sensing technologies.

Potential Technology	Location	How it works	Provided Functionality	Suitability
Frequency Modulated Radar	Infrastructure	Emits electromagnetic waves that are reflected by vehicles passing by.	Position Speed	Probably IDS suitable - Tested under IDS
Magnetic	Infrastructure	Magnetic field in the pavement is disturbed by passing vehicles	Position Speed	Probably IDS suitable - Untested
Video	Infrastructure	Image recognition algorithms track vehicles	Position Speed	Probably IDS suitable - Untested
DGPS	Vehicle	GPS signal and correction signal are read and processed to determine position and speed	Position Speed	Human Factors Testing
Accelerometer	Vehicle	Mechanical device transforms acceleration into electrical signal	Acceleration	Human Factors Testing
In-vehicle network	Vehicle	Sensing devices already measure speed; these data are available in the vehicle's information network. This function could be provided through the electronic control unit (ECU) or as a digital signal processor (DSP)	Speed Acceleration (through brake pedal status)	Human Factors Testing
RFID	Hybrid	Radio frequency tags and reader share information on their location and other properties	Position Speed	Probably IDS suitable - Untested

Driver Infrastructure Interface

Conclusions from the Top-Level Trade-Off Study

The top-level trade-off study presented in Table 15 was more useful in narrowing down the different DII options than for narrowing down sensing options. This process resulted in the elimination of two alternatives from DII consideration: auditory alarms and retractable pylons. Using auditory methods to alert a driver of an impending intersection violation was found to have significant weaknesses: the inability to address a specific vehicle/driver and the excessive audio amplitude that would be required at the DII source to make the warning noticeable. Using retractable pylons, which would impinge on the driver's intended path, was considered infeasible due to the unpredictable drivers' reactions to this type of impingement which might result in crashes more severe than those that the system was intended to mitigate. In addition, the costs of nuisance alarms would be high with retractable pylons.

Given the elimination of auditory DIIs based on the top-level trade studies, only two modalities remained for consideration: visual and haptic. Many experts have recommended against using visual DIIs alone or even as the primary warning: because they are fixed in space, drivers do not always see the warning in the increasingly complex visual driving environment. Furthermore, a visual warning could delay the driver's scanning of the visual field and cause delayed reaction time. However, visual warnings can give drivers very specific content that is easily understood.

A properly designed haptic warning addresses some of these drawbacks. For the purposes of a DII, the haptic modality would be used through intelligent rumble strips that only activate upon impending violation and are specific to the potential violator. Such a warning can be detected regardless of where the driver's visual attention is directed and directs the driver to the forward view. Disadvantages of such haptic warnings include possible adverse effects on vehicle control during bad weather, the practicality of implementation in the infrastructure, and driver learning curve.

The top-level trade-off study was followed by an in-depth expert evaluation of the different candidate technologies. This approach minimized the time and resources required for DII selection, while at the same time providing for a warning with high potential for safety improvements. Throughout this process, some key requirements were maintained: 1) a DII warning should not startle the driver, possibly causing sudden maneuvers more dangerous than the intersection approach, and 2) the DII's saliency and annoyance should be limited to reasonable levels and acceptable to the majority of drivers.

DII Trade-Off Study

To narrow down the technologies to be tested, the research team surveyed 12 experts representing both academic and state DOT perspectives. These experts were either human factors engineers or traffic engineers, and filled out a survey for each of nine proposed DII technologies, based on the results of the top-level trade-off study, as seen in Table 16.

The experts rated the proposed technologies according to ease of detection, ease of recognition, quickness of recognition, display-response compatibility, ability to address the violator, maintainability, resistance to adverse reaction, and value ("bang for the buck"). These criteria were weighted as shown in Table 17. The weights were determined based on project team consensus on the relative importance of each of the factors in the development of IDS technologies.

In contrast to the approach used for sensing technologies, the research team considered the results for signalized and stop-controlled intersection technologies separately. Final scores were close, but the experts rated the intelligent rumble strips and the augmented static sign as the highest- and second highest-rated DII technologies, respectively, for both signalized and stop-controlled intersections. Complete ratings are presented in Table 18.

The research team also organized the results according to technology alternatives receiving the best and worst scores for each criterion, as seen in Table 19 for signalized intersections and Table 20 for stop-controlled intersections.

Finally, the research team organized the results by variability in the expert's scores, as seen in Table 21.

Table 16. DII alternatives included in the expert review.

DII Alternative	Description	Signalized Intersection	Stop-controlled Intersection
Strobe lights on signals	Strobe lamps are placed on either side of the red signal head on the mast arm. Lamps flash when a warning is issued.	X	
Strobe lights on signal ahead sign	Strobe lamps are placed within a signal-ahead warning sign. Lamps flash when a warning is issued.	X	
Perpendicular in-pavement lighting	Several rows of in-pavement lights are placed across the approach lane, perpendicular to the direction of travel, at various distances from the intersection. Lamps flash when a warning is issued.	X	X
Longitudinal in-pavement lighting	Several rows of in-pavement lights are placed within the approach lane, in the direction of travel, at various distances from the intersection. Lamps flash when a warning is issued.	X	X
Augmented static sign	Small lights highlight the profiles of the sign and the word STOP and other sign features when a warning is issued. The normal STOP sign is visible otherwise.	X	X
Variable message sign	An LED-based variable message sign displays the word "STOP" increasing in size with time when a warning is issued.	X	
Intelligent rumble strip	Sets of rumble strips, normally imperceptible, rise from the pavement when a warning is issued.	X	X
Strobe lights on STOP sign	Strobe lamps are placed within a STOP sign. Lamps flash when a warning is issued. The normal STOP sign is visible otherwise.		X
Strobe lights on STOP ahead sign	Strobe lamps are placed within a STOP-ahead sign. Lamps flash when a warning is issued. The normal STOP ahead sign is visible otherwise.		X

Table 17. Weights used for the surveyed constructs.

Construct	Weight
Ease of detection	0.268
Ease of recognition	0.133
Quickness of recognition	0.133
D-R Compatibility	0.133
Ability to address the violator	0.100
Maintainability	0.050
Resistance to adverse reaction	0.133
Value	0.050
Total	**1.000**

Table 18. Ratings and rankings for the DII alternatives surveyed.

DII Alternative	Mean Weighted Score (Standard Deviation)	Rank
Signalized Intersections		
Strobe lights on signal	6.475 (1.339)	4
Strobe lights on signal ahead sign	5.593 (2.129)	7
Perpendicular in-pavement lighting	6.086 (1.242)	6
Longitudinal in-pavement lighting	6.582 (1.409)	3
Augmented static sign	6.597 (1.359)	2
Variable message sign	6.458 (1.173)	5
Intelligent rumble strip	7.362 (3.908)	1
Stop-controlled Intersections		
Strobe lights on STOP sign	6.740 (1.104)	4
Strobe lights on STOP ahead sign	6.621 (1.110)	5
Perpendicular in-pavement lighting	6.551 (1.206)	7
Longitudinal in-pavement lighting	6.564 (1.344)	6
Augmented static sign (using fiber-optic light strands)	6.806 (1.561)	2
Augmented static sign (using LED light)	6.798 (1.648)	3
Intelligent rumble strip	7.233 (3.855)	1

Table 19. Best and worst criteria scores for each proposed DII design for signalized intersections.

Criteria	Design w/ Best Factor Score	Design w/ Worst Factor Score
Ease of detection	Intelligent rumble strip	Perpendicular in-pavement lights
Ease of recognition	Augmented static sign & variable message sign	Strobe lights on signal ahead sign & Perpendicular in-pavement lights
Quickness of recognition	Augmented static sign	Strobe lights on signal ahead sign
D-R Compatibility	Augmented static sign	Strobe lights on signal ahead sign
Ability to address the violator	Longitudinal in-pavement lights	Strobe lights on signal ahead sign
Maintainability	Strobe lights on signal ahead sign	Intelligent rumble strip
Resistance to adverse reaction	Perpendicular in-pavement lights & Longitudinal in-pavement lights	Intelligent rumble strip
Value	Strobe lights on signal	Variable Message Sign

Table 20. Best and worst criteria scores for each proposed DII design for stop sign controlled intersections.

Factor	Design w/ Best Factor Score	Design w/ Worst Factor Score
Ease of detection	Intelligent rumble strips	Longitudinal in-pavement lights
Ease of recognition	Augmented static sign	Strobe lights on a STOP ahead sign & Perpendicular in-pavement lights
Quickness of recognition	Augmented static sign	Strobe lights on a STOP ahead sign & Perpendicular in-pavement lights
D-R Compatibility	Augmented static sign	Intelligent rumble strips
Ability to address the violator	Longitudinal in-pavement lights	Strobe lights on a STOP ahead sign
Maintainability	Strobe lights on a STOP ahead sign & Perpendicular in-pavement lights	Intelligent rumble strips
Resistance to adverse reaction	Longitudinal in-pavement lights & Augmented static sign	Intelligent rumble strips
Value	Strobe lights on a STOP sign	Intelligent rumble strips

Table 21. Experts' most and least agreement on criteria for each DII design.

DII	Most Agreement About…	Least Agreement About…
Signalized Intersection		
Intelligent Rumble Strip	Ease of detection	Maintainability
Augmented Static Sign	Ease of recognition	Resistance to adverse reaction
Longitudinal in-pavement lights	Display-Response Compatibility	Maintainability
Strobe lights on signal	Quickness of recognition	Resistance to adverse reaction
Variable Message Sign	Ease of detection	Value
Perpendicular in-pavement lights	Display-Response Compatibility	Ability to address the violator
Strobe lights on signal ahead sign	Maintainability	Ability to address the violator
Stop-controlled Intersection		
Intelligent Rumble Strip	Ease of recognition	Resistance to adverse reaction
Augmented Static Sign (fiber-optic)	Quickness of recognition	Value
Augmented Static Sign (LED)	Ease of recognition	Resistance to adverse reaction
Strobe lights on STOP sign	Ease of recognition	Resistance to adverse reaction
Strobe lights on STOP ahead sign	Ease of detection	Resistance to adverse reaction
Longitudinal in-pavement lights	Display-Response Compatibility	Value
Perpendicular in-pavement lights	Display-Response Compatibility	Resistance to adverse reaction

These results led to the selection of two DII technologies for use in the human factors tests. First, the intelligent rumble strips, given their high overall scores, were selected for initial use in the signalized intersection tests to prove the concept. If proven effective for the signalized intersection situation, their effectiveness would also be tested in a stop-controlled situation. The augmented static sign was also selected for both signalized and stop-controlled intersections. For the signalized intersection, the research team developed a 0.9-meter by 0.9-meter (3-foot by 3-foot) LED sign with integrated strobes and other conspicuity augmentation features. In addition, a dual flashing red light was selected for testing at the signalized intersection given the promising results of this technology at the Turner-Fairbank vehicle simulator. The dual flashing lights were not explicitly presented to the experts, although a similar alternative of strobes next to the signal head ranked very poorly.

For the stop-controlled intersection, the project team selected an LED-augmented stop sign. While similar to the LED sign used in the signalized case, this commercially available stop sign was thought to be more representative of a possible countermeasure at a stop-controlled intersection than the LED sign.

The remaining high-ranking alternative, in-pavement lights, received more detailed consideration, but was ultimately not tested. The technology was too costly to implement for rigorous experimental tests, and several traffic engineers expressed concerns regarding the maintainability and durability of the technology, especially in areas where snowplows are used.

Intersection State

IDS systems had two requirements related to intersection state. The first requirement was to obtain intersection state and use it in determining the need for a warning. The second requirement was to broadcast intersection state so that appropriately instrumented vehicles could use the information. As for sensing, there were two main thrusts in analyzing available intersection state technology. The first one dealt with whether the technology could be used for IDS deployment. The second dealt with the potential for the technology to support human factors testing.

The foremost purpose of the intersection state function is to provide signal phase and timing information to an IDS algorithm. However, within this function there are many features that could potentially be added to improve the performance of IDS systems. These include weather, traffic, and future phase and timing information. The benefits, if any, of most of these additional features are still unknown. Further experimentation will be required to determine which features are necessary to achieve adequate performance. As far as providing the basic intersection state information, only a few technologies have been identified, and these were subjected to scrutiny as part of this trade-off analysis.

Standard Signal Controller

Standard signal controller technology was not designed with the capability to provide many of the features necessary for IDS system operation. However, technology does exist to interface and poll standard signal controllers (e.g., the National Transportation Communications for Intelligent Transportation System Protocol [NTCIP]). This protocol makes properly equipped standard signal controllers suitable for testing with IDS, and the results of these tests are discussed in a later section. However, it was evident that using this technology for human factors testing would be infeasible, since the required quick and unique manipulations of the traffic signal were not supported by any standard controller.

Phase Sniffer

The term “phase sniffer” is used to represent a general class of devices that could be used to externally detect signal phase. For example, a phase sniffer could monitor the output voltage of the load switches on the lines that carry power to the signal heads. This method provides signal phase at any instant in time but is not capable of knowing the phase timing, next phase, or all red clearance. While a phase sniffer was not built as part of this project, this device would likely be simple, cheap, accurate, and reliable, once developed. Such a device is also believed to be suitable for use in an IDS system, and it should be tested in future efforts. Phase sniffers were not considered appropriate for human factors testing since the device is passive (i.e., reads the signal state, but does not control it) and an active control role of the signal was needed for these tests.

Multiplexing

Multiplexing would combine inputs from both the standard signal controller and a phase sniffer in a way that may make it possible to obtain both signal phase and timing. In an IDS application, both devices would be polled by an integration device. The standard signal controller would provide the signal phase change table. The phase sniffer would provide instantaneous signal phase information. These inputs would then be multiplexed to build the intersection state. When a signal change occurred, the integration device would use an internal clock to continually update the intersection state. Such a device should be simple to construct, would likely be suitable for use in an IDS system, and should be tested in future efforts. As was true for phase sniffers, multiplexing was not considered appropriate for human factors testing since the technology does not allow for control of the signal.

Advanced Traffic Controller

ATCs are viewed as a long-term solution to the intersection state function. At a minimum, ATCs could provide accurate signal phase and timing information at higher update rates than are currently available. ATCs may eventually house all of the intelligence functions necessary for IDS. For example, these devices could contain the algorithm as well as ports for the various sensors and communication equipment. However, ATCs with all of the necessary features were not available through the performance period of this project, and thus could not be tested. They are, however, suitable for use in IDS systems and might have been useful for human factors testing.

Thus, of the intersection state technologies, only standard signal controllers were available and selected for testing. The results of these tests are presented in a later section. The problem of human factors test support, however, was not addressed by any of these technologies, and had to be addressed by building a custom signal controller, which is described in more detail in the instrumentation section. Note that the purpose of this custom controller was simply to support the human factors tests, not to supplant or support the intersection state role for a deployable IDS system.

Wireless Communications Components and Format

The trade-off study for wireless communications technologies was aided by a report from Aeronautical Radio, Inc. (ARINC, 2001) that investigated the feasibility of many wireless communications technologies for intersection-based safety systems. Table 22 summarizes the most applicable technologies for IDS. Note that this table represents only a list of currently available technologies, and is likely to be outdated in the near future, given the fast pace of wireless communications technology evolution.

These technologies were considered independently of their use in signalized or stop-controlled intersections. While it is more likely that wireless communications will be used in signalized intersections, their use in stop-controlled intersections cannot be fully discounted (e.g., if provision of differential corrections or intersection geometry to the vehicle becomes necessary). Furthermore, the main consideration was whether the technologies had potential for use in a deployable IDS system. Support for human factors tests was determined by the ICAV project, which required testing of Dedicated Short Range Communications (DSRC). Given that the technology was already available within the testbed and that it was fully capable of supporting the communications load for human factors testing, it was selected to perform this function.

Table 22. Communications technologies.

Technology
Communication
DSRC
Other 5.9 GHz Protocols
Networking
802.11a
802.11b
RFID

DSRC

DSRC appears to be the communication technology most suitable for IDS. DSRC is intended to be used as a vehicle safety communications system, with the benefit of reduced protocol overhead to ensure short latency times with communications from the roadside to the vehicle. The major drawback lies in hardware availability, as hardware for direct DSRC implementation is not yet commercially available. However, such equipment may soon become available. Prior to the availability of a standardized DSRC communications protocol, experimental systems can be software-based utilizing 802.11a radio equipment.

802.11a

802.11a is a 5.2 MHz networking system. This system architecture will support roadside-to-vehicle communications at the required data rates. The main drawback, however, is the large network overhead associated with TCP/IP Protocols, which the technology requires. This overhead increases system latency and syncing in peer-to-peer networking modes (i.e., this technology makes it difficult to simulate the nearly instantaneous transmission expected to be available in true DSRC systems).

802.11b

802.11b is a 2.4 MHz wireless networking system with the same drawbacks as the 802.11a system, but with the addition of a decreased working range, as lowering the transmission frequency dramatically reduces the operational range of the radio system.

Radio Frequency Identification

Radio frequency identification (RFID) is a short range device that can transmit information from a tag to an antenna loop. The RFID system could be used to accurately transmit intersection state information to the vehicle. However, no RFID systems currently exist in the form factor necessary for this particular application and it appears substantial engineering development would be needed to make the technology work.

Given these technologies, only DSRC appeared suitable for further testing, and the results of these tests are described in a later section. As previously discussed, DSRC was also selected to support the human factors tests.

Algorithm

Trade-off studies of different algorithm alternatives could not be conducted at the same time as studies for the remaining IDS system components. The nature of the algorithm component is best evaluated using data for empirical intersection approaches that were not available at the time the trade-off studies were conducted. However, the initial human factors tests were designed to obtain some of these data, and algorithm development and evaluation ensued once these data were available. Given the level of detail and effort involved in performing these evaluations and the intricate relationship between algorithm development and the human factors tests, these results are presented in a separate section following the results of the human factors experiments.

DEVELOPMENT OF THE SMART ROAD INTERSECTION TESTBED

Design, development, prototyping, and building of the intersection testbed at VTTI were a major component of this project. Subsequent tests in the project depended on the accuracy and reliability of this testbed, and thus substantial time and effort were directed toward obtaining a final testbed that not only over-performed the foreseeable specifications for an IDS system, but that also was flexible enough to accommodate new technologies as they became available. Figure 20 depicts a diagram of the different testbed components.

In general, the driver controlled the test vehicle with inputs measured by vehicle-based sensors that transferred data to the data acquisition system (DAS) as well as the algorithm processor. The DAS and algorithm processors also received signal phase and timing information from the infrastructure. From an interface located in the back seat, an experimenter managed the data collection (through the DAS) and the experimental trials (through the algorithm processor). The infrastructure controller, in turn, controlled the light behavior as requested by the algorithm processor. When appropriate, the algorithm processor activated the DII.

This section discusses each of the components mentioned in the figure with the exception of the driver, who is the focus of the human factors research described later in this report. Due to its importance in the human factors experimental tests, a section is also devoted to the occlusion hardware.

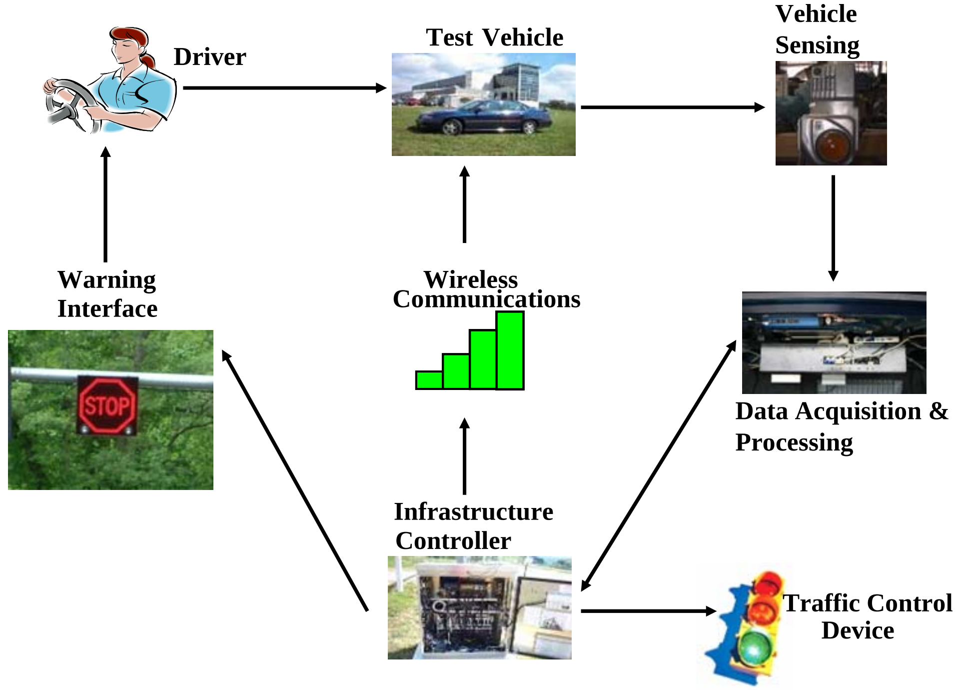

Figure 20. Overview of IDS testbed.

This section discusses both infrastructure and vehicle components of the intersection testbed. The reader should note that the testbed was built with funds from both the ICAV and IDS projects. In general, IDS funds were used to acquire and build the infrastructure components of the testbed (including wireless communications), whereas ICAV funds were used in the development of the testbed vehicle.

Infrastructure Testbed Components

The infrastructure portion of the testbed was built by VDOT on the Virginia Smart Road. The Smart Road is a state-of-the-art research facility used for the evaluation of ITS concepts, technologies, and products (Figure 21). It is currently a 2.2-mile, two-lane roadway with a high-speed banked turnaround at one end and a medium-speed flat turnaround on the opposing end. A fully equipped intersection (including standard signals, mast arms, controller cabinet, and lane markings) was installed in 2003 for the purpose of conducting intersection-related research (Figure 22). One of the adjacent legs has a straight alignment allowing higher-speed approaches, while the other is a lower-speed roadway connected to a wayside. Stop bars were located on all four approaches following Manual on Uniform Traffic Control Devices (MUTCD) recommendations. The intersection geometry allowed for an inter-stop bar distance of approximately 18.3 m (60 ft) on the main approach.

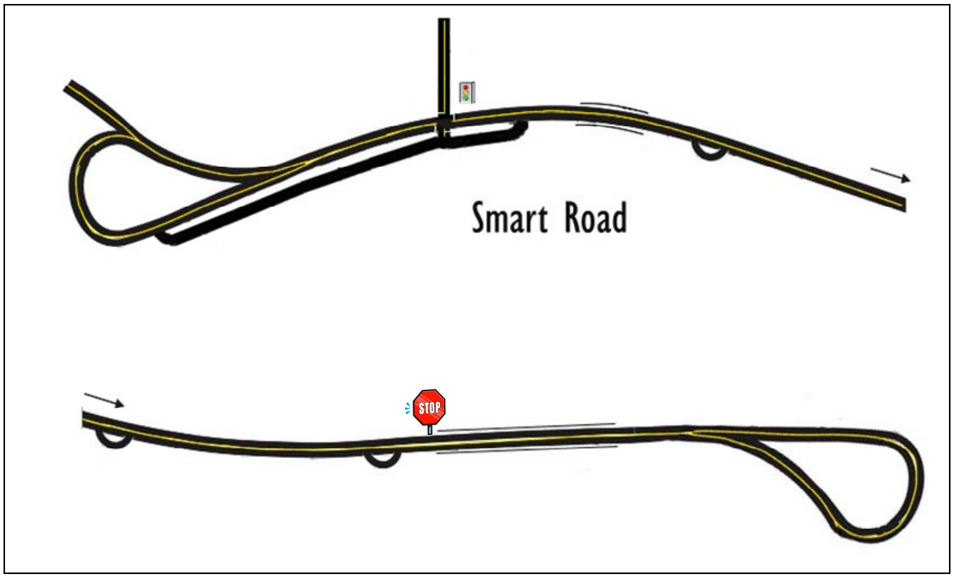

Figure 21. Plan view of the Smart Road. The signal head and stop sign indicate the signalized and stop-controlled intersections, respectively.

Figure 22. The Smart Road intersection.

Stop-controlled intersection tests required the development of a temporary stop-controlled intersection in a different area of the Smart Road. The temporary intersection was outfitted with a tape stop bar and consisted of a main approach on the Smart Road and a secondary approach from a feeder road into the Smart Road. This temporary stop-controlled intersection was located on the lower half of the Smart Road, about a mile away from the signalized intersection (see Figure 21).

Infrastructure Controller

Signalized Intersection

For research purposes, the signal controller needed additional capabilities such as on-demand rapid signal timing and phase changes as well as high-speed wireless communications. To support this level of performance, VTTI installed a 700-MHz PC104 computer in the controller box to manage the signal configuration and wireless data transfer (Figure 23). The PC104 received commands over the wireless communication system to signal-change sequence, timing, and phase-change initiation. The computer physically controlled the signal state through a 110-V interface built in-house at VTTI (Figure 24). Commands sent by the computer were received by a microcontroller on the interface that managed a bank of solid state relays, each of which was attached to an individual signal head.

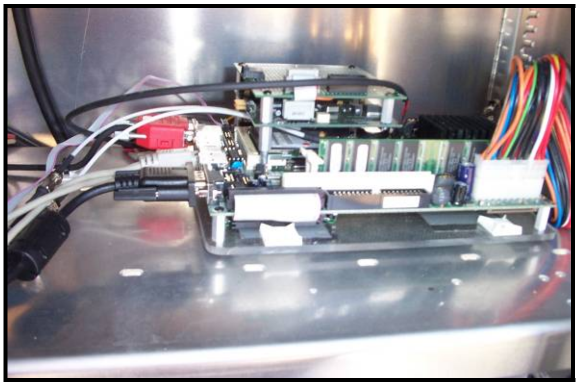

Figure 23. Single-board signal management computer.

Figure 24. Signal control interface.

As previously stated, the intersection cabinet was also configured to use a standard NEMA-type controller, but the controller was not used in any of the experimental tests described in this section. However, it was used in system component tests described as part of Task G.

Stop-Controlled Intersection

The stop sign in the stop-controlled intersection was normally hidden from the participant's view and was raised only for a surprise trial. The stop sign was raised pneumatically via a ram-rod, and its oscillations were dampened via a hydraulic damper. This allowed the stop sign to go from fully hidden to fully deployed (and static) in a little more than 2 s. An Aerocomm ConnexLink 900-MHz wireless transmitter (Model CL4490-1000, maximum range of 20 mi) in the vehicle activated a series of pneumatic valves that deployed the stop sign (Figure 25).

Figure 25. Stop-sign control hardware.

Traffic Control Device

Four masts were included in the signalized intersection design. The masts on the main approach contained three signal heads, two to signalize the straight approach and a third to signalize an optional left turn. Only the two lights that signalized the straight approach were used, and the additional lights were covered. The masts on the secondary approaches contained two signal heads. Both of these were operational during intersection tests. The signal heads were completely standard and representative of the signal heads that VDOT uses in southwest Virginia, where VTTI is located.

The stop-controlled intersection only contained the single, hidden, arm with an LED-enhanced stop sign attached to it. This stop sign is described in more detail in the next section.

Driver-Intersection Interface

The signalized intersection testbed was outfitted with two visual-modality DIIs (one of which could be augmented by additional reflectors) and one haptic-modality DII. These DIIs were used exclusively for signalized intersection tests. The temporary stop-controlled intersection used a third visual-modality DII, which was used exclusively for stop-sign tests.

The first visual DII consisted of an LED sign that hung between the two traffic control signals (Figure 26). The sign had an octagon with the word “STOP” in the center, all made of red LEDs that would light and become visible with warning activation. Specifications for the sign included:

- Size: 36 in (91.4 cm) by 36 in (91.4 cm) by 5.5 in (14 cm).
- Material: Aluminum.
- Red LED Octagon, 31 inches (78.7 cm) in height, centered within casing.
- Red LED “STOP,” 10 inches (25.4 cm) in height, centered within octagon.
- Tinted polycarbonate protective face.
- Brightness: not measured.

The sign’s conspicuity was augmented via two different mechanisms. First, it was outfitted with two strobe lights mounted on the bottom corners that activated along with the LEDs. Specifications for the strobes included:

- Luminous intensity: 6,930 candelas (cd) effective (combined)
- Power: 12-V DC input
- Adjustable flashing rate: 100 multi-flashes per min / 60 multi-flashes per min
- 5 single flashes per multi-flash
- Hi/low intensity settings (intensity reduction for low is not specified)

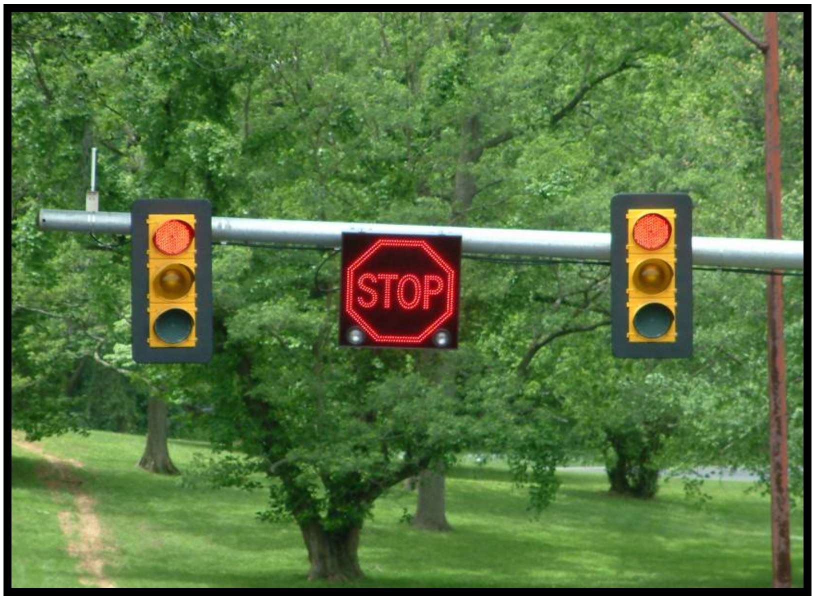

Figure 26. Lit LED stop sign. Unlit strobes are visible in the lower corners of the sign. The sign was completely opaque when unlit.

The second mechanism to augment the sign's conspicuity was the addition of traffic clearing lights (TCLs) to the bottom of the sign, which flashed along with the strobes (Figure 27). The TCLs were composed of a parabolic mirror assembly with a lamp socket and drive motor, a light bulb, and a housing. The housing was custom-made, and the remaining components were obtained from Federal Signal, Inc. Specifications for the TCLs include:

- Oscillating (M-sweep) parabolic mirror assembly with lamp socket and drive motor
  - Federal Signal Part No. TCLF2
  - Overall Dimensions: 11.9 cm W by 8.8 cm H by 9.6 cm D
  - Frequency of oscillation (full sweeps per second): 2.0
  - Federal Signal Part No. for the Drive Motor: Z8572233
- Light Bulb
  - Sylvania No. 795 X-12 V, Vertical Filament, Halogen, 50 W nominal at 12 V
  - Base: Bayonet
  - Federal Signal Part No. 28107141 A
- Bare bulb measured characteristics for applied voltage of 13.7 V:
  - Current: 4.22 A
  - Power: 57.8 W
  - Light output: 152 equivalent cd (measured at a distance of 2 m)
- Water-tight compartment housing the components, with lens at front aperture
- System on-axis light output in equivalent candelas (measured at 8 m with 13.7 V at lamp):
  - Max: 2,304
  - Min: 96
  - Average: 544

Figure 27. Lit LED stop sign along with fully functional strobes and TCLs.

The second visual modality DII was a pair of alternating flashing red lights placed on either side of the red signal head (Figure 28). The lights flashed at a frequency of 2 Hz with a duty cycle of 100 percent (i.e., one of the lights was always on). Each of the two light heads had a diameter of 30.5 cm (12 in) and was functionally equivalent to the red ball on a standard traffic light.

Figure 28. Dual flashing red lights.

The rumble strips were the sole haptic DII tested. Because true intelligent rumble strips were too costly to implement, the experiment used transducers driven by an amplifier and attached to the chassis (under the seats) and dashboard to produce simulated intelligent rumble strips (Figure 29). The specifications of the system are seen below, while the specifications for the actual rumble strip simulation are provided in the methods section of the DII effectiveness experiments discussion.

- Tactile response 10 to 800 Hz.

- Four ohm transducer impedance.
- Amplifier power was configurable as 100 W by 4 or 425 W by 2.
- Amplifier had a variable 24-dB crossover filter

Figure 29. Vibrotactile transducers used in the rumble strip simulation.

The stop-sign trials exclusively used the final visual DII, which was an LED-enhanced stop sign (Figure 30). This sign had dimensions of 91.44 cm H by 91.44 cm W by 2.54 cm D (36 in by 36 in by 1 in). When activated, the LEDs flashed at a frequency of 1 Hz with a duty cycle of approximately 50 percent. Each of the LEDs had a light output of 600 equivalent cd. The sign operated at 110 V. When the LEDs were turned off, the sign looked like a traditional stop sign. For experimental purposes, the sign had to be rigged to an automated deployment mechanism, as previously described. Pictures of the deployed sign are available within the stop-sign tests section.

Figure 30. LED-enhanced stop sign.

Vehicle Sensing—Infrastructure

Although most of the vehicle sensing was performed within the vehicle due to its higher accuracy, some experimental tests used vehicle sensing from the infrastructure; the equipment is described here, while the tests are described later. VTTI obtained and tested two different radars. The first unit was an advanced cruise control radar unit, which used monolithic microwave integrated circuitry operating at 76 to 77 MHz. The specifications of the radar unit were:

- Update rate: 25 Hz.
- Latency: 20 ms.
- Reliability: 95 percent.
- Accuracy:
  - Distance: 5 percent at D > 20 m.
  - Speed: 0.3 mi/h.
  - Acceleration: 0.05 g.
  - Heading: 0.3 deg.
- Power requirement: 12 V at 500 mA.
- Cost at the time of purchase: $5,000.

The second radar unit was an imaging radar that is typically used in the aviation market. The following specifications apply to this radar test unit:

- Operating frequency band: 94 GHz
- Update rate: approximately 70 ms
- Viewable area:
  - 5° vertical cone
  - 30° horizontal cone
- Range:
  - Maximum: 1 km
  - Minimum: 5 m
- Maximum error:
  - ± 1 m for distances between 1 m to 20 m
  - ± 1 percent for distances above 20 m
- Azimuth maximum error:
  - ± 1° for distances 1 m to 40 m
- Size: 9 in x 15 in x 6 in
- Weight: 29 lb.

In addition to the radar sensors, discrete vehicle tracking was performed as needed via long-range photoelectric sensors. These sensors (Figure 31) and their associated reflectors were placed on opposite sides of the road. Specifications for these devices follow:

- Latency: 1 ms.
- Reliability: 99 percent.
- Accuracy:
  - Longitudinal: Position – 150 mm at 7 m.
- Power requirement: 12 V at 50 mA.
- Cost per laser at the time of purchase: $100.

Figure 31. Laser beam projector.

Vehicle Testbed Components

The vehicle testbed was built with resources available under the ICAV project. The vehicle testbed was purposefully designed with performance capabilities in excess of those required by a deployable system so that minimum system requirements and specifications could be determined through systematic detuning and human performance experiments. The subsystems that made up the vehicle testbed and that were used in the IDS project are listed in Table 23. They are accompanied by a summary of the technologies that they used to achieve the subsystem function. Although components of the communications subsystem were included within both vehicle and infrastructure, they are only discussed here minimally, since roadway and vehicle transceivers used the same communications technology.

Table 23. Components used in vehicle testbed.

Subsystem	Purpose, Data Flow	Technology(ies)
Vehicle sensing	Provided data on vehicle's presence, range, range-rate, acceleration, and pedal positions. Sent data to the algorithm processor and the DAS.	Differential GPS, in-vehicle accelerometer, accelerator/brake pedal and steering wheel potentiometers.
Communications	Vehicle broadcast information about upcoming experimental trial such as desired signal phase timings to the infrastructure. The infrastructure broadcast the current signal phase and signal timing to the vehicle.	Simulated DSRC with custom-built message content and structure.
Experimenter interface	Controlled the experimental trials, managed data collection, and monitored system performance.	Custom software package and remote computer interface accessible to back-seat experimenter.
Algorithm processor	Integrated data from the various sensing sources available; determined warning state.	Custom-built algorithms.

The vehicle used in the testbed was a 2000 Chevrolet Impala (Figure 32). The vehicle was factory-equipped with conventional safety equipment such as anti-lock brakes, dual front and side airbags, and traction control. Several additional safety features were implemented in the test vehicle to minimize risk for participants and experimenters. For example, an emergency passenger-side brake was mounted so that an experimenter seated in the front passenger seat could take control of the vehicle if needed.

Figure 32. Chevrolet Impala experimental vehicle.

In addition, a custom steering lock was designed, manufactured, and installed so that participants could not freely steer the car as a reaction to surprise experimental trials or during periods of occlusion (participants wore goggles that occluded or blanked out for 2-second periods during data collection; these will be described in more detail in later sections of this report). The steering lock provided 5º of movement freedom at the steering wheel to make the locking process as unnoticeable to the participant as possible. This feature made it impossible for the participant to steer the vehicle off the roadway during the time the goggles were occluded.

Vehicle Sensing

A Novatel OEM4-G2 L DGPS unit was used to provide position and speed for data collection and algorithm computations (Figure 33). This unit received differential corrections from a base unit via an antenna on the roof of a nearby building. The corrections were transmitted via a Pacific Crest RFM96 W radio unit operating at 35 W (Figure 34). Specifications for this DGPS system were as follows:

- Update rate: 20 Hz maximum.
- Latency: 0.05 s.
- Reliability: 99 percent.
- Accuracy:
    - Longitudinal: Position – 1 cm, Speed – 0.03 m/s.
    - Lateral: Position – 1 cm, Speed – 0.03 m/s.
    - Heading: Not available.
- Power requirement: 2 W.

Figure 33. Novatel DGPS unit.

Figure 34. Pacific Crest radio unit.

Because the system was mounted in the vehicle, it required an internal vehicle map to allow the determination of position relative to the intersection. Stop-bar locations were used to fulfill this role. The DGPS unit provided the most accurate method of position and velocity detection within the testbed and was thus used for vehicle sensing and positioning for most of the IDS tests.

In designing the testbed, an accurate measure of acceleration was considered to be useful. This required the acquisition and incorporation of an accelerometer within the vehicle sensing suite. The accelerometer used was an Analog Devices ADXL202 AE. Specifications for this device follow:

- Update rate: 60 Hz.
- Latency: 0.01 s.
- Reliability: 99 percent.
- Accuracy:
    - Longitudinal: 2 mg at 60 Hz.
    - Lateral: 2 mg at 60 Hz.
- Power requirement: 5 V at 0.6 mA.

Communications

Off-the-shelf DSRC was not available at the time the testbed was under development. Therefore, the communications laptop used prototype 802.11a mini-PCI radios from Atheros® to interface with the DSRC system at the intersection. The radios were pre-installed in the DSRC test kit laptop computers provided to VTTI by the CAMP. The radios operated in the 5.2-GHz frequency band (true DSRC will use 5.9 GHz) with two sets of external antennas mounted on the roof of the vehicle and on top of the controller cabinet (Figure 35). This setup allowed for two-way communication of digital information packets between the intersection controller and the vehicle when it was within approximately 305 m (1,000 ft) of the intersection. The communications link used User Datagram Protocols (UDP, one of the two standard transport protocols for the Internet Protocol traffic) to receive signal information from the infrastructure controller. VTTI developed platform-specific software to address all communication packet needs.

Figure 35. Vehicle and intersection cabinet with DSRC antennas.

Time-synched signal phase and timing data were continuously transmitted from the infrastructure to the vehicle while it was in range. Information transmitted from the vehicle to the infrastructure included the desired signal setup for the current experimental trial (including signal-change characteristics and the onset of phase change) and DII activation signals.

Table 24 summarizes the capabilities of the testbed's communications system, which was designed to over-perform any foreseeable final system requirements. These specifications have been verified, and in some instances created, by VTTI.

Table 24. Testbed communications capabilities.

Specification Type	Specification Value
Communication path	Infrastructure-to-vehicle and vehicle-to-infrastructure, two-way, point-to-multipoint
Update rate	20 Hz maximum
Maximum range	1500 ft
Bandwidth	6 Mbps
Data reliability	99%
Data latency	18 ms
Content of data stream	From infrastructure: signal phase and timing. To infrastructure: desired signal setup, commands to change the light phase or trigger the warning. All information is synchronized through GPS time stamps.
Packet size	64 Bytes
Signal Power	17dBm @ 6 Mbps
Power requirement	3.3V @ 450 mA
Durability	Minimal adverse performance effects observed after ~2 yrs of regular use in experimental setting. Antennas were maintained outdoors, exposed to the elements, during this time period.

Experimenter Interface

The experimenter interface (Figure 36) was presented on an in-vehicle screen and controlled through a standard keyboard with a trackball. The interface allowed the experimenter to control any aspect of the intersection approach (e.g., distance at which to change the light, visual occlusion, type of warning that was presented) and the warning parameters. It also provided the experimenter with information on the intersection status, vehicle kinematics, and detuning operations.

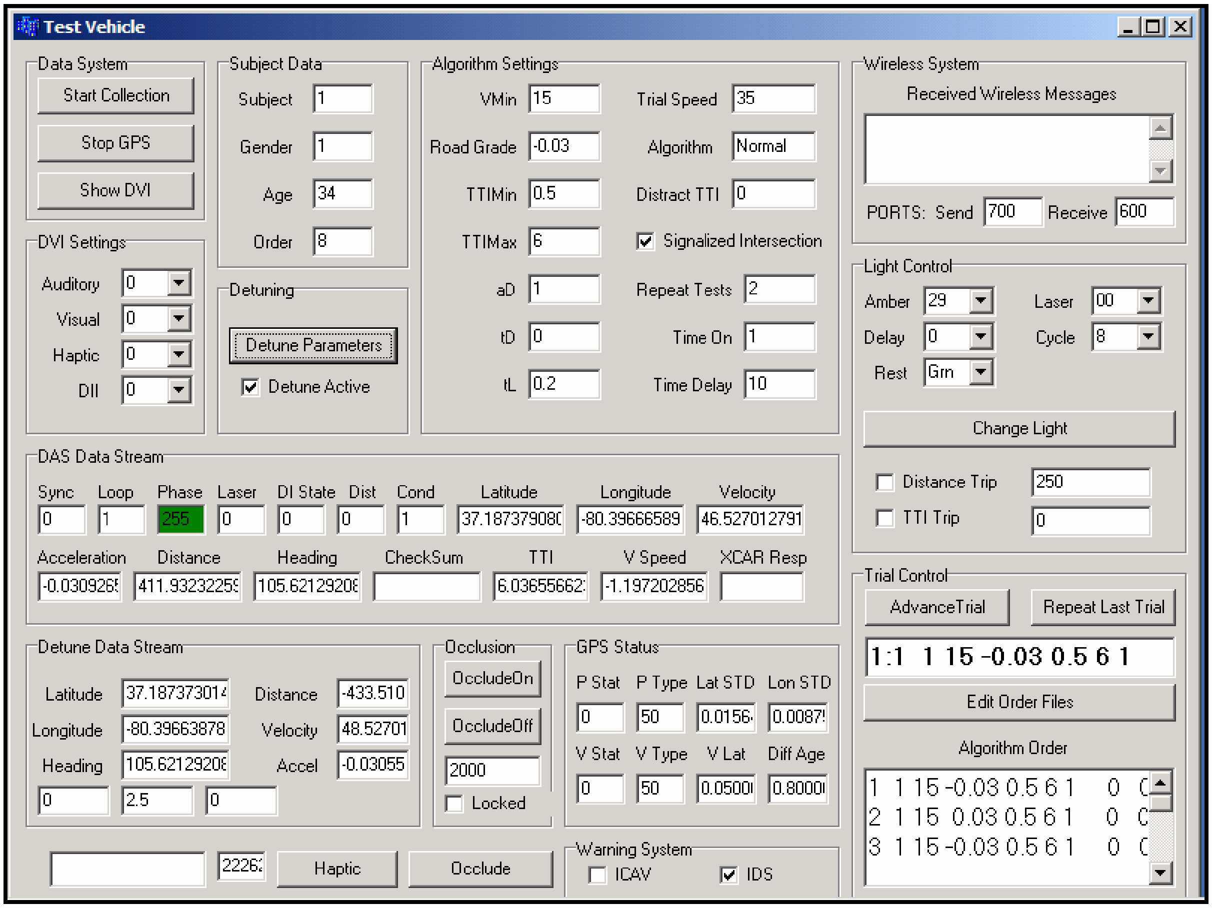

Figure 36. Experimenter interface.

A trial order file was created for each set of experimental conditions and loaded into the interface at the beginning of each test. With each intersection crossing, the interface automatically advanced to the next trial. Once in wireless range the interface would automatically transmit trial information to the infrastructure as appropriate. In case of a system malfunction, the experimenter maintained override control on occlusions, steering lock, and signal-phase changes. Finally, the interface provided information regarding the current algorithm timing and real-time data from the sensing equipment. This allowed the experimenter to verify data collection accuracy and trial characteristics.

Occlusion Hardware

In order to control the extent and duration of inattention, a distraction simulation method was employed for some studies. A set of occlusion goggles was used to simulate distraction (Figure 37). The portable liquid crystal apparatus for tachistoscopic occlusion (PLATO) was built by Translucent Technologies. The goggles housed a pair of liquid crystal lenses that could be switched to permit or occlude the driver’s vision as desired. The goggles were computer controlled and were activated either manually from the experimenter interface or at a specified TTI as needed.

Figure 37. PLATO occlusion glasses.

Data Acquisition System (DAS)

The DAS was contained within the vehicle and was custom built by VTTI. The DAS was located inside the trunk to be unobtrusive and to not limit visibility or create a distraction (Figure 38). A 200-MHz PC104 operating on a Microsoft Windows platform was at the heart of this DAS. A series of custom circuit boards that controlled the various functions of the acquisition device was attached to the system bus. This system included four video grabbers, an accelerometer/gyroscope, a vehicle network sniffer (to pull variables from vehicle network), and power management boards. The alignment and time stamping data retrieved from these boards were choreographed by X-Car, which was a customized VTTI proprietary software package. Hardware was contained in a custom mounting case designed to affix instrumentation in orientations necessary for accurate measurement and durability.

Data were transferred to the DAS in real time. The DAS sampled most of the data at 10 Hz, except for the pedal and steering wheel position data streams (sampled at 100 Hz) and the video data (sampled at 30 Hz). However, algorithm trips, green-to-amber phase changes, and experimental commands were interrupt-driven to avoid inducing latency errors. That is, the data stream was continuously sampled, and the command was sent the instant the defined threshold was surpassed, even if the time was not exactly in line with the 10 Hz data sampling clock; this allowed virtually instantaneous commands that were not limited by the update rate. As discussed earlier, all wireless communications occurred through a prototype DSRC kit operating in the 5.2-Gigahertz frequency band (true DSRC will use 5.9 GHz).

The video grabbers installed in the DAS converted the National Television System Committee (NTSC) signal from the cameras into MPEG, which was recorded to the hard drive in real time. Small cameras (1 in square by 1/4 in deep, with a 1/32-inch aperture) were mounted inconspicuously within the vehicle to collect the video data. For the current study, four cameras were installed (Figure 39). The camera views included:

1. Forward view – to provide a visual reference of the current vehicle location.
2. Driver's face – to record eye glances.
3. Passenger-side A-pillar camera – to capture the steering wheel, instrument panel, and the driver's hands from the side.

4. Driver's feet – to show accelerator and brake activation (due to the low-light conditions, this camera also required an infra-red light source).

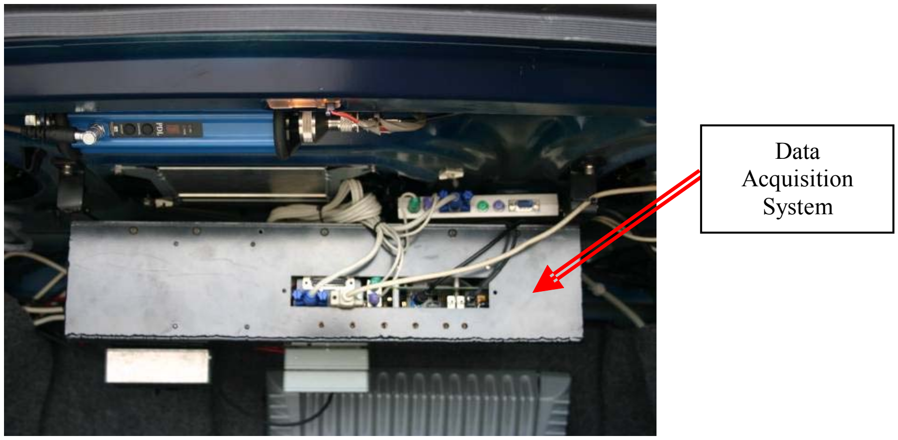

Figure 38. Data acquisition system.

Video data were recorded on the DAS computer at 30 Hz. For analysis, video data were multiplexed in a four-quadrant, split-screen display (Figure 40).

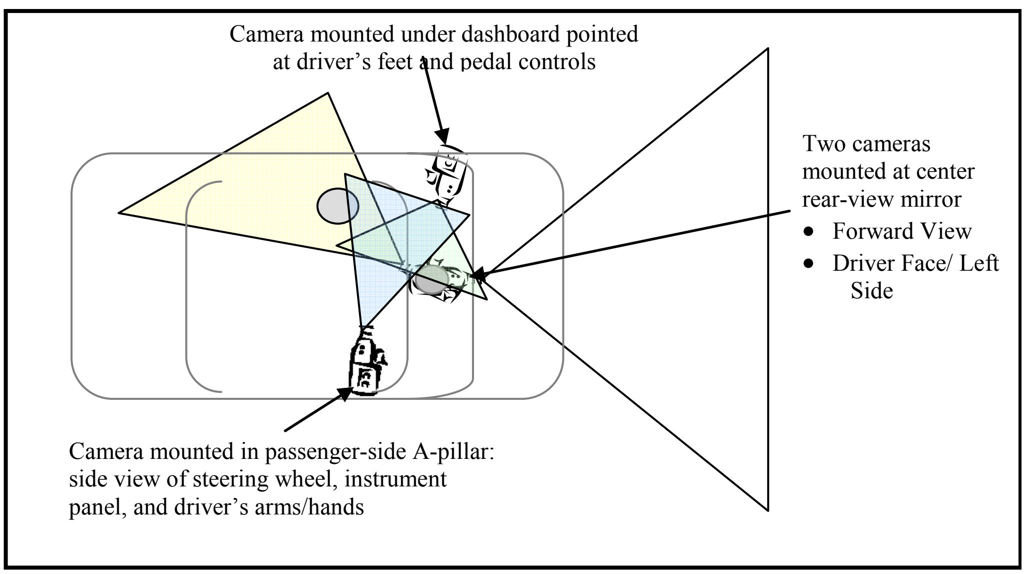

Figure 39. The four camera views recorded in the testbed vehicle.

Figure 40. Split-screen display for video analysis.

The prototype DAS installed in the Impala was complemented by an IBM Thinkpad® outfitted with the DSRC test kit (Figure 41). The Thinkpad was responsible for coordinating wireless communications, providing the experimenter interface, and computing the algorithm. To perform these tasks, the Thinkpad was also connected to the distributed DAS network, which provided redundant data recording and also increased reliability.

The distributed DAS network consisted of four primary components: three-axis accelerometer and network box, pedal and steering potentiometers and network box, DGPS subsystem, and wireless subsystem. Each component of the DAS network provided information to the DAS computers for recording. The accelerometer box was located near the vehicle pitch-center to minimize pitch-induced acceleration noise. The potentiometers reported the positions of the accelerator pedal, brake pedal, and steering wheel to an analog-to-digital network box. The DGPS subsystem provided vehicle position and speed. Each of these systems was discussed in further detail in the previous sensing section. The wireless communications equipment, which was discussed previously in the communications section, provided signal-phase and timing information to the DAS.

Figure 41. Algorithm processor, experimenter interface, and communications laptop.

The DAS was independent of the testbed system but remained linked to it to record and time-stamp key events (e.g., warning onsets). Other performance features of the DAS included automatic detection of sensor or software failures.

HUMAN FACTORS EXPERIMENTS

There were two types of human factors tests conducted as part of this project. The first set of tests were used to characterize baseline driver behavior at intersections with the purpose of defining what has been previously described as a "too-early" distribution (Kiefer et al., 1999). A too-early distribution characterizes those drivers who would have braked regardless of the warning, thereby indicating what would be a nuisance alarm. With knowledge about the too-early distribution, the second set of tests was designed to examine the potential effectiveness of different warnings in eliciting stopping behavior.

Successful algorithm design lies in carefully accounting for and controlling the location and shape of these distributions. This discussion is reserved for the Algorithm Development section. This section discusses the results of the human factors tests and some of their more general implications.

Baseline and Crash Avoidance Behavior at Intersections

The literature review completed as part of Task A yielded some basic information on driver baseline behavior. However, it also indicated substantial gaps in the understanding of this baseline behavior as it applies to the intersection approach scenario. The studies described in this section were designed to address some of these gaps. Specifically, the following research questions were posited.

RQ1: How does driver state (e.g., distracted) affect intersection performance?

RQ2: Can potential violators be predicted using questionnaire-based measures of aggressiveness?

Method

The data to address these research questions were obtained via an on-road, mixed-subject, full-factorial design testing drivers from high-risk age groups approaching a signalized intersection under various driver states. The experimental design manipulated driver state throughout a series of intersection stops. Furthermore, red-light violations were elicited by trapping drivers in the dilemma zone, where incorrect decisions were likely. Two nominal approach speeds of 56.3 km/h and 72.4 km/h (35 mph and 45 mph) were also compared. Performance measures such as reaction time and range rate provided the data needed to answer each of the research questions.

Experimental Design

Experimental Design Matrix

A 2 (Gender) x 2 (Age) x 2 (Speed) x 3 (Driver State) x 5 (Phase-Change Distance) complete factorial design was used. The independent variables and participants were organized as shown in the matrix below (Table 25). Driver State and Phase-Change Distance (PCD) represented the within-subject factors, while Age Group, Gender, and Speed represented the between-subject factors for this mixed design.

Table 25. Experimental design matrix.

		Speed / Age Group			
		56.3 km/h (35 mph)		72.4 km/h (45 mph)	
Driver State	**PCD**	**18-25**	**55+**	**18-25**	**55+**
Baseline	1	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	2	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	3	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	4	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	5	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
Distracted	1	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	2	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	3	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	4	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	5	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
Willful	1	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	2	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	3	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	4	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female
	5	S_{1-7} Male S_{8-14} Female	S_{15-21} Male S_{22-28} Female	S_{29-35} Male S_{36-42} Female	S_{43-49} Male S_{50-56} Female

Independent Variables

Age group (Between Subjects): Two age groups were used to represent the driving population. The drivers were classified as Younger (18–25) and Older (55+). These groups of drivers are selected because they exhibit the highest risk for intersection collisions. Subjects under 18 were eliminated from the study due to insurance, liability, and consent issues.

Gender (Between Subjects): Although there is little evidence for a gender effect in stopping behavior, there have been some mixed results in past studies. Thus, gender was evenly distributed across each condition for this study.

Speed (Between Subjects): Speeds of 56.3 km/h (35 mph) and 72.4 km/h (45 mph) were selected for the study. The purpose of testing various speeds was to observe any effects of this factor on the studied dependent measures. Some measures may remain constant across speed, while others may change. The relationship of any of the dependent measures to speed might affect the design of the algorithm. An IDS algorithm must be programmed to understand which variables remain constant and which tend to vary with speed so that it can take more accurate warning decisions.

Speeds higher than 72.3 km/h (45 mph) were not used for safety reasons, given that participants would be driving experimental vehicles. The use of speeds lower than 56.3 km/h (35 mph) was maintained as a possibility if speed was found to affect the results. As will be explained later in this report, this was not the case. Thus, only two levels of speed were used in the experiment.

Phase Change Distance (Within Subject): Phase Change Distance experimental levels were determined by altering the Time-to-Intersection Red Phase (TTIrp) for each intersection approach. TTI defines the predicted time interval in which a vehicle will cross the stop bar assuming no change in velocity. The TTIrp represents a TTI at which the amber change interval is replaced with a red. Negative values represent a condition in which a violation would not occur, whereas a violation would occur for positive values of TTIrp. For a given speed, this variable is analogous to vehicle distance from the intersection when the red light is first presented. The red, rather than amber, phase is used as a reference point in calculating TTIrp so that the measure is not dependent on the duration of the amber change interval. This allowed direct comparison between trials in which the amber change interval was altered, and also allowed for comparison of these results with those of future studies at different speeds. For this experiment, five levels of TTIrp were defined that distributed phase change distances through the intersection approach, but concentrated them around the dilemma zone.

The intersection at VTTI was designed to meet the geometric and timing standards set by ASHTO and ITE recommendations. The result is an intersection without a theoretical dilemma zone and a negligible option zone (an area near the intersection in which the vehicle can either stop in time or clear the intersection before the light turns red) at both experimental speeds. Thus, for this intersection, it is relatively simple for an aware and law-abiding driver to decide whether it is appropriate to stop or go, regardless of the approach speed and the signal phase change timing. However, for a willful or distracted driver, the distance at which the signal changes can affect the ability to make a correct decision in a timely fashion. For the distracted driver the difficulty stems from a large dilemma zone created by an increase of the reaction time. If the driver is inside this dilemma zone when the signal changes, it is difficult to discern whether it is more appropriate to stop or go. The willful driver may also find it more difficult to decide on the appropriate action because he or she is trying to use the entire amber phase, requiring accurate timing judgments. These judgments are particularly important when the signal will switch to a red phase when the “go” vehicle is close to the stop bar.

To determine TTIrps that would provide a complete set of driver intersection approach behaviors, merging of available data was necessary. A normal distribution was fit to the empirical data presented by ITE (1991) using the 10th and 90th percentile values as initial boundaries (i.e., percentage of drivers who stop at a specified distance). Pilot testing demonstrated that simply selecting the ITE distribution resulted in distances that were too conservative. At the furthest TTIrp it was apparent that a stop was necessary under all conditions. This was not a surprise given that the ITE values are a conservative generalization dependent on factors such as intersection design and the locality of measured installations. To better configure the TTIrp values for the Smart Road Intersection, the distributions were adjusted.

These adjustments were judiciously made based on pilot data, kinematics analysis, and information from the CAMP. CAMP developed useful metrics for forward collision avoidance systems (Kiefer et al., 1999). These metrics were combined with kinematics equations to roughly define intersection approach behavior at larger TTIrp values and interpolated to fit the ITE curves at shorter TTIrp values. Additional details of the methods used to obtain the final TTIrp values are omitted because they are based primarily on engineering judgment. The goal for this process was to generate an experimental TTIrp distribution that would place drivers from a region in which most would decide to go (10th percentile) to a region in which most drivers would decide to stop (90th percentile). A second set of pilot participants were used to verify the appropriateness of the new TTIrp settings. Results demonstrate that the stop decisions were better approximated by the new distribution than the original ITE distribution.

This process of determining appropriate distances was repeated for each experimental speed. Given that the experiments using different speed were run sequentially (the 56.3-km/h experiment was performed first), it was possible to make some adjustments to the TTIrps selected for the two different speeds. There were two substantial adjustments. The first was the elimination of the −1.62-second TTIrp level. Results from the 56.3-km/h (35-mph) study indicate that the −1.62-second TTIrp level was not providing useful data for algorithm development. It was rare for a driver to stop at this distance because it required an uncomfortable rate of deceleration. Also, it would be very unlikely for a driver to cross the intersection at a TTIrp this low after cross traffic has begun to flow. Without cross traffic in the intersection, a collision is unlikely to occur even if a driver makes a series of poor decisions.

The second change took advantage of the elimination of this TTIrp to include a larger TTIrp value of 1.50 s. This larger value was intended to create a situation in which it would be more likely for the vehicle to enter the intersection when a crash potential did exist. The 1.50-second TTIrp provided information about how drivers approach an intersection when the phase change occurs far from the intersection. In this situation, the decision to stop should be very clear to most drivers. A 1.50-second TTIrp implies that if the vehicle maintains a 72.4-km/h (45-mph) speed throughout the approach, it would cross the stop bar 1.50 s after the signal has turned red. It was impossible for the experimental vehicle (and most cars) to accelerate sufficiently to legally cross the intersection at this new TTIrp.

These two changes, the final TTIrp values, and the expected percentages of stopping drivers are outlined in Table 26. The table also shows the distances which these various TTIrp values represent at the two speeds.

Table 26. TTIrp Values - negative values indicate that the light will change to red after the vehicle has crossed the stop bar, assuming a constant speed. The resultant phase change distance is also provided.

PCD (56.3 km/h)	PCD (72.4 km/h)	TTIrp (seconds)	Intersection Phase Change Distance at 56.3 km/h (m)	Intersection Phase Change Distance at 72.4 km/h (m)	Expected Stopping Drivers (percent)
1		-1.62	30.48	XXX	10
2	1	-1.09	38.71	63.70	30
3	2	-0.51	47.85	75.59	50
4	3	0.04	56.39	86.56	70
5	4	0.87	69.49	103.33	90
	5	1.50	XXX	116.74	100

Driver State (Within Subject): To simulate a variety of driver states, participant behavior was modified through the experimental design. The driver states were created to represent normal drivers (Baseline) and drivers with a high violation propensity (Willful and Distracted). The three levels of driver state are briefly described below with further detailed discussions in the experimental procedure section.

Baseline: The baseline state represented an aware and undistracted driver's response to the traffic control device. Most drivers in this state react appropriately, either stopping the vehicle prior to entering the intersection or safely passing through the intersection during the amber change interval. Intersection violations are rare within this group of drivers when the intersection timing is set appropriately.

Distracted: The distracted driver is one who either does not notice the green-to-amber phase change or over-estimates the amber-phase duration. Reliably distracting drivers is difficult to accomplish. For instance, if an in-vehicle task is used for distraction, a temporary glance away from the roadway is required. This glance time is the duration during which the participant is distracted. However, some people may be willing to use long glances, while others will only use very short glances. It is also extremely difficult to synchronize the participant's glance with the actions of the TCD such that the phase change occurs during the distraction and at the desired location. Thus, to maintain control of the extent and timing of the distraction, a simulation method was used. To simulate distraction during a phase change, the amber interval was shortened. The subtracted amber presentation time is equivalent to the time during which a distracted driver would not perceive/recognize the signal. For instance, the amber change interval should be 3.6 s at 56.3 km/h (35 mph). To simulate a 1.6-second distraction, the amber-change interval was shortened to 2 s. Likewise, at 72.4 km/h (45 mph), the standard amber-change interval should be 4.3 s. To simulate a 1.6-second distraction, the amber-change interval was shortened to 2.7 s. The end result was to simulate a driver who is unaware of the signal at the beginning of the phase change and subsequently shifts their attention to the TCD partway through the amber light.

The duration of the simulated distraction was held constant across all distracted trials. Note that the objective of the simulated distraction was to approximate the actual time during which a driver may not be attending to the traffic signal or to approximate the extent to which the TCD is misjudged. Research in the area of distraction typically uses forward-gaze reduction as a surrogate measure of distraction since internal (mental) distraction is difficult to measure (Hanowski et al., 2001).

The duration of the simulated distraction was selected based on previous naturalistic research. Average distraction time ranged from 0.5 s (looking out left side) to 7.5 s (reading a paper). The mean distraction across all of the tasks was 1.45 s. The current study attempted to simulate a long, but realistic, distraction; thus, a 1.6-second distraction was used. Selection of this particular value also considered the likelihood that participants would detect the difference in amber times between different trials and modify their behavior accordingly. Various values were pilot tested before selection of 1.6 s. Interestingly, after the study, participants were asked if there was anything unusual about the TCD. Of the 56 participants, approximately half noticed that the amber light had shortened. However, most thought it had only occurred once, whereas it had actually occurred in 5 of the 15 experimental trials that included a phase change during the intersection approach.

Willful: This state represents the driver who purposefully attempts to beat the light. This driving group tends to have a high motivation for crossing through the intersection and believes the risk associated with a late crossing is acceptable. This behavior was coerced by adjusting the driver's perceived cost-benefit ratio regarding intersection crossing. This portion of the study was realized as a series of decision-making trials in which drivers were rewarded and penalized monetarily based on the success of their intersection crossing behavior.

Several reward methods were tested during a pilot study. In initial tests, drivers were told to try to imagine they were in a big hurry and that they might have a tendency to try to make later intersection crossings. Drivers were provided with verbal praise when successful attempts were made. However, results show that drivers quickly became complacent and did not exhibit high-motivation crossings after a few runs. Thus, a monetary incentive system was enacted in which drivers were paid for successful intersection crossings and assessed a monetary penalty for violations. Penalties were necessary to avoid having drivers drive through every light. A storage bin in the center console became a bank in which the experimenter physically deposited bonus cash after each successful intersection crossing and retrieved money after every violation. Pilot tests showed that this incentive system provided participants with the necessary motivation, even for relatively low monetary amounts.

Thus, willful behavior was coerced during the experiment by providing drivers with a $5 bonus for every successful intersection crossing. The penalty was set at $2 per violation. This penalty was set at a lower rate such that driver's behavior would be skewed toward beating the light. For drivers who opted to stop on the amber phase, or go on a green phase, no bonus or penalty was applied.

At the start of the willful block drivers received a $10 bonus in addition to the standard $10 per hour rate. The intention of this bonus was to provide an extra cushion for participants to lose money and to create a gambling attitude with the extra cash. The total bonuses received ranged from $5 to $25, with most participants receiving about $15.

Presentation Order: The within-subject portion of the experiment was divided into two separate blocks. These two blocks were necessary because information provided to the participant during the willful condition could affect their behavior in the other states. The following tables (Tables 27 and 28) display the 21 treatment conditions that each participant encountered. Note that for each state in the first block there were five PCD values and two green treatments. When the PCD was green, the participant was not presented with a changing signal as they approached the intersection; rather, the participant drove through a green indication (the signal did change a few seconds after crossing as could be verified if the driver looked in the rear view mirror). The green phases were placed into the design to enhance realism and to reduce the driver's anticipation of a signal status change. Within each block, participants received a Balanced Latin Square presentation order of the conditions (Tables 29 and 30) to reduce any bias in the results due to practice effects.

Table 27. Block 1 - Treatment conditions

Driver State	PCD	Treatment Condition
Baseline	1	A_1
	2	A_2
	3	A_3
	4	A_4
	5	A_5
	Green	A_6
	Green	A_7
Distracted	1	A_8
	2	A_9
	3	A_{10}
	4	A_{11}
	5	A_{12}
	Green	A_{13}
	Green	A_{14}

Table 28. Block 2 - Treatment conditions

Willful	1	A_{15}
	2	A_{16}
	3	A_{17}
	4	A_{18}
	5	A_{19}
	Green	A_{20}
	Green	A_{21}

Table 29. Block 1 – Presentation order.

Presentation Order	**Subject**													
	S_{1}	S_{2}	S_{3}	S_{4}	S_{5}	S_{6}	S_{7}	S_{8}	S_{9}	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}
1	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}
2	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}
3	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}
4	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}
5	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}
6	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}
7	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}
8	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}
9	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}
10	A_{6}	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}
11	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}	A_{9}
12	A_{7}	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}
13	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}	A_{8}
14	A_{8}	A_{9}	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{1}	A_{2}	A_{3}	A_{4}	A_{5}	A_{6}	A_{7}

Table 30. Block 2 – Presentation order.

Presentation Order	**Subject**													
	S_{1}	S_{2}	S_{3}	S_{4}	S_{5}	S_{6}	S_{7}	S_{8}	S_{9}	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}
1	A_{15}	A_{16}	A_{17}	A_{18}	A_{19}	A_{20}	A_{21}	A_{19}	A_{20}	A_{21}	A_{15}	A_{16}	A_{17}	A_{18}
2	A_{16}	A_{17}	A_{18}	A_{19}	A_{20}	A_{21}	A_{15}	A_{18}	A_{19}	A_{20}	A_{21}	A_{15}	A_{16}	A_{17}
3	A_{21}	A_{15}	A_{16}	A_{17}	A_{18}	A_{19}	A_{20}	A_{20}	A_{21}	A_{15}	A_{16}	A_{17}	A_{18}	A_{19}
4	A_{17}	A_{18}	A_{19}	A_{20}	A_{21}	A_{15}	A_{16}	A_{17}	A_{18}	A_{19}	A_{20}	A_{21}	A_{15}	A_{16}
5	A_{20}	A_{21}	A_{15}	A_{16}	A_{17}	A_{18}	A_{19}	A_{21}	A_{15}	A_{16}	A_{17}	A_{18}	A_{19}	A_{20}
6	A_{18}	A_{19}	A_{20}	A_{21}	A_{15}	A_{16}	A_{17}	A_{16}	A_{17}	A_{18}	A_{19}	A_{20}	A_{21}	A_{15}
7	A_{19}	A_{20}	A_{21}	A_{15}	A_{16}	A_{17}	A_{18}	A_{15}	A_{16}	A_{17}	A_{18}	A_{19}	A_{20}	A_{21}

Dependent Variables.

Range: Range is the distance from the intersection stop bar (front edge) to the participant vehicle (front edge of the front tire).

Range rate: Range rate is the instantaneous vehicle speed at a particular distance from the intersection.

Reaction time measures: Reaction time was measured using in-vehicle sensors mounted to the pedals and aided, for any non-traditional patterns, by a corresponding video image of the feet. There are many reaction time measures relating to stopping performance, but those of interest for this study were:

TAR: time from initial stimulus appearance to beginning of accelerator release. Operationally, the beginning of accelerator release was defined as the first decrease, after amber onset, in accelerator position of more than 2.5 percent in 0.1 s.

<u>*TB*</u>: time from initial stimulus appearance to beginning of brake depression. Operationally, the beginning of brake depression was defined as the increase in brake position of more than 5 percent in 0.1 seconds that occurred after amber onset.

<u>*Braking intensity (longitudinal acceleration)*</u>: Braking intensity is a measure of how hard a vehicle is slowed. It was measured in terms of G-force (*g*) along the longitudinal axis by an accelerometer mounted in the vehicle and analyzed in terms of the peak, average, and rate of change (i.e., jerk) values for the braking profile. Operationally, the braking profile included all sequential (at 10 Hz intervals) samples of longitudinal acceleration from the point in which an increase in this measure of more than 0.025 *g* in 0.1 s was observed to the point in which the vehicle stopped completely. Peak deceleration was the single sample maximum deceleration value within the profile.

Two measures of average deceleration rate were calculated: required deceleration parameter and time-weighted average deceleration. The required deceleration parameter (Equation 8) stems from a simplifying assumption currently made by the intersection violation algorithms discussed previously: that is, that the driver will brake at a constant deceleration rate. If this is assumed, speed and distance to the intersection at the onset of braking are known, and if a full stop ($V_{final} = 0$) is assumed, then the traditional kinematics equations for constant acceleration can be transformed to solve for that acceleration level:

$$a = \frac{V^2}{2 * WD} \qquad (8)$$

where:

a	=	Deceleration in m/s^2
V	=	Vehicle speed in m/s
WD	=	Distance at which braking began in meters

While this assumption is not absolutely true in any real-life deceleration pattern, it is used here in order to allow for comparison of these data to the existing intersection violation warning algorithms previously discussed. The applicability of this assumption was examined by comparison of this deceleration value to the peak deceleration. The bigger the difference between these two deceleration measures, the less accurately the deceleration profile can be represented using a constant deceleration model. The other measure, time-weighted average deceleration, was calculated as the arithmetic average of the deceleration measurements taken during the braking profile. It was used to compare the results of these tests with other published reports of driver deceleration.

Jerk measures were calculated during the first and last 25 percent of the braking profile (based on time, with total braking profile duration of 100 percent). The calculation used the longitudinal deceleration values at the endpoints of each 25 percent segment to determine the slope of the curve for that region. Thus, a line was fit to pass through the braking levels at the 0 percent and 25 percent time samples for each braking profile (initial jerk) and the 75 percent and 100 percent time samples (final jerk). This approach was deemed a reasonable estimate of the slope at these regions, as a substantial level of linearity was expected.

Braking onset TTI: The TTI value at the onset of deceleration was also determined. In addition to using the raw TTI for analysis, an additional measure derived from TTI was developed. The Adjusted TTI was defined as the absolute maximum of amber time remaining and TTI at the onset of braking. The main difference between TTI and Adjusted TTI is that Adjusted TTI allows for examination of driver reaction to the amber in some situations. The reason for inclusion of TTI is to determine whether drivers subjectively used TTI as a decision-making tool for stopping; that is, whether they subjectively decided to stop when faced with an amber or red light at a certain TTI value. Alternatively, drivers may make a similar determination, but the determination would be based on the perceived remaining amber time. In this case, the subjective decision would be to stop if the driver perceives the remaining amber time to be less than a certain amount, regardless of TTI. Drivers would then fall back to a constant TTI when the amber time is known to be very small or if drivers approach a red indication. This measurement is provided by the Adjusted TTI.

Intersection violator: This binary variable tallied the number of times that a crossing would not have been considered legal in most states. In general, a vehicle must have entered the intersection prior to the red phase or else it is considered in violation of the TCD. Similarly, any driver in this study who crossed the stop bar during the red phase was considered a violator. A second violation case occurs if a driver entered the intersection during the amber phase but failed to correctly clear the intersection. This occurred when a driver misjudged their ability to stop prior to the stop bar and instead stopped inside the intersection. For all violations, an 8-foot allowance was provided such that drivers could creep over the stop bar while stopping without being tagged as a violator. The reason for this 8-foot allowance was to eliminate approaches which, although technically a violation, negligibly increased collision risk and were unlikely to result in a ticket. This included drivers who creep over the stop bar and late stoppers. Creeping occurs when a vehicle nearly stops and then slowly passes over the stop bar by a few inches or feet. This does not represent a driver who is likely to have increased risk of a collision or traffic ticket and thus does not need to be tagged as a violator. Similarly, drivers who stop late by crossing over the stop bar without significantly entering the intersection have neither increased collision risk nor receive a ticket. Eight feet was selected as the criteria because it represents approximately half the length of a typical vehicle crossing over the stop bar. Late stoppers passing more than 8 ft over the stop bar significantly enter the intersection and could potentially receive a ticket. All other drivers were considered non-violators.

Driving aggressivity rating: The Driver Stress Inventory (DSI) and Dula Dangerous Driving Index (DDDI) were calculated from a pre-experimental questionnaire given to participants. Both scales have been shown to predict an individual's willingness to operate a motor vehicle in a dangerous and aggressive manner (Matthews et al., 1996; Dula and Ballard, 2003). The DSI has been in development for over a decade and has been validated in numerous studies. It measures the participant on five factors related to driving. These include aggression ("I really dislike other drivers who cause me problems"), dislike of driving ("I feel tense or nervous when overtaking another vehicle"), hazard monitoring ("I make an effort to look for potential hazards when driving"), thrill seeking ("I get a real thrill out of driving fast"), and fatigue ("I become inattentive to road signs when I have to drive for several hours") (Matthews et al., 1996). Matthews et al. (1996) characterized aggression items as relating to feelings of anger, impatience, hostility, and negative beliefs about other drivers. Dislike is associated with feelings of anxiety and tension and negative cognitive appraisals. Hazard monitoring is associated with safety-promoting behaviors and has shown high negative correlations with accident likelihoods. Thrill-seeking, as well as aggression, are related to dangerous behaviors, in particular, high-speed driving. In contrast to the DSI, the DDDI is a new scale that, to the authors' knowledge, had only been validated using other questionnaires.

It is believed that the DDDI may include questions that are more directly related to risk-taking and may thus be a better predictor of violation propensity. The DDDI is divided into three categorical subscales: aggressive driving, negative emotional driving, and risky driving (Dula and Ballard, 2003). Dula and Ballard (2003) identify aggressive driving as behaviors intentionally meant to annoy, irritate, or punish other drivers. Negative emotional driving reflects irritability and anger or the general tendency to become annoyed with other drivers. Lastly, risky driving represents the driver's willingness to engage in unsafe driving behaviors. The intention of these indices is to determine whether a driver's allowable level of risk is related to their intersection-crossing behavior.

These measures were only obtained for the 56.3-km/h (35-mph) experimental conditions. Because the results obtained for this condition do not suggest aggressivity as a predictor of intersection approach behavior, the questionnaires were not administered to participants of the higher-speed experimental trials.

Participants

Fifty-six participants (28 per speed condition), equally split by gender and age group, volunteered for this research. Each participant was pre-screened during initial phone contact to verify possession of a valid United States driver's license, lack of medical conditions precluding them from the experiment, and appropriate age and gender demographics. On the day of experimentation participants filled out an informed consent and a medical questionnaire that incorporated an additional verification of their abilities to participate. A standard Snellen eye test was performed to ensure a corrected visual acuity of 20/40 or better (as required by Virginia law). Finally, a red/green color blindness test was also administered. All participants passed the health screening and vision tests.

Previous experimental experience was also considered for selection during the pre-screening process. Most participants had not previously participated in any studies at VTTI. Those who had were only allowed to participate if the previous study did not include any surprise events to prevent driver expectancies about the experiment that might influence their intersection approach behavior. Participants received compensation of $10 per hour plus bonuses.

Procedure

Participant Screening

Participants underwent preliminary screening during initial phone contact. The screening ensured that only subjects of the required age and gender were invited to participate. Additionally, this provided an opportunity to exclude participants who had any medical conditions that represented safety concerns. Participants who were qualified and willing to perform the study were scheduled for testing. Participants were instructed to arrive at VTTI at a mutually agreeable time. An experimenter met them in the main lobby and escorted them to a screening room. Participants then completed an informed consent form, health-screening questionnaire, a W-9 tax form, a Snellen eye test, and the Ishihara color blindness test. The short health questionnaire was a safety measure to verify that the driver did not have any medical conditions that may be aggravated by rapid deceleration and was not under the influence of any drugs that could impair his or her ability to drive. The vision test ensured that all participants had a corrected acuity of at least 20/40 as prescribed by Virginia law. Finally, the Ishihara color blindness test was administered. Once these procedures were completed, orientation was able to begin.

Participant Orientation

Participants in the same speed groups underwent an identical orientation session prior to beginning the experiment. For participants in the 56.3-km/h (35-mph) conditions, the first step was to provide the pre-driving questionnaires. These were administered in successive order, beginning with the DDDI (Appendix B1), and followed by the DSI (Appendix B2) and a sleep hygiene questionnaire. The DDDI and DSI focused on driving and in particular aggressive driving. The sleep hygiene questionnaire was a ruse designed to dissipate any expectation that resulted from the driving questionnaires.

After the participants had completed the questionnaires (for the 56.3-km/h (35-mph) group) or immediately after the screening (for the 72.4-km/h (45-mph) group), they were escorted to the experimental vehicle where they were instructed to adjust the seat, mirrors, and steering wheel positions to their comfort. The experimenter then sat in the passenger seat and began describing the experiment. Participants were invited to ask questions at several points throughout the description. The description included where the experiment would take place, the type of drive being simulated, how information would be collected, speed limits, and legal intersection crossing behavior.

Block 1

<u>On-road Procedure</u>: With the experimenter in the front seat, the participant was instructed to drive onto the Smart Road. As they did so, the experimenter asked the participant to maintain 35 or 45 mph (56.3 or 72.4 km/h), as appropriate for the experimental condition.

During the experiment, the driver controlled the vehicle with inputs made through the pedals and steering wheel. The vehicle responded by exhibiting velocity and acceleration. These variables were transferred from the vehicle to the onboard DAS in real time. At about 457 m (1,500 ft) from the intersection, the experimenter, who controlled the experiment from the passenger seat, began the trial. This message was sent to the DAS, which in turn sent a wireless message to the signal controller. This message contained signal phase, signal timing, and phase-change distance information for the trial. The controller then listened for the photogate interrupt corresponding to the trial to trigger the signal phase change. In order to provide the controller with this information and to detect violations, photogates were located at each of the five phase-change distances and at the stop bar. When the vehicle interrupted the appropriate photogate, the controller initiated the phase change corresponding to the sent trial.

No trial was sent for the first complete loop around the test track. This provided the subject with a familiarization period prior to data collection. After the familiarization period, data collection began by sending the first trial. Each participant experienced the experimental conditions in a pre-determined presentation order as outlined previously in the experimental design section.

Baseline Driver State: The baseline condition used the standard ITE intersection timing algorithm for the amber change interval. The condition should represent exactly what a driver would encounter on an actual roadway. That is, as the intersection was approached, the signal changed from the green phase to the amber phase. After the standard change interval, the lamp switched to the red phase. For short phase-change distances, the baseline driver typically traveled through the intersection toward the beginning of the amber change interval. For longer phase-change distances, the baseline driver typically recognized that the risk of violation associated with crossing the intersection was too high and decelerated to a stop prior to the stop bar.

Distracted Driver State: The simulation method for this condition, as described previously, was to shorten the amber change interval. The time in which the amber phase was shortened was assumed to approximate the time of inattention. As a participant approached the intersection, the corresponding photogate sensed the vehicle crossing. However, rather than immediately initiating the phase change, the TCD awaited a 1.6-second distraction delay. Once this delay had elapsed, the amber phase-change began; however, the amber phase still ended at the same distance from the intersection as for the baseline condition. The result was a shorter amber phase for the same phase-change distance as the other driver states. The shorter interval increased the size of the dilemma zone and thus increased the number of violations.

Block 2

On-road Procedure: The second block counterbalanced the presentation of conditions for the willful driver state. In order to successfully modify participants' intersection crossing cost/benefit ratio, they had to be informed of the study's interest in the intersection.

Willful Driver State: When the first block was complete, participants were instructed to park along the roadway at the east end of the experimental loop. The experimenter then explained the second block in which they were asked to attempt to beat the light. Participants were told that a second experimental portion was starting. In this portion, the focus was to examine the circumstances under which people choose to beat the red light. Participants were asked to imagine that they were either late for an appointment or in a hurry to get to their destination. Thus, the scenario was developed in which a driver may be more likely to behave in a risky manner by attempting late crossings. The RLR behavior was further elicited from subjects by adjusting their cost-benefit ratio. That is, subjects were paid a bonus for each time they entered the intersection prior to the red light and had money deducted each time they violated the intersection. No money was added or subtracted from their bonus if they decided to perform a legal stop.

After the second orientation was complete, participants were instructed to begin driving the loop. The same TCD algorithm used during the baseline condition was repeated for this state. The only difference between the willful and baseline conditions was the extra motivation provided through the monetary incentives.

Debriefing: After completing all the experimental trials, subjects were instructed to return to the building. Upon arriving at the building, participants were debriefed. It was explained that the actual goal of the study was to analyze how stopping behavior changes across driving states. It was also explained to the participants why they were not fully informed of the purpose earlier. The experimenter answered any questions that arose and then asked the participant to sign a debriefing form. The form acknowledged that they had been debriefed and acted as a receipt for their participation. Participants were then compensated and asked not to discuss the details of the study with anybody for the next 3 months. The entire experimental procedure I (including participant greeting, orientation, driving, and debriefing) lasted approximately 1 hour 15 minutes.

Data Reduction and Analysis

After completion of the experiment, the data were downloaded to a server where they were accessible for data reduction. Most of the data reduction process used the Matlab® environment (Release 12; Mathworks®, Natick, MA). Although analysis was primarily based on data provided from vehicle sensors, the video files did have some utility for this study. First, it allowed for post hoc visualization of scenarios affording insight into data trends. The data analyzers occasionally watched the driver actions that caused particular trends in the numeric data collected. This allowed the test condition parameters to be verified when needed.

Analysis of variance (ANOVA) and chi-square tests were used to determine statistical differences for the dependent variables as a result of changes in the independent variables. In addition, means and standard deviations were determined for the various dependent variables, and these results were graphed to examine the statistical differences observed. Correlation analysis was also performed in some instances in which relationships between dependent variables were deemed of interest. SAS® software (Cary, NC) was used for all statistical tests. For all statistical tests, a Type I error of 0.05 was used to establish significance. When significant effects were identified, a Tukey-Kramer post hoc test was performed.

Results and Discussion

A typical stopping intersection approach is demonstrated below (Figure 42). As the intersection was approached, the traffic signal changed phase, switching from a green to an amber indication when the vehicle was 56.4 m (185 ft) from the intersection. Shortly after the amber light was presented, the driver released the accelerator pedal and subsequently pushed the brake pedal, as shown by the brake and throttle position plots. Once the brake was applied, the vehicle began to decelerate. Typically, the driver pressed the brake to approximately 79 percent of its maximum travel. The signal switched to the red phase when the vehicle was approximately 7.62 m (25 ft) from the intersection. Deceleration then continued until the driver reached a complete stop, approximately 1.5 m (5 ft) prior to the stop bar.

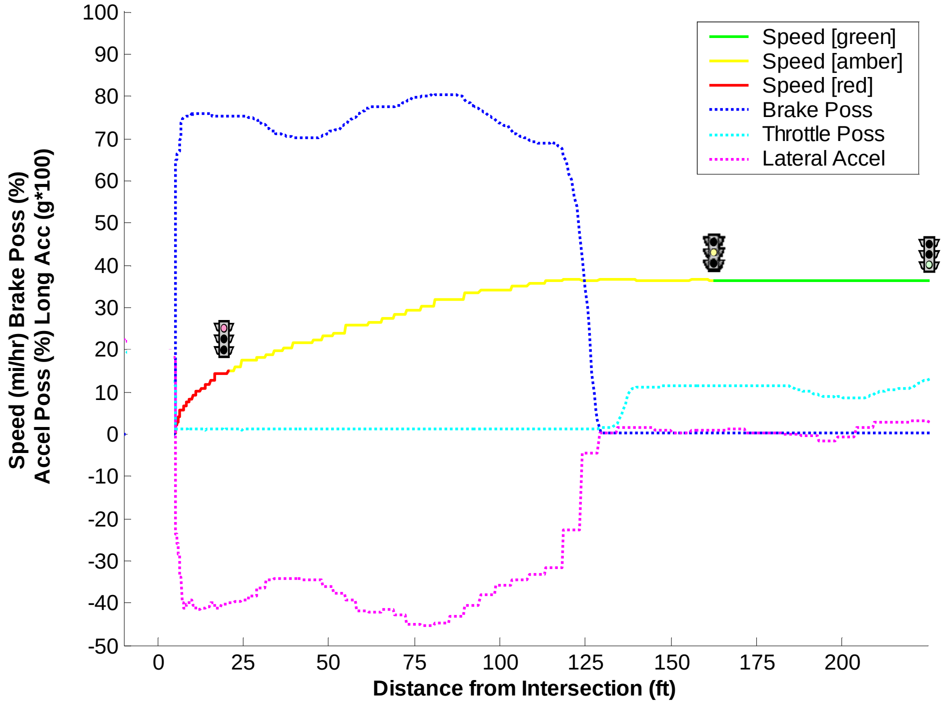

Figure 42. Typical intersection approach. The color of the solid line indicates the corresponding signal phase. Traffic signal icons indicate phase transition points. (Note: 1 ft = 0.305 m)

The complete data set consisted of 1,176 intersection crossings (56 participants multiplied by 21 crossings per participant). Four intersection crossings had to be removed from the 56.3-km/h (35-mph) data set because of hardware malfunctions caused primarily by wireless communication dropouts.

For the 72.4-km/h (45-mph) speed group, data were missing for two intersection crossings, which were inadvertently skipped by the in-vehicle experimenter. The remaining data for the 72.4-km/h condition are shown in Figure 44.

Drivers approaching the intersection were placed into two distinct groups: 1) drivers who choose to stop and 2) drivers who choose to go (Figures 45 and 46). Typically, a Stop driver begins decelerating as the intersection is approached, while the Go driver maintains the approach speed or accelerates slightly. This distinction between Stop and Go drivers will be used throughout this discussion. Note that a side effect of looking at data in a distance domain is the inflection point visible near the stop bar. When the signal phase returns to green, the vehicle drives away increasing the average speed at that point and causing the inflection. Data in this region should be disregarded.

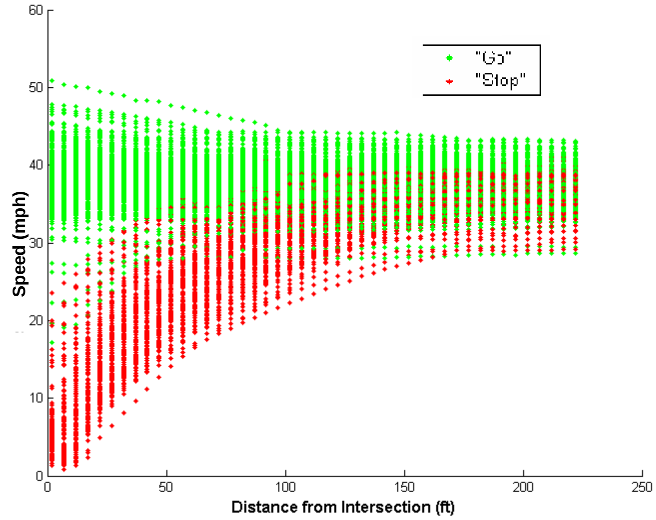

Figure 43. Scatter plot of all speed data points for the 56.3-km/h (35-mph) nominal speed group. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

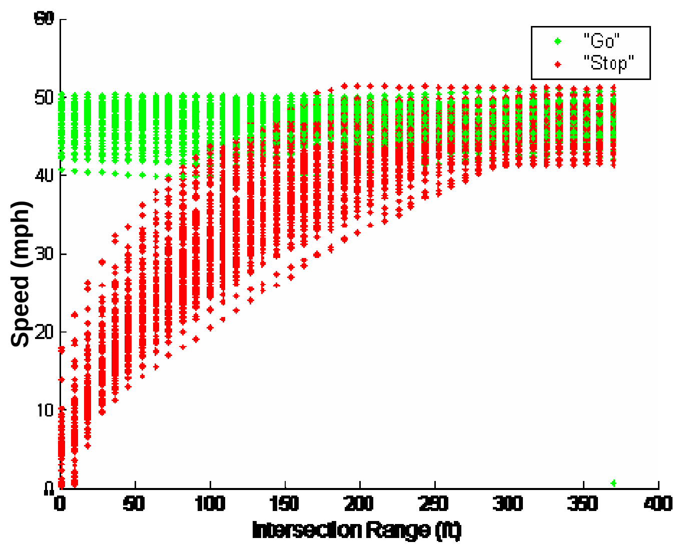

Figure 44. Scatter plot of all speed data points for the 72.4-km/h (45-mph) nominal speed group. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

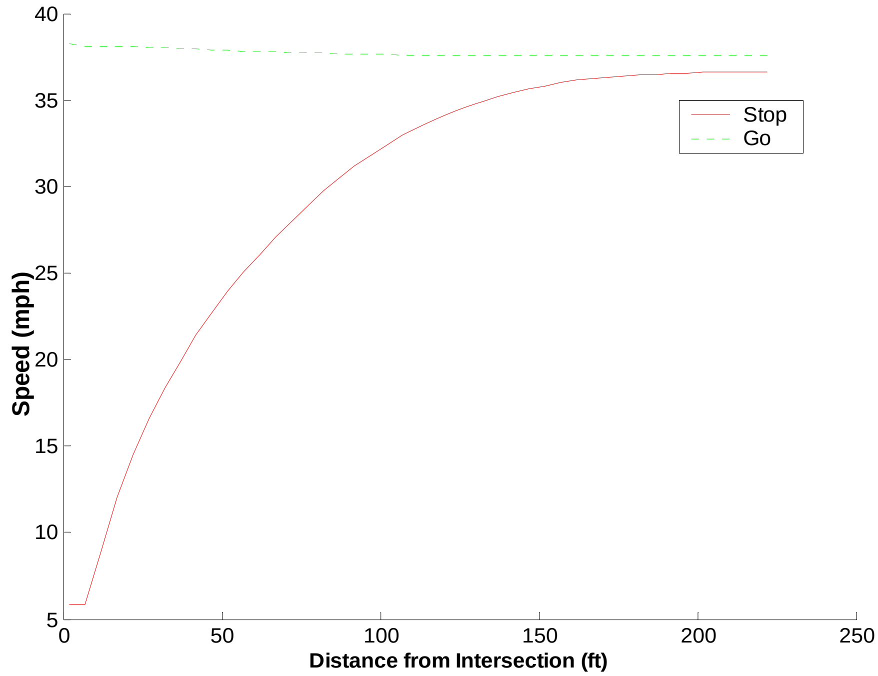

Figure 45. Average vehicle speed approach profile across all conditions and divided into Stop and Go drivers for the 56.3-km/h (35-mph) nominal speed group. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

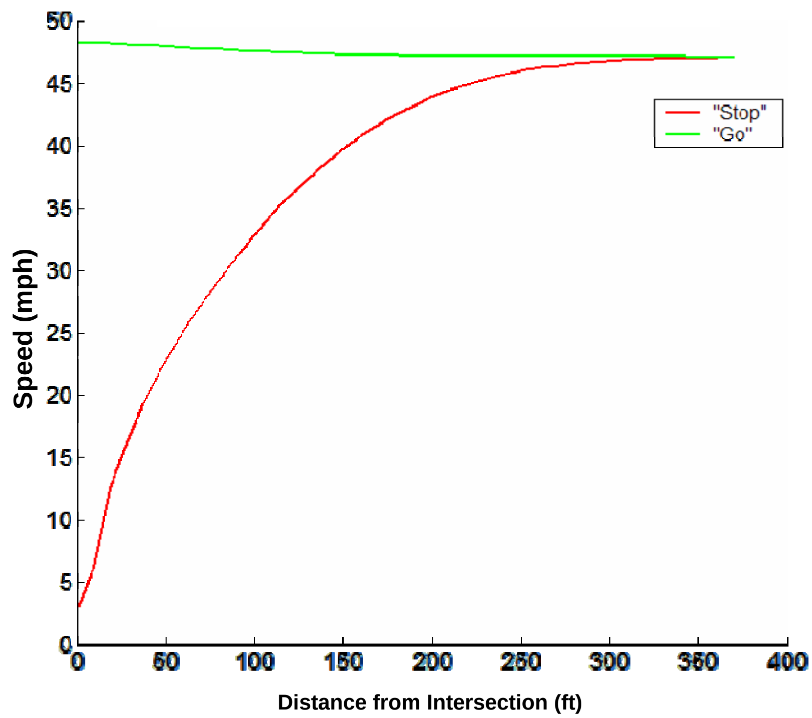

Figure 46. Average vehicle speed approach profile across all conditions and divided into Stop and Go drivers for the 72.4-km/h (45-mph) nominal speed group. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The remaining portion of the data analysis section is devoted to addressing the two research questions directly.

RQ 1: How does driver state affect intersection performance?

Driver state can affect the intersection approach in many ways. It can influence the driver's decision on whether to stop, when to brake, and how quickly to stop, or alternatively, when to press the throttle and how hard to accelerate. A top-down approach is used to discuss the effects of driver state. First, its influence on the driver's decision to stop will be analyzed using chi-squared techniques. Then approach profiles will be discussed using summary statistics and subsequently decomposed with an inferential analysis of speed, reaction time, acceleration, and violation rate. Driver demographic (age and gender effects) will be briefly integrated throughout this discussion as appropriate.

The Stop or Go Decision – a Chi-Squared Analysis

The Driver State factor significantly affected a driver's decision to stop for both speed groups. Results from a chi-square analysis for the 56.3-km/h (35-mph) group demonstrate a higher tendency for drivers to stop in the baseline condition than in the distracted condition ($\chi^2(2, N = 582) = 71.77, p < 0.0001$). There were a total of 154 stops (out of 420 amber phase approaches). Most of these stops (N = 82, 59 percent) occurred in the baseline state; willful drivers performed 62 stops (44 percent), while distracted drivers stopped in only 10 instances (7 percent).

Results for the 72.4-km/h (45-mph) group demonstrate a higher tendency for drivers to stop in the baseline condition than in the distracted condition ($\chi^2(2, N = 419) = 71.50$, $p < 0.0001$). There were 259 stops (out of 419 amber phase approaches). Most of these stops (N = 120, 46 percent) occurred in the baseline state, while willful drivers performed 87 stops (34 percent), and distracted drivers stopped in 52 instances (20 percent). The disparity of distracted drivers against baseline and willful driver states demonstrates that drivers with an inadequate amber phase (due to distraction, poor phase timing, or poor judgment) are less likely to stop and may thus be more likely to violate a TCD. This finding has important implications for the subsequent human factors experiments. The motivation experienced by willful drivers adjusted their cost/benefit ratio, resulting in increased attempts to beat the light.

Comparing both speed groups, drivers in the 72.4-km/h (45-mph) study tended to stop more often (259 stops) than drivers in the 56.3-km/h (35-mph) study (154 stops). However, this was somewhat expected, as the 72.4-km/h (45-mph) study included a longer phase-change distance at which most drivers were expected to recognize that a stop was necessary. The proportion of stops in the baseline state was higher for the 56.3-km/h (35-mph) study (59 percent versus 46 percent), as was the proportion of willful drivers who stopped (44 percent versus 34 percent). The proportion of distracted drivers who stopped in the 56.3-km/h (35-mph) study, however, was smaller than the proportion for the 72.4-km/h (45-mph) study (7 percent versus 20 percent). This is also a side effect of the new distances, which made the stopping decision clearer even for distracted drivers.

While no statistical test of this effect was performed due to insufficient degrees of freedom, Phase Change Distance and Driver State also appeared to interact to affect a driver's decision to stop (Figures 47 and 48). For instance, at a phase-change distance of 185 ft, nearly 90 percent (25) of the drivers in the baseline condition stopped, while less than 5 percent (1) of distracted drivers did so. Distracted drivers exhibited a lower propensity to stop because the simulated distraction did not provide them with the opportunity to react to the full duration of the phase change.

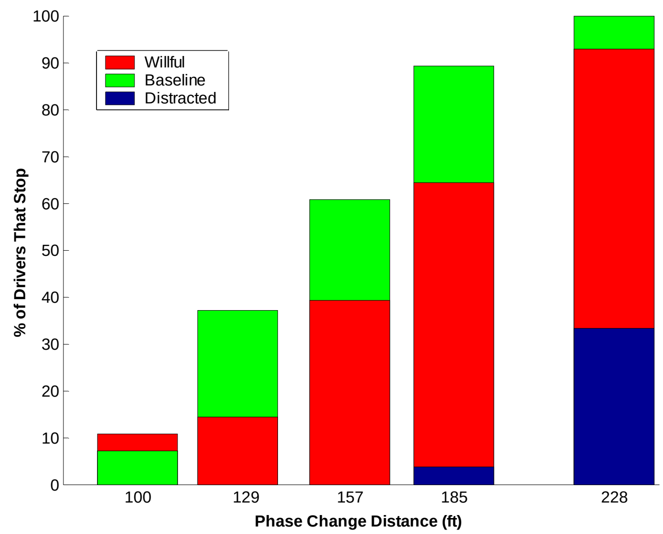

Figure 47. Percentage of baseline, willful, and distracted drivers who chose to stop at the five phase change distances for the 56.3-km/h (35-mph) nominal speed. (Note: 1 ft = 0.305 m)

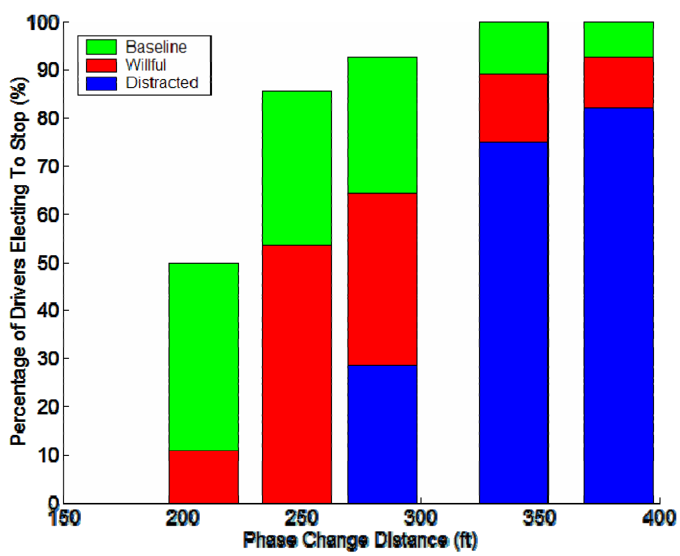

Figure 48. Percentage of baseline, willful, and distracted drivers who chose to stop at the five phase change distances for the 72.4-km/h (45-mph) nominal speed. (Note: 1 ft = 0.305 m)

Figures 47 and 48 clearly demonstrate the decreased likelihood for distracted drivers to stop during the intersection approach. For the 56.3-km/h (35-mph) speed group, the TCD was timed such that in the distracted case, the red phase was presented after the driver entered the intersection when the amber phase change was triggered at distances of 30.48 m (100 ft) and 39.32 m (129 ft). At 47.85 m (157 ft), the distracted driver would be required to stop at an uncomfortably high rate of deceleration. At phase-change distances of 56.39 m (185 ft) and 69.49 m (228 ft), the distracted driver received the amber indication far enough from the intersection that most drivers would be expected to stop. The distribution of baseline to willful stops at the 30.48-meter (100-foot) phase-change distance should be interpreted cautiously. This distribution is based on only five stops and lacks sufficient power to make any conclusions. It also demonstrates an unintended consequence of the bonus system. On rare occasions, the bonus may have caused drivers to be over-attentive to the signal, thus stopping when they normally would not. However, it is foreseeable that some drivers may act similarly when they are in a hurry outside the experimental environment.

Similar observations can be made for the 72.4-km/h (45-mph) speed group. By delaying the amber presentation, drivers were led to assume they could pass through the intersection prior to the red indication. While this was a valid assumption for the first two phase-change distances, the middle distance could result in a violation if the driver failed to accelerate, and the farthest distances would have resulted in violations even under heavy vehicle acceleration. It is interesting to note that the motivation in the willful case was sufficient to cause violations even at 116.74 m (383 ft), where the decision to stop was very clear for baseline drivers.

The proportion of drivers stopping at different phase-change distances was also different between studies, even after ensuring that the distances conformed to similar TTIrp values. For example, at the -1.09-second TTIrp distance, approximately 35 percent of 56.3-km/h (35-mph) baseline drivers stopped; the proportion was closer to 50 percent for baseline drivers in the 72.4-km/h (45-mph) condition.

For the 56.3-km/h (35-mph) speed group, driver demographics also had an influence on a driver's decision to stop. A Chi-squared analysis of Age (χ^2 [1, N = 582] = 5.31, p = 0.021) and Gender (χ^2 [1, N = 582] = 3.68, p = 0.055) indicated a varying propensity for stopping for age, with younger drivers stopping less often (Table 31). While this propensity was not statistically significant for Gender, the results indicate a tendency for male drivers to stop less often.

Table 31. Stop decision frequency counts for Age and Gender for the 56.3 km/h (35 mph) speed group.

		Age		
		Younger	Older	Total
Gender	Male	38	28	66
	Female	37	51	88
	Total	65	89	154

However, these results are not evident for the 72.4-km/h (45-mph) study, in which driver demographics did not have an influence on a driver's decision to stop. A Chi-squared analysis of Age (χ^2 [1, N = 419] = 2.96, p = 0.085) and Gender (χ^2 [1, N = 419] = 0.984, p = 0.321) indicated that demographics did not influence the stop decision for drivers at this nominal speed. The differences between the studies are likely due to the differences in the TTIrp sample used for both studies.

The age effect and gender trend found for the 56.3-km/h (35-mph) group agree with results of past research indicating that younger drivers are less likely than older drivers to stop at the traffic signal (Sivak et al., 1989). Similarly, research by Wang and Knipling (1994) suggests that males are more likely to collide with other vehicles during intersection crossings. It may be that the males' tendency to stop less frequently increases the number of opportunities for late crossings. These late crossings are likely to increase the potential for a collision, possibly explaining the results reported by Wang and Knipling. This trend was also reflected during the analysis of violation rates, discussed in a subsequent section. To better understand how drivers stop, approach profiles are discussed in the next section.

The Intersection Approach

General intersection approach information can be gathered by examining intersection approach profiles. Plots of speed over distance make it possible to get qualitative information about braking points, braking intensity, acceleration, and speed, as well as differences in these factors between driving groups. For drivers who stop, the baseline state exhibited the earliest brake application and the most relaxed deceleration profile (Figures 49 and 50). The willful state resulted in a slightly steeper profile than the baseline state for a region of the approach profile. This does not appear to be primarily a result of a later decision to brake. Rather, it seems to be caused by the higher initial speed of willful drivers. In contrast, the distracted driver state demonstrates a much later brake application with a steep deceleration profile. This is expected, given the nature of the simulated distraction. Distracted drivers saw the amber later than their counterparts; accordingly, they reacted later. However, it is expected that a truly distracted driver who is not attentive to the signal change would respond similarly.

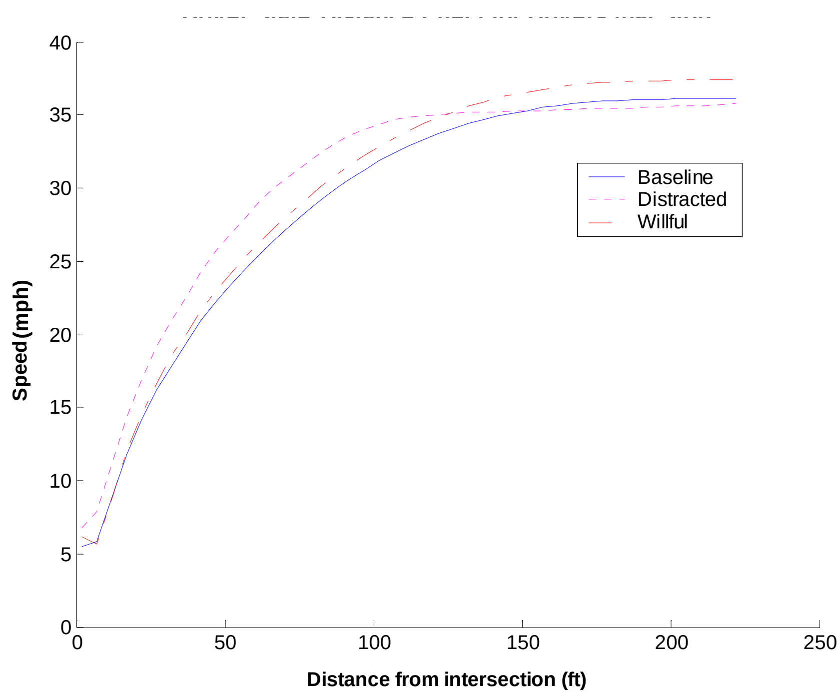

Figure 49. Average stop profiles for baseline, distracted, and willful driver states for the 56.3-km/h (35-mph) nominal speed. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

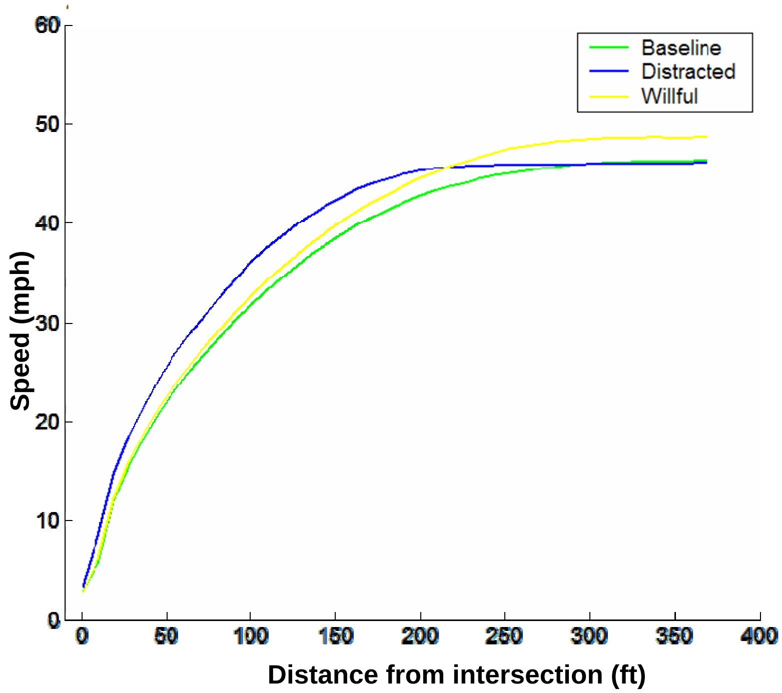

Figure 50. Average stop profiles for baseline, distracted, and willful driver states for the 72.4–km/h (45-mph) nominal speed. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

For drivers who go, the willful driving state resulted in a tendency to drive faster and to accelerate through the intersection (Figures 51 and 52). This is likely a result of the driver trying to reduce the chance of a violation that would reduce their bonus pay. Willful drivers represented a group of individuals who are motivated to cross the intersection. A side effect of this motivation is an increased likelihood to speed in anticipation of the signal change. However, the effect size was small; willful drivers in the 56.3-km/h (35-mph) group went on average 2.4 km/h (1.5 mph) faster than drivers in the baseline and distracted conditions. In the 72.4-km/h (45-mph) group, willful drivers on average went 4.5 km/h (2.77 mph) faster than drivers in the baseline and distracted conditions.

Differences in the approach profiles for both go and stop cases can be used to help develop IDS signal violation prevention algorithms. Assuming that the distracted driver approach represents the latest that a driver would be likely to stop, it may be reasonable to warn any driver who exceeds that approach profile (Figure 52). On the other hand, drivers whose approach falls near the baseline profile should not be warned. Warning drivers near the baseline profile would result in an unacceptable number of annoyance alarms and degrade the overall system performance by decreasing driver confidence in the system.

The algorithm may also need to identify the willful violator early in the approach. If the speed (and/or acceleration) profile of the willful driver is such that the intersection is likely to be entered prior to a conflict situation, the algorithm should not call for a warning. However, if the vehicle is not moving sufficiently fast (and/or accelerating to do so), the warning will need to be provided early during the approach to alter the willful driver's motivation and allow for sufficient time to stop the vehicle from a higher than average speed.

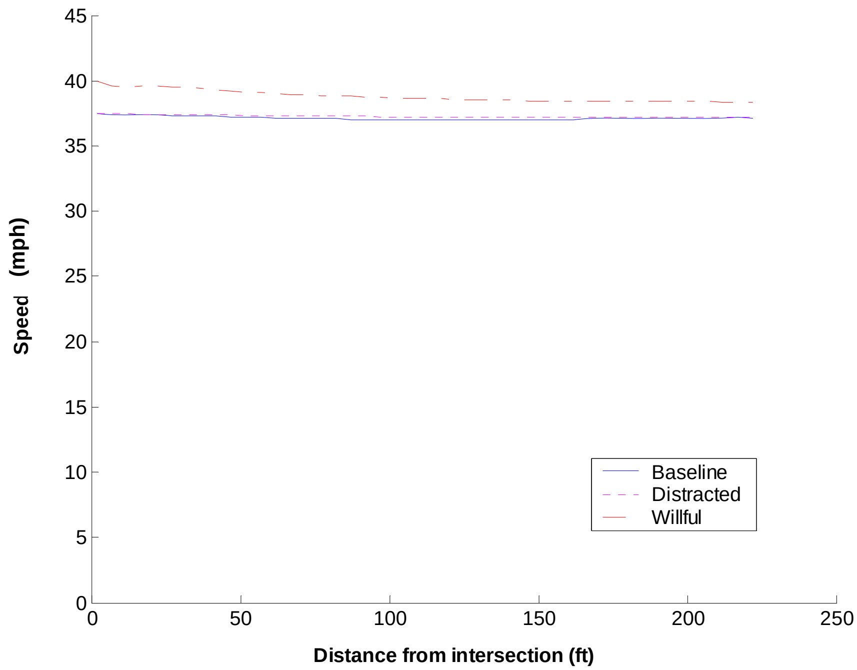

Figure 51. Average go profiles for baseline, distracted, and willful driver states for the 56.3-km/h (35-mph) nominal speed. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

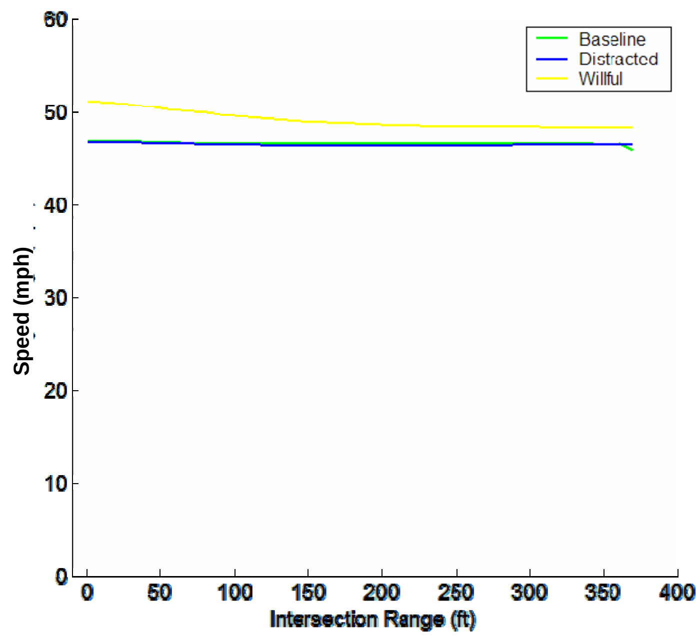

Figure 52. Average go profiles for baseline, distracted, and willful driver states for the 72.4–km/h (45-mph) nominal speed. Note that the baseline and distracted lines overlap considerably (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Different phase-change distances also produced clearly differentiable average approach profiles. For drivers who chose to stop, the farther from the intersection the phase change occurred, the more gradual the deceleration profile (Figures 53 and 54). Though the average 30.5-meter (100-foot) phase-change profile does not conform very well to profiles at other distances, it is important to note that this may be due to the relatively small sample on which it was based. The five drivers who stopped at this distance had an unusually early decrease in speed, possibly indicating an expectation for the signal to change. The difference in slope with each phase-change distance indicates the increased deceleration required for a driver to stop. This information may be useful for algorithm development because drivers can be expected to follow different approach profiles depending upon when the amber signal was presented.

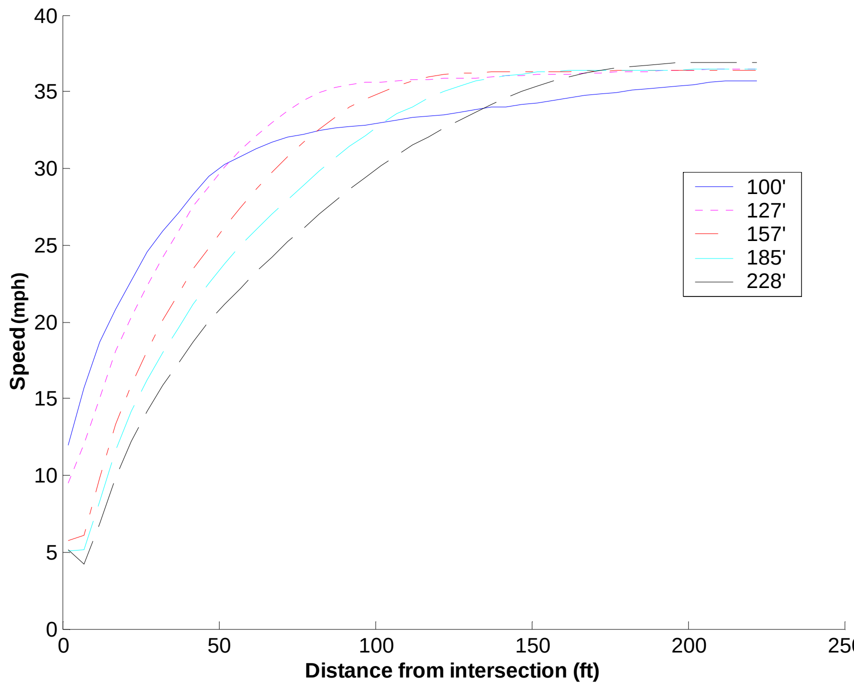

Figure 53. Average stop intersection approach by signal phase change distance for the 56.3- km/h (35-mph) nominal speed. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

For drivers who decided to go, phase change distance had a less noticeable effect (Figures 55 and 56). In general, the farther from the intersection a phase change occurred, the sooner drivers started accelerating and the higher their speed during an intersection crossing. Drivers appeared to have estimated the level of acceleration necessary to legally cross the intersection and attempted to obtain it. Note that for the farthest phase-change distance (located at 116.7 m (383 ft)) in the 72.4-km/h (45-mph) case, there was a sharp deceleration near the intersection. At this farthest distance, the driver violated severely if he or she did not stop, so much so that the red light was presented with sufficient time for the driver to see the mistake. Drivers in this instance likely decelerated with the intent of decreasing the affect of a potential conflict at the intersection.

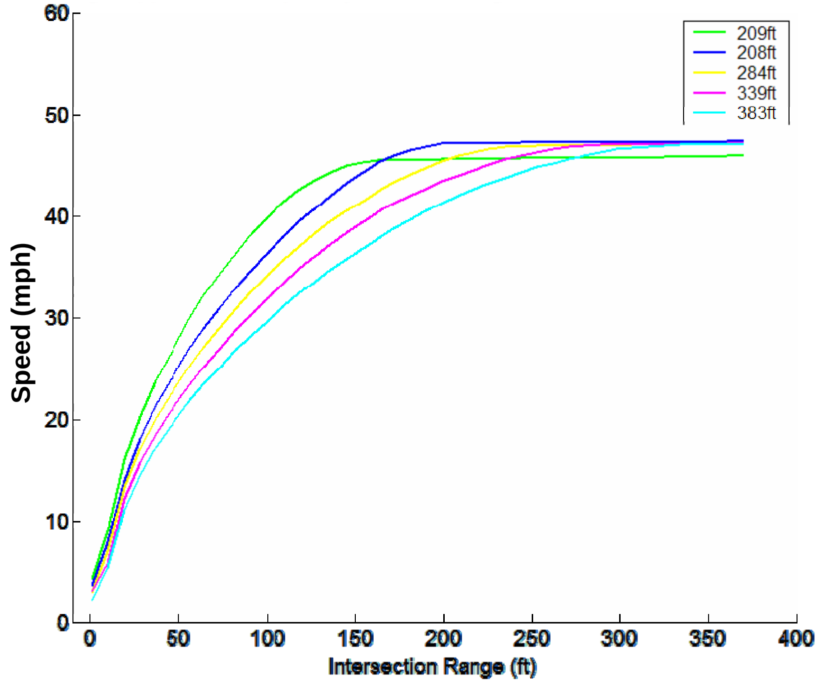

Figure 54. Average stop intersection approach by signal phase change distance for the 72.4-km/h (45-mph) nominal speed. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

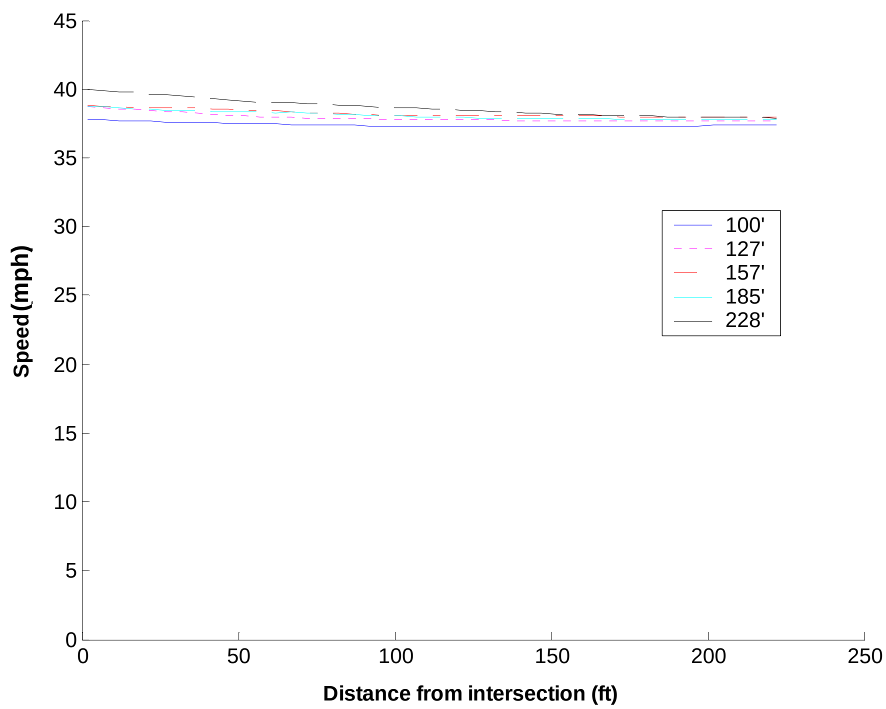

Figure 55. Average go intersection approach by phase change distance for the 56.3-km/h (35-mph) nominal speed. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

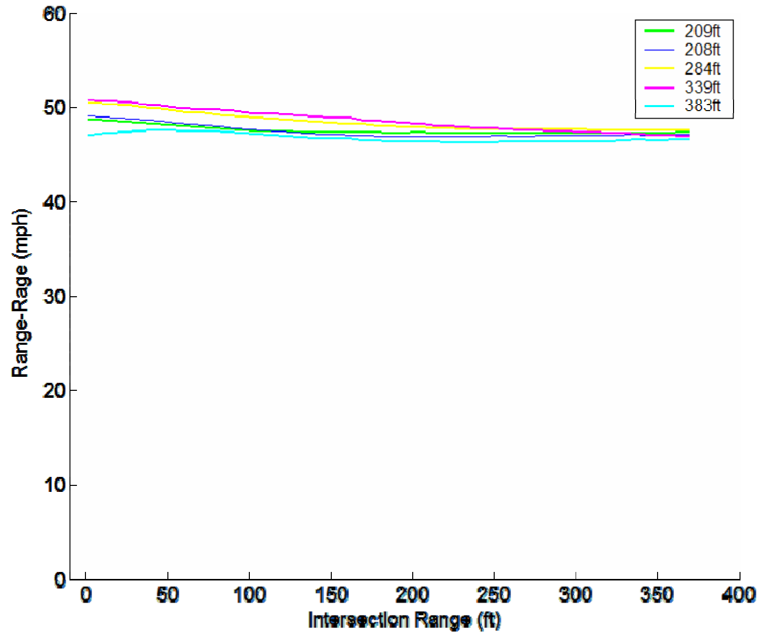

Figure 56. Average go intersection approach by phase change distance for the 72.4-km/h (45-mph) nominal speed. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Overall, qualitative observation of general approach patterns produced similar observations for both speeds. Distracted drivers tended to exhibit steeper decelerations than the baseline and willful drivers. Willful drivers tended to travel at slightly higher speeds than other drivers. When approach profiles were observed as a function of phase-change distance, steeper profiles were observed as the phase change occurred closer to the intersection.

Based on the previous plots, driver state and phase-change distance were expected to have a statistically significant effect on the intersection approach behavior of participants. To statistically analyze this possibility, the intersection approach was decomposed into different driver performance variables. The dependent performance variables analyzed (perception-reaction times, speed, deceleration, and violation rate) combine to define different aspects and characteristics of each approach profile.

Response Time Analysis

To further explore stopping behavior, the TAR and TB reaction times were compared with driver state. To test TAR and TB, the data set was filtered to include instances in which the driver chose to stop and was contacting the throttle prior to stimulus presentation. The new data set consisted of 222 sample points, distributed across both speeds.

ANOVAs were run for the TAR- and TB-dependent variables considering Age, Gender, Driver State, Phase-Change Distance (based on similar TTIrp values), and Speed as independent variables. Only two-way interactions of interest were included in the model to conserve the scarce degrees of freedom available. TAR was not significantly different within the levels of any of the independent variables of interest. TB was significant for Driver State (F (2, 32) = 3.67, p = 0.0366) and the Driver State by Speed interaction (F (2, 32) = 4.07, p = 0.0266). All driver states exhibited significantly different TB values. Distracted drivers had the lowest TB (0.67, SD = 0.09), followed by baseline (0.76, SD = 0.18), and willful drivers (0.82, SD = 0.22). The differences between averages, however, encompass only approximately 0.15 s. At 72.4 km/h (45 mph), this represents less than 3.02 m (9.9 ft). Thus, the difference seems to offer little practical application. Note also that the distracted driver group appeared to brake more consistently; the standard deviation for distracted drivers is at about 50 percent smaller than the standard deviation for the remaining two driver states. This might be interpreted as a sense of urgency in the braking effort. While baseline and willful drivers had more time to consider their option to stop or go, distracted drivers had to make a quick decision. Interestingly, this quick decision is reflected on the TB and not the TAR, suggesting that drivers tended to release the accelerator within similar time frames, then made the decision to stop or go.

Post hoc tests using the Tukey procedure indicated that the significant driver state and speed interaction for TB was due to willful drivers at the 72.4-km/h (45-mph) speed (Figure 57). These drivers required significantly more TB than baseline drivers going 56.3 km/h (35 mph) and distracted drivers going 72.4 km/h (45 mph), but were similar to drivers in other conditions. In this case, the difference between means was less than 0.2 s, representing approximately 4.0 m (13.1 ft) at 72.4 km/h (45 mph), a small practical difference. Reasons for the statistical difference most likely do not extend beyond statistical uncertainties caused by unequal sample sizes.

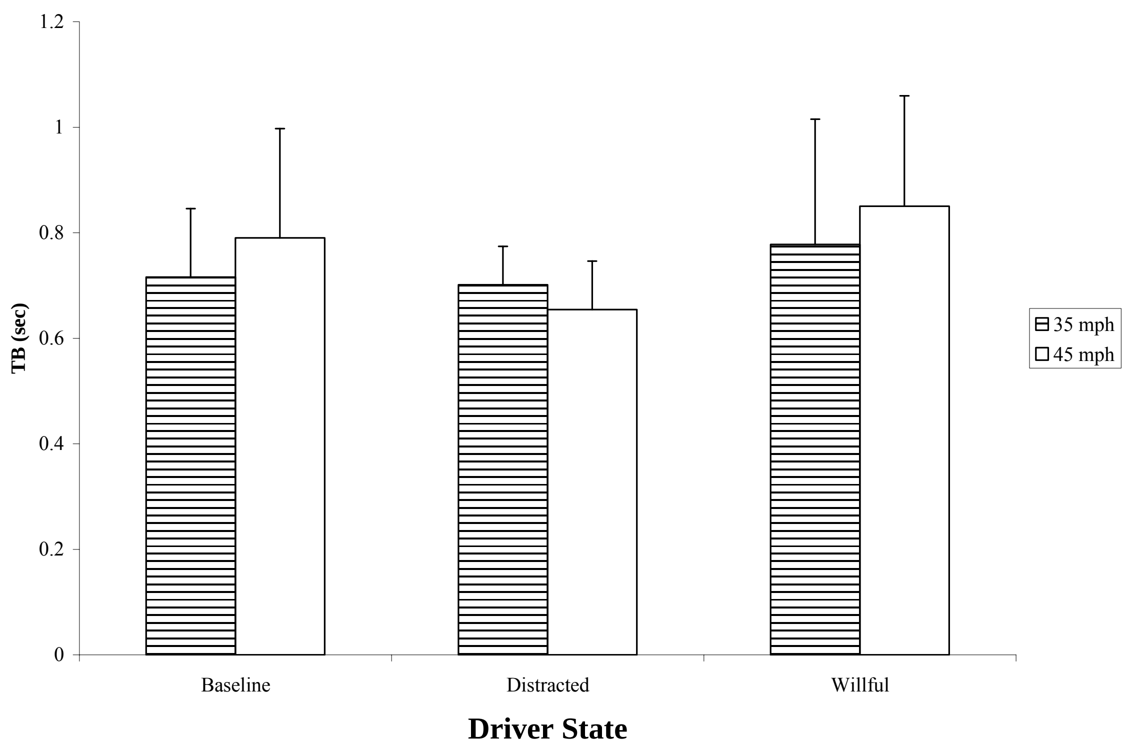

Figure 57. TB as a function of driver state and speed. Error bars indicate one standard deviation from the mean.

Speed Analysis

56.3 km/h (35 mph): Analysis on speed data was completed twice, once for drivers who chose to go (n = 262) and once for drivers who chose to stop (n = 154). Both ANOVAs included the independent variables gender, age group, and either driver state or phase-change distance. The interaction between the driver state and phase change distance independent variables was not tested due to insufficient degrees of freedom in the data. One should thus be aware that there is likelihood for these two factors to be confounded.

For drivers who go, only the driver state factor showed statistically significant speed effects ($F(2, 45) = 17.65$, $p < 0.0001$). A Tukey post-hoc test isolated the willful driver state from the other two ($p < 0.0001$). This is likely a result of the driver trying to reduce the chance of a violation that would reduce their bonus pay. As with willful drivers in the real world, these willful drivers are motivated to cross the intersection. A side effect of this motivation is an increased propensity to speed in anticipation of the signal change. However, as discussed previously, the effect size was small; willful drivers on average went 2.6 km/h (1.6 mph) faster than the baseline and distracted conditions (62.4 km/h versus 59.7 km/h and 60.0 km/h, respectively).

The distribution of significant speed effects by driver state changed when a driver decided to stop ($F(2, 28) = 3.64$, $p = 0.0394$). The baseline state became statistically isolated from the willful and distracted states ($p < 0.001$). Baseline drivers received the amber phase in a timely fashion and did not have an elevated motivation to cross the intersection. This caused an earlier decision to stop and a reduction in speed farthest from the intersection, resulting in a lower average speed. Again the effect size was small, with baseline drivers traveling 2.2 km/h (1.3 mph) slower on average (46.1 km/h) when compared with distracted and willful drivers (48.8 km/h and 47.8 km/h, respectively). The phase-change distance main effect was also significant ($F(24, 47) = 28.47$, $p < 0.0001$). A post-hoc Tukey test showed that several of the PCDs differences were significant (Table 32). In general the average speed increased with decreasing phase-change distance. This effect further supports the belief that drivers begin slowing earlier the further from the intersection an amber indication is presented. Both the stop-and-go effects for driver state and phase-change distance are apparent in the approach profiles discussed previously (Figures 49 through 56).

Table 32. Average speed by phase change distance for drivers who stop. Distances with the same letter are not statistically different from each other. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Phase Change Distance (ft)	Grouping	Average Speed (mph)
100	A	32.00
129	AB	31.21
157	B	30.38
185	C	29.27
228	D	27.87

72.4 km/h (45 mph): Analysis on speed data was completed twice, once for drivers who chose to go (n = 160) and once for drivers who chose to stop (n = 259). Both ANOVA analyses included the independent variables gender, age group, driver state, and phase-change distance.

The interaction between the driver state and phase-change distance independent variables was not tested due to insufficient degrees of freedom in the data.

For drivers who go, both the driver state ($F(2, 36) = 31.69$, $p < 0.0001$) and phase-change distance ($F(4, 58) = 3.93$, $p < 0.0068$) factors showed statistically significant speed effects. A Tukey post hoc test of driver state isolated the willful driver state from the baseline state ($p = 0.0209$) and the distracted driver state ($p = 0.0022$). However, the effect size was small; willful drivers on average drove 4.5 km/h (2.8 mph) faster (81.3 km/h, SD = 3.51) than drivers in the baseline (77.0 km/h, SD = 1.93) and distracted (75.2 km/h, SD = 3.96) conditions (Figure 58). Although phase-change distance was significant, the Tukey post hoc test could not separate the effect.

Drivers who received a phase change at 116.7 m (383 ft) and chose to go must have violated. It was speculated that these drivers may have decreased their speed during the violation, thus explaining the trend reversal shown in Figure 59. Thus, for a more sensitive test, drivers who violated the signal were removed from the analysis. Despite removal of these outliers, this test continued to produce insufficient separation. All of this implies that average speed for drivers who go is not influenced by phase change distance.

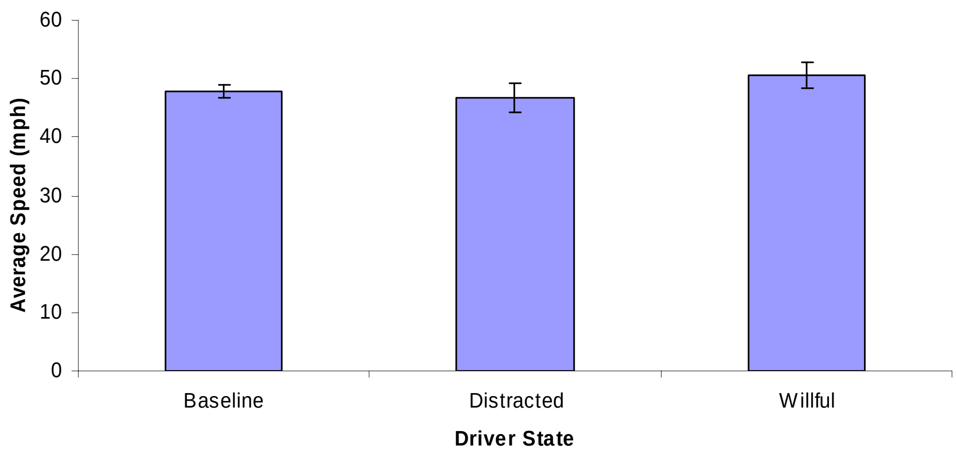

Figure 58. Average speed of intersection approach for the driver state factor considering only drivers who decided to go. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

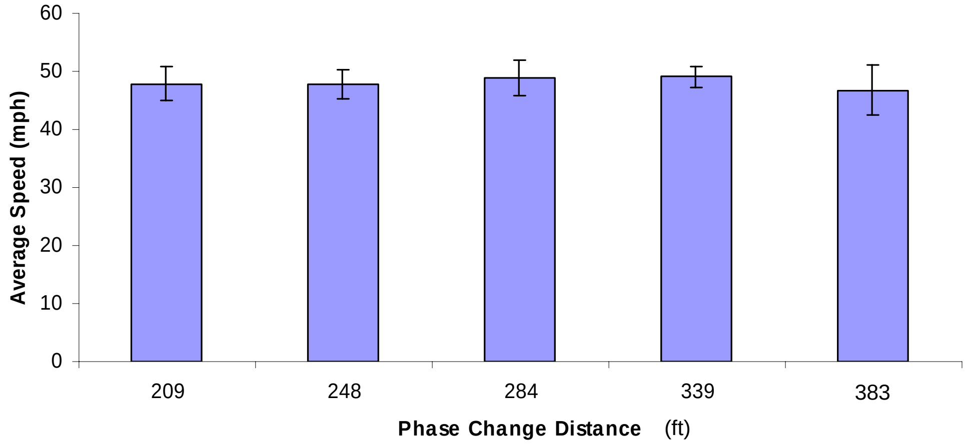

Figure 59. Average speed of intersection approach for the phase change distance factor considering only drivers who decided to go. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The distribution of significant speed effects by driver state changed when a driver decided to stop (Figure 60, $F(2, 49) = 109.58$, $p < 0.0001$). Note that the average speeds for drivers who stopped were lower than for drivers who went because the speed was averaged from the start of trial to the point of full stop. All three driver states demonstrated significant separation ($p < 0.001$ in all cases). Baseline drivers received the amber phase in a timely fashion and did not have an elevated motivation to cross the intersection. This caused an earlier decision to stop and a reduction in speed farthest from the intersection, resulting in a lower average speed. The phase-change distance main effect was also significant (Figure 61, $F(4, 87) = 81.39$, $p < 0.0001$). A post hoc Tukey test showed that all of the PCDs were significantly different from one another (Table 33). In general the average speed increased with decreasing phase-change distance. This effect further supports the logical result that drivers begin slowing earlier the farther from the intersection an amber indication is presented. It is also interesting to note that the variance in average speed increased with increasing phase-change distance. This may be due to the extra time available to drivers while making the stop-or-go decision. Both the stop and go effects for driver state and phase-change distance are apparent in the approach profiles discussed previously (Figures 49 through 56).

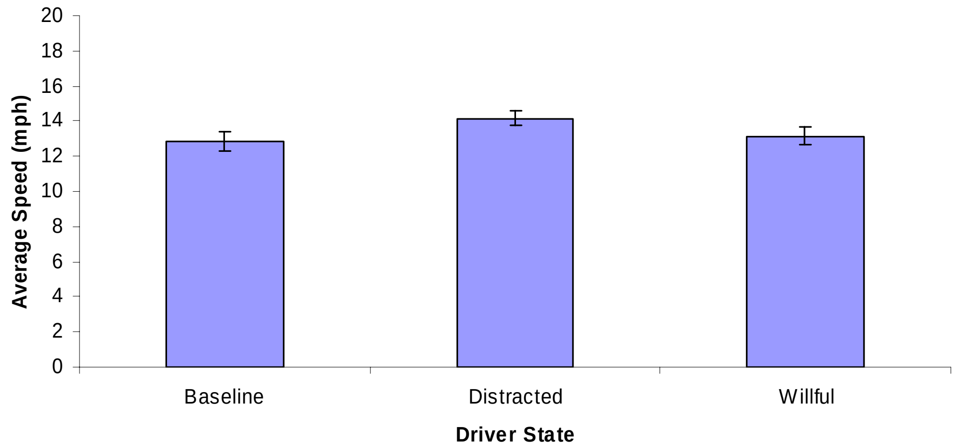

Figure 60. Average speed of intersection approach for the driver state factor considering only drivers who stop. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

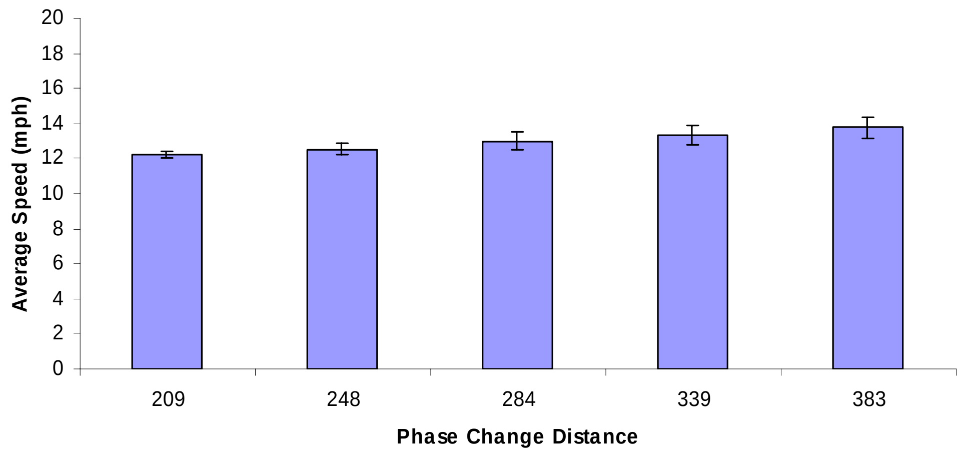

Figure 61. Average speed of intersection approach for the phase change distance factor considering only drivers who stop. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table 33. Average speed by phase change distance for drivers who stop. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h).

Phase Change Distance (ft)	Average Speed (mph)	Standard Deviation
209	12.23	0.21
248	12.53	0.33
284	12.91	0.51
339	13.35	0.56
383	13.76	0.58

Deceleration Analysis

ANOVAs were conducted for peak deceleration, required deceleration parameter, and time-weighted deceleration, using age, gender, speed, driver state, and phase-change distance as the independent variables. Due to restricted degrees of freedom, only the driver state by speed and phase-change distance by speed interactions were included in the analysis.

Peak deceleration was significantly different across levels of age group ($F(1, 51) = 5.47$, $p = 0.0231$), speed ($F(1, 51) = 88.39$, $p < 0.0001$), driver state ($F(2, 78) = 74.72$, $p < 0.0001$), phase-change distance ($F(3, 114) = 153.57$, $p < 0.0001$), the driver state by speed interaction ($F(2, 78) = 4.28$, $p = 0.0173$), and the phase-change distance by speed interaction ($F(3, 114) = 11.50$, $p < 0.0001$). The age group difference was not reflected in the post hoc test, although the older drivers had a lower mean peak deceleration. The peak deceleration at 56.3 km/h (35 mph, mean = 0.47 *g*, SD = 0.11 *g*) was higher than the peak deceleration at 72.4 km/h (45 mph, mean = 0.34 *g*, SD = 0.08 *g*). All three driver states exhibited different levels of peak deceleration, with baseline drivers exhibiting the least (mean = 0.39 *g*, SD = 0.11 *g*), followed by willful drivers (mean = 0.40 *g*, SD = 0.12 *g*) and distracted drivers (mean = 0.44 *g*, SD = 0.11 g). All phase-change distances (represented now by their respective TTIrp values) required significantly different levels of peak deceleration, which decreased with increased phase change distance (Table 34).

Table 34. Peak deceleration as a function of phase change distance (represented as TTIrp).

TTIrp (s)	Mean Peak Deceleration (*g*)	SD
-1.09	0.52	0.13
-0.51	0.44	0.11
0.04	0.40	0.10
0.87	0.35	0.09

Post hoc analysis of the driver state by speed interaction (Figure 62) using the Tukey procedure showed that the 56.3- and 72.4-km/h (35- and 45-mph) distracted drivers exhibited different levels of peak deceleration. However, drivers in other classifications did not decelerate differently for the same speed (i.e., the 56.3-km/h baseline-driver peak deceleration was not significantly different from the 56.3-km/h willful-driver peak deceleration). The post hoc analysis of the phase-change distance by speed interaction (Figure 63) showed statistical differences between some levels of the interaction, but no logical pattern or explanation for their occurrence could be found.

The required deceleration parameter was significantly different across levels of driver state ($F(2, 78) = 85.76$, $p < 0.0001$) and phase-change distance ($F(3, 114) = 175.37$, $p < 0.0001$). Given that these factors were significant for each of the studies independently, this finding is not surprising. All three driver states showed significant differences for this measure as did all levels of phase-change distance. Baseline drivers (mean = 0.32 *g*, SD = 0.07 *g*) exhibited the smallest required deceleration parameter levels, followed by willful drivers (mean = 0.34 *g*, SD = 0.08 *g*) and distracted drivers (mean = 0.41 *g*, SD = 0.08 *g*). All phase-change distances (represented now by their respective TTIrp values) required significantly different levels of the required deceleration parameter, which decreased with increased phase change distance (Table 35).

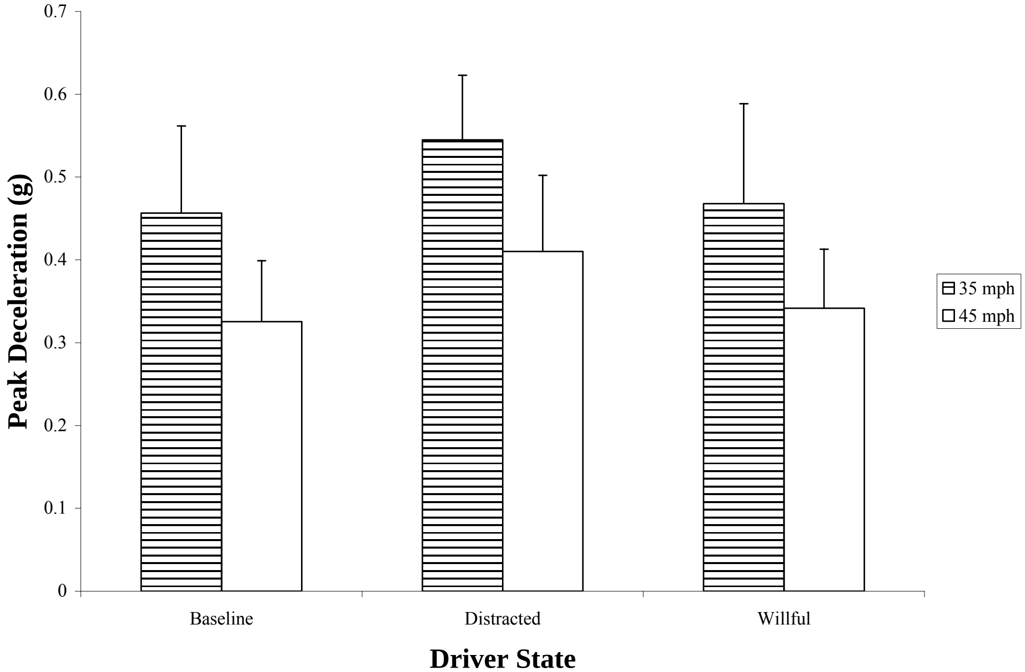

Figure 62. Peak deceleration as a function of driver state and speed. (Note: 1 mph = 1.61 km/h)

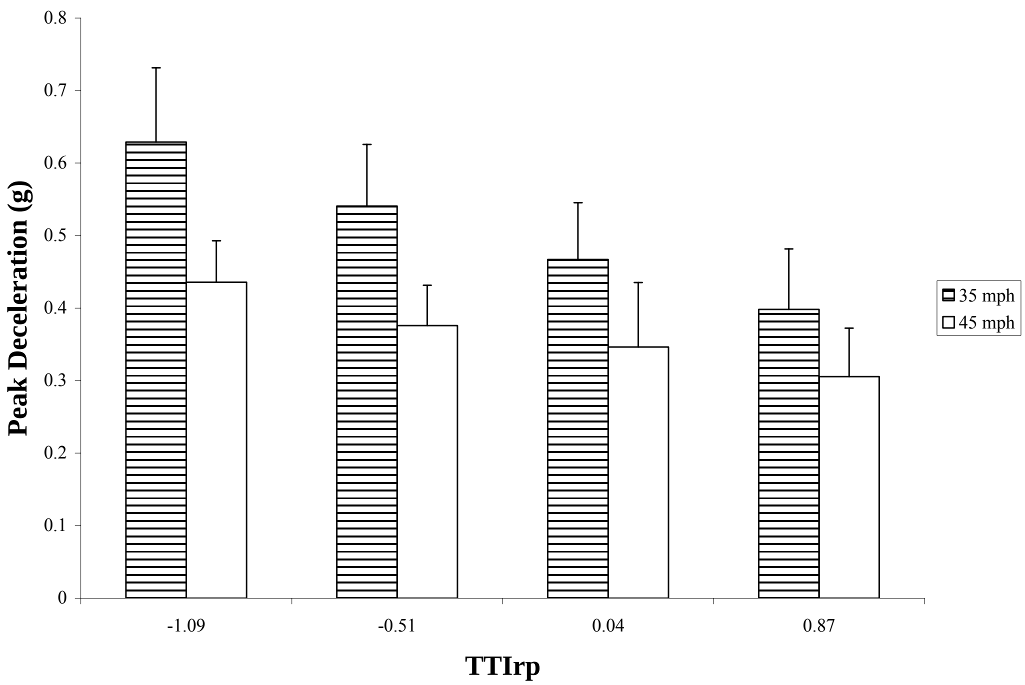

Figure 63. Peak deceleration as a function of phase change distance (TTIrp) and speed. (Note: 1 mph = 1.61 km/h)

Table 35. Required deceleration parameter as a function of phase change distance (represented as TTIrp).

TTIrp (sec)	Mean Constant Deceleration (g)	SD
-1.09	0.44	0.06
-0.51	0.38	0.06
0.04	0.34	0.08
0.87	0.29	0.07

Time-weighted deceleration was significantly different across levels of driver state (F (2, 78) = 85.39, p < 0.0001) and phase-change distance (F (3, 114) = 169.78, p < 0.0001). This finding was expected given that these factors had been significant in the independent analyses of the two studies. The distracted driver state (mean = 0.41 *g*, SD = 0.07 *g*) had the highest level of time-weighted average deceleration, while the baseline (mean = 0.33 *g*, SD = 0.07 *g*) and willful states (mean = 0.34 *g*, SD = 0.07 *g*) exhibited smaller and statistically indistinguishable levels of this measure. All levels of phase-change distance exhibited significant differences for this variable. All phase-change distances (represented now by their respective TTIrp values) required significantly different levels of required deceleration parameter, which decreased with increased phase change distance (Table 36).

Table 36. Time-weighted deceleration as a function of phase change distance (represented as TTIrp).

TTIrp (sec)	Mean Time-weighted Deceleration (g)	SD
-1.09	0.44	0.06
-0.51	0.38	0.05
0.04	0.35	0.07
0.87	0.30	0.06

Initial jerk was significantly affected as a function of speed (F (1, 51) = 9.77, p = 0.0029), driver state (F (2, 78) = 112.98, p < 0.0001), phase-change distance (F (3, 114) = 2.43, p = 0.0686), the driver state by speed interaction (F (2, 78) = 3.15, p = 0.0482), and the phase-change distance by speed interaction (F (3, 114) = 144.89, p < 0.0001). Final jerk was significant for the same variables except for the driver state by speed interaction (speed: F (1, 51) = 8.53, p = 0.0052; driver state: F (2, 78) = 47.27, p < 0.0001; phase-change distance: F (3, 114) = 37.83, p < 0.0001; phase-change distance by speed: F (3, 114) = 2.90, p = 0.0379). In addition, final jerk showed a significant age group effect (F (1, 51) = 4.63, p = 0.0362).

Post hoc tests considering the effects of speed detected a difference for the final jerk but not for the initial jerk. In both cases, the jerk decreased with increase in speed. However, while the difference in initial jerk was approximately 0.01 *g*, the difference in final jerk was closer to approximately 0.05 *g* (56.3 km/h: mean = -0.22 g, SD = 0.16 *g*; 72.4 km/h: mean = -0.18 *g*, SD = 0.16 *g*).

For both initial and final jerk, post hoc tests showed statistical differences between the distracted driver state and the remaining two states. However, no statistical differences were detected between baseline and willful drivers. In all cases, the distracted driver state required the largest amount of initial and final jerk (Table 37).

Table 37. Time-weighted deceleration as a function of phase-change distance (represented as TTIrp).

TTIrp (sec)	Initial/final jerk (*g*)	SD initial/final
Baseline	0.23 / -0.18	0.11 / 0.13
Distracted	0.35 / -0.31	0.13 / 0.26
Willful	0.24 / -0.19	0.11 / 0.15

All post hoc tests considering phase change distances resulted in statistically different levels for both initial and final jerk (Table 38). As the phase-change distance increased, the initial and final jerk decreased in absolute magnitude.

Table 38. Time-weighted deceleration as a function of phase-change distance (represented as TTIrp).

TTIrp (sec)	Initial/final jerk (g)	SD initial/final
-1.09	0.43 / -0.31	0.13 / 0.22
-0.51	0.30 / -0.23	0.08 / 0.14
0.04	0.25 / -0.21	0.11 / 0.19
0.87	0.19 / -0.14	0.08 / 0.10

The driver state by speed interaction (Figure 64) was significant for initial jerk. Tukey post hoc tests indicated that the significant interaction in that case was due to the baseline 72.4-km/h (45-mph) trial. The initial jerk for that case is significantly smaller than the remaining baseline and willful cases (56.3 km/h and 72.4 km/h).

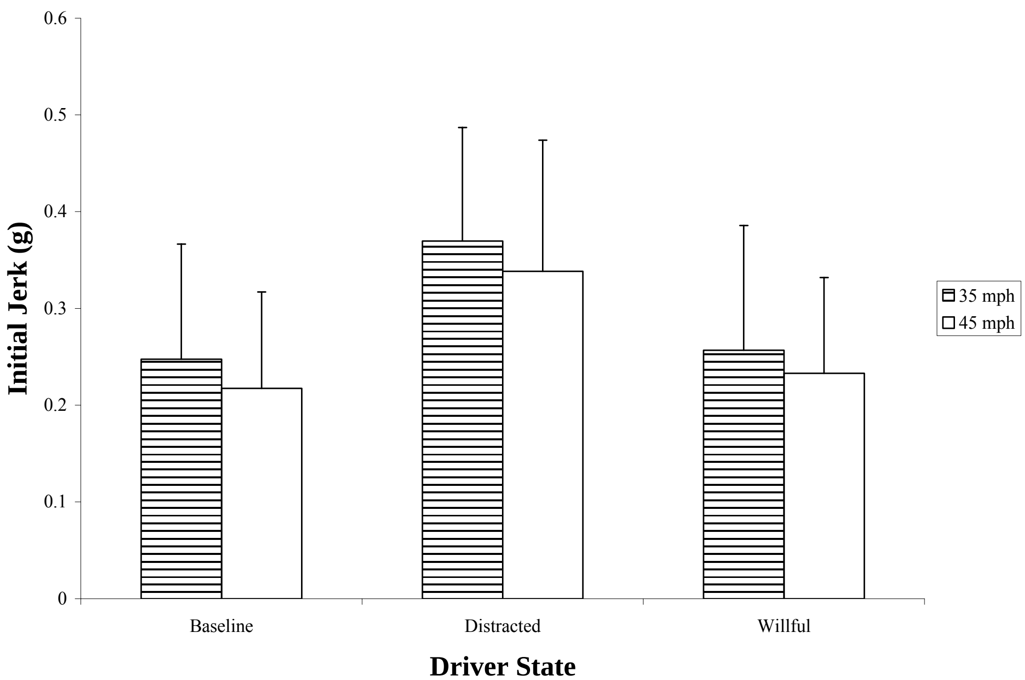

Figure 64. Initial jerk as a function of driver state and speed. (Note: 1 mph = 1.61 km/h)

The phase-change distance by speed interaction was also significant for the initial and final jerk dependent variables. The initial jerk for the -0.51-second TTIrp at 72.4 km/h (45 mph) was not significantly different from the initial jerk for the 0.04-second TTIrp (at both speeds,

Figure 65). All other phase changes were statistically different. The final jerk for the -1.09-second TTIrp at 56.3 km/h (35 mph) was statistically different from all other combinations (Figure 66).

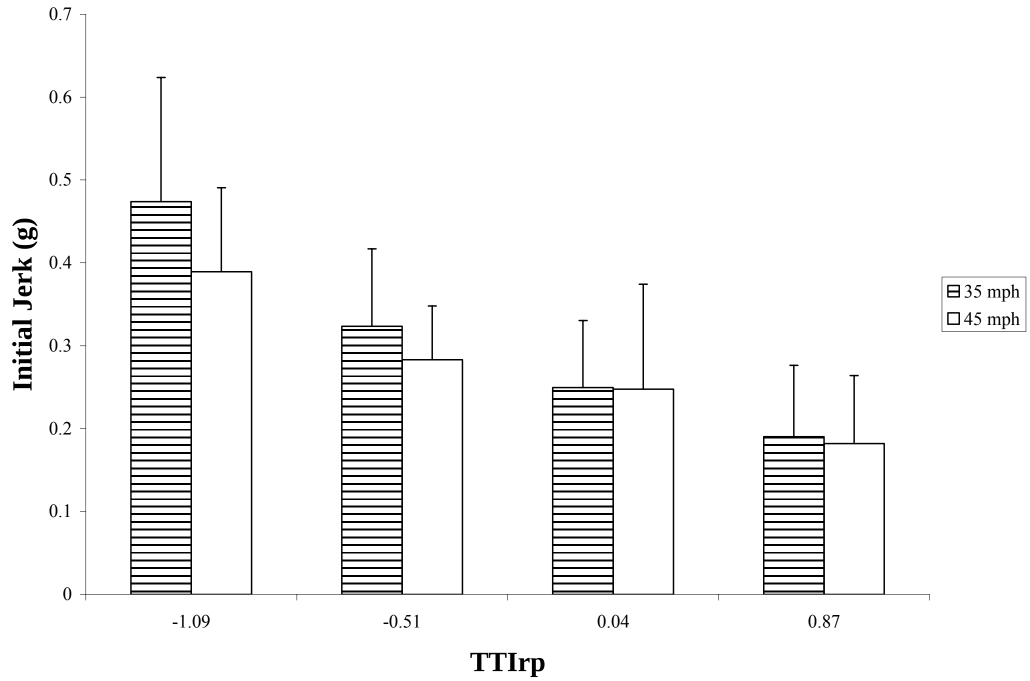

Figure 65. Initial jerk as a function of phase change distance (TTIrp) and speed. (Note: 1 mph = 1.61 km/h)

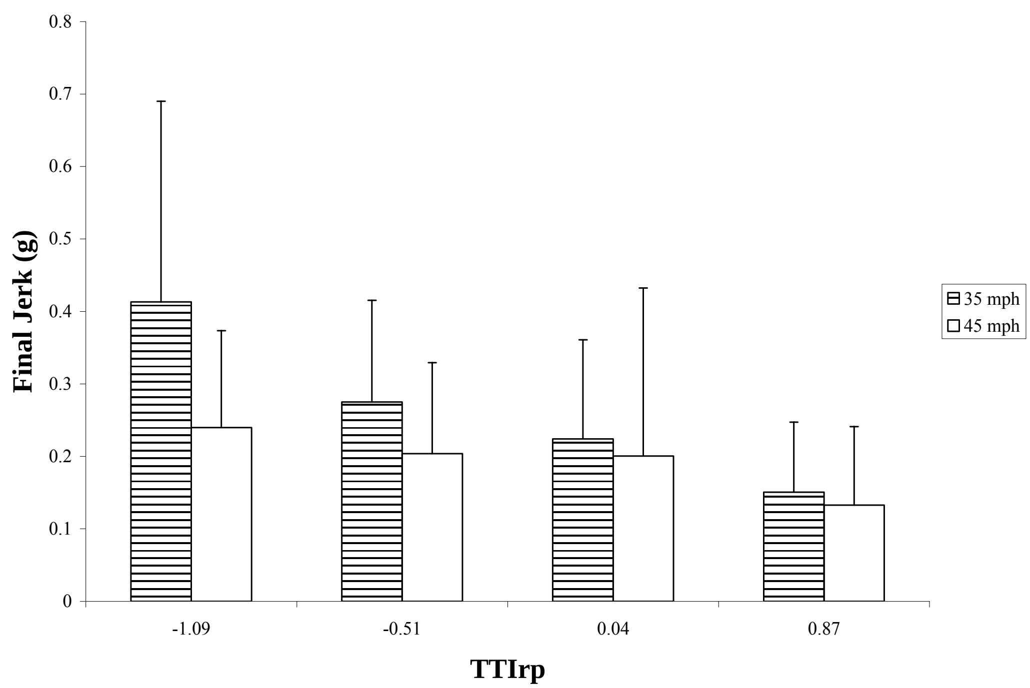

Figure 66. Final jerk as a function of phase change distance (TTIrp) and speed. (Note: 1 mph = 1.61 km/h)

Time-to-Intersection Analysis

Two ANOVAs were run to analyze the TTI and adjusted TTI variables, combining the data from the 56.3- and 72.4-km/h (35- and 45-mph) studies. Both ANOVAs considered the effects of age, gender, driver state, and the speed used in the data collection on these TTI variables.

The first ANOVA considered TTI, for which speed ($F(1, 51) = 284.80$, $p < 0.0001$), driver state ($F(2, 78) = 132.61$, $p < 0.0001$), phase-change distance ($F(3, 114) = 349.20$, $p < 0.0001$), and the interaction of phase-change distance and speed ($F(3, 114) = 8.85$, $p < 0.0001$) were significant. TTI increased significantly with speed (56.3 km/h mean = 2.86 s, SD = 0.67 s; 72.4 km/h mean = 4.74 s, SD = 0.99 s). TTI was also significantly smaller, as expected, for the distracted case (mean = 3.38 s, SD = 0.92 s), whereas the willful (mean = 3.92, SD = 1.27) and baseline (mean = 3.99, SD = 1.32) cases were statistically indistinguishable. Increasing phase-change distance also monotonically increased the TTI, as expected. For the -1.09-second TTIrp, the corresponding mean TTI at brake onset was 2.75 s (SD = 0.92 s); at the highest TTIrp of 0.87 s, the mean TTI at brake onset was 4.43 s (SD = 1.28 s). A Tukey post hoc test showed that the significant interaction between phase-change distance and speed (Figure 67) was due to the statistical similarity between the -0.51-second, 72.4-km/h condition and the 0.87-second, 56.3-km/h condition. All other data levels of the interaction were significantly different from one another.

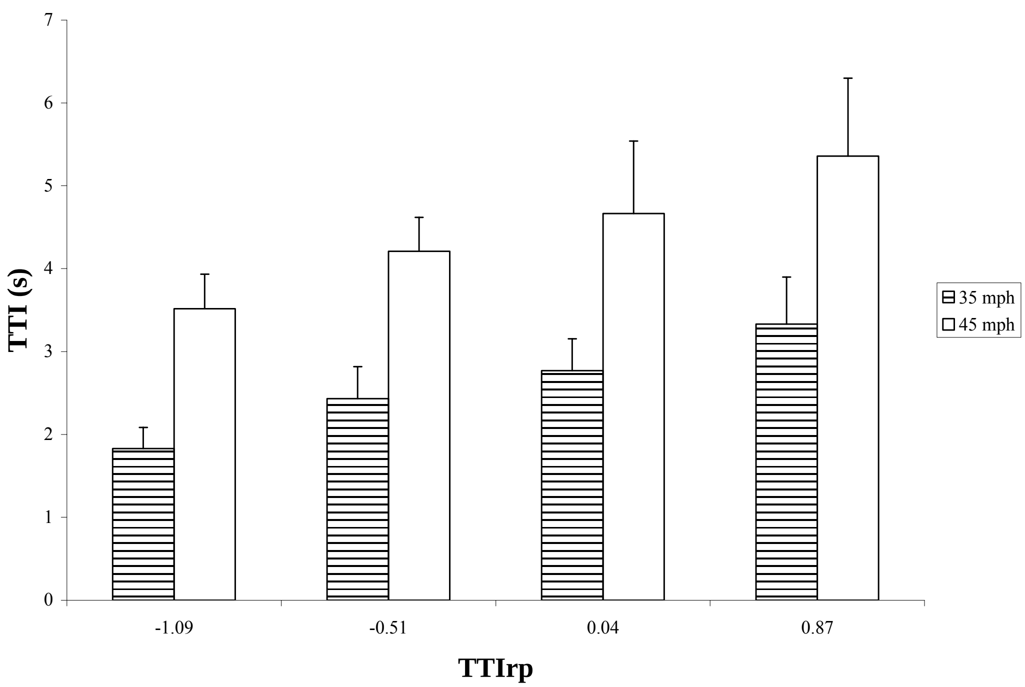

Figure 67. TTI at brake onset as a function of phase change distance (TTIrp) and speed. (Note: 1 mph = 1.61 km/h)

Adjusted TTI showed similar trends as TTI. For adjusted TTI, speed ($F(1, 51) = 143.84$, $p < 0.0001$), driver state ($F(2, 78) = 74.71$, $p < 0.0001$), phase-change distance

(F (3, 114) = 188.11, $p < 0.0001$), the interaction of driver state and speed (F (2, 78) = 16.90, $p < 0.0001$), and the interaction of phase-change distance and speed (F (3, 114) = 71.31, $p < 0.0001$) were significant. Adjusted TTI increased significantly with speed (35 mph mean = 3.20 s, SD = 0.39 s; 45 mph mean = 4.75 s, SD = 0.97 s). Adjusted TTI was also significantly smaller, as expected, for the distracted case (mean = 3.58 s, SD = 0.68 s), but the willful (mean = 4.07, SD = 1.10) and baseline (mean = 4.15, SD = 1.14) cases were statistically indistinguishable. Increasing phase-change distance also monotonically increased the adjusted TTI, as expected. For the -1.09-second TTIrp, the corresponding mean adjusted TTI at brake onset was 3.38 s (SD = 0.42 s); at the highest TTIrp of 0.87 s, the mean adjusted TTI at brake onset was 4.47 s (SD = 1.21 s). A Tukey post hoc test showed that the significant interaction between phase-change distance and speed (Figure 68) was due to a statistical difference between the 0.87-second, 56.3-km/h adjusted TTI and the adjusted TTIs for the remaining TTIrp values. Another Tukey post hoc test to evaluate the driver state by speed interaction (Figure 69) showed that at 72.4 km/h the distracted driver state was significantly different from the remaining 72.4-km/h trials, while none of the 56.3-km/h trials were significantly different, regardless of driver state.

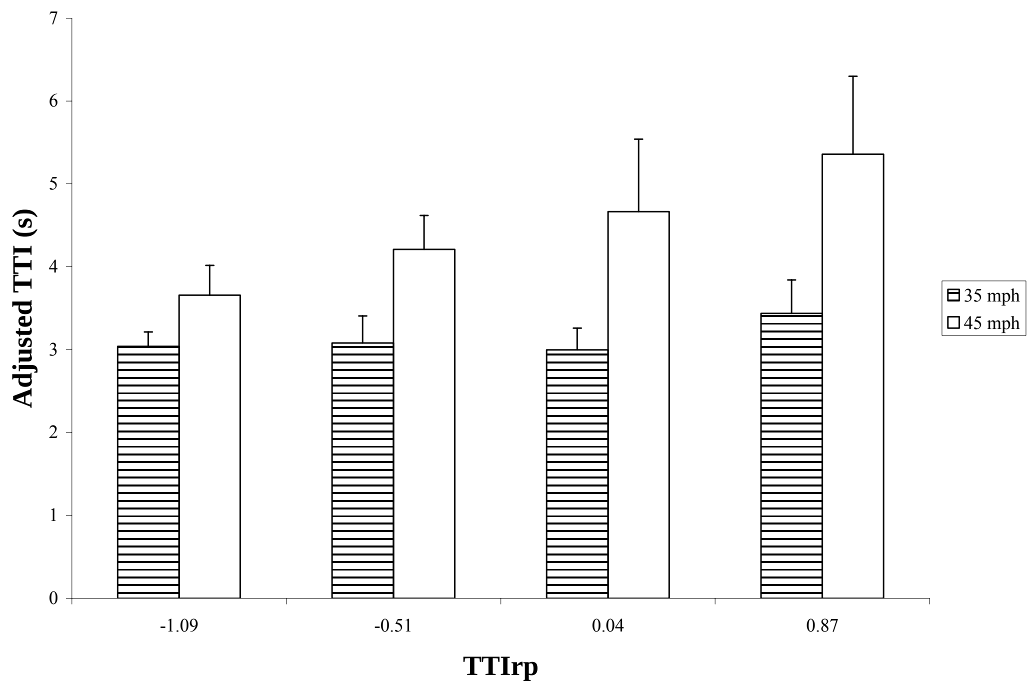

Figure 68. Adjusted TTI at braking onset as a function of TTIrp and speed. (Note: 1 mph = 1.61 km/h)

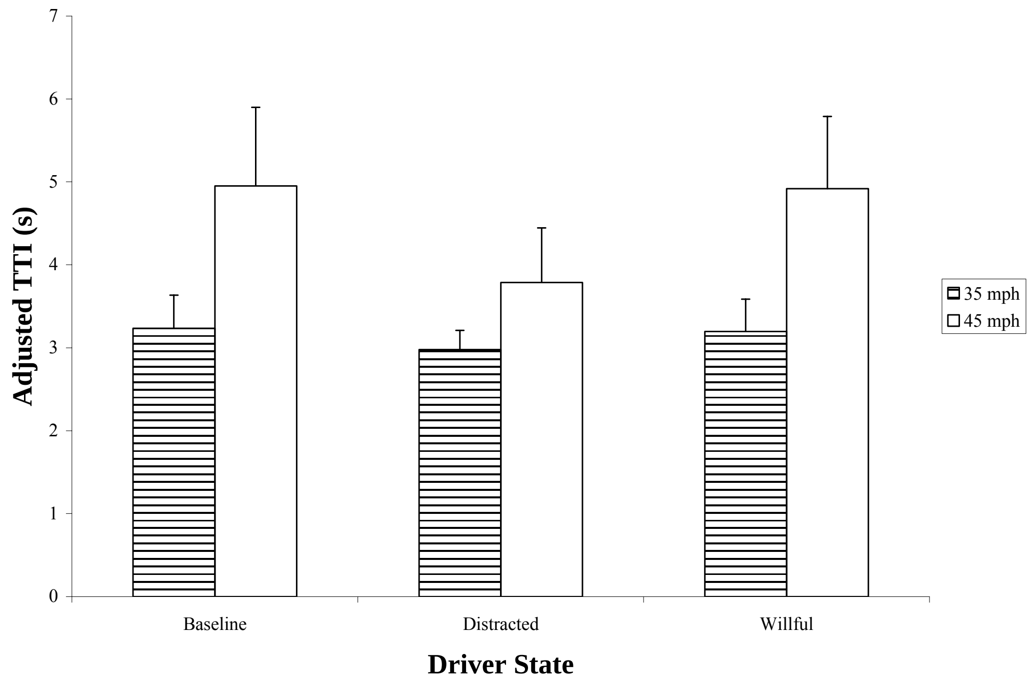

Figure 69. Adjusted TTI at brake onset as a function of driver state and speed. (Note: 1 mph = 1.61 km/h)

Violations

An ANOVA was run on the violation rates obtained from studies at both speeds as a function of age, gender, driver state, and the speed used in the data collection. ANOVAs performed independently on the 56.3- and 72.4-km/h datasets had shown a significant effect for driver state, and the same significant effect was also observed here ($F (2, 104) = 67.73$, $p < 0.0001$). A post hoc Tukey test revealed differences between the distracted driver state (mean = 0.16, SD = 0.12) and the remaining two states (i.e., willful, (mean = 0.03, SD = 0.06) and baseline mean = 0.01, SD = 0.05). The interaction between driver state and speed was also significant ($F (2, 104) = 13.11$, $p < 0.0001$). The post hoc test showed that the difference was due to differential speed effects in the distracted driver state (Figure 70). While no significant differences were present at any speed for the willful and baseline driver states, distracted drivers in the 56.3-km/h (35-mph) study violated at a significantly higher rate than those in the 72.4-km/h (45-mph) study. This effect likely reflects in part the proportion of amber signal represented by the simulated distraction. The distraction length was constant for both studies at 1.6 s, but this represented 44.4 percent of the 56.3-km/h (35-mph) amber time and 37.2 percent of the 72.4-km/h (45-mph) amber time. Thus, 72.4-km/h (45-mph) distracted drivers were exposed to a longer amber time and likely reacted to it by stopping more often. Although this effect should have been offset by the additional speed, it appears that a driver's perception of the need to stop on an amber light is not necessarily a direct function of the amber time; rather, the decision might be taken based on a combination of factors.

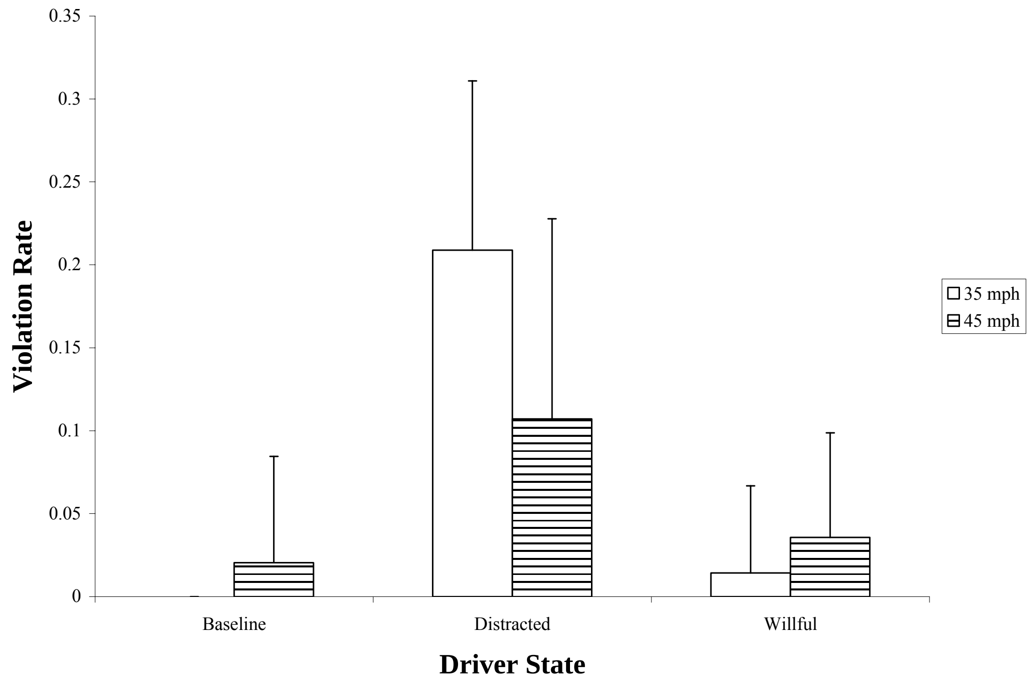

Figure 70. Violation rate as a function of driver state and speed. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Overall, the results suggest that driver state has some marked effects on intersection approach performance. These changes are observed in reaction time and deceleration aspects of the approach, as well as on the decision to stop itself. This addresses the first research question posed earlier in this section. The second research question, dealing with the prediction of violators using subjective measures, still remains and is addressed within the next section.

RQ 2: Can potential violators be predicted using the questionnaire-based measures of aggressiveness?

To explore the utility of the questionnaire data in an intersection violation scenario, Pearson correlation analysis was performed. First, the total scores as well as subscale partial scores for each of the two questionnaires, DDDI and DSI, were tallied. Then the driving performance measures were independently averaged across all stops for each participant. This resulted in a data set with 28 observations (one for each participant; recall that questionnaires were only issued to drivers in the 56.3-km/h [35-mph] conditions), with scores for the questionnaires' total scale and subscales and the driving variables TB, TAR, peak deceleration, and required deceleration parameter (RDP). The correlation demonstrated several significant relationships among the driving variables and the questionnaires (Table 39).

The correlation analysis did not demonstrate particularly strong relationships among the questionnaires and intersection approach behaviors. Age group had the highest number of significant correlations with both driving questionnaires. For the DDDI, younger drivers tended to score higher on the total score and the aggressive driving subscale. Past research has demonstrated a tendency for younger drivers to be more aggressive at intersections (e.g., Sivak et al., 1989). This trend is further verified by the DSI, in which younger drivers tended to be more aggressive, show a lower regard for hazard monitoring, and a have high tendency for thrill seeking. Interestingly, unlike the DDDI, the total DSI score was not significant and had a low correlation with age group. This is likely due to differences in the measures of the two scales. The DDDI subscales measure dangerous driving in a consistent direction (i.e., dangerous drivers tend to score low on all subscales). The DSI switches direction in that high scores on measures such as thrill seeking are more dangerous, while high scores on hazard monitoring indicate a safer driver. Thus it is probably inappropriate to use the total DSI score, as indicated by the lack of correlation across all measures. A search of past studies using the DSI indicated that only the subscales are typically evaluated whereas the authors of the DDDI recommend using the total score as well as the subscales.

Table 39. Correlation matrix of pre-driving questionnaires, classification, and performance measures.

	Subscale	Age Group	Gender	TB	TAR	Peak Accel.	RDP
DDDI (p-value)	**Aggressive Driving**	-0.410* (.034)	0.035 (.860)	-0.360 (.060)	-0.202 (.303)	0.110 (.579)	0.127 (.521)
	Negative Emotions	-0.340 (.076)	0.097 (.623)	0.339 (.078)	0.206 (.293)	0.340 (.077)	0.190 (.333)
	Risky Driving	-0.324 (.092)	-0.154 (.434)	0.148 (.519)	0.148 (.454)	0.411* (.030)	0.330 (.087)
	Total Score	-0.389* (.045)	0.034 (.865)	0.187 (.350)	0.210 (.294)	-0.411 (.030)	0.362 (.063)
DSI (p-value)	**Aggression**	-0.487* (.009)	0.111 (.573)	0.356 (.063)	0.256 (.188)	0.291 (.133)	0.273 (.289)
	Dislike of Driving	-0.463* (.013)	0.175 (.374)	0.195 (.320)	0.232 (.235)	0.219 (.264)	0.120 (.542)
	Hazard Monitoring	0.377* (.048)	0.248 (.204)	-0.387* (.042)	-0.478* (.010)	0.076 (.700)	0.076 (.700)
	Fatigue Proneness	-0.313 (.112)	0.103 (.609)	-0.044 (.8230	0.0650 (.743)	-0.180 (.360)	-0.262 (.178)
	Thrill Seeking	-0.515* (.005)	-0.528* (.004)	0.253 (.195)	0.242 (.215)	0.377* (.048)	0.388* (.041)
	Total Score	0.114 (.570)	-0.193 (.335)	-0.051 (.798)	0.030 (.881)	-0.197 (.315)	-0.273 (.159)

The literature review demonstrated mixed results for gender differences in intersection behavior. Although males are often categorized by society as tending to be riskier drivers, results of the correlation did not support this belief. The exception is with males tending toward thrill seeking as defined by the DSI. Previous analysis showed males were more likely to decide to go when faced with a changing signal phase, which may reflect this thrill-seeking measure.

Both reaction time variables are correlated with the hazard monitoring subscale of the DSI. This may indicate that drivers who carefully observe the driving environment to identify hazards also react faster. That is, these drivers have a defensive driving style that may better prepare them to react to a hazardous situation. These drivers may view the changing signal as a hazard to which the driver is prepared to react more quickly.

Peak deceleration is correlated with risky driving and the total DDDI scales. Both peak deceleration and average deceleration are correlated with thrill seeking under the DSI. As discussed previously, thrill seeking and risky driving are defined similarly. Drivers who tend to be more aggressive or thrill seeking also appear to be willing to decelerate at higher rates than those who score lower on those scales.

From an applied standpoint, none of the correlations are high enough to represent good predictors of signal-approach behavior. It may be that the experimental conditions or surrogate measures used during this study were not sufficiently sensitive to the scales. However, it is more likely that the dangerous driving characteristics measured by the questionnaires were not highly reflected during the course of this experiment. The experimental setting and duration may cause drivers to drive in a more cautious manner than they typically would. Thus there may have been a less dramatic difference in driving performance measures of dangerous verses safe drivers. A longer, naturalistic-driving experiment may demonstrate higher correlations between intersection-approach performance and the questionnaire measures.

The DDDI is a relatively recent scale that has been validated with several other behavioral scales (Dula and Ballard, 2003). These scales included the Propensity for Angry Driving scale, the Trait Anger Expression Inventory, and the Interpersonal Behavior Survey Short Form. However, to date the DDDI has not been validated with a robust time-tested driving questionnaire such as the DSI. To explore the relationship between the two scales, a correlation of the two was computed (Table 40).

Table 40. Correlation matrix of pre-driving questionnaires.

Questionnaire		DSI (p-value)					
	Subscale	Aggression	Dislike of Driving	Hazard Monitoring	Fatigue Proneness	Thrill Seeking	Total Score
DDDI (p-value)	Aggressive Driving	**0.528 (.005)**	**0.517 (.006)**	**-0.420 (.029)**	0.337 (.092)	**0.405 (.036)**	**-0.407 (.040)**
	Negative Emotions	**0.665 (<.001)**	0.343 (.074)	-0.253 (.213)	0.160 (.425)	0.324 (.092)	-0.039 (.845)
	Risky Driving	**0.408 (.031)**	0.225 (.225)	-0.224 (.253)	0.090 (.654)	**0.490 (.008)**	0.282 (.154)
	Total Score	**0.630 (<.001)**	**0.441 (.021)**	-0.311 (.114)	0.249 (.220)	**0.448 (.012)**	**0.421 (.032)**

Results from the Pearson correlation indicate that the DDDI is weighted toward the DSI's definition of aggression. All of the DDDI subscales are correlated with aggression, several of which show relatively high correlations. The DDDI's definition of aggressive driving also tends to be correlated with most of the subscales of the DSI. However, aggressive driving is difficult to define and may thus be measured to some extent by other subscales. Thrill seeking also correlates well with aggressive and risky driving. It is logical that a thrill-seeking driver would tend to drive in a more aggressive or risky manner.

Overall, the pattern of correlation indicates that the two scales measure different but complementary attributes of the driver behavior. Both scales appear to measure an overall level of aggression while driving. However, the lack of correlation among most pairs of the subscales indicates uniqueness between the scales. In particular, the DSI subscale of fatigue proneness is uncorrelated with all DDDI scales. Because of the significant correlation between many of the factors, future researchers should consider selecting the scale that more directly measures the attributes of interest rather than using both questionnaires. This simple correlation was not intended to be a complete comparative analysis of the two questionnaires. Researchers wishing to do further comparisons should consider other explorative methods (e.g., cluster analysis). Based on the current analysis, however, prediction of violation behavior based on these questionnaires would be very inaccurate.

Generation of Too-Early Thresholds

An appropriately timed algorithm should provide a timely warning to potential violators while avoiding nuisance alarms. If a warning occurs before the point at which an attentive driver would have initiated braking, it is categorized as too early. Alarms that are too early will likely deflate the safety benefits of collision avoidance systems because of annoyance and loss of user trust in the system (Dingus et al., 1998). This section summarizes how the data from the 56.3-km/h and 72.4-km/h baseline studies described previously can be used in the approximation of a too-early distribution for intersection approaches.

The baseline studies looked at how attentive drivers approach a changing traffic signal. Fifty-six licensed drivers, equally split by age and gender, participated in the study. Half the participants were asked to drive at 35 mph (56.3 km/h) and the other half at 45 mph (72.4 km/h). The signal was timed to the values recommended by ITE (1991). As the test vehicle approached the intersection, a green-to-yellow phase change occurred at five different locations. The phase-change locations were determined by the TTI at which the red phase occurred. Linking the locations to the red phase permitted changing of the yellow-phase length to accommodate the differing speed conditions (as dictated by the ITE [1991] equations). For each intersection approach, the driver made a decision about whether or not to stop.

One of the phase-change distances occurred at a TTI red phase of 0.04 s. Thus, a driver moving at the speed limit would cross the stop bar just 0.04 s before the red. This condition represents that last instant in which a driver could cross the intersection without committing a signal violation (assuming constant speed). Thus, the next instant after this is the point at which the algorithm would need to begin monitoring vehicles for potential violations. This represents the worst-case scenario and is the most difficult region for segregating violators from compliant drivers. As phase changes occur at distances farther from the intersection, attentive drivers should react earlier than non-attentive (distracted) drivers, simplifying the classification of the violating and compliant groups. To determine the too-early point, an assumption is first made that an algorithm will be able to sense a driver who initiates braking (using brake pedal or acceleration sensors). Thus, if a warning occurs before the point at which an attentive driver would begin to brake, the warning is too early. The initial braking points of attentive drivers from the IDS studies were extrapolated and fit to a normal distribution to create the too-early point.

56.3-km/h (35-mph) Tests: Drivers approaching the intersection in the lower speed condition initiated braking at a TTI between 2.53 s and 3.14 s, with an average of 2.78 s (SD = 0.15 s). The distribution indicates that, in order to avoid nuisance alarms for 95 percent of the drivers who receive a phase change at the worst-case threshold described above, the warning would need to be initiated at a TTI of less than 2.55 s. This may be a difficult goal to achieve, because a driver traveling the speed limit and having a 1-second reaction time would need to stop at approximately 0.54 *g*. However, recall that this is only true for drivers in the worst-case scenario described above. Thus, it may be reasonable to shift the warning criteria to reduce the required deceleration at the expense of increasing the number of nuisance alarms for drivers at or near a TTI equivalent to the yellow length. The cumulative distribution for the too-early point is depicted in Figure 71.

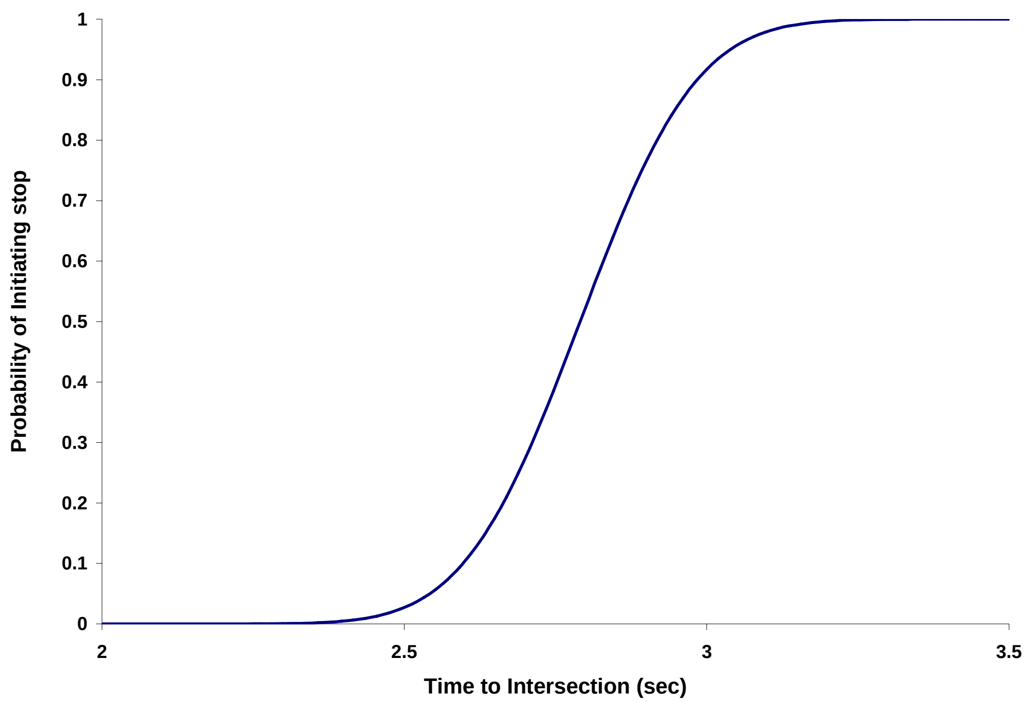

Figure 71. Cumulative fit to the normal distribution for time-to-intersection at which an attentive driver initiates braking during a 56.3-km/h (35-mph) approach.

Another way to look at the point at which drivers initiated braking is through the required deceleration parameter (RDP). This was defined earlier as the deceleration required in order for the driver to stop the vehicle at the stop bar. It is calculated using a kinematics equation considering the vehicle's speed and distance from the intersection when the driver initiates the braking maneuver. Here, RDP indicates the braking effort needed, after brake onset, by drivers receiving the phase change at the green-to-yellow transition threshold described previously. It depends substantially on the reaction time of the driver in response to the yellow light. Results of the IDS tests indicate that RDP ranged from 0.27 *g* to 0.33 *g* with an average of 0.30 *g* (SD = 0.02 *g*). To avoid nuisance alarms for 95 percent of the population, the RDP for a warning would need to exceed 0.33 *g*. Considering that a driver receiving the warning will also have a reaction time, this value would likely exceed most of the deceleration results from the on-road ICAV tests (Lee et al, 2005). The cumulative distribution for RDP is provided in Figure 72.

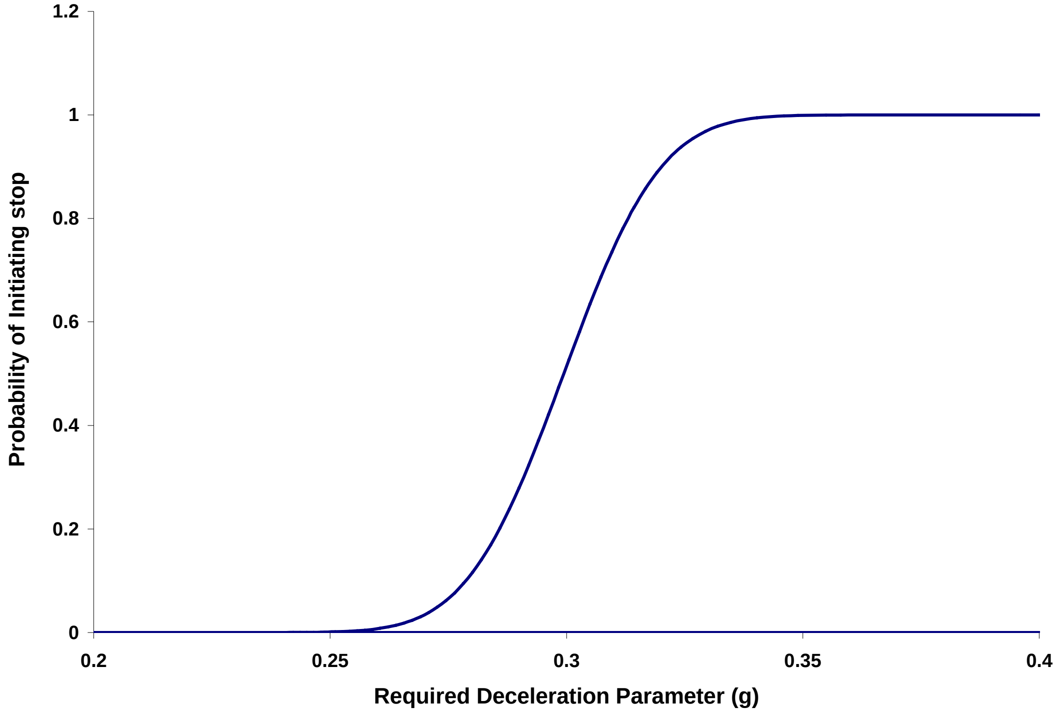

Figure 72. Cumulative fit to the normal distribution for the required deceleration parameter at which an attentive driver initiates braking during a 56.3-km/h (35-mph) approach.

72.4-km/h (45-mph) Tests: Drivers at the higher speed began braking between a TTI of 3.60 and 4.30 s. Drivers initiated braking prior to an average TTI of 3.82 s (SD = 0.21 s). Care should be exercised when making comparisons between the two speeds. Recall that the TTIrp was constant between the two speeds; however, the yellow-phase length was longer at the higher speed (3.6 s versus 4.3 s). Thus, drivers in the higher speed condition received the green-to-amber phase change 0.7 s earlier, which likely contributed to the earlier average initial braking. To avoid nuisance alarms for 95 percent of the drivers who receive the threshold phase change, warnings would need to occur at a TTI of less than 3.59 s (Figure 73). The resulting deceleration rate required by a driver with a 1-second reaction time is 0.39 *g* (compare to 0.54 *g* at the lower speed). This indicates that violating drivers may be identified earlier at higher speeds, most likely due to the longer amber interval.

The reduction in required braking effort at the higher speed is also reflected in the RDP plot (Figure 74). Drivers in this group initiated braking between an RDP of 0.24 *g* and 0.29 *g* with an average of 0.27 *g* (SD = 0.01 g). An RDP of 0.29 *g* would be required to avoid nuisance alarms for 95 percent of the attentive drivers receiving a phase change at the threshold distance. The decrease in braking effort associated with the longer amber phase at higher speeds suggests that extending the amber phase beyond ITE recommendations could be considered for IDS-enabled intersections in order to minimize nuisance alarms.

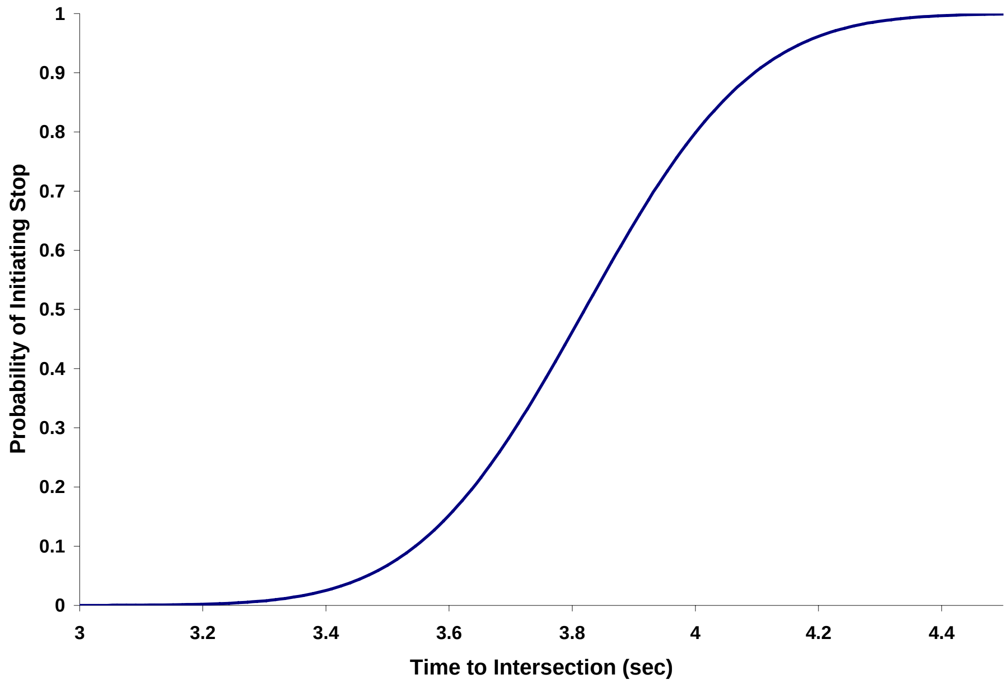

Figure 73. Cumulative fit to the normal distribution for time-to-intersection at which an attentive driver initiates braking during a 72.4-km/h (45-mph) approach.

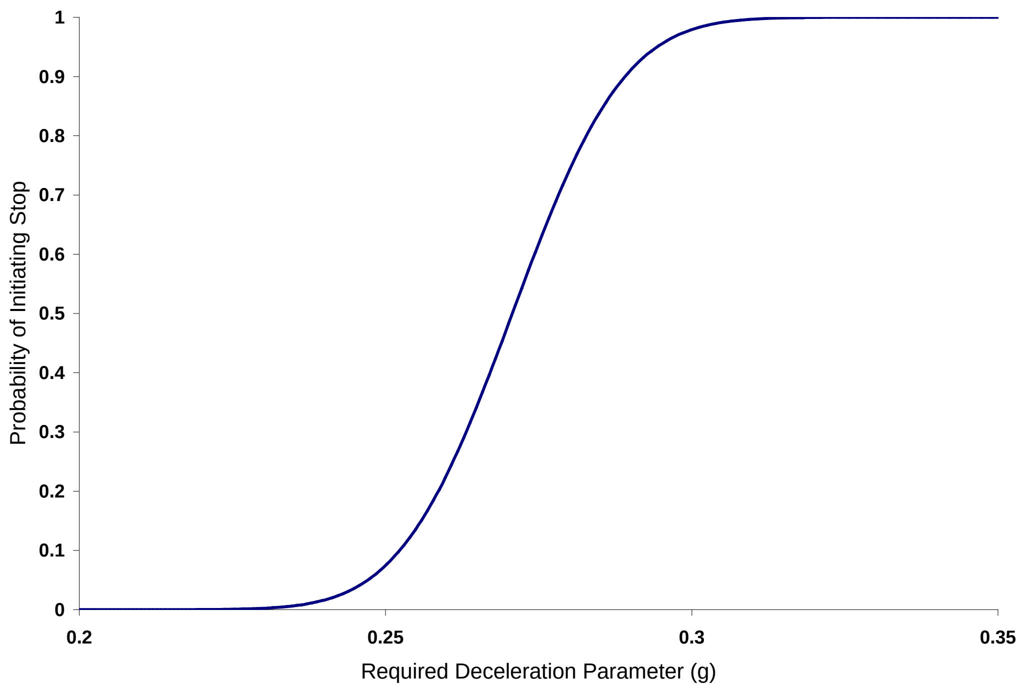

Figure 74. Cumulative fit to the normal distribution for the required deceleration parameter at which an attentive driver initiates braking during a 72-km/h (45-mph) approach.

Using the Too-Early Results

The too-early distributions can be used to determine the appropriateness of an IDS warning. The too-early distribution indicates the area in which an aware driver will respond to a changing traffic signal. In theory, once an approaching driver has passed the too-early distribution, the driver will violate the signal. Thus, an optimized IDS countermeasure should not initiate until after the driver clears the too-early region. This concept provides the framework from which warning appropriateness and subsystem specifications are derived.

Essentially, any warning that occurs within the too-early region will result in some nuisance alarms for drivers at or near the distance at which their TTI equals amber-phase length. Warnings that occur further into the too-early distribution will result in additional nuisance alarms for a larger portion of the approaching drivers. To determine specifications, an allowable percentage of nuisance alarms was determined and referred to as the too-early point. The area between the too early-point and the warning point represents the allowable error. Accuracy specifications for each subsystem can then be derived based on this allowable error.

Conclusions

The design of IDS systems requires knowledge about driver behavior during the intersection approach. The primary use of the information provided herein is to decide when and how a countermeasure should be deployed. The present study attempted to create the worst-case scenario in terms of intersection approaches and compare it with the baseline approaches. The distracted driver had a very large simulated distraction and the willful driver an unusually high motivator. Thus, the data gathered should represent the most imprudent and aggressive drivers, respectively. In this regard, the information presented can be considered as a tool for designers of IDS solutions.

Driver state appears to have a substantial effect on a driver's intersection approach profile. Distracted drivers stop significantly less often than other driving groups and are thus at the highest risk for violation. Consequently, distracted drivers likely represent the highest collision risk. The tendency for willful drivers to speed and to accelerate through the intersection may result in more severe injuries if collisions occur. It will be important for future experimenters and designers to consider the approach profiles of these two groups and to better define methods for discriminating between these groups and the baseline drivers.

This information may also help the designers of collision countermeasure systems tailor their devices to drivers that are at highest risk for violation. Control algorithms may be able to identify patterns of behavior in approaching vehicles and react accordingly. For instance, it may recognize the early stages of deceleration of a baseline driver and assume that driver will stop even if the speed is higher than average.

Values for average acceleration, speed, and perception-reaction times may be used for algorithm development. Continuous and multi-point detection algorithms are in development. The current iteration of these algorithms makes use of basic kinematics equations of motion. To use these equations, assumptions on driver reaction times and deceleration must be made. Interestingly, the difference in the urgency of the stop was only reflected on the deceleration level and not on the reaction time, suggesting that an average of the reaction time parameter can be implemented into an algorithm without considerable negative effects on accuracy. The values presented here may be used for preliminary inputs into those algorithms. IDS designers can also look at the differences in allowable deceleration values between the driver states to help isolate violating drivers.

With these results in mind, the next section discusses the human factors experiments that evaluated different DIIs. These results complement the baseline data obtained in the previously described experiments and represented the main human factors effort in this project.

Experiments on DII Effectiveness

Completion of the baseline experiments aided in establishing normal driver behavior during intersection approaches. However, none of these drivers were exposed to warnings, and understanding driver behavior in response to a warning was considered essential for the design of an effective IDS countermeasure. This section presents the method used to test several potential IDS warnings, the results obtained from these tests, and conclusions inferred from those results.

Method

The IDS project benefited greatly from the protocol development efforts undertaken as part of the ICAV project. In particular, the IDS project was able to use modified versions of the ICAV standardized test protocol for its DII and warning onset threshold tests (Lee et al., 2005). These methods are discussed in this section for the reader's convenience.

The standardized test method was developed based on the relationship between the DII of interest and the algorithm settings. For example, optimal warning onsets were expected to differ as a function of different interfaces. The original intent of this test-track testing phase was three-fold: 1) to conduct iterative tests to optimize both the warning itself and the warning onset threshold, 2) to test a sample of interfaces that covered the spectrum of alternatives available to future designers of IDS systems, and 3) to determine the implications of these results on algorithm development. To achieve these goals within the imposed time constraints, the following steps were taken:

1. Gathered insights from the ICAV studies, which indicated the much-too-late bounds of warning timing. These data would prevent testing warning timings that were not acceptable for large proportions of drivers. In general, the limits suggested that the warning onset timing should not be closer to the intersection than 41.1 m (135 ft) at 56.3 km/h (35 mph). This limit represents a TTI of 2.65 s and a required deceleration parameter of 0.30 *g*.
2. Began testing optimal warning onsets for DIIs selected due to the results of the trade studies conducted previously (see section on trade studies).
    - Ran a group of participants at what is likely to be considered a too-late warning onset.
    - As soon as one of the drivers did not stop or stopped within the collision zone (see definition in the dependent variables section), increased the warning onset by a

pre-determined increment of TTI (0.1 s in the 56.3-km/h [35-mph] case) and began running a new group.
- As long as participants were stopping at a certain warning onset TTI, continued to run until 16 participants had been run and all stopped before reaching the collision zone. Balanced the group by age and gender. This provided a 95th percentile warning compliance confidence interval of approximately 80 to 100 percent.
- Ran a baseline group of 16 participants at the same warning onset TTI, but providing no warning.
- If the warning design reached the too-early boundary (determined as part of the too-early studies discussed previously), terminated the search for an optimal timing (i.e., did not continue to increase the TTI as in Step 2b). Instead, ran a set of 16 participants at a pre-selected timing for comparison (baseline) purposes. For IDS, this point was located at 53.3 m (175 ft) from the intersection when traveling at 56.3 km/h (35 mph).
- Ran tests using this same method for each warning design.
- Ran additional baseline groups if needed for modeling purposes.

3. The optimal warning onset TTI for any particular warning design was the point at which all 16 participants stopped before reaching the collision zone. Any warning onset TTI smaller than the optimal was considered too late.

As will be discussed later, this approach did not result in an optimal warning timing for any DII before the too-early warning timing threshold was reached. Thus, a slight modification on the testing philosophy was applied:

1. Selected a set of warning timings distributed across the space delimited by the much-too-late warning timing and the too-early warning timing, resulting in four warning timings:
    - 32.0 m (105 ft) at 56.3 km/h (35 mph), 2.03 s TTI, 0.39 *g* RDP
    - 41.1 m (135 ft) at 56.3 km/h (35 mph), 2.65 s TTI, 0.30 *g* RDP
    - 47.2 m (155 ft) at 56.3 km/h (35 mph), 3.02 s TTI, 0.26 *g* RDP
    - 53.3 m (175 ft) at 56.3 km/h (35 mph), 3.41 s TTI, 0.23 *g* RDP
2. Changed the traffic signal's timing so that it was red when the occlusion goggles cleared instead of the previous amber indication (further justification for this change is presented in the next section).
3. Tested a group of eight participants, balanced across age and gender, at each of the four warning timings described in Step 1.
4. Completed a similarly composed group of eight participants under each of the four timings described in Step 1 but without any DII (baseline condition).

The same approach was then used to test an off-the-shelf DII for a stop-sign violation scenario. Results from the first set of experiments, which attempted to obtain an optimal warning timing for each DII, allowed for the comparison of the effectiveness of different DIIs at the same warning onset threshold. Results from the second set of experiments, which established DII effectiveness as a function of warning onset threshold, also allowed for between-DII comparisons. Furthermore, these results were useful in establishing rates of nuisance alarms and too-late alarms for each tested DII as a function of its warning timing, given that 100 percent compliance could not be attained within the pre-established warning timing limits.

The standardized protocol for the too-late warning timing tests involved use of occlusion goggles for 2 s at random intervals as the participant was driving up and down the Smart Road. The participant occasionally encountered cross traffic (a confederate vehicle) at the intersection, although never at the same time as an occlusion. For the surprise presentation of the DII, a second confederate vehicle followed the participant vehicle (at a safe distance) and an occlusion occurred just before the intersection. The DII (visual or haptic) was presented at the same time that the goggles cleared. The participant was expected to think that there may have been cross traffic and thus respond to the amber light more urgently than might otherwise have been the case, while at the same time being aware of the following vehicle. This protocol, originally developed for the ICAV project, seemed to present the most realistic scenario for use in intersection studies in terms of having the drivers aware of the possibility of traffic threats (both cross traffic and following traffic). Another advantage to this scenario was that it seemed to represent a worst-case scenario in that the driver might not be willing to brake hard because of the threat of a rear-end collision with the following vehicle. A system that showed promise in encouraging a driver stop for the following vehicle scenario would be expected to show even more promise when no following vehicle was present.

Since none of the DIIs tested elicited 100 percent compliance prior to the too-early limit, the protocol was modified to represent the change in philosophy discussed in the previous section (i.e., from determining a 100 percent compliance point to characterizing compliance percentage as a function of warning timing). Furthermore, instead of presenting the participant with an amber indication at the end of the occlusion period, a red indication was presented. This manipulation was expected to avoid the conflicting information provided by an amber indication and a DII that indicated stopping. This manipulation was also considered to be more representative of a crash avoidance system (as opposed to a violation warning system), which was justified by the failure to determine an optimal warning point based on the results of the first set of experiments. This is further justified given that most signal violations do not result in a crash. Any experienced driver has likely violated traffic signals at times with no negative consequences. This is because most violations are relatively minor, occurring a low time-into-red (TIR).

A study of 541 signal phases including at least one violator indicated the mean TIR was less than 0.5 s. Approximately 80 percent of the drivers entered the intersection within 1 s after the start of the red (Zimmerman and Bonneson, 2005). These researchers investigated the TIR for 63 crashes using data collected from red-light-enforcement cameras. Results indicate that LTAP/OD crashes occur in the first few seconds of red for intersections that do not have a protected left-turn phase. This is because the POV driver, who is under pressure to clear the intersection before the adjacent traffic receives the right-of-way, wrongly assumes the SV will stop at the red light. Right-angle crashes did not begin occurring until after 5 s and as much as 45 s after the onset of red, with nearly all right-angle crashes occurring between 5 and 12 s after red. Thus, although most violations occur immediately after the light has turned red, most crashes occur several seconds after the light has turned red. Therefore, drivers expect that violating at a very short TIR will not have adverse consequences.

Protocols

Two types of tests were run to evaluate DII effectiveness. The first set of tests was completed at the signalized intersection, and explored the performance of DIIs tailored for that application. The second set of tests explored a DII designed to function at stop-controlled intersection.

Signalized Intersection Tests

Before participating, the candidate had to read and sign an informed consent form and complete basic health and vision screening tests. If no reasons for exclusion could be identified based on these tests, the participant was led to the vehicle and given time to make the necessary adjustments to the seat, mirrors, and climate control. The participant was then instructed to drive toward the Smart Road, where the study was to be conducted. Once on the Smart Road, the front seat experimenter (FSE) asked the participant to stop near the entrance gate, where the FSE read further instructions on the purpose of the study. The participant was initially told that the experiment concerned the use of occlusion goggles to simulate distracted driving. The participant was told to follow all the normal traffic rules and was also told that maintenance vehicles would occasionally be entering and leaving the road (this was really the first confederate vehicle). At this time, the occlusion goggles were given to the participant and demonstrated while the car was still parked. The participant was told that the goggles would occlude their vision for 2 s at random intervals to simulate driver distraction, during which time information would be recorded on speed maintenance and lane position accuracy. The participant was asked to place the car in third gear and maintain 56.3 km/h (35 mph) through the entire study. After being presented with an opportunity to ask any questions, the participant began driving.

On the first drive down the Smart Road, there was a confederate vehicle (POV) parked on a parallel road to the Smart Road. The driver of the POV, who was really an experimenter, appeared to be working on a rain-making tower. After the SV circled through the lower turnaround and approached the intersection for the second time, the POV drove to the crossing road's stop bar so it appeared that the light signal was triggered by the POV, although the signal was really being controlled by the back seat experimenter (BSE). The participant then received a red light, during which time the POV crossed and exited the road. The participant then continued to drive up and down the road, crossing the intersection multiple times, while being occluded at random intervals. On the sixth intersection approach, the POV reentered the road and crossed through the intersection toward the parallel road. When the SV continued to the lower turnaround, the POV inconspicuously exited the road.

On the SV's 10^{th} intersection approach, a second confederate vehicle (following vehicle [FV]) followed the SV up the road. The researchers felt that this vehicle was necessary to simulate real-world conditions in which a signal violation warning might be presented, as well as to obtain a driver's realistic reaction to such a warning with following traffic and the possibility of cross traffic. As the SV reached the intersection, the participant's vision was occluded while the light was still green. During the occlusion the light changed to the amber phase (for the first set of experiments) or the red phase (for the second set of experiments), and then the occlusion goggles cleared as the participant simultaneously received the violation warning. Participants might have been expected to believe that the maintenance vehicle (really the first confederate vehicle) was again entering or leaving the road, since this was the case for previous phase changes. However, the first confederate vehicle was not near the intersection at this time. The FV stayed 2 to 3 s behind the participant vehicle. At this point, participants decided either to stop or to continue through the intersection. If the participant had stopped, experimenters then made sure the vehicle's transmission was in "Park." If the participant did not stop, experimenters asked the participant to bring the vehicle to a stop and then place the transmission in "Park." Participants were then asked to fill out a brief questionnaire (Appendix C) on the warning just received (or on the situation just encountered for the baseline participants). The participant was then informed of the true purpose of the experiment and asked to read and sign a new informed consent form. Once the new informed consent was completed, participants returned to the main building for payment.

The experiment used the method of limits (adapted to a macro scale from the field of psychophysics). Initial participants were run at what was known to be a fairly late timing. Once one or more participants failed to stop in response to the warning, the warning timing was shifted toward an earlier point. This process continued until either 100 percent compliance was attained or the too-early limit was reached. The former occurred when the first 16 participants receiving a particular warning at a particular timing complied with the warning. The latter occurred when 100 percent compliance was not reached at any warning timing prior to the too-early point (located 53.3 m [175 ft] from the intersection for the 56.3-km/h [35-mph] speed used in these tests). When either of these two situations occurred, a matched set of drivers with no warning was run under the exact same timing conditions to provide baseline data (to show whether the warning provides a benefit above and beyond what a driver would do in the absence of a warning). Baseline conditions also used 16 participants.

The experiment took approximately 45 min per participant and required a staff of at least four experimenters:

- An FSE to read scripts, monitor speed, and use the experimenter brake pedal if required.
- A BSE to start and monitor data collection and silently signal the confederate vehicle when to approach the intersection.
- A confederate vehicle driver to drive both confederate vehicles in an elaborate choreography involving precise timing and the ability to keep the confederate vehicle hidden until the secret signal was received.
- An in-building experimenter to screen and schedule participants, prepare paperwork, and enter questionnaire and demographic data into the database.

Despite the complexity of training and scheduling experimenters, as well as scheduling participants, up to 10 participants could be run per day. Participants were only run when the road was dry because the experiment potentially involved hard braking. Luckily, the weather was generally favorable. However, to make up for lost days, participants were scheduled and run on several of the weekends throughout this time period.

Although the occlusion method did not include eye-transition time, the occlusion lasted for 2 s, which was felt to be representative of a typical distraction, including transition time. In addition, previous studies by the VTTI have shown that a typical eye transition time is less than 0.1 s, except in rare cases.

In testing the paradigm and method, pilot subjects reported a feeling of having to “snap back” to the driving task when the goggles cleared. Possible reasons for this phenomenon are the need to adjust to the ambient light level and to reorient to the visual driving scene (specifically, the location and status of the intersection). Participants were not aware that this was an intersection study, and they had been driving for about 45 min with numerous occlusions before the presentation of the intersection violation warning. Therefore, their experience of snapping back was probably even stronger, thus representing real-world transition times. Based on all these factors, the influence of excluding transition time from the distraction simulation paradigm was expected to be minimal.

Stop-Controlled Intersection Tests

The stop-controlled intersection tests used a very similar protocol, with a few key differences:

There was no participant interaction with confederate vehicles. The single confederate vehicle on the road was parked on the stop-controlled intersection approach, with the ostensible maintenance worker performing tasks in the area behind the road’s guardrail. As the participant approached the intersection for their surprise trial, the worker entered the vehicle as if ready to drive off. This ruse was developed to add an element of urgency to the warning. The signalized intersection methods achieved this through the presentation of the test intersection as a real intersection (through two traffic crossings); at a signalized intersection, stopping is not needed unless the light is red (or late in the amber), and the surprise was thus achieved via an unexpected signal phase change. For a stop-controlled intersection, stopping is always required, so surprise required that the intersection itself remain hidden until the surprise trial.

No following traffic was present. It was considered extremely unlikely that two successive drivers would not be aware of a stop sign, which always requires a stop (or at least a large reduction in velocity). Thus, the risk of a driver being faced with the threat of a rear-end collision while aggressively stopping for a stop sign was considered low enough to eliminate this aspect of the protocol. This does not imply that rear-end crashes seldom occur at stop-controlled intersections. Indeed, analysis of 2003 GES data suggests that about nine percent of stop-sign controlled intersection crashes were rear-end collisions. However, these crashes are likely due to factors related to the following (i.e. striking) vehicle, and we posit that the situation where two drivers in a row miss a stop sign (and thus the following driver is surprised by the sudden braking of the lead vehicle) is unlikely enough to allow for this simplification of the protocol.

The stop-controlled intersection was placed about a mile away from the signalized intersection to reduce the chance of drivers being confused as to their expected response. In fact, the signalized intersection was not visible from the site of the stop-controlled intersection.

Participants drove approximately three loops on the road before receiving the surprise trial. Note that although this was slightly fewer than the five loops used for the signalized intersection case, this was considered sufficient to familiarize participants with the occlusion goggles prior to the surprise trial (based on extensive experience with the methodology).

The stop sign was hidden from the participant's view throughout the study via a mechanical linkage. The linkage and associated actuators required less than 2.4 s (slightly longer than the maximum occlusion duration used in the earlier studies) to fully deploy the stop sign. On the surprise trial, the participant approached the stop-controlled intersection (which was not marked as an intersection except for a stop bar) and received an occlusion. While the participant was occluded (for less than 2.4 s), the stop sign deployed and the DII was activated (except for baseline conditions, in which no DII was present). At the moment of occlusion clearing, the participant was exposed to the stop sign and DII (Figure 75).

Questionnaires and informed consent forms were also edited as necessary to replace any references to a signalized intersection (or a specific signal phase) with references appropriate to a stop sign.

Once participants were done with the questionnaires following their surprise event, they were asked to approach the stop-controlled intersection (with a fully deployed stop sign) as they normally would. Participants did not wear occlusion goggles for this portion of the experiment. These data were used in estimating the too early distribution for the stop-sign case.

a) b)

Figure 75. Fully-deployed stop sign, a) side view, and b) front view.

Independent Variables

The independent variables were specific to each test being conducted and are fully described in the appropriate sections of this report. In general, the primary independent variable for interface-evaluation tests was DII type, with participant age and gender used as blocking factors. Blocking factors are those nuisance factors that may influence the results but are not the primary area of interest in the study. They are therefore controlled to the degree possible to account for their effects.

Dependent Variables

A substantial number of dependent variables were collected for the behavioral and computational tests. The majority of these variables were objective, but some subjective data were collected through questionnaires. In all cases, the set of variables attempts to uniquely characterize each participant's surprise intersection approach.

The variables available in raw form from the vehicle data collection system were used to generate (by selection or derivation) the following dependent variables:

- *Trial outcome (stop or did not stop)*: Whether the trial resulted in a participant stopping prior to entering the collision zone.
- *Distance before the stop bar (m)*: Vehicle distance to intersection once its speed was less than 0.2 m/s (0.4 mph). The threshold was selected to eliminate incorrect triggers due to noise in the positioning data.
- *Stopping zone (signalized intersection)*: Four different zones were defined, depending on the vehicle's distance with respect to the stop bar. These zones are specific to the Smart Road signalized intersection and its approach configurations, although they could be defined for any intersection. The zones were defined as:
    - Collision Zone – Vehicles that did not stop or that stopped at or more than 9.1 m (30.0 ft) into the intersection. For the Smart Road signalized intersection, this distance represented the location at which cross traffic could first be encountered.
    - Intrusion Zone – Vehicles that stopped less than 9.1 m (30.0 ft) and at or more than 4.6 m (15.0 ft) into the intersection. The testbed vehicles measured close to 4.6 m in length, so at this distance the rear end of the vehicle would be completely over the stop bar.
    - Violation Zone – Vehicles that stopped less than 4.6 m (15.0 ft) and more than 0.0 m (0.0 ft) into the intersection. In this zone, some portion of the testbed vehicle would be over the stop bar.
    - No-violation zone – Vehicles that stopped at or less than 0.0 m (0.0 ft) into the intersection (i.e., did not cross the stop bar during their stop).
- *Stopping zone (stop sign intersection)*: Four different zones were defined, depending on the vehicle's distance with respect to the stop bar. These zones are specific to the Smart Road stop sign intersection and its approach configurations, although they could be defined for any intersection. The zones were defined as:
    - Collision Zone: Vehicles that did not stop or that stopped at or more than 6.1 m (20.0 ft) into the intersection. For the Smart Road stop sign intersection, this distance represented the location at which cross traffic could first be encountered.
    - Intrusion Zone: Vehicles that stopped less than 6.1 m (20.0 ft) and at or more than 3.0 m (10.0 ft) into the intersection. The testbed vehicles measured close to 4.6 m in length, so at this distance the front end of the vehicle would be completely over the stop bar.
    - Violation Zone: Vehicles that stopped less than 3.0 m (10.0 ft) and more than 0.0 m (0.0 ft) into the intersection. In this zone, some portion of the testbed vehicle would be over the stop bar.
    - No-violation zone: Vehicles that stopped at or less than 0.0 m (0.0 ft) into the intersection (i.e., did not cross the stop bar during their stop).
- *Peak deceleration (g)*: Maximum driver-induced deceleration during the stop.

- *Constant deceleration (g)*: Driver-induced deceleration through the braking period as calculated in Equation 9:

Error! Objects cannot be created from editing field codes. (9)

Where:
a = constant deceleration as a proportion of g
V = vehicle speed at the point when the driver initiated braking (m/s)
g = gravitational acceleration constant (9.81 m/s^2)
D_i = Distance to intersection when the driver initiated braking (m)
D_f = Distance to intersection at which the vehicle stopped (m)

- *Required deceleration (g)*: Driver-induced deceleration that would be needed for the vehicle to stop at the stop bar based on the point when the driver initiated braking as calculated in Equation 10:

Error! Objects cannot be created from editing field codes. (10)

Where:
a = constant deceleration as a proportion of g
V = vehicle speed at the point when driver initiated braking (m/s)
g = gravitational acceleration constant (9.81 m/s^2)
D_i = Distance to intersection when driver initiated braking (m)

- *Time to accelerator release (TAR, s)*: Time from the onset of the stimulus to the onset of accelerator pedal release (operationally defined as the first decrease in accelerator position, after stimulus onset, of more than 2.5 percent in 0.1 s). For the warning conditions, the stimulus was the simultaneous presentation of the warning and the amber or red light or stop sign (because the occlusion was cleared simultaneously with the warning, after the light phase had changed or the stop sign deployed). For the no-warning conditions, the stimulus was the presentation of the amber or red light or stop sign without an accompanying DII.
- *Time to brake (TB, s)*: Time from the onset of the stimulus to the onset of brake application (operationally defined as the first increase in brake position, after stimulus onset, of more than 5 percent in 0.1 s). The stimuli for the warning and no-warning conditions were the same as previously described.
- *Time from accelerator to brake (TSAB, s)*: Time from the onset of accelerator pedal release (operationally defined as the first decrease in accelerator position, after stimulus onset, of more than 2.5 percent in 0.1 s) to the onset of brake application (operationally defined as the first increase in brake position, after stimulus onset, of more than 5 percent in 0.1 s). The stimuli for the warning and no-warning conditions were the same as previously described.
- *Time to peak deceleration (s)*: Time from the onset of the stimulus to maximum driver-induced deceleration. The stimuli for the warning and no-warning conditions were the same as previously described.
- *Time from brake to peak deceleration (s)*: Time from the onset of brake application (operationally defined as the first increase in brake position, after stimulus onset, of more than 5 percent in 0.1 s) to maximum driver-induced deceleration.

- *Maximum brake velocity (percent/s)*: Maximum increase in brake position per unit time. Calculated based on successive brake position samples down-sampled to 10 Hz (from the original 100-Hz rate).

For the sign conspicuity study, the main dependent variable was conspicuity, which was measured as the percentage of drivers who answered affirmatively as to whether they noticed the DII. Since the goal of this particular experiment was to examine only trends in conspicuity, no statistical analyses were conducted on its results.

Participants

Participants were recruited through the newspaper, word of mouth, and a database of local residents who had expressed interest in participating in studies. On initial contact (usually over the phone), participants were screened to ensure they were eligible for the study, including assurance that they had not previously participated in a surprise-scenario experiment with the contractor (this may have predisposed them to expect a surprise condition). They were then scheduled for an available time.

In order to gain information on how people initially react to warnings, a mild form of deception was used in this study. Participants were first given an informed consent form informing them that they would be involved in a study to evaluate occlusion goggles as a method for simulating driver distraction. After agreeing to the study and signing the informed consent, a health screening was conducted to ensure that participants did not have any conditions that would impair their ability to safely operate the test vehicle. A Snellen vision test was conducted to make sure the participants' visual abilities were within legal limits of 20/40 or better. Their color vision was also tested and recorded. If their health was not good or their vision results fell outside the tolerable limits, participants were excused from the study and paid for their time.

Two age groups were used for the experiments using the occlusion goggles standardized protocol: younger drivers aged 18 to 30 years and older drivers aged 50 and older. Appendix D shows the number, age group, and gender of participants run for each condition tested. Altogether, 367 subjects were run using this protocol, of which 282 provided valid data points (resulting in an invalid response rate of 23.2 percent). Invalid data points were caused by several factors, the most common of which were drivers removing their foot from the gas pedal as they approached the intersection or as the goggles were occluded (most of the dependent variables could not be calculated for these cases). Relatively rare factors included experimenter error (e.g., opened the wrong program or forgot to start data collection) and equipment failure (testbed vehicle, intersection, or communications). In general, the standardized protocol was an efficient method for obtaining the necessary data, which provided for comparison of results across many of the experiments (for example, a baseline group run at a certain distance and speed could be used as a comparison group for all DII trials that used an equivalent timing).

Equipment

In order to make the occlusion goggles scenario as safe as possible, a steering wheel limiter was designed and installed in the testbed vehicle. This prevented the participant from steering the vehicle more than ±5° from the direction of travel when the steering limiter was activated (at the same time as goggle occlusion and warning). This was done in lieu of a second steering wheel such as has been used in other studies (e.g., CAMP studies). Given that the goggles were only occluded for 2 s, this was felt to be an adequate solution (in other studies, the goggles had remained mostly occluded with occasional clearing episodes, so the experimenter had to do all of the actual steering). For more details on testbed and DAS equipment, refer to the previous discussion on testbed instrumentation.

Several DIIs were created and tested. The first visual DII included a 0.9-meter by 0.9-meter (3-foot by 3-foot) LED sign that reproduced a red hexagonal shape with the word "STOP" in its center when illuminated (Figure 76) and two round red lights (0.3 m [1 ft] in diameter) that alternated flashing at 2 Hz (Figure 77). Both of these warnings were located on the signal mast arm, with the LED stop sign positioned in the midpoint between the two signal heads and the dual flashing lights positioned on either side of the signal head's red light. Two configurations were used in testing the LED stop sign. First, the sign was augmented with two strobe lights, located symmetrically in the lower half of the sign (as seen on Figure 76). Second, when the expected levels of effectiveness were not attained using this configuration (see Results), the sign was outfitted with customized TCLs (not pictured). When a warning was presented in this second configuration, both the strobes and the TCLs were activated.

Figure 76. LED stop sign visual warning. Unlit strobes can be seen at the two bottom corners.

Figure 77. Dual flashing lights visual warning.

In addition to the two visual DIIs, a haptic warning was created via the simulation of rumble strips. Creation of the rumble strip simulation was accomplished by using a high-fidelity gyroscope to detect vertical vehicle acceleration while traveling over a set of rumble strips at approximately 16.1 km/h (10 mph). The frequency spectrum from this vertical acceleration (i.e., vibration) was obtained and key frequencies were gathered, along with their relative magnitudes. These key frequencies were then used as sine wave parameters that were combined additively to create a sound file that could be reproduced through the vibrotactile transducers in the test vehicle. Eight different sine waves were superimposed to create this sound file:

- Frequency of 1 Hz at -4 dB relative magnitude
- Frequency of 10 Hz at -4 dB relative magnitude
- Frequency of 20 Hz at -4 dB relative magnitude
- Frequency of 40 Hz at -4 dB relative magnitude
- Frequency of 50 Hz at 0 dB relative magnitude
- Frequency of 60 Hz at 0 dB relative magnitude
- Frequency of 70 Hz at -4 dB relative magnitude
- Frequency of 80 Hz at -4 dB relative magnitude

The resulting sound pattern represented the vehicle traveling over a single rumble strip, and thus had to be combined into meaningful sets. The spacing was selected based on the Ohio MUTCD specifications, as reported in Harwood (1993), but using only the three pads closer to the intersection stop bar. These pads (from closest to the intersection to farthest) consisted of 6, 6, and 10 rumble strips. The farthest pad and the middle pad were 15.24 m (50 ft) apart, and the middle pad and the closest pad were 10.67 m (35 ft) apart. The final pattern was presented once, taking approximately 3 s for complete playback.

The final DII tested was the LED-enhanced stop sign (Figure 78). The same sign was used for stop-sign baseline condition, but the flashing LEDs were turned off, allowing the sign to simulate a traditional stop sign.

Figure 78. LED-enhanced stop sign.

Conditions Tested

Several DIIs were tested as part of this effort; the technical aspects of these DIIs were discussed in detail in a previous section of this report. For the convenience of the reader, they are summarized here in the order in which they are presented in the report:

- Baseline Experiments (with Amber at Occlusion End): A baseline (no warning) condition was run at every warning-onset TTI for which an optimal timing (i.e., achieving 100 percent compliance) was obtained for a particular DII type. Since all of the warnings tested under the amber at occlusion protocol were stopped at the same warning onset (due to reaching 100 percent compliance or reaching the too-early point), the only baseline group needed was at a TTI value of 3.41 s at 56.3 km/h (35 mph). As previously discussed, the protocol for this baseline condition was exactly the same as for other DII tests, except that no warning was presented when the occlusion cleared. In order to allow for direct comparisons, the timing of the end of the occlusion was the same for these baseline conditions as for the warning conditions having the same warning-onset TTI.
- DII Experiments (with Amber at Occlusion End): Two different visual warnings were tested, the operation of which has been described as part of the apparatus section: the LED Stop Sign (in strobes-only and strobes + TCLs configurations) and the Dual Flashing Red Lights. In addition to these visual warnings, a haptic warning (in the form of a simulated rumble strip) was also tested in this experimental configuration.
- Baseline Experiments (with Red at Occlusion End): A baseline (no warning) condition was run at 2.03-second, 2.65-second, 3.02-second, and 3.41-second TTIs. As previously discussed, the protocol for these baseline conditions was exactly the same as for other DII

tests except that no warning was presented when the occlusion cleared. In order to allow for direct comparisons, the timing of the end of the occlusion was the same for these baseline conditions as for the warning conditions having the same warning-onset TTI.

- DII Experiments (with Red at Occlusion End): The previously described (Figure 77) LED stop sign, in its strobe-augmented configuration, was used as the visual DII in this experimental stage. Likewise, the previously described rumble strip simulation was used as the DII for tests of the haptic modality under the revised protocol.
- LED-enhanced Stop-Sign Experiments: The occlusion method, with the modifications discussed in the Signalized Intersection Tests section, was used for these tests. Following the philosophy of the signalized intersection tests with a red light at the end of the occlusion, full groups of 16 participants were run at each of four different warning timings: 2.03-second, 2.65-second, 3.02-second, and 3.41-second TTI. Eight of the participants were exposed to the DII at each warning timing; the remaining eight were not exposed to the DII and experienced a baseline condition. The protocol for these baseline conditions was exactly the same as for the DII conditions, except that no warning was presented when the occlusion cleared. In order to allow for direct comparisons, the timing of the end of the occlusion was the same for these baseline conditions as for the warning conditions having the same warning-onset TTI. Also note that no baseline condition was run for the 2.03-second TTI timing. After running a group of eight participants exposed to the DII at this timing, a baseline group was deemed unnecessary given their low compliance percentage with the warning (12.5 percent). It would be expected that for a baseline condition at this timing, the compliance percentage would be smaller, but the magnitude of that reduction was considered negligible.

Data Reduction and Analysis Techniques

The dependent variables for the study were examined for consistency before being subjected to any analysis process. Custom software was created to identify the surprise trial within these data, calculate the dependent variables of interest, and produce plots that aided in data integrity verification (Figure 79). The figures created illustrated all essential aspects of the intersection approach and allowed the identification of incorrectly processed, incomplete, or corrupt data.

These graphs also allowed the exclusion of participants whose data could not be used in the analysis. Participants were excluded from data analysis if they were not pressing the gas pedal at the time the goggles cleared and the warning was issued (for those trials for which a warning was indicated). These participants were excluded because their reaction time was significantly faster than the reaction time of participants who *were* pressing on the gas pedal at warning onset. This faster reaction time was proven in a pilot data analysis effort performed under the ICAV project to test the necessity of maintaining this exclusion criterion. Figure 80 shows a sample intersection approach plot for a participant who was excluded. The figure shows that the participant completely removed his or her foot from the accelerator before the warning onset.

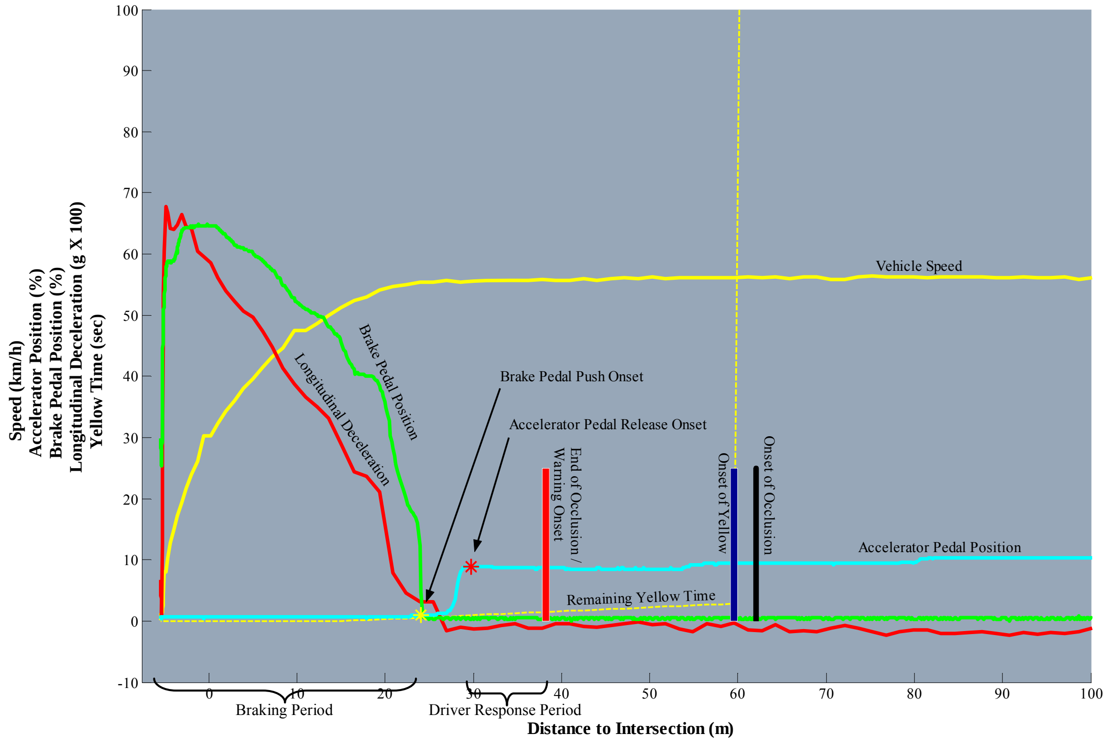

Figure 79. Sample intersection approach plot used to aid in data integrity verification. There was no indication of amber onset for stop sign trials.

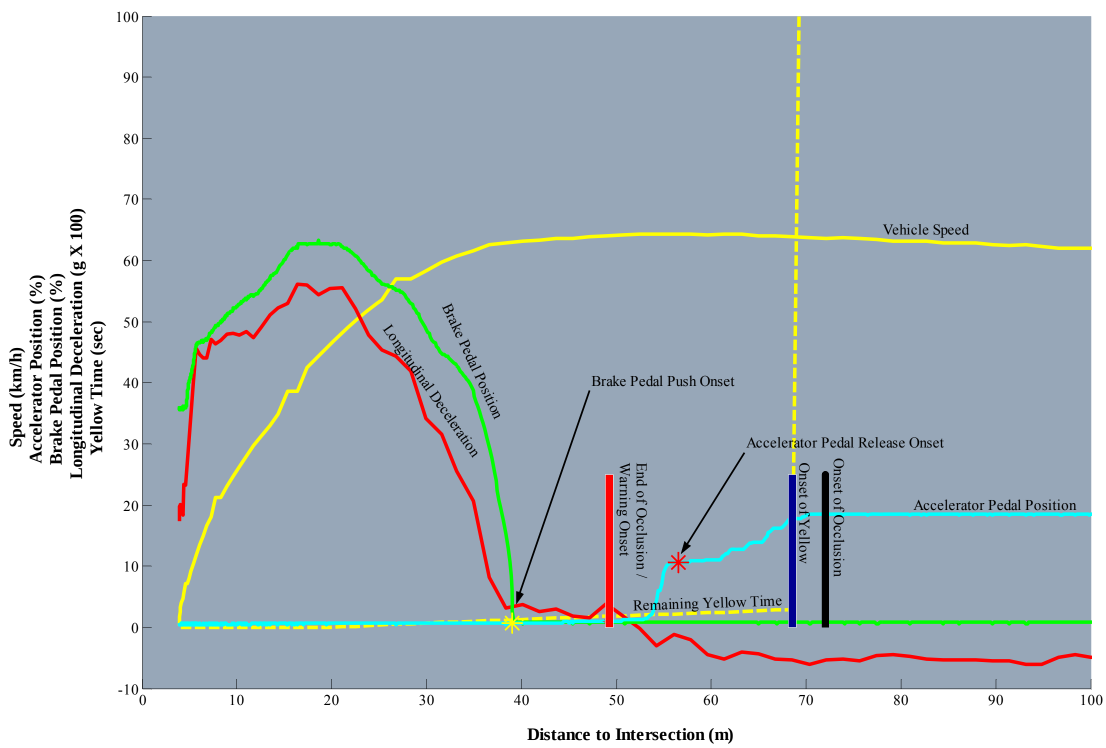

Figure 80. Sample graph for excluded participant. Amber onset was not indicated for stop sign trials.

Participants were also excluded from the study if they were traveling, at warning onset, more than 7.9 km/h (5 mph) over or under the nominal speed for the warning condition. Once data validity had been established and the exclusion criteria applied for a participant, his or her data were included in the analysis database. After data collection was complete, all dependent variables were further examined for consistency and the presence of outliers. Any outliers whose occurrence could be attributed to a particular flaw in data collection or data processing were either corrected or removed (e.g., either the software had selected incorrect brake-onset or accelerator-release thresholds or a sensor required calibration).

The cleaned data were then analyzed to determine their dependence with the construct of driver response time. Conceptually, there are two steps required for a successful intersection stop. These steps are: 1) analyze, formulate, and initiate a response plan to the stimulus requiring the stop and 2) adapt and complete the execution of the plan based on any sensory feedback. Both steps can be quantified using different dependent variables. However, the dependent variables that characterize the second step might not be independent of those that characterize the first step. For example, it is possible that a driver who takes longer to react to the DII stimulus (Step 1) would brake harder (Step 2) in order to stop at the same point as a driver with a faster reaction time. Any dependence found between variables in Step 1 and Step 2 would have to be accounted for and corrected for in any analyses using Step 2 variables. All of the dependent variables described above can be classified according to the step that they quantify:

- Analysis, formulation, and initiation of the response plan (Step 1, plan initiation).
  - TAR
  - TB
  - TSAB
- Adaptation and completion of the response plan (Step 2, plan execution).
  - Time to peak deceleration.
  - Time from brake to peak deceleration.
  - Distance before the stop bar.
  - Peak deceleration.
  - Constant deceleration.
  - Required deceleration.
  - Maximum brake velocity.

In order to determine the need for correction factors, a correlation analysis was performed between the Step 1 and Step 2 variables. Given that correlation analysis quantifies the degree of linear relationship between variables, transformation of variables was also examined in this process as a means of maximizing the correlations.

Once the correlations were completed and any relationships between Step 1 and Step 2 variables established, statistical ANOVA was performed. Dependent variables for which no correction was needed (i.e., all Step 1 variables and Step 2 variables that exhibited no correlation with Step 1 variables) were analyzed using traditional ANOVA techniques. Dependent variables that required a correction were analyzed using either analysis of covariance (ANCOVA) for the blocking factors or multivariate regression for comparisons between DII types. As previously discussed, the independent variable in these analyses was the DII type, with participant age and gender used as blocking factors.

When significant main effects were found, post-hoc Student-Newman-Keuls (SNK) tests were performed to determine the source of those differences. Significant interaction effects were examined with post hoc t-tests using the Tukey correction for multiple comparisons. A Type I error level of 0.05 was assumed for all tests.

The trial outcome and stopping zone variables were considered and analyzed separately because they were discrete variables which did not require any correction. These variables were analyzed based on proportion of occurrence for each trial. Confidence intervals (95^{th} percentile) were established for trial outcome to determine overlap between different experimental groups and infer statistically significant differences. These confidence intervals were based on the binomial distribution, which describes the probability of discrete outcomes when observations are independent.

Results of Baseline Experiments (with Amber at Occlusion End)

The baseline experimental condition presented below represented a comparison group for all of the DIIs evaluated in this set of experiments because DIIs for which no optimal warning timing was found were tested with full participant groups at this specific warning timing. Again, this was due to this particular timing representing the pre-established too-early point.

Results for Baseline, 56.3 km/h (35 mph), and 3.41-s TTI Condition

For this baseline (no warning) condition, drivers were instructed to drive at 56.3 km/h (35 mph). The amber change was presented at a nominal TTI of 5.30 s, or 1.89 s before the occlusion-clearing TTI of 3.41 s (the occlusion cleared at the same TTI at which participants in the warning conditions received a warning). This baseline condition produced an 81.3 percent compliance rate across 16 participants (Table 44). Compliance was defined as stopping in the no violation, violation, or intrusion zones as previously defined for this intersection. The dependent variables related to stopping behavior were available for the 13 (out of 16) participants who elected to stop (Table 45). Participants were traveling on average at 57.1 km/h (35.5 mph) when their occlusion cleared, revealing the amber light.

Some of the correlations between the plan initiation and plan execution variables were significant. TAR was correlated with peak, constant, and required deceleration. TB was correlated with distance beyond stop bar, peak deceleration, constant deceleration, and required deceleration. TSAB was correlated with distance beyond stop bar, peak deceleration, and required deceleration. These correlated variables were analyzed with ANCOVAs, while the other variables were analyzed with ANOVAs; the significant results for these analyses are included in Table 41. Post hoc tests showed that the male drivers stopped farther into the intersection than the female drivers (-3.65 m versus -0.60 m).

Table 41. ANOVA/ANCOVA results. Only dependent variables with one or more significant effects are included. Blank cells and missing dependent variables indicate *p*-values > 0.05.

Independent Variable / Dependent Variable	Distance before stop bar (g)
Age	
Gender	p=0.0363
Age X Gender	

Participant responses to the questionnaire statements showed few trends. Drivers in both groups rated the surprise event expectancy as relatively low, although several participants indicated a higher expectancy. Drivers who stopped and drivers who did not stop rated the timing of the end of the occlusion (comparable to the presentation of the warning) as neither early nor late. Drivers who stopped tended to rate the stop as slightly uncomfortable, although they tended to feel in control of the vehicle. Drivers who did not stop thought that stopping the car would have been slightly difficult. Finally, drivers had a relatively high feeling of safety during the surprise event. Graphs representing these subjective responses are shown in Appendix E. When asked why they did not stop, two participants indicated that they were aware that there was no other traffic at the intersection, and one participant did not provide a reason.

Results of Visual Warnings: Too-Late Determination (with Amber at Occlusion End)

Results for the LED Stop Sign plus Strobes Visual Warning

At an instructed speed of 56.3 km/h (35 mph), the LED stop sign plus strobes did not result in 100 percent compliance with 16 participants (95 percent CI: >81.9 to 100 percent) until a nominal warning onset TTI of 3.41 s (Table 44). The corresponding amber change was presented at a nominal TTI of 4.0 s (i.e., 0.59 s before the warning onset). All dependent variables were captured for the 16 participants (Table 45). Participants were traveling at an average speed of 58.4 km/h (36.3 mph) when they received the warning.

Some of the correlations between the plan initiation and plan execution variables were significant. Time to accelerator release and time to brake were correlated with distance beyond stop bar, peak deceleration, constant deceleration, required deceleration, and time to peak deceleration. TSAB was correlated with required deceleration. The correlated variables were analyzed with ANCOVAs while the other variables were analyzed with ANOVAs; no significant effects were detected for any of the dependent variables.

Participant responses to the questionnaire statements showed few trends (Appendix E). Driver expectancy of the surprise event was relatively low across all drivers; only two drivers marked answers on the “Agree” side of the scale. The timing of the warning tended to be rated as slightly late. The comfort of the stop was not consistently rated; some drivers considered it uncomfortable, but others felt that it was comfortable. Drivers tended to feel very much in control of the vehicle during the stop. The feeling of safety during the stop, perhaps influenced by the presence of a following vehicle, was not consistently rated. However, a slight majority of drivers indicated that they felt safe during the stop. Of the 16 drivers, 12 noticed the DII.

Results for the LED Stop Sign plus Strobes plus TCLs Visual Warning

At an instructed speed of 56.3 km/h (35 mph), the LED stop sign plus strobes plus TCLs did not result in 100 percent compliance with 16 participants, even at the too-early point of 3.41 s TTI. A full group of 16 participants was run at this TTI in order to allow for inter-DII comparisons (recall that the LED stop sign plus strobes was optimal at this 3.41-second TTI). The LED stop sign plus strobes plus TCLs elicited a compliance rate of 93.8 percent (95 percent CI: 81.9 percent to 100 percent) at this warning onset timing (Table 44). The corresponding amber change was presented at a nominal TTI of 4.0 s (i.e., 0.59 s before the warning onset). All dependent variables were captured across the 15 participants who stopped (Table 45). Participants were traveling at an average speed of 57.6 km/h (35.8 mph) when they received the warning.

Some of the correlations between the plan initiation and plan execution variables were significant. TSAB and TB were correlated with peak deceleration, constant deceleration, and required deceleration. These correlated variables were analyzed with ANCOVAs, while the other variables were analyzed with ANOVAs; the significant results for these analyses are included in Table 42. Post hoc tests showed that the younger drivers had a longer transition time from accelerator to brake (0.50 s) than the older drivers (0.34 s). For maximum brake pedal velocity, the significant age effect indicated that younger participants braked with a lower pedal velocity (1.44 percent/s) than older participants (1.92 percent/s). The significant interaction indicated that this effect was stronger for male participants than female participants.

Table 42. ANOVA/ANCOVA results. Only dependent variables with one or more significant effects are included. Blank cells and missing dependent variables indicate *p*-values > 0.05.

Independent Variable / Dependent Variable	Time from Accelerator to Brake (s)	Maximum Brake Velocity (%/s)
Age	p=0.0277	p=0.0066
Gender		
Age X Gender		p=0.0139

Participant responses to the questionnaire statements showed few trends (Appendix E). Driver expectancy of the surprise event was relatively low across all drivers; only one driver marked the "Agree" side of the scale. The timing of the warning tended to be rated as slightly late. The comfort of the stop was not rated consistently; some drivers considered it uncomfortable, but others felt that it was comfortable. Most drivers felt in control of the vehicle during the stop. The feeling of safety during the stop, perhaps influenced by the presence of a FV, was not rated consistently. However, a small majority of drivers indicated that they felt safe during the stop. The driver who did not stop indicated that the decision was made because he or she would have had to "slam on the brake"; in the questionnaire, this driver indicated that it would have been "slightly difficult" to stop the vehicle. Of the 16 drivers, 14 noticed the DII.

Results for the Dual Flashing Red Lights Visual Warning

At an instructed speed of 56.3 km/h (35 mph), the Dual Flashing Red Lights did not result in 100 percent compliance with 16 participants, even at the too-early point of 3.41-second

TTI. A full group of 16 participants was run at this TTI in order to allow for inter-DII comparisons (recall that the LED stop sign plus strobes was optimal at this 3.41-second TTI). The dual flashing red lights elicited a compliance rate of 62.5 percent (95 percent CI: 38.8 percent to 86.2 percent) at this warning onset timing (Table 44). The corresponding amber change was presented at a nominal TTI of 4.0 s (0.59 s before the warning onset). All dependent variables were captured across the 10 participants who stopped (Table 45). Participants were traveling at an average speed of 58.4 km/h (36.3 mph) when they received the warning.

Some of the correlations between the plan initiation and plan execution variables were significant. TAR was correlated with constant deceleration and required deceleration. TB was correlated with peak deceleration and required deceleration. TSAB was correlated with constant deceleration. These correlated variables were analyzed with ANCOVAs, while the other variables were analyzed with ANOVAs; however, no significant effects were detected.

Participant responses to the questionnaire statements showed few trends (Appendix E). Driver expectancy of the surprise event was relatively low across all drivers; only three drivers marked answers on the "Agree" side of the scale. In fact, most drivers disagreed strongly with a statement that indicated a high expectancy of the event. The timing of the warning tended to be rated as slightly late. The comfort of the stop was not rated in a consistent manner; some drivers considered the stop uncomfortable, while others felt it was comfortable. Drivers tended to feel in control of the vehicle during the stop. The feeling of safety during the stop or intersection crossing, perhaps influenced by the presence of a FV, was not rated consistently. However, drivers who stopped tended to rate their feeling of safety as higher than drivers who did not stop. The six drivers who did not stop were inconsistent in their rating of perceived difficulty of the braking task; some rated it as high while others rated it as low. Two of these drivers indicated that they did not stop because they would have "jerked" the occupants, one indicated that they were too close to the intersection, two thought they could "make it," and one did not stop because it was not "a real situation." Of the 16 drivers, 14 noticed the DII.

Haptic Warning: Too-Late Determination (with Amber at Occlusion End)

Results for the Rumble Strip Simulation Haptic Warning

At an instructed speed of 56.3 km/h (35 mph), the rumble strip simulation did not result in 100 percent compliance with 16 participants, even at the too-early point of 3.41-second TTI. A full group of 16 participants was run at this TTI in order to allow for inter-DII comparisons (recall that the LED stop sign plus strobes was optimal at this 3.41-second TTI). The rumble-strip simulation elicited a compliance rate of 93.8 percent (95 percent CI: 81.9 percent to 100.0 percent) at this warning onset timing (Table 44). The corresponding amber change was presented at a nominal TTI of 4.0 s (i.e., 0.59 s before the warning onset). All dependent variables were captured across the 15 participants who stopped (Table 45). Participants were traveling at an average speed of 58.4 km/h (36.3 mph) when they received the warning.

Some of the correlations between the plan initiation and plan execution variables were significant. TAR was correlated with peak and constant deceleration. TB was correlated with distance beyond stop bar, peak deceleration, constant deceleration, and required deceleration. TSAB was correlated with distance beyond stop bar and required deceleration. These correlated variables were analyzed with ANCOVAs, while the other variables were analyzed with ANOVAs; the significant results for these analyses are included in Table 43. Post hoc tests showed that the younger drivers had a larger peak deceleration (0.55 *g*) than older drivers (0.50 *g*); younger drivers also exhibited a longer time from brake to peak deceleration (2.82 s) than the older drivers (2.07 s). Females had lower brake pedal velocities (1.54 percent/s) than males (2.30 percent/s). For maximum brake pedal velocity, the significant age effect indicated that younger participants braked with a lower pedal velocity (1.44 percent/s) than older participants (1.92 percent/s).

Table 43. ANOVA/ANCOVA results. Only dependent variables with one or more significant effects are included. Blank cells and missing dependent variables indicate *p*-values > 0.05.

Independent Variable / Dependent Variable	Peak deceleration (g)	Time from brake to peak deceleration (s)	Maximum Brake Velocity (%/s)
Age	p=0.0016	p=0.0423	
Gender			p=0.0210
Age X Gender			

Participant responses to the questionnaire statements showed few trends (Appendix E). Driver expectancy of the surprise event was relatively low, with most drivers rating it on the low side. The timing of the warning tended to be rated as neither early nor late. The comfort of the stop was not consistently rated; some drivers considered it uncomfortable, while others felt comfortable with it. Drivers tended to feel very much in control of the vehicle during the stop. The feeling of safety during the stop, perhaps influenced by the presence of a following vehicle, was not consistently rated. The driver who did not stop indicated that he or she thought the light had changed back to green; in the questionnaire, the driver indicated that it would have been somewhat difficult to stop. Of the 16 drivers, 14 noticed the vibrations caused by the DII. However, not all of these drivers correctly identified rumble strips as the vibration source. One driver indicated that the vibration felt like a flat tire, one thought that the anti-lock brakes had been activated, and six simply identified it as a vibration without specifying the assumed source.

Comparisons between Conditions with Amber at Occlusion End

Each of the visual and haptic warnings discussed in the previous two sections had an associated baseline for which occlusion ended at an equivalent TTI. The incremental beneficial effects for each optimized warning could be determined by comparing the warnings to their equivalent baseline conditions. The warnings were tested at a TTI of 3.41 s. Results for compliance percentage and distribution of drivers within the stopping zones show that the warnings did not provide much incremental benefit over the baseline condition (Table 44). In fact, the dual flashing red light visual warning resulted in a lower compliance percentage than the baseline condition (where no warning was presented). Following the comparison table, a similar table is presented for comparison of the performance variables across the same conditions (Table 45).

Statistical comparisons based on the objective variables showed there were no significant differences in plan initiation variables (i.e., TAR, TB, and TSAB) among the different warning and baseline groups. However, some significant differences were detected for the plan execution variables:

- Distance before stop bar was significantly affected by the Gender by DII Type interaction ($F(9, 58) = 2.58$, $p = 0.0144$). However, the source for this difference could not be isolated using post hoc tests.
- The peak deceleration was significantly affected by DII Type ($F(4, 63) = 3.27$, $p = 0.0168$)
  - The baseline group had a significantly higher level of peak deceleration (0.57 *g*) than the dual flashing red lights group (0.51 *g*).
  - Peak deceleration was not significantly different between the baseline group and any other DII types or between the DIIs
- Time to peak deceleration was significantly affected by the Age by DII Type interaction ($F(5, 53) = 2.53$, $p = 0.0398$), but this difference was not strong enough to be detected by post hoc tests.
- Time from brake to peak deceleration was significantly affected by the Age by DII Type interaction ($F(5, 54) = 2.48$, $p = 0.0427$). This difference was not strong enough to be detected by post hoc tests.

These differences were not conducive to any conclusions concerning the relative effectiveness of each of the warnings. The only obvious DII type that could be eliminated was the dual flashing red lights, given that compliance levels for this type were lower than for the other DII types and even the baseline (no warning) condition. Furthermore, given that none of the DII types offered significantly better performance than was observed for the baseline case, recommending the use of any of these warnings to address SCP violation scenarios does not seem to be appropriate. However, consider that the SCP crash scenario includes two possibilities:

- The warning is issued when the amber light is illuminated. This condition represents situations in which the violation would occur within the first few seconds of the red phase.

- The warning is issued when the red light is illuminated. This condition represents situations in which the violation would occur well into (e.g., more than a few seconds) into the red phase. The probability of a crash is higher in this situation because cross traffic has been receiving a green indication for some time, so they have had time to accelerate into the intersection.

Of these two possibilities, only the warning issued during an amber light has been considered thus far. The situation in which a warning is issued only under a red light had not been explored on the tests up to this point because it was expected that a warning eliciting high compliance when issued during an amber light would elicit equal or higher levels of compliance under a red light.

Table 44. Comparison of compliance percentage and stop zone distributions across the warning and baseline conditions with an amber light at occlusion end.

Condition	Number of participants	Compliance Percentage (95% CI)	Participants Stopping in "No Violation" Zone (%)	Participants Stopping in "Violation" Zone (%)	Participants Stopping in "Intrusion" Zone (%)	Participants Stopping in "Collision" Zone (%)	Participants that Did Not Stop (%)
3.41 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)							
Baseline at 35 mph, 3.41 s TTI	16	81.3 (N = 13) (62.2% - 100%)	31.3	43.8	6.3	0.0	18.8
"STOP" LED sign + Strobes + TCLs	16	93.8 (N = 15) (81.9% - 100%)	25.0	62.5	6.3	0.0	6.3
"STOP" LED sign + Strobes	16	100.0 (N = 16) (>81.9% - 100%)	12.5	68.8	18.8	0.0	0.0
Dual flashing red	16	62.5 (N = 10) (38.8% - 86.2%)	12.5	37.5	12.5	0.0	37.5
Rumble strip simulation	16	93.8 (N = 15) (81.9% - 100.0%)	56.3	31.3	6.3	0.0	6.3

Table 45. Comparison of performance variable averages across a subset of warning and baseline conditions with an amber light at occlusion end.

Condition	N	Distance before stop bar (m)	Peak deceleration (g)	Constant deceleration (g)	Required deceleration (g)	Time to accelerator release (s)	Time to brake (s)	Time from accelerator to brake (s)	Time to peak deceleration (s)	Time from brake to peak deceleration (s)	Maximum brake velocity (%/s)
3.41 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)											
Baseline at 35 mph, 3.41 s TTI	13	-0.83	0.54	0.35	0.36	0.45	0.82	0.38	3.64	2.87	1.51
"STOP" LED sign + Strobes + TCLs	15	-1.51	0.56	0.38	0.40	0.68	1.10	0.42	3.75	2.71	1.67
"STOP" LED sign + Strobes	16	-2.12	0.55	0.38	0.41	0.72	1.12	0.40	3.89	2.83	1.71
Dual flashing red	10	-2.94	0.52	0.36	0.39	0.66	1.06	0.40	3.96	2.96	1.76
Rumble Strip Simulation	15	-0.08	0.53	0.39	0.39	0.59	1.03	0.44	3.42	2.43	1.96

Given that the tests considering warning under amber showed little or no benefit from the warning, the decision was made to test the remaining case, in which a warning is issued when the light is red. The main purpose of these ensuing tests was to determine whether the warnings would produce higher levels of compliance when combined with a red light. If these levels of compliance were higher than baseline levels of compliance, then it would be possible to recommend the use of these warnings to address these late violations that: 1) have a higher probability of crash risk and 2) allow for the presentation of the warning solely under a red light.

This protocol change was not undertaken lightly, and approved only after considering the possibility that conflicting information was being presented to the driver when the warnings were presented along with an amber light. Thus, while the warnings were meant to elicit a stopping response, the amber light provides a choice to drivers, who must decide whether they feel more comfortable stopping or trying to make it. If the warning is presented to a driver who feels he or she can make it, then the warning conflicts with this decision. While this is not necessarily undesirable (because drivers make wrong decisions in many cases), the results of the experiments discussed thus far show that these infrastructure-based DII types did not seem to be salient or urgent enough to effectively counteract the driver's desire to make it through the intersection. Some in-vehicle warnings, which have the advantage of being more salient, have been shown to more effectively reduce this desire and generate the desired stopping behavior (Lee et al., 2005).

Thus, a data collection effort began that was experimentally similar to the one described up to this point with three main exceptions:

- The driver would see a green light until the beginning of the occlusion period. During the occlusion period, the light was changed from green to red (instead of amber). When the driver received the warning, which was coincidental with the moment of occlusion clearing, they also saw that the light had turned red.
- Instead of shifting warning timing to determine the timing that resulted in 100 percent compliance, a set of four warning timings was selected, and groups of eight participants were run at each of these timings for each of the DII types of interest.
- Given that no practical differences could be established between most DII types when they were presented along with an amber light, and in the interest of effectively using project resources, only two DII types were tested. The LED stop sign plus strobes was selected as being most representative of the visual warning modality since it resulted in the highest compliance level among all visual warnings and was the only DII that could be optimized. The rumble strip simulation was the second DII type selected and was the sole representative of the haptic warning modality.

The warning timings were selected based on engineering judgment of the amount of spacing between sampled timings that would provide meaningful differences between successive timings while still completely characterizing the timing region of interest. Accordingly, the latest timing tested was a 2.03-second TTI (based on the latest timing tested on the ICAV project for soft braking). At this timing, a very low compliance was expected. The earliest timing tested was a 3.41-second TTI (based on the known too-early point). At this point, a high level of compliance was expected. The two intermediate timings selected were a 2.65-second TTI and a 3.02-second TTI.

Baseline Experiments (with Red at Occlusion End)

Results for Baseline, 56.3-km/h (35-mph), and 2.03-second TTI Condition

For this baseline (no warning) condition, drivers were instructed to drive at 56.3 km/h (35 mph). The red change was presented at a nominal TTI of 4.00 s, or 1.97 s before the occlusion-clearing TTI of 2.03 s (the occlusion cleared at the same TTI at which participants in the warning conditions received a warning). This baseline condition produced a 22.2 percent compliance rate (N = 2, 95 percent CI: 0.0 percent to 51.0 percent) across nine participants (Table 46, data from nine participants were available since an experimenter inadvertently ran an additional subject for this condition). The dependent variables related to stopping behavior were available for the five (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 57.5 km/h (35.7 mph) when their occlusion cleared, revealing the red light. The low number of participants in the sample did not allow for statistical analysis of differences between the dependent variables due to age or gender effects for this or any of the other experimental conditions.

Participant responses to the questionnaire statements showed few trends. Drivers rated the surprise event expectancy as relatively low although there were several exceptional ratings indicating a higher expectancy. These exceptions were observable in the group of drivers who stopped. Drivers who stopped tended to rate the timing of the end of the occlusion (comparable to the presentation of the warning) as earlier than drivers who did not stop. Drivers who stopped tended to rate the stop as neither comfortable nor uncomfortable although they felt in control of the vehicle. Most drivers who did not stop thought that stopping the car would have been difficult. Their reasons for not stopping included insufficient time to stop (two drivers), knew that there would not be any cars at the intersection (one driver), did not notice the light (one driver), would have to stop too hard (one driver), and the presence of a following vehicle (one driver). Finally, drivers who stopped indicated a tendency toward a feeling of safety, which shifted toward a feeling of less safety for those who did not stop. Graphs representing these subjective responses are shown in Appendix E.

Results for Baseline, 56.3-km/h (35-mph), and 2.65-second TTI Condition

For this baseline (no warning) condition, drivers were instructed to drive at 56.3 km/h (35 mph). The red change was presented at a nominal TTI of 4.00 s, or 1.35 s before the occlusion-clearing TTI of 2.65 s (the occlusion cleared at the same TTI at which participants in the warning conditions received a warning). This baseline condition produced a 50.0 percent compliance rate (N = 4, 95 percent CI: 15.4 percent to 84.6 percent) across eight participants (Table 46). The dependent variables related to stopping behavior were available for the five (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 57.5 km/h (35.7 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed few trends. Without exception, drivers in both groups rated the surprise event expectancy as very low. Drivers who stopped and drivers who did not stop rated the timing of the end of the occlusion (comparable to the presentation of the warning) as late. Drivers who stopped tended to rate the stop as uncomfortable and were not consistent in rating their feeling of vehicle control during the stop. Drivers who did not stop indicated that this action was the result of compromised safety (two drivers) and the knowledge that this was a study (one driver). Two of these drivers indicated that it would have been difficult to stop the vehicle, whereas the third indicated it would have been easy. Finally, drivers were not in agreement regarding their feeling of safety, with answers to this question covering the spectrum of the scale. Graphs representing these subjective responses are shown in Appendix E.

Results for Baseline, 56.3-km/h (35-mph), and 3.02-second TTI Condition

For this baseline (no warning) condition, drivers were instructed to drive at 56.3 km/h (35 mph). The red change was presented at a nominal TTI of 4.00 s, or 0.98 s before the occlusion-clearing TTI of 3.02 s (the occlusion cleared at the same TTI at which participants in the warning conditions received a warning). This baseline condition produced a 62.5 percent compliance rate (N = 5, 95 percent CI: 29.0 percent to 96.0 percent) across 8 participants (Table 46). The dependent variables related to stopping behavior were available for the six (out of eight, five that stopped prior to the collision zone and one that stopped within the collision zone) participants who elected to stop (Table 47). Participants were traveling on average at 56.2 km/h (34.9 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed few trends. Most drivers rated the surprise event expectancy as low. Drivers tended to rate the timeliness for the end of the occlusion (comparable to the presentation of the warning) as slightly late. Drivers who stopped tended to rate the stop as uncomfortable, although they tended to feel in control of the vehicle. Drivers who did not stop were not in agreement regarding whether it would have been difficult to stop the car had they chosen to do so. Finally, drivers were not consistent in rating their feeling of safety during the surprise event. Some drivers indicated that they felt safe, while other drivers felt unsafe during the trial. Graphs representing these subjective responses are shown in Appendix E. When asked why they did not stop, one participant indicated that he or she was aware that there was no other traffic at the intersection, and one participant indicated that it was too late to brake.

Results for Baseline, 56.3-km/h (35-mph), and 3.41-second TTI Condition

For this baseline (no warning) condition, drivers were instructed to drive at 56.3 km/h (35 mph). The red change was presented at a nominal TTI of 4.00 s, or 0.59 s before the occlusion-clearing TTI of 3.41 s (the occlusion cleared at the same TTI at which participants in the warning conditions received a warning). This baseline condition produced a 100.0 percent compliance rate (N = 8, 95 percent CI: more than 64.6 percent to 100.0 percent) across eight participants (Table 46). The dependent variables related to stopping behavior were available for the eight (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 57.1 km/h (35.5 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed few trends. Drivers rated the surprise event expectancy as low and were neutral with respect to the timing of the end of the occlusion (comparable to the presentation of the warning). Drivers who stopped tended to rate the stop as slightly uncomfortable but tended to feel in control of the vehicle. Finally, drivers had a relatively high feeling of safety during the surprise event. Graphs representing these subjective responses are shown in Appendix E.

Visual Warnings: Too-Late Determination (with Red at Occlusion End)

Results for the LED Stop Sign plus Strobes Visual Warning, 56.3-km/h (35-mph), and 2.03-second TTI Condition

The red change for this condition was presented at a nominal TTI of 4.00 s, or 1.97 s before the occlusion-clearing TTI of 2.03 s. At an instructed speed of 56.3 km/h (35 mph), the LED stop sign plus strobes resulted in 50.0 percent compliance with eight participants (Table 46, N = 4, 95 percent CI: 15.4 percent to 84.6 percent). The dependent variables related to stopping behavior were available for the four (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 57.4 km/h (35.7 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed some trends. Most drivers rated the surprise event expectancy as relatively low. Drivers who stopped did not agree on the timing of the warning, but drivers who did not stop tended to indicate that the warning timing was late. Drivers who stopped tended to rate the stop as somewhat comfortable and tended to feel in control of the vehicle. Drivers who did not stop thought that stopping the car would have been difficult. Finally, drivers who did not stop tended to feel more unsafe during their intersection crossing than drivers who stopped did during their stop. Graphs representing these subjective responses are shown in Appendix E. When asked why they did not stop, three participants indicated that it was too late to stop, and one indicated that the expectancy of the event was too low. All drivers saw the DII.

Results for the LED Stop Sign plus Strobes Visual Warning, 56.3-km/h (35-mph), and 2.65-second TTI Condition

The red change for this condition was presented at a nominal TTI of 4.00 s, or 1.35 s before the occlusion-clearing TTI of 2.65 s. At an instructed speed of 56.3 km/h (35 mph), the LED stop sign plus strobes resulted in 62.5 percent compliance with eight participants (Table 46, N = 5, 95 percent CI: 29.0 percent to 96.0 percent). The dependent variables related to stopping behavior were available for the six (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 57.3 km/h (35.6 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed some trends. Most drivers rated the surprise event expectancy as relatively low. One driver in the group that did not stop and one driver in the group that stopped rated event expectancy as high. Ratings of the warning timeliness tended to indicate that drivers felt that the timing of the warning was slightly late. Drivers who stopped tended to rate the stop as somewhat comfortable and tended to feel very much in control of the vehicle. Drivers who did not stop thought that stopping the car would have been very difficult. Finally, drivers who did not stop tended to feel more unsafe during their intersection crossing than drivers who stopped. Graphs representing these subjective responses are shown in Appendix E. When asked why they did not stop, one participant indicated that he or she did not see the red light and one participant indicated that he or she did not see the red light until passing it. Seven of the eight drivers saw the DII.

Results for the LED Stop Sign plus Strobes Visual Warning, 56- km/h (35-mph), and 3.02-second TTI Condition

The red change for this condition was presented at a nominal TTI of 4.00 s, or 0.98 s before the occlusion-clearing TTI of 3.02 s. At an instructed speed of 56.3 km/h (35 mph), the LED stop sign plus strobes resulted in 62.5 percent compliance with eight participants (Table 46, N = 5, 95 percent CI: 29.0 percent to 96.0 percent). The dependent variables related to stopping behavior were available for the five (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 57.4 km/h (35.7 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed some trends. Most drivers rated the surprise event expectancy as relatively low. Ratings of the warning timeliness were not in agreement, although drivers who stopped tended to rate the warning timeliness as earlier than drivers who did not stop. Drivers who stopped were neutral with respect to the comfort of their stop and tended to feel in control of the vehicle. Drivers who did not stop thought that stopping the car would not have been very difficult. Finally, drivers who did not stop tended to feel more unsafe during their intersection crossing than drivers who stopped did during their stop. Graphs representing these subjective responses are shown in Appendix E. When asked why they did not stop, one driver indicated that his or her reaction was slower than it should have been, one driver indicated “no time” to react, and a third driver indicated that he or she thought it would be safer for the vehicle occupants because there were no nearby vehicles representing a possibility of collision. All eight drivers saw the DII.

Results for the LED Stop Sign plus Strobes Visual Warning, 56.3-km/h (35-mph), and 3.41-second TTI Condition

The red change for this condition was presented at a nominal TTI of 4.00 s, or 0.59 s before the occlusion-clearing TTI of 3.41 s. At an instructed speed of 56.3 km/h (35 mph), the LED stop sign plus strobes resulted in 100.0 percent compliance with eight participants (Table 46, N = 8, 95 percent CI: more than 64.6 percent to 100.0 percent). The dependent variables related to stopping behavior were available for all eight participants (Table 47). Participants were traveling on average at 58.7 km/h (36.5 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed some trends. Drivers tended to rate the surprise event expectancy as low. Ratings of the warning timeliness were not in agreement between drivers. Drivers were also in disagreement with respect to the comfort of the stop, with ratings over the spectrum of responses. However, drivers agreed that they felt in control of the vehicle during the stop and felt slightly safe during the surprise trial. Graphs representing these subjective responses are shown in Appendix E. All eight drivers saw the DII.

Haptic Warnings: Too-Late Determination (with Red at Occlusion End)

Results for the Rumble Strip Simulation Haptic warning, 56.3-km/h (35-mph), and 2.03-second TTI Condition

The red change for this condition was presented at a nominal TTI of 4.00 s, or 1.97 s before the occlusion-clearing TTI of 2.03 s. At an instructed speed of 56.3 km/h (35 mph), the rumble strip simulation resulted in 37.5 percent compliance with eight participants (Table 46, N = 3, 95 percent CI: 4.0 percent to 71.0 percent). The dependent variables related to stopping behavior were available for the four (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 58.3 km/h (36.2 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed some trends. Except for one driver in the group that did not stop, all other drivers rated the surprise event expectancy as low. Drivers tended to agree that the timing of the warning was slightly late. Drivers who stopped tended to rate the stop as somewhat uncomfortable but were not in agreement about their level of perceived vehicle control. Drivers who did not stop tended to indicate that stopping the vehicle would not have been difficult. Finally, drivers who did not stop tended to feel more unsafe during their intersection crossing than drivers who stopped did during their stop. Graphs representing these subjective responses are shown in Appendix E. When asked why they did not stop, two participants indicated that they believed there was a malfunction in the car, one indicated that he or she did not know that the vibration was a warning, and one indicated that he or she did not see any cross traffic.

Results for the Rumble Strip Simulation Haptic Warning, 56.3-km/h (35-mph), and 2.65-second TTI Condition

The red change for this condition was presented at a nominal TTI of 4.00 s, or 1.35 s before the occlusion-clearing TTI of 2.65 s. At an instructed speed of 56.3 km/h (35 mph), the rumble strip simulation resulted in 50.0 percent compliance with eight participants (Table 46, N = 4, 95 percent CI: 15.4 percent to 84.6 percent). The dependent variables related to stopping behavior were available for the five (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 57.7 km/h (35.9 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed some trends. Drivers rated the surprise event expectancy as low. Drivers also tended to agree that the timing of the warning was slightly late. Drivers who stopped tended to rate the stop as neither comfortable nor uncomfortable and were not in agreement about their level of perceived vehicle control. Drivers who did not stop were not in agreement regarding the difficulty of the stop. Finally, drivers who did not stop tended to feel more unsafe during their intersection crossing than did drivers who stopped. Graphs representing these subjective responses are shown in Appendix E. When asked why they did not stop, one driver indicated that he or she did not know that the vibration was a warning; one indicated that he or she was not told to stop, and a third was worried about stopping too quickly and possibly losing control.

Results for the Rumble Strip Simulation Haptic Warning, 56.3-km/h (35-mph), and 3.02-second TTI Condition

The red change for this condition was presented at a nominal TTI of 4.00 s, or 0.98 s before the occlusion-clearing TTI of 3.02 s. At an instructed speed of 56.3 km/h (35 mph), the rumble strip simulation resulted in 87.5 percent compliance, with eight participants (Table 46, N = 7, 95 percent CI: 64.6 percent to 100.0 percent). The dependent variables related to stopping behavior were available for the seven (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 59.1 km/h (36.7 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed some trends. Drivers rated the surprise event expectancy as low. Drivers also tended to agree that the timing of the warning was late. Drivers who stopped did not agree on their comfort during the stop but agreed that they felt in control of the vehicle during their stop. Finally, drivers tended to feel fairly safe during the surprise trial. Graphs representing these subjective responses are shown in Appendix E. When the single non-stopping participant was asked why he or she did not stop, the participant indicated that he or she was following previous directions to travel at 56.3 km/h (35 mph).

Results for the Rumble Strip Simulation Haptic Warning, 56.3-km/h (35-mph), and 3.41-second TTI Condition

The red change for this condition was presented at a nominal TTI of 4.00 s, or 0.59 s before the occlusion-clearing TTI of 3.41 s. At an instructed speed of 56.3 km/h (35 mph), the rumble strip simulation resulted in 87.5 percent compliance with eight participants (Table 46, N = 7, 95 percent CI: 64.6 percent to 100.0 percent). The dependent variables related to stopping behavior were available for the seven (out of eight) participants who elected to stop (Table 47). Participants were traveling on average at 57.1 km/h (35.5 mph) when their occlusion cleared, revealing the red light.

Participant responses to the questionnaire statements showed some trends. Most drivers rated the surprise event expectancy as low, with the exception of one driver in the stopping group. Drivers also tended to feel neutral about the timing of the warning (i.e., neither early nor late). Drivers who stopped did not agree on their comfort during the stop but tended to report that they felt in control of the vehicle during their stop. Finally, drivers were not in agreement regarding their feeling of safety during the surprise trial. Graphs representing these subjective responses are shown in Appendix E. When asked why they did not stop, the participant indicated that they were not asked to stop.

Comparisons between Conditions with Red at Occlusion End

Results for compliance percentage and distribution of drivers within the stopping zones show that the warnings did not provide much incremental benefit over the baseline condition (Table 46). In some situations, the compliance with the baseline (no warning) condition was higher than compliance with the warnings. A similar table is then presented for comparison of the performance variables across the same conditions (Table 47).

Statistical comparisons based on the objective variables showed some significant differences, which are summarized in Table 48. As indicated on the table, both plan initiation variables and plan execution variables were significantly affected by the independent variables.

For the plan initiation variables:

- Shorter TARs were obtained for the 2.03-second TTI warning (0.41 s) when compared against the remaining warning timings (0.70 s to 0.77 s). However, note that the sample size of drivers who stopped (on which these data depend) is somewhat smaller for the 2.03-second TTI case when compared to the remaining timing. The 2.03-second TTI warning timing has data from 11 drivers, whereas the closest timing has data from 16 drivers. Thus the difference could be due to low statistical power.
- For TB, drivers in the 2.03-second TTI warning timing took less time to brake (0.73 s) when compared to drivers in other timing conditions (1.06 s to 1.13 s).
- TSAB increased for the rumble strip simulation haptic warning (0.42 s) when compared to the visual warning group and the baseline group (0.31 s for both).

For the plan execution variables:

- Distance before stop bar was reduced for later timings from -9.81 m for the 2.03-second TTI timing to -0.59 m for the 3.41-second TTI timing.
- Peak deceleration increased significantly with later timings, from 0.54 *g* for the 3.41-second TTI timing to 0.75 *g* for the 2.03-second TTI timing. This timing effect was even more evident based on gender, with males exhibiting much higher levels of deceleration than females for the two later timings, but similar levels as females for earlier timings.
- Constant deceleration increased significantly from 0.38 *g* at the 3.41-second TTI timing to 0.55 *g* at the 2.03-second TTI timing. As for peak deceleration, this effect was modulated by the participant's gender.
- Required deceleration increased significantly as the warning onset occurred later (from 0.38 *g* at the 3.41-second TTI timing to 0.81 *g* at the 2.03-second TTI timing), but in this case the effect was not modulated by participant gender.
- Time to peak brake was significantly affected by the Age by Warning Timing interaction, but post hoc tests did not identify any sources for this significant effect.
- Maximum brake velocity was significantly affected by the DII type and the Age by Warning Timing interaction. The rumble strip simulation elicited higher maximum brake velocities than the baseline conditions (2.29 percent/s versus 1.91 percent/s). Causes for the interaction effect were not detected by the post hoc tests.

These results show that DII type, as a main effect or interaction, failed to improve driver braking performance over the baseline conditions. In those instances in which DII type showed a significant effect, differences in performance were slight.

Table 46. Comparison of compliance percentage and stop zone distributions across the warning and baseline conditions with a red light at occlusion end.

Condition	Number of participants	Compliance Percentage (95% CI)	Participants stopping in "No Violation" zone (%)	Participants stopping in "Violation" zone (%)	Participants stopping in "Intrusion" zone (%)	Participants stopping in "Collision" zone (%)	Participants that Did not Stop (%)
2.03 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)							
Baseline at 35 mph, 2.03 s TTI	9	22.2 (N = 2) (0.0% - 51.0%)	0.0	22.2	0.0	11.1	66.7
"STOP" LED sign + Strobes	8	50.0 (N = 4) (15.4% - 84.6%)	0.0	12.5	37.5	0.0	50.0
Rumble Strip Simulation	8	37.5 (N = 3) (4.0% - 71.0%)	0.0	12.5	25.0	12.5	50.0
2.65 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)							
Baseline at 35 mph, 2.65 s TTI	8	50.0 (N = 4) (15.4% - 84.6%)	0.0	37.5	12.5	12.5	37.5
"STOP" LED sign + Strobes	8	62.5 (N = 5) (29.0% - 96.0%)	12.5	50.0	0.0	12.5	25.0
Rumble Strip Simulation	8	50.0 (N = 4) (15.4% - 84.6%)	0.0	12.5	37.5	12.5	37.5
3.02 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)							
Baseline at 35 mph, 3.02 s TTI	8	62.5 (N = 5) (29.0% - 96.0%)	12.5	37.5	12.5	12.5	25.0
"STOP" LED sign + Strobes	8	62.5 (N = 5) (29.0% - 96.0%)	0.0	37.5	25.0	0.0	37.5
Rumble Strip Simulation	8	87.5 (N = 7) (64.6% - 100%)	25.0	50.0	12.5	0.0	12.5
3.41 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)							
Baseline at 35 mph, 3.41 s TTI	8	100.0 (N = 8) (>64.6% - 100%)	37.5	50.0	12.5	0.0	0.0
"STOP" LED sign + Strobes	8	100.0 (N = 8) (>64.6% - 100%)	12.5	75.0	12.5	0.0	0.0
Rumble Strip Simulation	8	87.5 (N = 7) (64.6% - 100%)	62.5	12.5	12.5	0.0	12.5

Table 47. Comparison of performance variable averages across a subset of warning and baseline conditions with a red light at occlusion end.

Condition	N	Distance before stop bar (m)	Peak deceleration (g)	Constant deceleration (g)	Required deceleration (g)	Time to accelerator release (s)	Time to brake (s)	Time from accelerator to brake (s)	Time to peak deceleration (s)	Time from brake to peak deceleration (s)	Maximum brake velocity (%/s)
2.03 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)											
Baseline at 35 mph, 2.03 s TTI	3	-5.45	0.70	0.48	0.60	0.34	0.59	0.25	3.17	2.63	2.06
“STOP” LED sign + Strobes	4	-5.67	0.75	0.53	0.69	0.37	0.67	0.30	2.95	2.33	2.28
Rumble Strip Simulation	4	-8.09	0.71	0.54	0.80	0.50	0.89	0.39	2.95	2.10	2.37
2.65 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)											
Baseline at 35 mph, 2.65 s TTI	5	-6.00	0.71	0.50	0.64	0.84	1.16	0.32	3.56	2.46	1.93
“STOP” LED sign + Strobes	6	-2.77	0.74	0.51	0.57	0.74	1.03	0.29	3.35	2.38	2.42
Rumble Strip Simulation	5	-5.93	0.68	0.49	0.64	0.73	1.22	0.49	3.54	2.38	2.35
3.02 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)											
Baseline at 35 mph, 3.02 s TTI	6	-3.20	0.59	0.44	0.50	0.79	1.10	0.31	3.18	2.13	1.94
“STOP” LED sign + Strobes	5	-3.57	0.66	0.44	0.50	0.77	1.11	0.34	3.40	2.34	2.07
Rumble Strip Simulation	7	-1.66	0.63	0.45	0.48	0.58	1.02	0.44	3.44	2.46	2.28
3.41 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)											
Baseline at 35 mph, 3.41 s TTI	8	-1.28	0.53	0.38	0.39	0.74	1.07	0.33	3.29	2.28	1.76
“STOP” LED sign + Strobes	8	-1.92	0.56	0.38	0.41	0.80	1.13	0.33	3.76	2.69	2.05
Rumble Strip Simulation	7	0.35	0.55	0.39	0.38	0.61	0.99	0.38	3.00	2.09	2.14

Table 48. Statistical analysis results. Only dependent variables with one or more significant effects are included. Blank cells and missing dependent variables indicate *p*-values > 0.05.

Independent Variable / Dependent Variable	Time to accelerator release (s)	Time to brake (s)	Time from accelerator to brake (s)	Distance before stop bar (m)	Peak Deceleration (g)	Constant Deceleration (g)	Required Deceleration (g)	Time to peak deceleration (s)	Maximum brake velocity (%/s)
Age									
Gender									
DII Type			p=0.0015						p=0.0293
Age X DII Type									
Gender X DII Type									
Age X Gender									
Warning Timing	p=0.0037	p=0.0007		p<0.0001	p <0.0001	p <0.0001	p <0.0001		
Age X Warning Timing								p=0.0337	p=0.0137
Gender X Warning Timing					p=0.0005	p=0.0005			
DII Type X Warning Timing									

Results of LED-Enhanced Stop Sign Tests

Results for Baseline, 56.3-km/h (35-mph), and 2.65-second TTI Condition

For this baseline (no warning) condition, drivers were instructed to drive at 56.3 km/h (35 mph). The stop sign was lifted from its hidden location when the driver reached a TTI of 5.0 s. This was approximately 2.4 s before the end of the occlusion and represented the time necessary to raise the arm with the stop sign. Note that the occlusion cleared at the same TTI at which participants in the warning conditions received the warning. This baseline condition produced a 75.0 percent compliance rate (N = 6, 95 percent CI: 45.0 percent to 100.0 percent) across eight participants (Table 49). Compliance was defined as stopping in the no-violation, violation, or intrusion zones as previously defined for the stop-controlled intersection. The dependent variables related to stopping behavior were available for the seven (out of eight) participants who elected to stop (Table 50). Participants were traveling on average at 55.4 km/h (34.4 mph) when their occlusion cleared, revealing the stop sign. The low number of participants in the sample did not allow for statistical analysis of differences between the dependent variables due to age or gender effects for this or any of the other experimental conditions.

Participant responses to the questionnaire statements showed few trends. Drivers rated the surprise event expectancy as low. Drivers who stopped tended to rate the timing of the end of the occlusion (comparable to the presentation of the warning) as later than drivers who did not stop. Drivers who stopped tended to be neutral about their comfort during the stop and felt in control of the vehicle. Drivers who did not stop tended to indicate that stopping the car would have been difficult. Their reasons for not stopping included fear (one driver) and failure to notice the stop sign until going past it (one driver). Finally, drivers who stopped indicated a tendency toward a feeling of safety, which shifted toward a feeling of less safety for those who did not stop. All drivers reported seeing the stop sign. Graphs representing these subjective responses are shown in Appendix E.

Results for Baseline, 56.3-km/h (35-mph), and 3.02-second TTI Condition

For this baseline (no warning) condition, drivers were instructed to drive at 56.3 km/h (35 mph). The stop sign was lifted from its hidden location when the driver reached a TTI of 5.4 s. This was approximately 2.4 s before the end of the occlusion, and represented the time necessary to raise the arm with the stop sign. Note that the occlusion cleared at the same TTI at which participants in the warning conditions received the warning. This baseline condition produced a 25.0 percent compliance rate (N = 2, 95 percent CI: 0.0 percent to 55.0 percent) across eight participants (Table 49). The dependent variables related to stopping behavior were available for the three (out of eight) participants who elected to stop (Table 50). Participants were traveling on average at 56.6 km/h (35.2 mph) when their occlusion cleared, revealing the stop sign.

Participant responses to the questionnaire statements showed few trends. Drivers rated the surprise event expectancy as low, regardless of whether or not they stopped. Drivers who stopped were not in agreement regarding the timing of the end of the occlusion (comparable to the presentation of the warning). Drivers who did not stop tended to rate this timing as late. Drivers who stopped were not in agreement regarding the comfort of the stop or their feeling of control over the vehicle. Drivers who did not stop were not in agreement regarding the perceived difficulty of stopping the vehicle; some drivers indicated that stopping the driver would be very difficult, while others that it would have not been at all difficult. Their reasons for not stopping included not expecting the event (two driver), did not see the sign until going past it (one driver), and being told not to stop by co-pilot (one driver; however, none of the experimenters talked to the participant during the surprise trial). Finally, drivers were not in agreement regarding their feeling of safety. All drivers reported seeing the stop sign. Graphs representing these subjective responses are shown in Appendix E.

Results for Baseline, 56.3-km/h (35-mph), and 3.41-second TTI Condition

For this baseline (no warning) condition, drivers were instructed to drive at 56.3 km/h (35 mph). The stop sign was lifted from its hidden location when the driver reached a TTI of 5.8 s. This was approximately 2.4 s before the end of the occlusion and represented the time necessary to raise the arm with the stop sign. Note that the occlusion cleared at the same TTI at which participants in the warning conditions received the warning. This baseline condition produced a 50.0 percent compliance rate (N = 4, 95 percent CI: 15.4 percent to 84.6 percent) across eight participants (Table 49). The dependent variables related to stopping behavior were available for the five (out of eight) participants who elected to stop (Table 50). Participants were traveling on average at 57.4 km/h (35.7 mph) when their occlusion cleared, revealing the stop sign.

Participant responses to the questionnaire statements showed few trends. Drivers rated the surprise event expectancy as low. Regardless of whether they stopped, drivers tended to indicate that the perceived timing for the end of the occlusion (comparable to the presentation of the warning) was slightly late. Drivers who stopped were not in agreement about the perceived comfort of the stop or their feeling of vehicle control. Drivers who did not stop were not in agreement regarding the perceived difficulty of stopping the vehicle. Their reasons for not stopping included being focused on maintaining speed (one driver), not realizing that they needed to stop (one driver), and not being provided with an explicit instruction (one driver). Drivers who did not stop indicated a tendency toward a feeling of safety, which shifted toward a feeling of less safety for those who stopped. Six out of the eight drivers (75.0 percent) reported seeing the stop sign. Graphs representing these subjective responses are shown in Appendix E.

Results for LED-Enhanced Stop Sign Visual Warning, 56.3-km/h (35-mph), and 2.03-second TTI Condition

For this condition, drivers were instructed to drive at 56.3 km/h (35 mph). The LED-enhanced stop sign was lifted from its hidden location when the driver reached a TTI of 4.4 s. This was approximately 2.4 s before the end of the occlusion, and represented the time necessary to raise the arm with the stop sign. This warning condition produced a 12.5 percent compliance rate (N = 1, 95 percent CI: 0.0 percent to 35.4 percent) across eight participants (Table 49). The dependent variables related to stopping behavior were available for the two (out of eight) participants who elected to stop (Table 50). Participants were traveling on average at 56.6 km/h (35.2 mph) when their occlusion cleared, revealing the stop sign.

Participant responses to the questionnaire statements showed few trends. Without exception, drivers rated the surprise event expectancy as very low. Drivers were not in agreement regarding the timing of the warning, although the tendency was to rate it on the late side of the scale. Drivers who stopped tended to rate their stop as uncomfortable but they were not in agreement regarding their perceived level of vehicle control. Most drivers who did not stop thought that stopping the car would not have been difficult, but two of these drivers indicated that it would have been very difficult. Their reasons for not stopping included not expecting the event (2 drivers), not believing they could stop in a safe manner (1 driver), not noticing the sign (2 drivers), being confused by the situation (1 driver), and perceiving no intersection in the area the test occurred (1 driver). Finally, drivers were in disagreement about their feeling of safety during the surprise trial. Seven out of eight participants indicated seeing the stop sign and the LED lights. Graphs representing these subjective responses are shown in Appendix E.

Results for LED-Enhanced Stop Sign Visual Warning, 56.3-km/h (35-mph), and 2.65-second TTI Condition

For this condition, drivers were instructed to drive at 56.3 km/h (35 mph). The LED-enhanced stop sign was lifted from its hidden location when the driver reached a TTI of 5.0 s. This was approximately 2.4 s before the end of the occlusion, and represented the time necessary to raise the arm with the stop sign. This warning condition produced a 37.5 percent compliance rate (N = 3, 95 percent CI: 4.0 percent to 71.0 percent) across eight participants (Table 49). The dependent variables related to stopping behavior were available for the four (out of eight) participants who elected to stop (Table 50). Participants were traveling on average at 57.5 km/h (35.7 mph) when their occlusion cleared, revealing the stop sign.

Participant responses to the questionnaire statements showed few trends. Drivers who stopped and did not stop rated the surprise event expectancy as low. Drivers who stopped tended to rate the timing of warning as earlier than drivers who did not stop. Drivers who stopped tended to rate the stop as uncomfortable, although they tended to indicate feeling in control of the vehicle. Drivers who did not stop tended to believe that stopping the car would have been difficult, although two drivers indicated that it would not have been at all difficult. Their reasons for not stopping included not realizing they had to stop (1 driver), not noticing the sign until driving past it (2 drivers), and being unsure if the sign was part of the test (2 drivers). Note that one of the drivers cited more than one reason for not stopping. Finally, drivers were not in agreement regarding their feeling of safety during the surprise trial, marking responses all over the answer scale. All eight drivers noticed the stop sign. Graphs representing these subjective responses are shown in Appendix E.

Results for LED-Enhanced Stop Sign Visual Warning, 56.3-km/h (35-mph), and 3.02-second TTI Condition

For this condition, drivers were instructed to drive at 56.3 km/h (35 mph). The LED-enhanced stop sign was lifted from its hidden location when the driver reached a TTI of 5.4 s. This was approximately 2.4 s before the end of the occlusion, and represented the time necessary to raise the arm with the stop sign. This warning condition produced a 62.5 percent compliance rate (N = 5, 95 percent CI: 29.0 percent to 96.0 percent) across eight participants (Table 49). The dependent variables related to stopping behavior were available for the five (out of eight) participants who elected to stop (Table 50). Participants were traveling on average at 58.1 km/h (36.1 mph) when their occlusion cleared, revealing the stop sign.

Participant responses to the questionnaire statements showed few trends. Drivers rated the surprise event expectancy as low with the exception of a driver who stopped and rated their expectancy as high. Drivers who stopped tended to rate the timing of the warning as later than drivers who did not stop. Drivers who stopped tended to rate the stop as uncomfortable, although they tended to indicate feeling in control of the vehicle. Most drivers who did not stop thought that stopping the car would have been difficult. Their reasons for not stopping included insufficient time to stop (2 drivers) and the sign not being "quick" enough (1 driver). Finally, drivers were not at all in agreement regarding their feeling of safety during the stop. All participants reported seeing the stop sign, and seven out of the eight participants reported seeing the flashing lights on the stop sign. Graphs representing these subjective responses are shown in Appendix E.

Results for LED-Enhanced Stop Sign Visual Warning, 56.3-km/h (35-mph), and 3.41-second TTI Condition

For this condition, drivers were instructed to drive at 56.3 km/h (35 mph). The LED-enhanced stop sign was lifted from its hidden location when the driver reached a TTI of 5.8 s. This was approximately 2.4 s before the end of the occlusion, and represented the time necessary to raise the arm with the stop sign. Two participants had to be eliminated from this data set when the analysis process began because their data were found to be corrupted. This warning condition produced a 68.7 percent compliance rate (N = 4, 95 percent CI: 31.6 percent to 100.0 percent) across these six participants (Table 49). The dependent variables related to stopping behavior were available for the four (out of six) participants who elected to stop (Table 50). Participants were traveling on average at 56.5 km/h (35.1 mph) when their occlusion cleared, revealing the stop sign.

Participant responses to the questionnaire statements showed few trends. Drivers rated the surprise event expectancy as relatively low, with one exception of a participant who stopped indicating a relatively high expectancy. Drivers who stopped tended to rate the timing of the warning as later than drivers who did not stop. Drivers who stopped tended to rate the stop as somewhat comfortable and tended to feel in control of the vehicle. Drivers who did not stop tended to indicate that stopping the car would not have been difficult. Their reason for not stopping was that the sign was unexpected (both drivers). Drivers were neutral with respect to their feeling of safety during the surprise trial. All participants indicated being aware of the stop sign. Graphs representing these subjective responses are shown in Appendix E.

Results for the Aware Stop-Sign Approaches: Too-Early Determination

Recall that in addition to the surprise trial, participants in the stop-sign experiment also performed two additional normal stop-sign approaches. For these approaches, participants were aware of the stop sign and asked to approach it as they normally would. Analogous to the baseline experiments performed for the previously discussed signalized intersections, these approaches allowed the characterization of the too-early distribution for the stop-sign situation. While it could be argued that the stop-sign case is equivalent to the signalized case in which the light remains red for the vehicle's approach, this specific case was not tested in the original baseline tests. Furthermore, there are several aspects of the stop-sign approach that might make it unique. For example, when approaching a red light at a signalized intersection, the driver is aware that they may receive a green light before they arrive at the stop bar and might time their approach accordingly, while this never occurs in the stop-sign case. As another example, many drivers use rolling stops at stop signs in low-traffic-density conditions. This is not the case for a signalized intersection in which driver receiving a red light must wait for the green light before proceeding, at least for continuing in a straight path.

Determining the too-early point is important for warning threshold determination and, consequently, for any algorithm that makes warning decisions. An appropriately timed algorithm should provide a timely warning to potential violators while avoiding nuisance alarms. As previously discussed, if a warning occurs prior to the point at which an attentive driver would have initiated braking, it is categorized as too early. Alarms that are too early will likely deflate the safety benefits of collision avoidance systems because of annoyance and loss of user trust in the system.

A total of 60 participants were included in this analysis for a total of 119 stop-sign approaches (one participant performed only one approach). The braking points reported here were adjusted for grade (thus, grade must be considered in any ensuing calculations if the travel surface is not horizontal).

Statistical analysis of any age or gender effects on the selected braking point showed no significant differences. However, drivers selected braking points that were closer to the intersection on their second approach, presumably because they had become more familiar with the vehicle kinematics and intersection characteristics and could use them to their advantage to arrive more quickly at the intersection. Thus, braking points for the second approach are likely more representative of the real-world behavior than braking points for the first approach. For this reason, the braking point descriptions for the rest of this section only use the data obtained for the second stop sign approach.

Drivers approaching the stop-sign intersection initiated braking at a TTI between 2.85 s and 12.3 s. On average, drivers initiated braking at 6.22 s (SD = 1.68 s) (Figure 81). Note that these values are much higher than those obtained for a similar condition in the signalized intersection case. Specifically, the associated standard deviation is at least an order of magnitude higher, and the mean braking point is about 4 s longer (it was around 2 s in the earlier study). The distribution indicates that, in order to avoid nuisance alarms for 95 percent of the drivers approaching a stop sign without noticing it, the stop-sign warning would need to be initiated at a TTI of less than 3.54 s. Note that this is slightly higher than the timings tested for the surprise condition in this experiment.

Assuming that compliance percentages are sufficiently high, this result has two important implications. First, assuming any selected warning timing is within those tested and previously described, its associated rate of nuisance alarms will be small. Second, again making the same assumption, performance specifications will be relatively loose, since there is some room for error between the too-early point and the selected warning onset. This is an important finding, because it would allow for less accurate (and consequently inexpensive) equipment to be prescribed for IDS implementation at a stop-controlled intersection.

An alternative way to look at the point at which drivers initiated braking is through the RDP. This was defined earlier as the deceleration required in order for the driver to stop the vehicle at the stop bar. It is calculated using a kinematic equation considering the vehicle's speed and distance from the intersection when the driver initiated the braking maneuver. Here, RDP indicates the braking effort needed after brake onset. RDP ranged from 0.06 *g* to 0.28 *g* with an average of 0.14 *g* (SD = 0.04 *g*). To avoid nuisance alarms for 95 percent of the population, the RDP for a warning would need to exceed 0.19 *g*. As was true for TTI values, these results compare favorably to the warning timings tested in the stop-sign experiment.

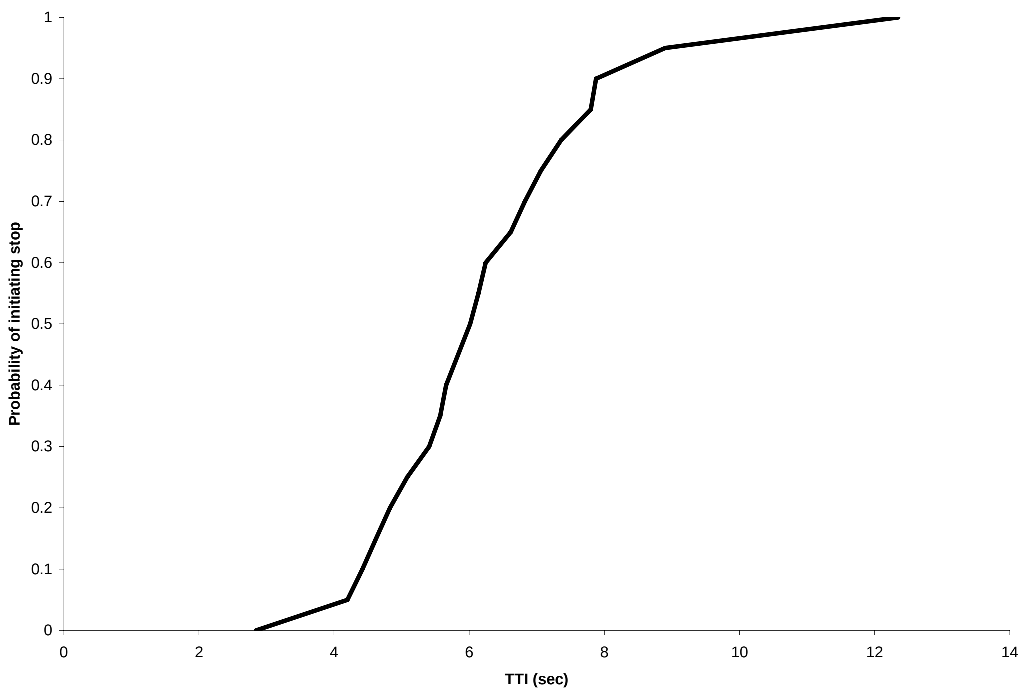

Figure 81. Empirical distribution for time-to-intersection at which an attentive driver initiates braking during a normal 56.3-km/h (35-mph) approach at a stop sign.

Comparisons between Stop Sign Conditions

Results for compliance percentage and distribution of drivers within the stopping zones show that the warnings provided some incremental benefit over the baseline condition (Table 49), but the magnitude of this benefit was relatively small and not statistically significant. For the 2.65-second TTI, the compliance with the baseline (no warning) condition was higher than compliance with the warning. A similar table is then presented for comparison of the performance variables across the same conditions (Table 50).

Table 49. Comparison of compliance percentage and stop zone distributions across the warning and baseline conditions for the stop sign trials.

Condition	Number of participants	Compliance Percentage (95% CI)	Participants stopping in "No Violation" zone (%)	Participants stopping in "Violation" zone (%)	Participants stopping in "Intrusion" zone (%)	Participants stopping in "Collision" zone (%)	Participants that Did Not Stop (%)
2.03 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)							
LED-enhanced stop sign	8	12.5 (N = 1) (0.0% - 35.4%)	0.0	12.5	0.0	12.5	75.0
2.65 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)							
Baseline at 35 mph, 2.65 s TTI	8	75.0 (N = 6) (45.0% - 100%)	37.5	12.5	25.0	12.5	12.5
LED-enhanced stop sign	8	37.5 (N = 3) (4.0% - 71.0%)	0.0	37.5	0.0	12.5	50.0
3.02 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)							
Baseline at 35 mph, 3.02 s TTI	8	25.0 (N = 2) (0.0% - 55.0%)	12.5	12.5	0.0	12.5	62.5
LED-enhanced stop sign	8	62.5 (N = 5) (29.0% - 96.0%)	0.0	62.5	0.0	0.0	37.5
3.41 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)							
Baseline at 35 mph, 3.41 s TTI	8	50.0 (N = 4) (15.4% - 84.6%)	50.0	0.0	0.0	12.5	37.5
LED-enhanced stop sign	6	68.7 (N = 4) (31.6% - 100%)	50.0	16.7	0.0	0.0	33.3

Table 50. Comparison of performance variable averages across a subset of warning and baseline conditions with a red light at occlusion end (standard deviation in parentheses).

Condition	N	Distance before stop bar (m)	Peak deceleration (g)	Constant deceleration (g)	Required deceleration (g)	Time to accelerator release (s)	Time to brake (s)	Time from accelerator to brake (s)	Time to peak deceleration (s)	Time from brake to peak deceleration (s)	Maximum brake velocity (%/s)
2.03 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)											
LED-enhanced stop sign	2	-6.29	0.67	0.55	0.77	0.43	0.77	0.34	2.20	1.50	2.57
2.65 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)											
Baseline at 35 mph, 2.65 s TTI	7	-3.47	0.57	0.43	0.49	0.31	0.64	0.33	2.87	2.29	2.03
LED-enhanced stop sign	4	-5.47	0.61	0.45	0.56	0.45	0.79	0.35	3.38	2.63	1.95
3.02 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)											
Baseline at 35 mph, 3.02 s TTI	3	-3.00	0.47	0.35	0.39	0.19	0.50	0.30	2.67	2.23	2.36
LED-enhanced stop sign	5	-1.13	0.64	0.46	0.48	0.51	0.88	0.36	3.50	2.68	2.06
3.41 sec time to intersection conditions (56.3 km/h (35 mph) nominal vehicle speed)											
Baseline at 35 mph, 3.41 s TTI	5	1.17	0.55	0.43	0.45	0.49	0.87	0.38	2.90	2.08	2.04
LED-enhanced stop sign	4	0.8.0	0.52	0.37	0.37	0.21	0.62	0.40	3.18	2.63	1.58

None of the *plan initiation* variables were significantly affected by any of the independent variables. Some significant differences were present for the *plan execution* variables and are discussed below:

- Distance beyond stop bar was significantly affected by the warning timing ($F (3, 25) = 3.24$, $p = 0.0388$). Drivers went farther past the stop bar as the warning onset occurred later.
- Required deceleration was also significantly affected by warning timing ($F (3, 25) = 3.24$, $p < 0.0001$). The magnitude of the deceleration increased significantly as the warning onset occurred later.

These results show that the LED-enhanced stop sign failed to improve driver braking performance over the baseline conditions. There were no instances in which this factor was significant. Combined with the results observed for compliance percentages with the warning, these findings indicate that the LED-enhanced stop sign considered in this investigation for the stop-sign case would provide only marginal benefit in addressing SCP crashes due to stop-sign violations. This finding makes the future application of this countermeasure doubtful in the context of an IDS system. However, this does not imply that the countermeasure is not useful in improving the conspicuity of a hidden stop sign by flashing continuously, which is the typical use of this type of stop sign. The experiments described in this section were not meant to test that aspect of sign functionality, but rather to test how useful it would be in a last-second effort to prevent a violation.

Experiments on Conspicuity of the LED Stop Sign plus Strobes Visual Warning

The purpose of this experiment was to determine the conspicuity of the "STOP" LED sign plus strobes DII for drivers who may be looking elsewhere in the vehicle upon DII activation. This conspicuity test was used to ensure that any driver failure to respond to this DII was due to factors other than lack of awareness of the sign. While different DIIs were tested as part of this project, the conspicuity study was only conducted on the "STOP" LED sign plus strobes (*without* the TCLs) because it was the least conspicuous visual interface tested. If the results showed that this sign was conspicuous, then it would be reasonable to expect that the remaining DIIs were sufficiently conspicuous as well.

Method

The experiment was conducted in the same 2000 Chevrolet Impala that was used in the rest of the experiments. The experimenter, who sat in the back seat throughout the protocol, instructed the participants on where to direct their gaze and activated the DII once the participants were looking in the intended direction. Twelve participants provided a verbal answer as to whether they noticed the DII while looking at prescribed locations within the vehicle. Their response was not timed or pressured in any way. For each glance location the DII was activated for 5 s, off for 3 s, and then activated for 5 s more. Three glance patterns were used to encompass a wide range of locations:

- Six horizontal glances starting at the driver's side window (-90°) and shifting sequentially to the passenger's side window (+90°). Participants were asked sequentially to fixate on the driver's side (left) window, the left side mirror, straight ahead, towards the passenger's (right) side of the windshield, the right side mirror, and the right side window.
- Six vertical glances in the forward view starting at the bottom of the steering wheel (-50°) and shifting up to eye level (0°). For these glances, participants were instructed to sequentially fixate on the bottom of the steering wheel, the center of the steering wheel (two locations), the speedometer, the top of the dashboard, and straight ahead.
- Seven glances in the vertical plane of the vehicle's control (center) stack (+30° horizontal), ranging from the gear selection stick (-50°) up to the rear view mirror (+5°). Participants were instructed to sequentially direct their gaze to the gear selection stick, a storage bin, the HVAC controls, the clock, the top of the center dashboard, the center of the windshield at eye level, and the rear-view mirror.

These gaze patterns were repeated with the vehicle stopped at four different locations (32.0, 41.1, 47.2, 53.3 m [105, 135, 155, and 175 ft]) from the intersection's stop bar. These locations were selected because they approximated the warning timings at which the "STOP" LED sign plus strobes had been tested in the previous experiments.

Results

Results of Horizontal Glance Pattern

Glance angles and corresponding DII conspicuity for the horizontal pattern are shown in Figure 82. The general pattern of conspicuity for this glance sequence was U-shaped, with peak conspicuity occurring when participants were looking straight ahead. Conspicuity then tended to drop as the participant's gaze was directed to the left or the right of a forward gaze. Participants looking straight out the windshield noticed the DII at least 94 percent of the time regardless of distance from the stop bar. Participants looking at a +30° (to the right) angle out of the windshield noticed the DII at least 86 percent of the time regardless of distance from the stop bar. Participants glancing at the left mirror noticed the DII 78 percent of the time at the two closest distances. Other combinations of glances and distances resulted in conspicuity below 60 percent. In general, conspicuity tended to improve as the distance to the intersection was reduced.

Results of Vertical Glance Patterns

Recall that two vertical glance patterns were tested, one vertically centered over the steering column and another vertically centered over the control stack. Similar conspicuity was observed for both of these glance patterns.

When the glances were vertically centered over the steering column (Figure 83), participants looking straight ahead or at the dashboard noticed the DII at least 94 percent of the time. Conspicuity tended to decrease rapidly as the gaze was directed to lower locations, especially as the distance to the intersection increased. For example, at the closest two distances, participants looking at the speedometer noticed the DII 86 percent and 81 percent of the time, respectively. This was reduced to less than 60 percent for the further distances.

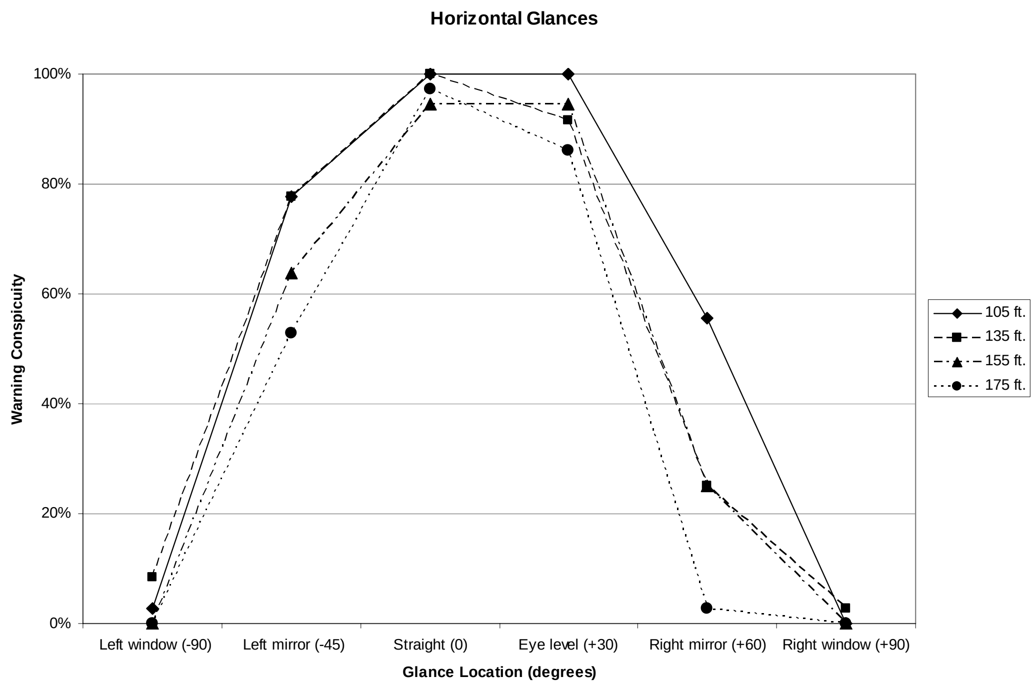

Figure 82. DII conspicuity during a horizontal sequence of glances. The numbers next to the glance locations represent angular deviation from looking straight ahead. (1 ft = 0.30 m)

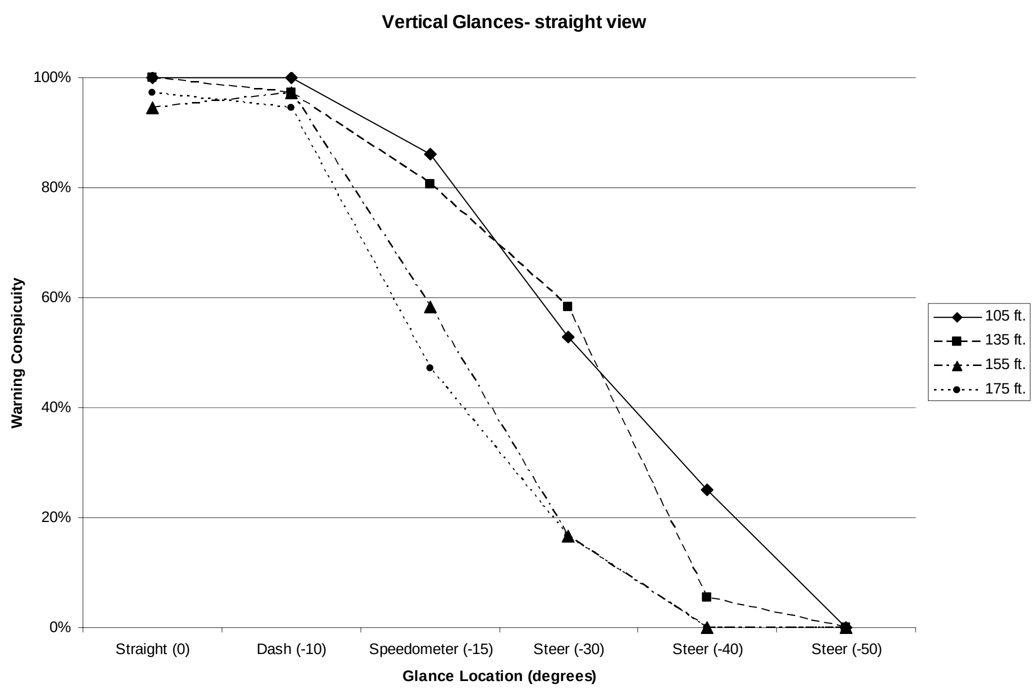

Figure 83. DII conspicuity during a vertical sequence of glances centered over the steering column. The numbers next to the glance locations represent angular deviation from looking straight ahead. (1 ft = 0.30 m)

A similar pattern was observed for a vertical sequence of glances centered over the control stack (Figure 84). However, in this condition the distance effect was more marked. For example, at the closest distance glances as low as -20° yielded no less than 92 percent conspicuity. Glances to the rear view mirror seemed to slightly detract from the DII's conspicuity in comparison to straight ahead glances, but still resulted in at least 80 percent detectability. In general, conspicuity decreased as the gaze was directed to lower locations and as the vehicle was farther from the intersection.

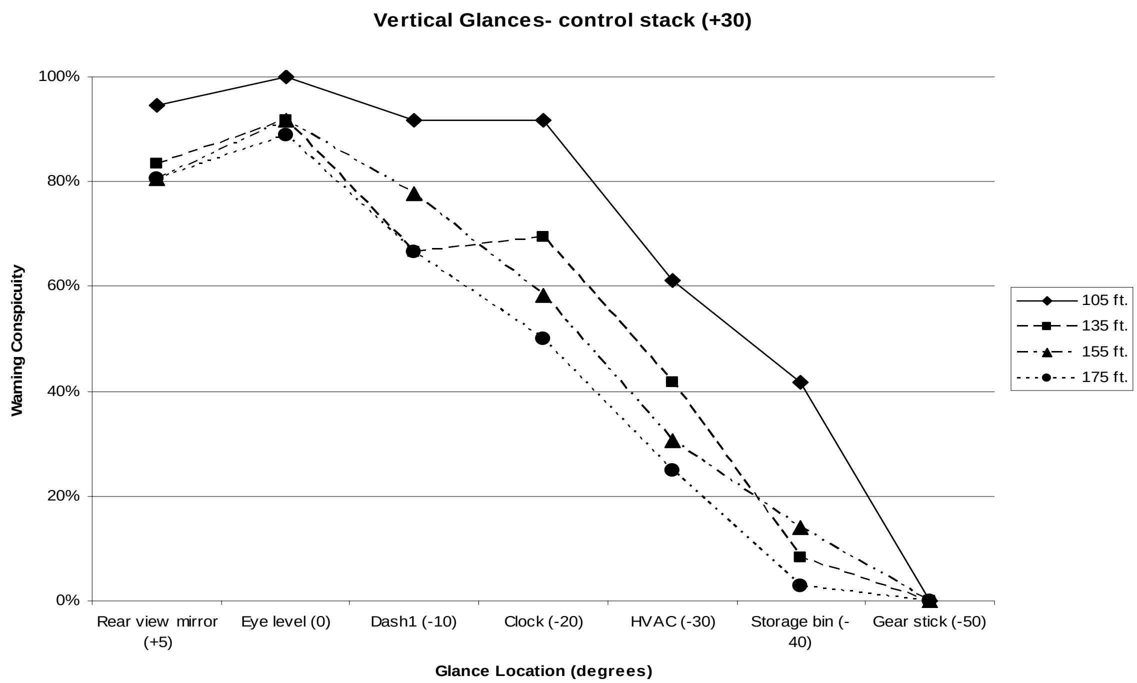

Figure 84. DII conspicuity during a vertical sequence of glances centered over the control stack. The numbers next to the glance locations represent angular deviation from looking straight ahead. (1 ft = 0.30 m)

These results indicate that the sign was very conspicuous under the conditions tested during the previously discussed experiments. This supports the finding that a large proportion of participants reported having seen the "STOP" LED sign plus strobes DII during the surprise trials. Thus, the inability of drivers to stop in response to the DII cannot be attributed to limited sign conspicuity, but instead to other factors. These factors are unknown at this point, but it can be speculated that while conspicuous, the sign was not commanding enough to elicit a stopping response from the driver.

In addition, the results support to a certain extent the ability of this DII to attract a driver's attention, via their peripheral vision, when their gaze is not directed forward. Horizontally, effectiveness seems optimal when the gaze is deviated less than 45° from the forward view. Vertically, this number is reduced to approximately 10° from the normal eye level view. These effects are somewhat distance dependent, but the effects of distance are relatively minor when compared to the effects of location.

Conclusions

In general, these findings indicate that the DII types considered in this investigation for the signalized and stop-controlled cases would provide only marginal benefit in addressing SCP crashes due to violations. To further expand on the results, it is helpful to also consider the results of the ICAV study. Figure 85 compares the results of the "STOP" LED sign plus strobes in this study, tested along with a red light (simulating a crash prevention scenario), against the results obtained for two ICAV Driver-Vehicle Interfaces (DVIs), tested along with an amber light (simulating a violation prevention scenario). As shown in the figure, the DII resulted in much smaller compliance increases over baseline conditions than did the ICAV DVIs. Again, note that the ICAV DVIs were accompanied by an amber light, which can be considered a much less urgent situation (with an associated smaller urge to stop) than the situation in which the DII was tested. In spite of this, the DII still failed to elicit a large willingness of drivers to stop in reaction to the warning. Furthermore, the effect of the DVI warnings tested under ICAV was not limited to higher compliance percentages; there were also changes in the driver approach behavior through either reduced reaction times or increased deceleration. These changes were not observable for any of the DIIs tested, under any of the warning timing conditions.

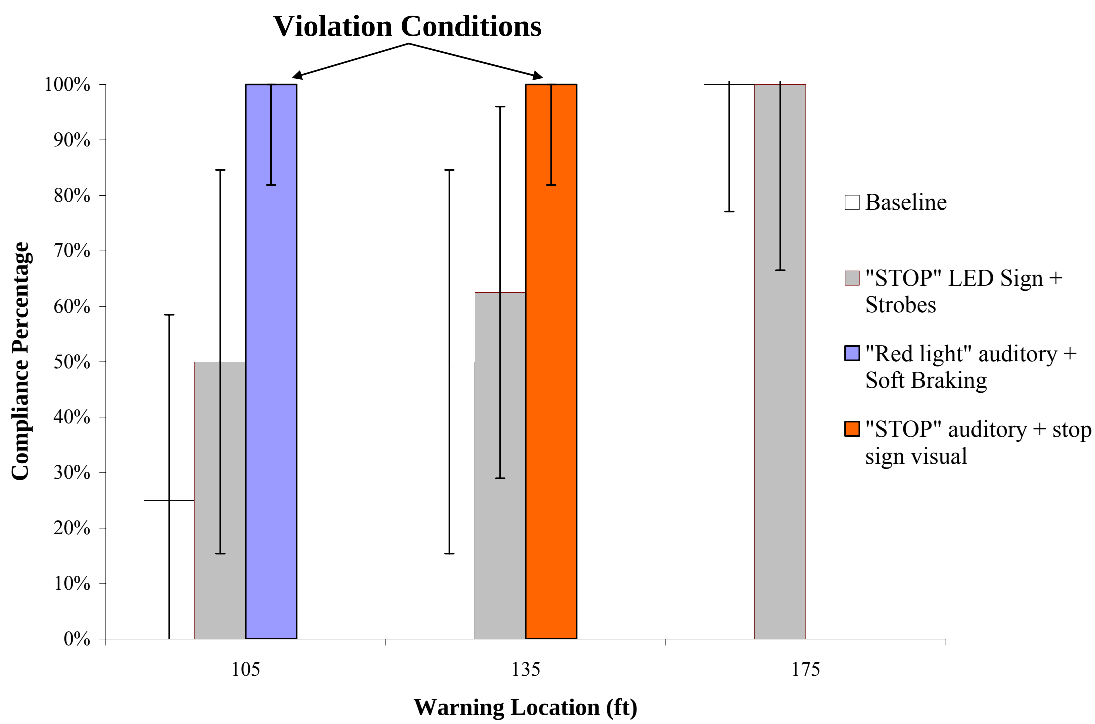

Figure 85. Comparison of elicited compliance percentage between the LED stop sign plus strobes DII and two in-vehicle warnings tested for the ICAV project. Error bars illustrate the 95 percent confidence interval for each of the means.

In interpreting these results, the reader should be aware of the possibility of a slight improvement in DII performance in situations that were not tested. For example, DIIs might perform better in conditions in which there is no following traffic. It could be argued that this situation would be representative of a very late violation (i.e., more than 5 s into the red), in which it is unlikely that two consecutive drivers would be sufficiently distracted to miss the presence of a traffic light ahead. However, it is important to note that even in that case, visual DIIs are unlikely to benefit distracted drivers whose gaze is well off the forward roadway, since the conspicuity test results show that drivers perceived the sign less frequently as their gaze shifted further from the forward view.

The logical question prompted by these results is why the DIIs failed to elicit driver compliance. One consideration is the experimental technique using occlusion goggles, implying that the DII would perform better under a more "realistic" scenario. However, this is an unlikely culprit. The occlusion technique was selected after a long evaluation process of different experimental approaches, including the use of actual distracters. In this evaluation process, the technique proved to work better for the intersection tests than any other technique. It allowed the experimenter complete control over the visual field for the time necessary to modify the participant's visual scene and create the surprise. Pilot testing highlighted the extreme difficulty of distracting a participant to a sufficient extent to encourage a red-light violation (consecutive seconds of inattention without a forward glance are required for a realistic phase change). This is particularly true near the intersection where drivers are naturally more attentive due to the increased opportunity for conflicting traffic. Further, eliciting an inattentive response at the desired intersection headway and corresponding phase change (which had to occur while the driver was distracted) was impossible to control since drivers have a natural tendency to look up at the forward roadway periodically.

A potential limitation of the occlusion technique is that the spectacles take away the entire visual scene, requiring a reacquisition of the visual scene at the end of the occlusion. However, there is no reason to believe that such a reacquisition is not perceptually similar, at least from a practical standpoint, to a driver being visually distracted. That is, if a driver is looking away from the forward roadway, he or she must also "reacquire" the forward roadway perceptually upon looking back.

A second limitation in considering the occlusion results in isolation is that the use of the occlusion goggles took away the ability for a visually distracted driver's attention to be captured by the DII. In the experimental protocol, when the occlusion cleared, the DII was on. This is different than the case of a visually distracted driver whose attention may be drawn forward by onset of the DII. Indeed, additional experiments revealed that the DII has a significant, although limited, beneficial feature of potentially being able to draw the attention of a visually distracted driver forward. However, due to driver behavior (e.g., glances that are too far from the roadway center for such a signal to gain attention) and the driving environment (e.g., sunlight glare), it is believed that such benefits would be limited in practice.

Another potential criticism of the occlusion technique is that it does not simulate mental distraction. Indeed, participants are not cognitively involved in another task when an occlusion is provided. However, this does not invalidate the experimental results, since participant performance and compliance with the warning would be expected to decrease as cognitive involvement in a secondary task (and thus, reaction time) increase. This would make the marginal improvements provided by the DIIs in this investigation even smaller under a more "realistic" distraction scenario. Thus, the results provided here are considered, from a cognitive distraction viewpoint, to be a "best-case scenario" in terms of warning effectiveness.

Another possible argument regarding the validity of the results is that the tests were conducted within a test-track environment, thus making drivers less likely to stop because they felt safe. However, subjective questionnaire data indicate that most drivers tended to feel relatively unsafe during the surprise trial. It is nonetheless possible that this low level of perceived safety would be substantially lower in the real world and would thus prompt a more aggressive response from drivers to the warning. This hypothesis would likely have to be confirmed using naturalistic data collection at an intersection where the DII has been activated; this was not a goal of this project, but could be an avenue for further research.

Even considering the potential criticisms discussed above, it is clear from this research that the DII is ineffective relative to the DVIs tested as part of the ICAV study simply because it did not compel the drivers to stop. The experimental protocols between the two studies was identical, thus there is no reason to believe that the differences would not translate to an actual driving environment.

There are several possible reasons why the DII was less effective than the ICAV DVIs in eliciting a driver braking response. Two of these are worthy of discussion. First, DVIs are in closer physical proximity to the driver than are DIIs, and thus might be more conspicuous and therefore more compelling than infrastructure-based warnings. Second, visual modality warnings are seldom appropriate by themselves, in-vehicle or otherwise, because they require the warning to be visible within the driver's central or peripheral vision (i.e., they are not omnipresent like auditory warnings) and because they tend to imply lower urgency. Most of the DIIs were visual in nature, given the practical limitations in providing warnings from the infrastructure, and were thus at a disadvantage to haptic and auditory DVIs. The haptic DII, in the form of a simulated rumble strip, failed to convey the need to stop to drivers, at least for this simulation of an imminent crash condition.

Finally, the ineffectiveness of DIIs in this series of studies should not be taken to indicate that no DII can be effective, but rather that none of the DIIs that could be feasibly developed and tested within the scope of this investigation was effective. It is possible that as technology evolves a future design effort may yield a DII that might be more effective in addressing the SCP crash problems than the DIIs investigated here. For example, directional sound is slowly evolving into a mainstream application and might be a useful DII option in the future. In any case, the results presented can be used as a starting point in the development, testing, and evaluation of future DIIs.

TECHNOLOGY TESTS

The original trade-off studies (see the Trade-Off Analyses section) not only allowed for the selection of technologies to be used within the testbed for the human factors experiments, but also showcased the potential of several technologies to assist the IDS function. Evaluating these technologies on a test track in realistic scenarios was one of the main goals of the IDS project, and this section reports on the findings from the tests.

The technologies tested can be divided according to the IDS function that they perform. Recall that the system functions originally identified were: sensing, communications, decision algorithm, DII, system integration hardware, and human behavior. This section is focused on technologies to perform the sensing, communications, and system integration functions (in the form of obtaining the necessary intersection state information from a signal controller). The decision algorithm and human behavior aspects have been discussed in detail in previous sections and are thus not considered in this section. Furthermore, these two system functions are not directly dependent on any particular technology. The final function, DII, while technology-related, has been addressed in a previous section from a human factors perspective.

The technologies discussed in this section were bench-tested prior to being tested in a test-track environment. These bench tests were meant to verify in an ideal environment that the devices complied with their advertised specifications   The results of these bench tests are not included within this report because that they represent a basic engineering level test and are superseded by the dynamic tests. Instead, the section focuses on the results of test-track evaluations for the different technologies.

Sensing Technologies

Proper functioning of the sensing subsystem is one of the key elements to overall IDS system effectiveness. To appropriately identify a potential violator, the sensing system must provide accurate and timely information about approaching vehicles. Radar technology was selected during the trade-off analysis as the best candidate to perform the vehicle sensing function for IDS.

The Smart Road intersection and existing IDS testbed was used to validate the sensing equipment. The sensing equipment was integrated into the testbed and synchronized to the onboard vehicle DGPS. After testing, the sensing equipment output was compared with the high-accuracy DGPS to determine and compare the performance of sensing options.

ACC Radar

The initial radar tested was a radar unit designed for Adaptive Cruise Control (ACC) applications in automobiles. The Autocruise radar uses MMIC- (Monolithic Microwave Integrated Circuit) based radar sensing technology to detect vehicles (Figure 86). The device generates a radar signal and then detects echoes from all vehicles located in the radar beam. It was selected for this test because of its market-leading performance, availability, and cost. The following specifications were provided with the radar:

1. Operating frequency band of 76-77 MHz
2. Acquisition time for new target: 320-560 ms
3. Transfer Function Bandwidth: 1.5 Hz
4. Multi-target compatibility: Up to 20 simultaneous tracks
5. Update rate: approximately 40 ms
6. Velocity
    - Maximum: 180 km/h
    - Maximum error: 0.5 km/h
7. Viewable area
    - 2.5 degree vertical cone

- 12 degree horizontal cone

8. Range
   - Maximum: 150 m
   - Minimum: 1 m
   - Maximum error:
     — ± 1m for distances between 1 m to 20 m
     — ± 5% for distances above 20 m
   - Noise on measurement: approximately 0.2 m rms
9. Azimuth maximum error:
   - ± 5.5˚ for distances 1 m to 40 m
   - ± 4.0˚ for distances 40 m to 100 m
10. Acceleration
    - Range: ± 10 m/s
    - Accuracy: ± 0.5 m/s^2
    - Measurement delay: 250 ms

Figure 86. TRW Autocruise ACC radar front and side views with ball-mount attachment point used to place radar on signal mast arm and along the side of the roadway.

Methods

The Autocruise radar was placed through a battery of testing across two radar mounting positions (Figure 87). The first position was a 1 m high mount located 1.5 m from the lane line directly even with the stop bar. This location was selected primarily to represent the stop-controlled intersection scenario in which the radar would be mounted to the stop-sign support. To cover as much of the lane as possible, the radar was mounted such that the 12° cone was horizontally oriented (2.5° vertical cone). This side-mount configuration was not expected to perform well in multi-lane approaches due to vehicles in the near lane occluding those in the further lanes. For this reason the second configuration placed the radar overhead, primarily to represent signal-controlled intersections which tend to have multiple lanes. The overhead mount positioned the radar on the signal mast-arm at a height of 4.5 m and directly centered on the approach lane. To cover the necessary range the radar was mounted with the 12° cone in the vertical orientation. This orientation limits the lane coverage but permits a significantly longer detection range.

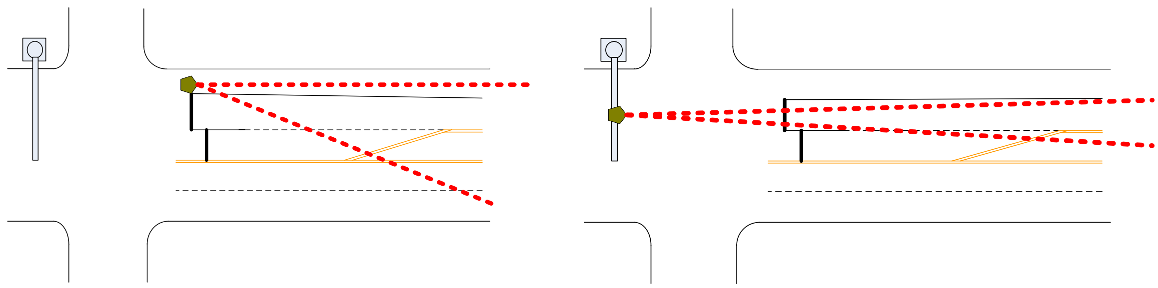

Figure 87. Left: Radar mounted on the side of the roadway with the 12° cone mounted in the horizontal direction. Right: Radar mounted on the signal arm with the 12° cone in the vertical orientation. The red dashed lines represent the approximate radar viewable cone.

Both single and dual vehicle scenarios were tested for each of the two radar configurations (Table 51). Single vehicle approaches were used primarily to explore radar measurement error, while the dual vehicle approaches were used to evaluate radar tracking ability. Single vehicle scenarios included approaches in which the vehicle came to a stop as well as approaches in which the vehicle maintained speed through the intersection without stopping. These two approach types were completed at initial speeds of 40.2 km/h (25 mph) and 112.6 km/h (70 mph). Three dual vehicle configurations were selected using a light vehicle as the SV (Chevrolet Impala) and a heavy vehicle as the POV (a large bucket truck constructed from a Ford Series F 25,000-pound chassis). The scenarios included situations in which the SV was the lead vehicle (1-second headway), SV was following vehicle (1-second headway), and SV initially beside and slightly trailing a POV but continuing through the intersection after the POV stopped. The bucket truck was presumed to have a large radar signature relative to the Impala, which was expected to further test the radar's discrimination capabilities. All multiple vehicle tests were performed at a median speed of 72.4 km/h (45 mph). Every condition included five replications for a total of 70 intersection approaches. Trained drivers completed all approaches using the Smart Road intersection and the IDS testbed.

Table 51. Experimental design for testing Autocruise radar

		Overhead Mount		Side Mount	
Single Vehicle	**SV stop**	40.2 km/h (25 mph)	112.6 km/h (70 mph)	40.2 km/h (25 mph)	112.6 km/h (70 mph)
	SV go	40.2 km/h (25 mph)	112.6 km/h (70 mph)	40.2 km/h (25 mph)	112.6 km/h (70 mph)
Dual Vehicles	**SV lead**	72.4 km/h (45 mph)		72.4 km/h (45 mph)	
	SV follow	72.4 km/h (45 mph)		72.4 km/h (45 mph)	
	Side by Side	72.4 km/h (45 mph)		72.4 km/h (45 mph)	

Output from the radar was recorded to a PC104 single stack computer within the intersection controller cabinet. Data from the radar were GPS time stamped for post hoc synchronization with the vehicle DAS. Comparisons between the information received from the radar and the DAS provided accuracy measures. Measures of performance included the following:

- Maximum detection range: The furthest distance at which the radar first acquired the SV as a target
- Maximum stable detection range: The furthest distance at which the radar track was reported continuously for 1 consecutive second (during initial vehicle track it was common for tracks to drop out).
- Dropouts: Occurred when a vehicle was being tracked in one frame and absent in the next. Dropouts were measured by counting number of frames in which the vehicle was absent. Dropouts were only computed between the maximum stable detection range and the intersection stop bar.
- Noise: Occurred when an unknown object was reported on the radar track. Noise was measured as the number of frames in which an invalid track was present. Noise was only computed between the maximum stable detection range and the intersection stop bar.
- Percentage of key approaches in which the vehicle was visible. The key range was specified as the area from 30-122 m (100-400 ft) in which a warning was likely to be administered.

Results

The Autocruise radar performed well during single vehicle testing. For all testing, the radar acquired a stable track of the test vehicle at a range sufficient for IDS functionality (Tables 52 and 53). Further, the stable maximum range exceeded the manufacturer's specifications for all single vehicle tests performed. Dropouts and noise were relatively rare events and could be filtered out in all instances. For example, the 11 dropouts noted in the side-mount 70-mph GO case occurred at distances greater than 198 m, which is well beyond the warning range expected. The noise obtained during the same approach was clearly a component of the SV, but incorrectly interpreted as a separate signal by the radar (the noise was offset by 1m from SV). This was a common trend across noise events. Noise in general could be filtered out with ease as the longest sequential noise event was seven frames (0.35 s) and tended to appear at distances greater than 150 m.

Table 52. Single vehicle side mounted radar results

	Absolute Max (m)		Stable Max (m)		Dropouts	Noise
	Average	StDev	Average	StDev		
Low Speed stop	243.84	4.49	234.08	12.31	0	3
Low Speed go	239.82	6.98	235.68	10.25	1	0
High Speed stop	242.81	2.06	242.81	2.06	0	1
High Speed go	238.46	6.38	236.50	4.54	11	17

Table 53. Single vehicle overhead mounted radar averages

	Absolute Max (m)		Stable Max (m)		Dropouts	Noise
	Average	StDev	Average	StDev		
Low Speed stop	233.12	3.29	233.12	3.29	0	1
Low Speed go	237.04	5.52	237.04	5.52	0	1
High Speed stop	228.56	11.04	228.56	11.04	0	10
High Speed go	234.92	7.16	234.92	7.16	0	12

To further explore the capabilities of the Autocruise radar, accuracy was evaluated by comparing the radar and vehicle DAS outputs. Data from the radar were collected at 20 Hz while the DAS collected at 10 Hz. To directly compare the radar and DAS, the 20 Hz data were reduced to 10 Hz by averaging the radar data into 0.1-second bins corresponding to the DAS. The high-accuracy DAS was then used as a ground truth to determine the radar measurement precision from the stop bar to 225 m from the intersection. In general the radar performed satisfactorily, although errors in excess of 8 m were encountered (Table 54). Errors of this magnitude would drastically impact the warning timing of an IDS system if they were to occur in the critical warning region. However, as depicted in the figures below (Figures 88 through 93), the errors are *not* evenly distributed across the intersection approach, with larger errors typically occurring at regions beyond the critical warning region. Errors in the critical warning region were within 2 m.

In the side-mount configuration, the variance in range error tended to decrease as the POV approached the intersection (Figure 88). The measured range performance would be improved if the required maximum range was reduced to 150 m or less (the maximum range specified by the manufacturer). Speed and acceleration errors exhibited the opposite effect (Figures 89 and 90), in that errors increased as the POV approached the intersection.

For the overhead-mount position, the error in the reported measures tended to be slightly less but exhibited the same general trends as the side-mount position. This is an interesting finding given that the vehicles were traveling more directly at the radar in the side-mount position. It is also noteworthy that the radar was unable to detect vehicles closer than about 30 m from the intersection. This may be a result of mounting the radar beam with the 12° cone vertically rather than horizontally as called for in the design. The internal threat algorithm may interpret vehicles driving across this cone as non-threatening, and may thus stop reporting them. Alternatively the roadway may also produce so much noise that the radar cannot obtain a clean signal at closer distances when more reflection from the roadway is present.

Table 54. Single vehicle accuracy results.

	25 mph Side Mount Stop				25 mph Side Mount Go			
	Average	StDev	Min	Max	Average	StDev	Min	Max
Distance (m)	0.776	0.945	-1.933	3.379	-0.333	1.269	-4.274	1.171
Speed (Km/h)	0.123	0.518	-0.814	4.275	0.002	0.190	-0.679	0.904
Accel (g)	0.002	0.023	-0.287	0.136	0.003	0.012	-0.065	0.063

	70 mph Side Mount Stop				70 mph Side Mount Go			
	Average	StDev	Min	Max	Average	StDev	Min	Max
Distance (m)	-0.392	1.254	-3.483	5.292	-0.051	1.320	-3.825	8.044
Speed (Km/h)	-0.140	0.371	-2.114	1.251	0.261	0.597	-1.239	3.269
Accel (g)	0.014	0.028	-0.170	0.179	-0.012	0.039	-0.462	0.122

	25 mph Overhead Stop				25 mph Overhead Go			
	Average	StDev	Min	Max	Average	StDev	Min	Max
Distance (m)	-0.182	0.840	-2.723	1.326	-0.190	0.832	-3.348	1.339
Speed (Km/h)	0.019	0.258	-1.866	2.257	-0.010	0.140	-1.159	0.509
Accel (g)	-0.011	0.021	-0.227	0.115	-0.008	0.011	-0.112	0.029

	70 mph Overhead Stop				70 mph Overhead Go			
	Average	StDev	Min	Max	Average	StDev	Min	Max
Distance (m)	0.005	0.875	-3.018	1.683	0.367	0.834	-1.824	2.614
Speed (Km/h)	0.228	0.709	-1.110	3.094	-0.151	0.393	-1.000	1.038
Accel (g)	-0.015	0.031	-0.097	0.088	0.000	0.017	-0.100	0.048

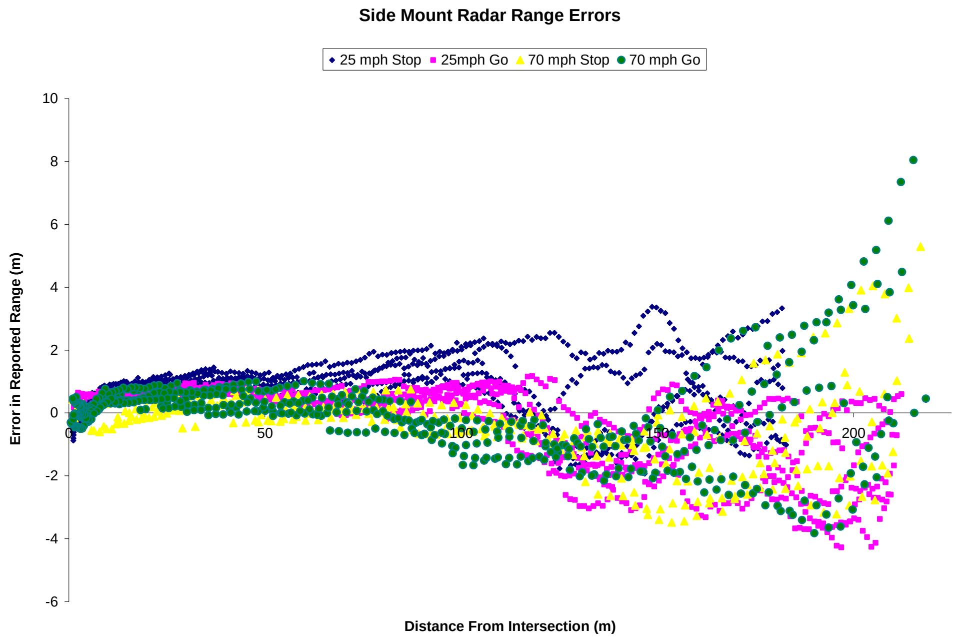

Figure 88. The difference between the range reported by the side mounted radar and the "true" range as reported by the vehicle DAS plotted as a function of distance from the intersection. Each color/shape plots all five intersection approaches for the corresponding condition.

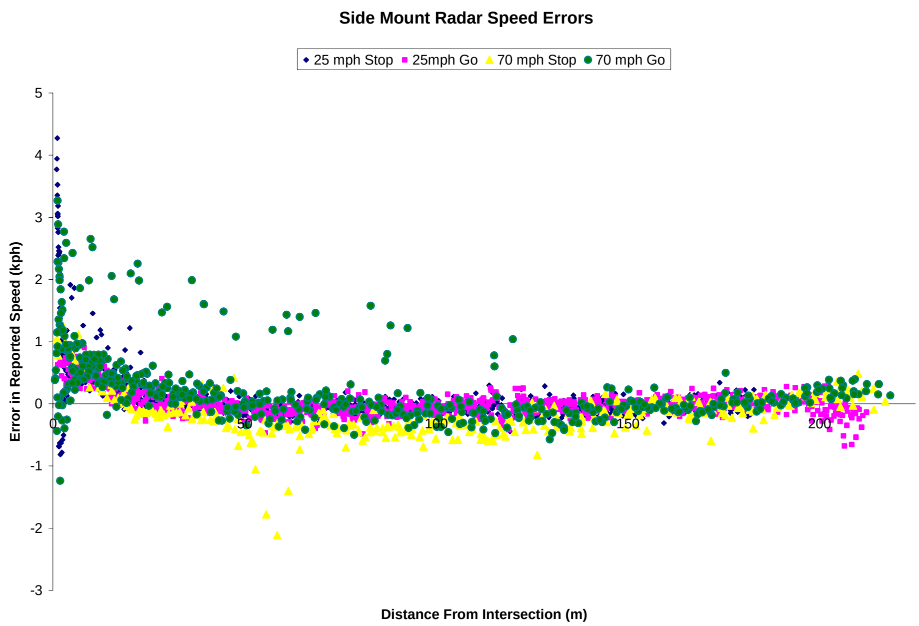

Figure 89. The difference between the speed reported by the side mounted radar and the "true" speed as reported by the vehicle DAS plotted as a function of distance from the intersection. Each color/shape plots all five intersection approaches for the corresponding condition.

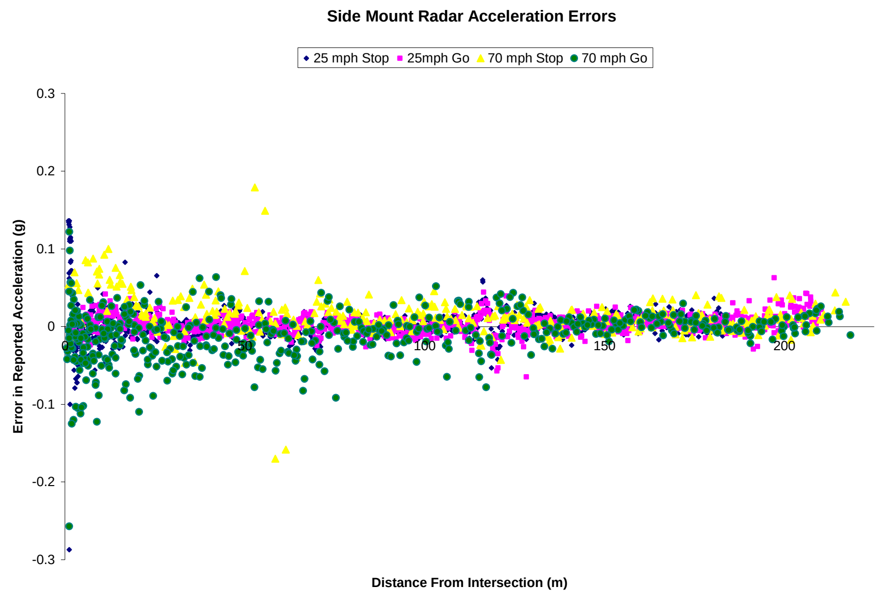

Figure 90. The difference between the acceleration reported by the side mounted radar and the "true" acceleration as reported by the vehicle DAS plotted as a function of distance from the intersection. Each color/shape plots all five intersection approaches for the corresponding condition.

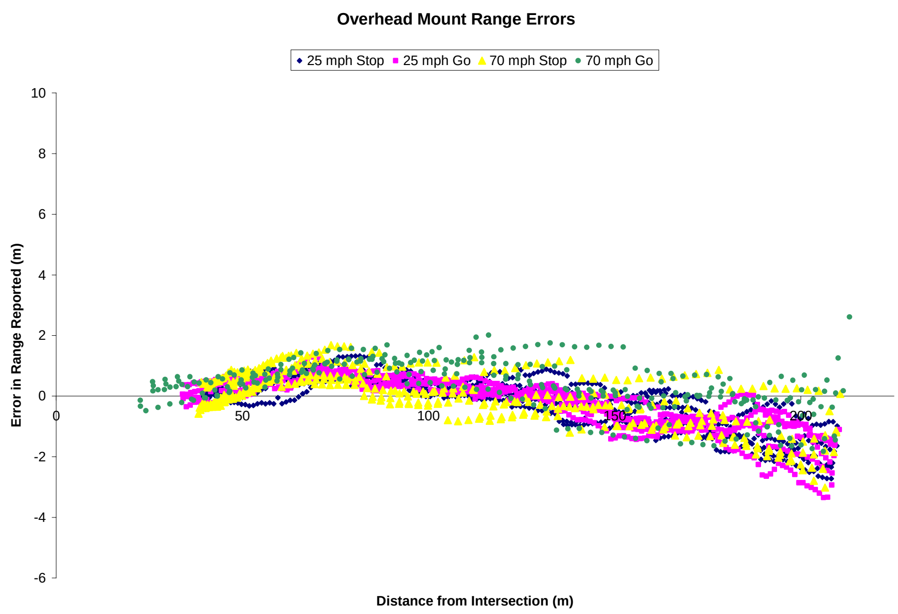

Figure 91. The difference between the range reported by the overhead mounted radar and the "true" range as reported by the vehicle DAS plotted as a function of distance from the intersection. Each color/shape plots all five intersection approaches for the corresponding condition.

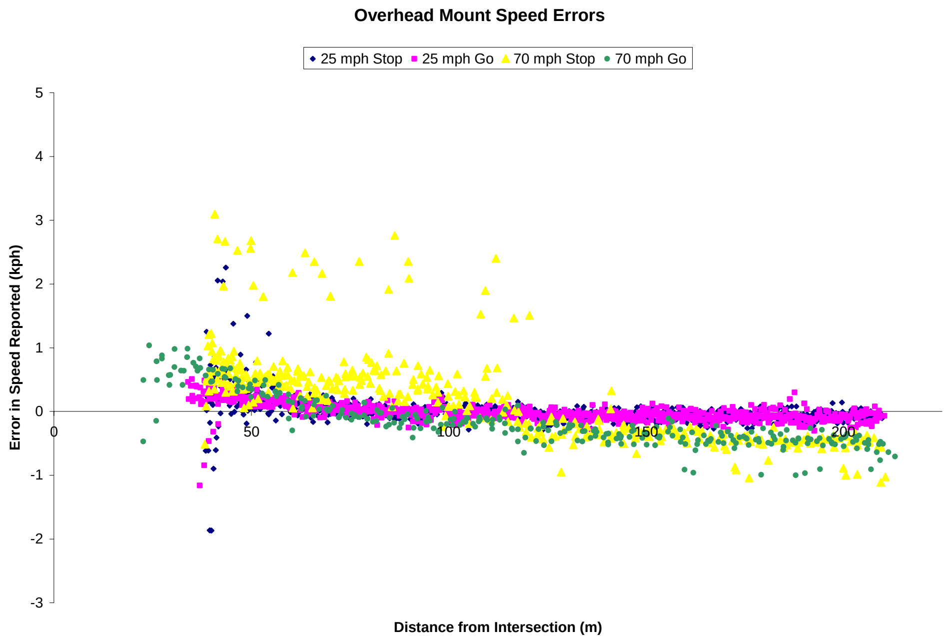

Figure 92. The difference between the speed reported by the overhead mounted radar and the "true" speed as reported by the vehicle DAS plotted as a function of distance from the intersection. Each color/shape plots all five intersection approaches for the corresponding condition.

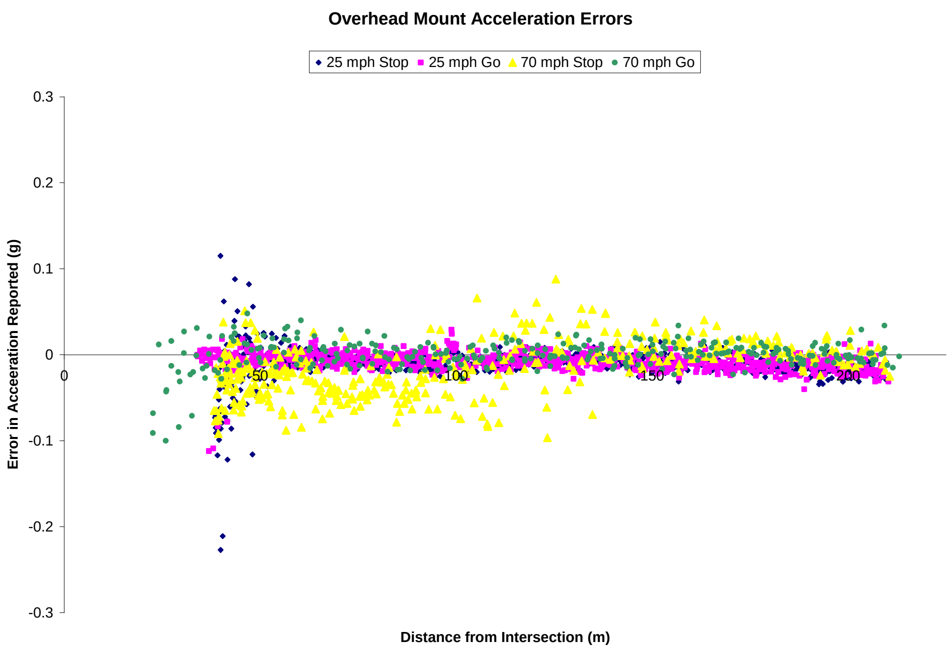

Figure 93. The difference between the acceleration reported by the overhead mounted radar and the "true" acceleration as reported by the vehicle DAS plotted as a function of distance from the intersection. Each color/shape plots all five intersection approaches for the corresponding condition.

Single vehicle test results suggest that the Autocruise radar performs satisfactorily for use in an IDS system. However, since it is common for vehicles to arrive in platoons, the radar's ability to track multiple vehicles needed to be validated. For these tests only the 30 to122 m (100 to 400 ft) range was considered in the results; this represents the likely area for a countermeasure to be issued. The percentage of time each vehicle was tracked by the radar in this range was used as the performance metric (Table 55). The first test configuration put the POV in front of the SV following with 1-second headway. Under this condition the POV was nearly always visible; however, the SV was only visible for 16.6 percent of the range. An even lower performance trend was observed for the next scenario in which the POV followed the SV. For this case the POV was only apparent for 0.1 percent of the range; a surprising result given the large radar signature of the bucket truck. Although the following vehicle tracking was better for the overhead mount, the radar still exhibited clear limitations when tracking following vehicles. The lead vehicle appears to shadow the following vehicle in all the experimental trials. While the side-mount radar performed well in the side-by-side trials, the overhead mount demonstrated a poor ability to track either vehicle; possibly an artifact of mounting the radar on its side.

Table 55. Average percentage of warning region (30-122 m) in which the SV and POV were tracked by the radar. Higher percentage indicates the vehicle was tracked for a greater portion of the range.

		% apparent in 30-122 m (100-400 ft) range			
		SV	StDev	POV	StDev
Side Mount	SV Follow	16.6%	2.4%	100.0%	0.0%
	SV Lead	100.0%	0.0%	0.1%	0.2%
	Side by Side	100.0%	0.0%	99.8%	0.5%
Overhead Mount	SV Follow	62.4%	32.9%	82.3%	14.1%
	SV Lead	98.1%	2.6%	93.6%	0.9%
	Side by Side	46.4%	7.8%	71.6%	13.4%

The multiple-vehicle tracking limitation is graphically demonstrated by the tracks shown in Figure 94. The SV in this case is clearly visible throughout the approach. However, the POV is nearly invisible through the entire critical warning region. Although of less importance, the radar also incorrectly assigned a third vehicle track to both vehicles (at different ranges). These tracking limitations would preclude the use of this radar in a multi-lane approach.

Implications

Overall results for the Autocruise radar suggest that it has limited utility for the IDS scenario. In general, the radar appears sufficient for most stop-controlled intersections if only the lead vehicle is assumed to be of concern. With this assumption, a non-stopping following vehicle is considered a forward-collision warning problem and outside the scope of IDS. The radar consistently tracked the lead vehicle in the side-mount configuration (overhead was slightly less favorable). Further, in the side-mount configuration the radar performed well in the side-by-side vehicle tests. This implies that it will also work for stop-sign approaches with two lanes (i.e., through and turn lanes).

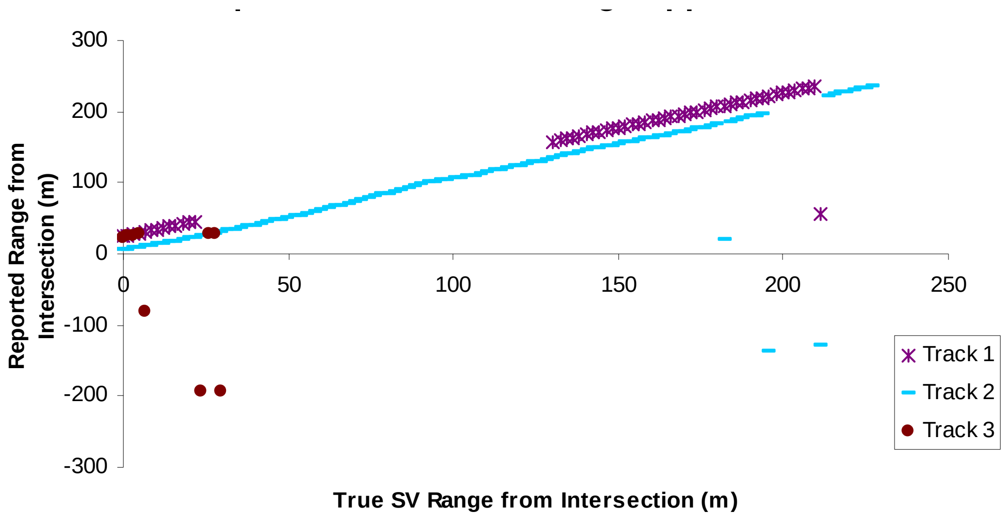

Figure 94. Example radar output from a multiple vehicle approach. The SV lead the bucket truck through this intersection approach and was visible through the critical region. However, the bucket truck was largely invisible to the radar.

However, it will sometimes be necessary to warn the following vehicle in signalized intersections. This situation occurs when the phase change permits the first vehicle to pass through the intersection but not the second. In this circumstance the Autocruise radar would not identify a second vehicle, and would thus fail to issue the warning. It is unknown whether this deficiency is due to the antenna itself or the internal processing algorithms. In either case, the failure rates of the following vehicle tests preclude the use of this radar at all signalized intersections.

The sub-optimal performance is not surprising; considering the intended adaptive cruise control application of this antenna. However, commercial availability of the radar makes the sensor relatively inexpensive. For this reason the radar may be recommended for simple stop-controlled intersections where only the first vehicle is considered. Additional field testing at live stop-controlled intersections should be undertaken to verify the radar's performance in the real-world environment with heaver traffic. In addition, a few new ACC radar options have emerged in the time since the testing was completed. TRW now makes an updated version of this antenna and Delphi has produced a newer ACC radar as well. These ACC radars are still unlikely to provide sufficient performance for a multi-lane signalized intersection because of their context-specific design (ACC radar purposefully singles out a single lead vehicle). Nevertheless, additional testing on the new ACC radars would be appropriate before moving to the more costly option described next.

Imaging Radar

In light of ACC radar limitations, a search of available technologies for a more broadly applicable vehicle sensing system was undertaken. No commercially available radar technologies with sufficient vehicle tracking, coverage, range, and/or processing algorithms were located as a result of this search. However, the search did result in the acquisition of a millimeter wave (MMW) imaging radar.

This radar is typically used in the aviation market, but it was envisioned to be adaptable to the IDS application. The radar antenna was an engineering prototype and would require further development for use in an IDS application, primarily due to a lack of weatherproofing and onboard processing. Manufacturer's radar specifications follow:

- Operating frequency band: 94 GHz
- Update rate: approximately 70 ms
- Viewable area:
    - 5° vertical cone
    - 30° horizontal cone
- Range:
    - Maximum: 1 km
    - Minimum: 5 m
- Maximum error:
    - ± 1 m for distances between 1 m to 20 m
    - ± 1 percent for distances above 20 m
- Azimuth maximum error:
    - ± 1° for distances 1 m to 40 m
- Size: 9 in x 15 in x 6 in
- Weight: 29 lb.

Methods

A custom bracket was fabricated to mount the antenna on the signal mast arm (Figure 95). The antenna sat at a height of 4.5 m; it was attached to the power supply and DAS (located on the shoulder of the roadway).

The antenna was mounted between the signal heads and oriented to collect data from vehicles as they approached the intersection. The power supply, data recorder, and post-processor were contained in the DAS cabinet placed on the roadway shoulder.

The imaging radar does not currently have a real-time tracking algorithm (though it does perform near-real-time radar imaging). Raw data from the antenna are transmitted in real-time to the DAS which displays the radar image (Figure 96). However, the raw radar data output is extremely large and contains primarily irrelevant information (e.g., radar signatures of various static objects). Once these data were collected they could be reduced using a moving-target indicator (MTI) filter (Figure 96). The MTI filter essentially discards all static information and returns only the pixels that are in motion, thus substantially reducing data bandwidth. The MTI data represent a basic tracking algorithm and were used for all the analysis reported here. Future imaging radar, if further developed for the IDS application, would likely have a more sophisticated, real-time tracking algorithm that should further enhance the sensor performance.

Figure 95. Imaging radar test setup.

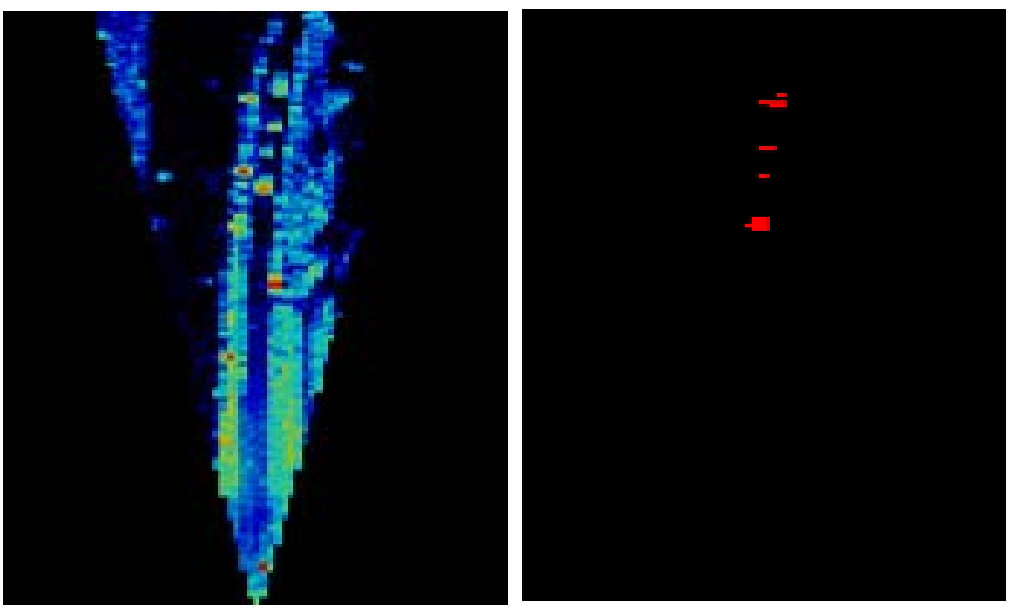

Figure 96. Left – raw radar image of four vehicles approaching the Smart Road intersection. Right – The same four vehicles but after MTI filtering.

The imaging radar was tested across a variety of approach conditions to validate both the accuracy and tracking abilities of the radar. Early in the testing phase it became clear that the radar would differentiate between multiple vehicles. As a result, a substantial number of multiple vehicle passes were performed to evaluate the tracking abilities of the antenna for several common intersection scenarios. Five test vehicles were used in the multiple vehicle trials. These vehicles were selected to represent a variety of vehicle classes ranging from a small motorcycle to a large bucket truck (Figure 97).

Figure 97. Test vehicles approaching the intersection during the radar testing session. From first to last the vehicles were: 1) a Ford Series F 25,000-pound bucket truck, 2) a Ford Contour, 3) a Chevrolet Impala, and 4) a Chevrolet 2500 series work truck, and 5) a Yamaha XL motorcycle (not visible in picture).

All tests were performed under overcast conditions and moderate temperatures. An effort was made to develop realistic multiple-vehicle situations that would test the limitations of the radar. This was accomplished by using a combination of light and heavy vehicles driving at the intersection in a tight formation. The following eleven scenarios were selected and replicated five times each. There were two exceptions to this: one occurred on the side-by-side trial which suffered a data storage malfunction resulting in only three usable approaches and the other was the pedestrian trial which was collected in a single long file with continuous pedestrian motion. In total, there were 52 usable approaches.

- Single vehicle approaches (used to determine accuracy)
    - High speed approach at 112.6 km/h (70 mph)
        - Scenario #1: Complete stop
        - Scenario #2: Drive through
    - Low speed approach at 40.2 km/h (25 mph)
        - Scenario #3: Complete stop
        - Scenario #4: Drive through
- Multiple vehicle approaches (used to evaluate tracking resolution)
    - Four vehicles following inline following each other and traveling at 72.4 km/h (45 mph). The bucket truck led the platoon followed by the Contour, the Impala, and finally the work truck. The first three vehicles passed through the intersection while the fourth vehicle came to a stop.
        - Scenario #5: 1.0-second headway
        - Scenario #6: 0.5-second headway
        - Scenario #7: Four vehicles traveled in side-by-by side pairs. The bucket truck drove in the right lane beside the work truck in the left lane. The Contour then followed the bucket truck while the Impala followed the

work truck both with 1-second headway. Only the Contour stopped at the intersection while all other vehicles drove through.

- Scenario #8: Four vehicles approaching the intersection simulated an overtaking maneuver. The bucket truck was in the right lane at was traveling at 56.32 km/h (35 mph). The work truck drove in the left lane and initially tailed the bucket truck by several hundred meters but traveled at 88.5 km/h (55 mph). The Contour followed by the Impala initially tailed the bucket truck by about a hundred meters but traveled at 72.4 km/h (45 mph). As the vehicles neared the intersection, the Contour and Impala would catch the bucket truck in the right lane at which time the work truck would pass in the left lane. The Contour, followed by the Impala, would then change lanes and pass the bucket truck about 50 m from the intersection. The bucket truck would stop at the intersection while all the other vehicles would drive through.
- Scenario #9: Four vehicles, two traveling in each direction, simulated a left turn maneuver. The work truck followed by the Impala drove toward the radar antenna. As the vehicles approached the intersection the work truck prepared to make a left turn. The bucket truck then passed in the opposite direction, the work truck yielded and then made the left turn before the Contour (which followed the bucket truck) arrived at the intersection. Once the work truck was clear the Impala drove through. All vehicles were initially moving at 72.4 km/h (45 mph).
- Scenario #10: A motorcycle followed the Chevy work truck at 1-second headway both traveling 72.4 km/h (45 mph).
- Scenario #11: Four pedestrians traversed the roadway in the crosswalk.

Data from the runs were recorded to the imaging radar's DAS for later analysis. The following metrics were used to determine radar performance:

- Maximum detection range: The furthest distance at which the radar first acquired the SV as a target.
- Maximum stable detection range: The furthest distance at which the radar track was reported continuously for 1 consecutive second (during initial vehicle track it was common for tracks to drop out).
- Dropouts: Occurred when a vehicle was being tracked in one frame and absent in the next. Dropouts were measured by counting number of frames in which the vehicle was absent. Dropouts were only computed between the maximum stable detection range and the intersection stop bar.
- Noise: Occurred when an unknown object is reported on the radar track. Noise was measured as the number of frames in which an invalid track was present. Noise was only computed between the maximum stable detection range and the intersection stop bar.
- Percentage of key approach in which the vehicle was visible. The key range was specified as the area from 30 to 122 m (100 to 400 ft) in which a warning was likely to be administered.

Results

During single vehicle approaches the imaging radar began tracking vehicles earlier than the Autocruise radar. The range results suggest that the radar will track vehicles at ranges substantially higher than necessary for the IDS application (Table 56). Dropouts (counted from the maximum stable detection range until the intersection was entered) occurred primarily at the long ranges. In nearly all instances the dropouts occurred over 300 m from the intersection, which is well beyond the warning region. Noise was rare, occurring a maximum of once per approach. In general both noise and dropouts could be filtered out with a more advanced tracking algorithm that considers history (most instances lasted only a few frames).

Table 56. Average single vehicle imaging radar results. Nearly all dropouts noted occurred at high ranges from the intersection where a warning will not be issued

		Absolute Max (m)		Stable Max (m)		Dropouts	Noise
Scenario	**Short Description**	**Average**	**StDev**	**Average**	**StDev**		
1	Single vehicle 70 mph stop	449.39	16.31	381.90	2.02	14	1
2	Single vehicle 70 mph go	452.82	36.20	381.29	7.61	32	3
3	Single vehicle 25 mph stop	454.64	41.33	402.51	48.40	51	1
4	Single vehicle 25 mph go	481.92	1.24	403.11	48.30	102	0

To further explore the imaging radar capabilities, accuracy was evaluated by comparing the radar and vehicle DAS outputs. Due to time and funding constraints the DAS could not be equipped to use a GPS time stamp. The large bandwidth requirements and customization requirements precluded attaching the antenna to the VTTI DAS. As a result, these data could not be matched on a time basis to the data recorded from the vehicle DAS (as was done for the Autocruise testing). Instead the two data sets were matched on a distance basis.

As mentioned above, the imaging radar does not currently have a tracking algorithm. The MTI filter removes all the static data; however, it does not return a single value for an approaching target. Rather it provides the range to each pixel consumed by the approaching vehicle (i.e., a single vehicle may be represented by several pixels in a single frame). To approximate a tracking algorithm, the minimum pixel in each frame was selected as the vehicle location. The data were then down-sampled to approximate the collection rate of the vehicle DAS (converted from about 12 Hz to about 10 Hz). The two data sets were then synchronized at 122 m, the maximum foreseeable warning range. Interpretation of the results should be made with caution considering the limitations of this method. In particular, the independent DAS clocks could have resulted in data drift, calibration errors, and latency.

As with the previous radar test, the high-accuracy vehicle DGPS was used as a ground truth to determine the radar measurement precision in the likely warning region (30 to 122 m). In general the radar performed well in the warning region despite a maximum error of 3 m (Table 57). Typical errors were within ± 1 m. This level of accuracy should be sufficient for an IDS application, although some warnings may be untimely (particularly if the maximum error occurs near the warning onset region)

Table 57. Single vehicle accuracy results for imaging radar

	25 mph Side Fire stop				25 mph Side Fire Go			
	Average	StDev	Min	Max	Average	StDev	Min	Max
Distance (m)	0.019	0.498	-1.019	2.104	-0.001	0.609	-1.508	2.237

	70 mph Side Mount stop				70 mph Side Mount Go			
	Average	StDev	Min	Max	Average	StDev	Min	Max
Distance (m)	0.068	0.825	-2.176	3.071	0.000	0.733	-1.608	2.127

A scatter plot of the single vehicle errors is presented below (Figure 98). The errors tended to begin negative and move toward positive values. It is unknown whether this is an artifact of data drift from the unsynchronized DAS systems or an actual phenomenon of the antenna. Large errors are dispersed across the approach but typically only occur for a few sequential time frames. This may indicate that these could be filtered in future iterations of the radar.

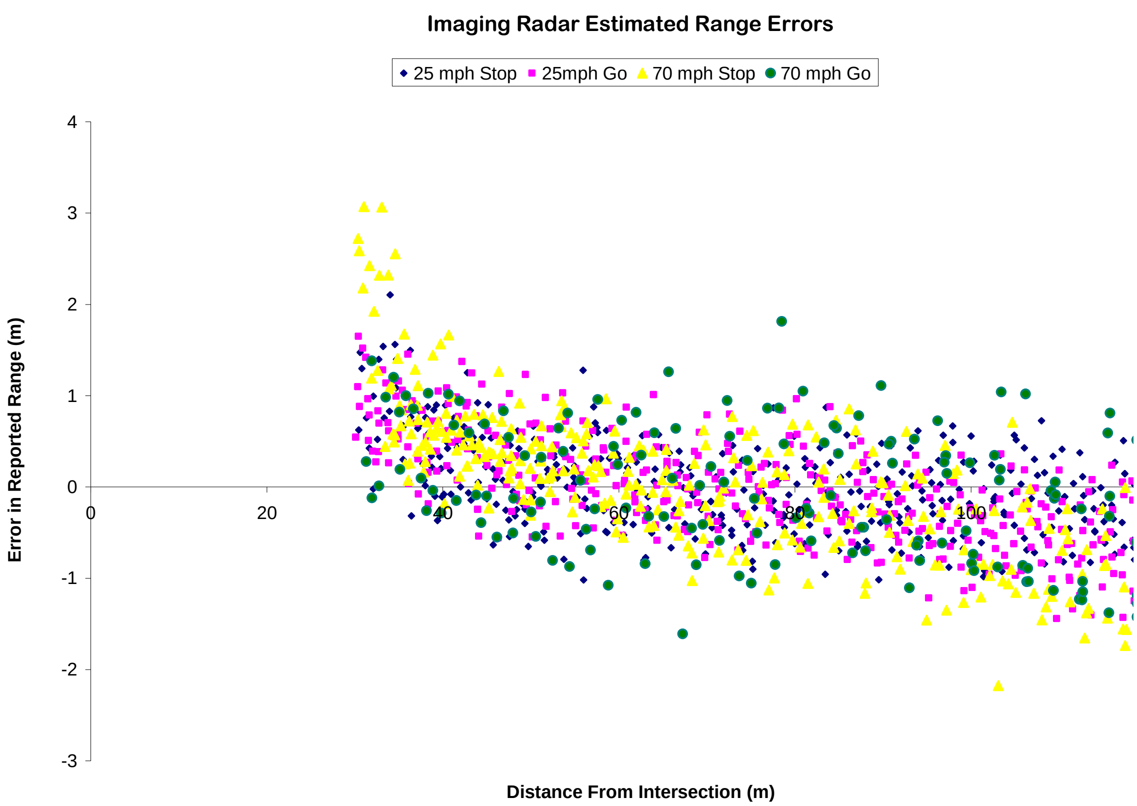

Figure 98. The difference between the range reported by the imaging radar and the "true" range as reported by the vehicle DAS plotted as a function of distance from the intersection. Each color/shape plots all five intersection approaches for the corresponding condition.

The primary reason for selecting the imaging radar for testing was its apparent ability to track multiple vehicles during an intersection approach. To investigate the antenna's capabilities in realistic intersection scenarios, five multiple-vehicle scenarios were tested. The selected scenarios (described in the methods section) were intended to test the limitations of the radar by using a combination of vehicles types driving in a tight formation. A graphical example of one approach is provided below (Figure 99). The figure is one of the five trials completed for scenario eight in which several vehicles passed the bucket truck. For this approach all four vehicles are nearly always visible. In other approaches, multiple tracks would sometimes appear as a single track and were thus considered un-resolvable (decreasing the percent visible measure). Also note the instances of noise during the approach.

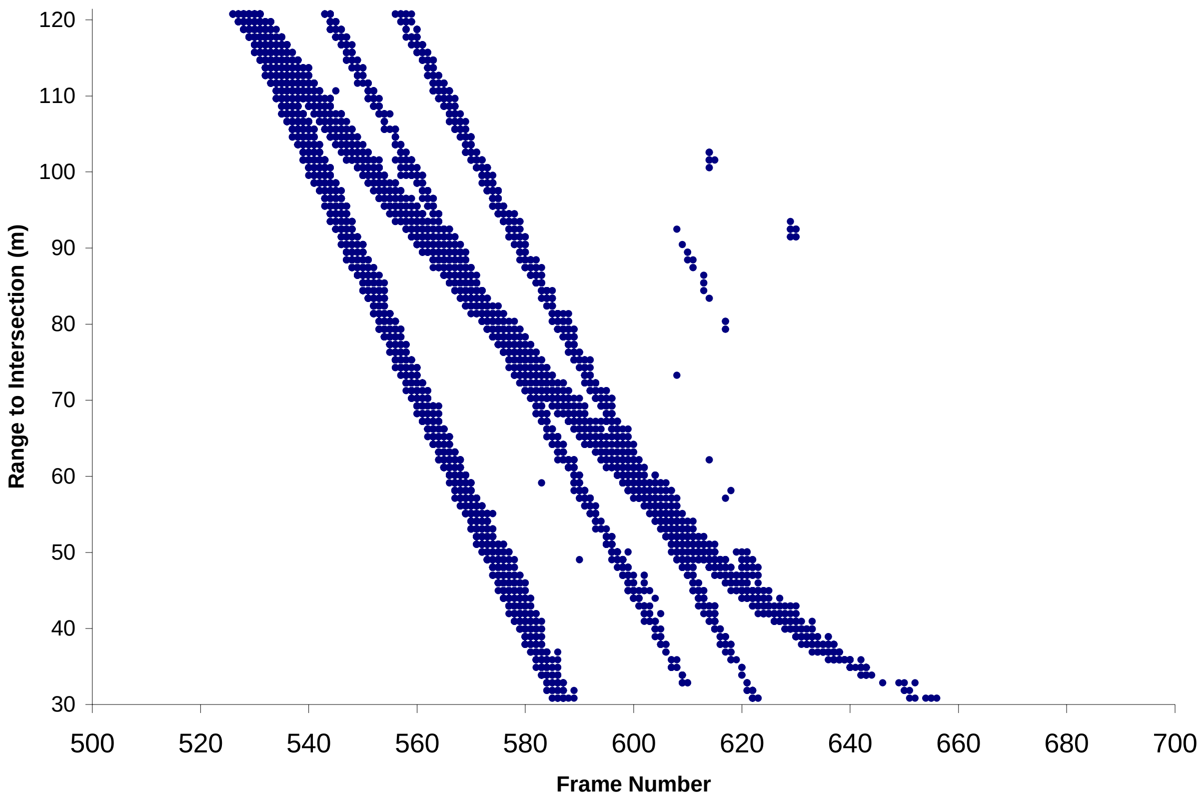

Figure 99. Example radar output from a multiple vehicle approach in scenario #8. Each point represents a single pixel return from the MTI filter. The wider trace represents the bucket truck which is the only vehicle stopping at the intersection. The second widest line is the work truck, followed by the Impala and the Contour.

For these tests, only the 30 to 122 m (100 to 400 ft) range was considered in the results, since this is the likely area for issuance of a countermeasure. The percentage of time each vehicle could be identified as an independent track was used as the performance metric (Table 58). The results imply that the antenna will sufficiently track vehicles for many of the foreseeable scenarios, but highlights the limitation of observing light vehicles that are in the shadow of a heavy vehicle.

Table 58. Average percentage of warning region (30-122 m) in which the SV and POV could be individually identified in the radar track. Higher percentage indicates the vehicle was tracked for a greater portion of the range.

		% apparent in 30-122 m (100-400 ft) range									
Scenario	**Short Description**	**Bucket Truck**	**SD**	**Work Truck**	**SD**	**Impala**	**SD**	**Contour**	**SD**	**Motor-cycle**	**SD**
5	Four vehicle platoon with 1 sec headway	100%	0%	100%	0%	97%	4%	71%	0%	--	--
6	Four vehicle platoon with ½ sec headway	100%	0%	99%	1%	63%	12%	1%	1%	--	--
7	Four vehicles in side by side pairs	100%	0%	56%	6%	99%	1%	0%	6%	--	--
8	Four vehicles in overtake maneuver	98%	1%	99%	1%	98%	2%	100%	1%	--	--
9	Four vehicles left turn into gap	98%	1%	100%	0%	100%	0%	91%	0%	--	--
10	Motorcycle following at 1 sec headway	--	--	100%	0	--	--	--	--	68%	45%
11	Pedestrian walking	100 %									

For most scenarios, all vehicles were tracked individually during most of the run. However, there are some clear deficiencies that would impact the performance of an IDS system. It appears that small light vehicles will hide in the shadow of a heavy vehicle, particularly at short following distances. A second limitation occurs when vehicles are driving side-by-side at the same speed. The large work truck was only in view 58 percent of the time when it approached the intersection beside the bucket truck. Essentially the two targets appear as one extremely wide vehicle. It may be possible for an advanced tracking algorithm to separate these two vehicles during this multi-lane scenario. It may also not be necessary to differentiate them as a warning would be necessary for both (the exception occurs when one lane has a green indication and the other a red).

The cause of the large variability observed in the motorcycle approaches is unclear. The visibility of each individual approach in order was 100, 100, 92, 1, and 48 percent. Perhaps variability in the headway or lateral location of the motorcycle sometimes caused it to be located in the work truck's radar shadow.

Future development work should include improvements to increase the percentage of the approach in which each type of vehicle is apparent. It is expected that a more advanced tracking algorithm could increase the visibility of many approaches. A tracking algorithm could consider history and project the future location of a target. This would eliminate the short dropouts that are present in many of the approaches above.

The pedestrian trial was intended to evaluate the potential for radar to detect the presence of a pedestrian crossing the roadway. Pedestrians crossed laterally on the roadway as though walking through a crosswalk. For this trial, a single long data file was collected while the pedestrians traversed the roadway. The resulting MTI data indicated that pedestrian detection is a possibility and may be a reliable method for adjusting the IDS algorithm, particularly in urban LTAP scenarios in which pedestrian information is very important to the warning timing.

Implications

While improvements would be preferred, tests in general indicate that the antenna should be sufficient for the IDS application. The antenna could be improved by increasing the pixel resolution and tuning for the required range (the range was three times the required range). These changes may increase the radar's ability to differentiate vehicles even when they are traveling in close proximity.

The tracking algorithm, however, must be improved prior to use in the IDS context. The tracking algorithm should be improved to reduce the frequency of dropouts and noise by considering target history and projecting future location. It may also be possible to increase the radar's ability to differentiate vehicles by overlaying a roadway map and considering azimuth to determine lane presence. The radar must also be updated to provide an accurate measure of speed. Accurate speed data are paramount to accurate warning timing, which implies that the speed measure should be based on Doppler shift algorithms rather than simple range integration.

Finally, the imaging radar would need to be packaged for the roadway environment. This would require a weatherproof enclosure, real-time processing, and a compatible interface. These required updates to the radar appear feasible and could be accomplished with a short development cycle.

Communications Technologies

The trade-off analysis indicated that the DSRC protocol and hardware represented the best current alternative to perform the wireless communication of intersection state for an IDS system. Consequently, a prototype DSRC system was obtained and tested by VTTI near the beginning of the project. However, due to the lengthy duration of the project (3+ yrs), it was also possible to test the second generation of the system, which is closer in packaging factor to a production system. The results for both tests are included in this section.

First Generation Simulated DSRC

This DSRC system was tested on an infrastructure-to-vehicle configuration, in which data were transmitted unidirectionally from the infrastructure to the vehicle (i.e., point-to-multipoint). The DSRC protocol was simulated using the hardware and software provided with the prototype system, as it was preliminary at the time that the tests were conducted. Specifications for the system are provided in the section: Development of the Smart Road Intersection Testbed, but in general, the system was operated using a 10 Hz update rate with an operating frequency of 5.2 GHz. When the tests were conducted, the main research questions were the effective range of the communications equipment and the number of packets that could be reliably received per second. These questions were examined as a function of speed and packet size. Other issues, such as the content and format of the data stream, were under development at the time the tests were conducted, and thus were standardized through the experiments.

Methods

Several communications tests were conducted in the evaluation process, focused toward characterizing communications technology performance as a function of variations of packet characteristics and vehicle speed. A total of four tests were conducted. The first test was a static test of communications capability over various distances and packet sizes. These data were collected over 2 days for a period of approximately 2 hours/day. The experimental design varied the distance to intersection at which the vehicle was located (6 distances: 182.9, 167.6, 152.4, 137.2, 121.9, 106.7 m; 600, 550, 500, 450, 400, 350 ft) and the packet size (3 packet sizes: 128, 256, 512 bytes). Each of the resultant 18 conditions (6 distances by 3 packet sizes) was performed four times for a total of 72 trials. The packets for this test consisted of random ASCII characters with a size of 512 bytes. Ten of these packets were created and they were rotated in each of the tests. Depending on the condition, the first 128, 256, or 512 bytes of the message were sent. Knowledge of the size and package content allowed for checks on the completeness and correct order of the data that were received.

The second test evaluated the dynamic capability of the communications system as a function of the approach speed and the packet size. As with the first test, data were collected over 2 days for a period of approximately 2 hours/day. The experimental design examined combinations of three speeds (48.3, 80.5, 112.7 km/h; 30, 50, 70 mph) and three packet sizes (128, 256, 512 bytes), with three to four replications for each of the resultant nine conditions. Speed was maintained constant, and data were collected when the vehicle was located within 182.9 m (600 ft) of the intersection stop bar and lasted until the vehicle had crossed the stop bar.

The third test also evaluated the dynamic capability of the communications system, but as a function of the distance to intersection. As for the previous tests, data were collected for 2 days, for a period of approximately 2 hours/day. Although data were collected continuously throughout the approach (while the vehicle was located within 182.9 m (600 ft) of the intersection and prior to stop bar crossing), they were grouped into six different bins: 0-30.5, 30.6-61.0, 61.1-91.4, 91.5-121.9, 122.0-152.4, 152.5-182.9 m (0-100, 101-200, 201-300, 301-400, 401-500, 501-600 ft). A total of 65 runs were completed at a nominal speed of 80.5 km/h (50 mph).

The fourth and final test was a static test designed to measure the latency of the message. Full 512-byte messages were sent with the vehicle located at 182.9 m (600 ft) from the stop bar in both uphill and downhill approaches. In each case, latency was measured and averaged over more than 1,900 packet transmissions.

Results

Static Test Varying Distance and Packet Size

The 72 trials within this test required the transmission of 24.9 MB, with a data loss of 0.02 MB (0.10 percent). These 24.9 MB included 88,798 packets, with a data loss of 75 packets (0.084 percent). None of the packets were received incorrectly or incompletely. Plotting the results by distance from the intersection and packet size (Figure 100) demonstrates some effect of packet size on the percentage of dropped packets, but this effect appears to be modulated by the distance to the intersection. Interestingly, the 137.2 m (450 ft) distance exhibited a larger proportion of dropped packets than other distances, including those that were farther away. This indicates the presence of a “dead-spot” near that range.

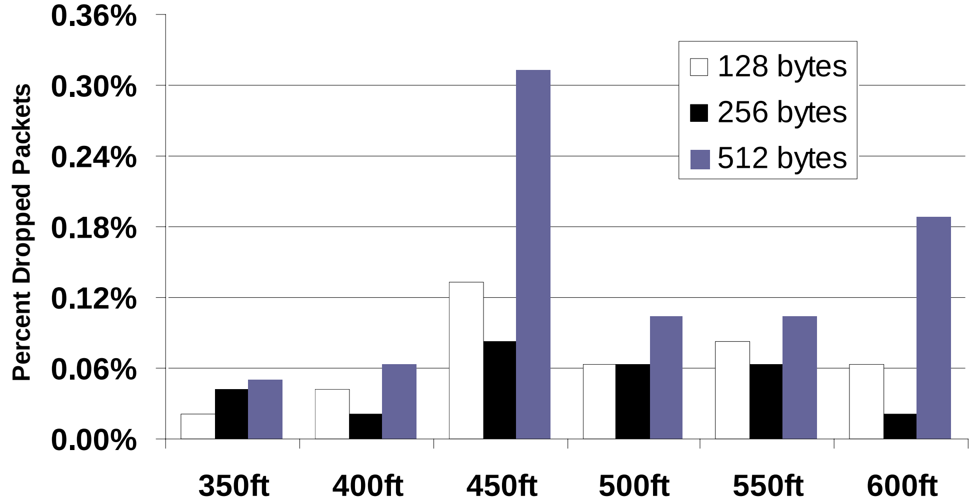

Figure 100. Dropped packets as a function of distance to the stop bar and packet size for the static condition. (1 ft = 0.30 m)

Dynamic Test Varying Speed and Packet Size

The test resulted in the transmission of 1.79 MB and a loss of 0.02 MB (1.4 percent) of data. These 1.79 MB included 6,855 packets, whereas the lost 0.02 MB represented 75 packets (1.1 percent packet loss). None of the received packets were incomplete or incorrect. Examination of lost data by speed and packet size (Figure 101) indicated little effect of speed on the proportion of packets received. However, increases in packet size tended to increase the proportion of lost data. Interestingly, the percentage of dropped packets seemed to be affected by the approach toward the antenna (Figure 102), suggesting that data reception is dependant on the location of the antennas. In the downhill case, the vehicle antenna (receiver) was higher than the TCD antenna (transmitter). This suggests that care must be taken when ultimately placing the infrastructure antenna to provide the best coverage zones for the wireless system.

Dynamic Test at Constant Speed, Examining Distance at Which Packets were Dropped

The results of this test show that all of the distance bins exhibited over a 95 percent received packet rate (Figure 103). A substantial drop in this percentage, however, was observed for the 30.6-61.0 m (101-200 ft) bin. This drop is similar to that observed for the 137.2 m (450 ft) distance in the static condition, and also suggests the presence of a dead-spot in the transmission area. Given that the static experiment did not examine distances smaller than 106.7 m (350 ft), it is unknown whether this dead-spot is also present in the static condition. In general, 63 percent of the dropped packets occurred at less than 61.0 m (200 ft) from the intersection, 21 percent occurred between 61.0 m (200 ft) and 122.0 m (400 ft), and 16 percent occurred between 122.0 m (400 m) and 182.9 m (600 ft).

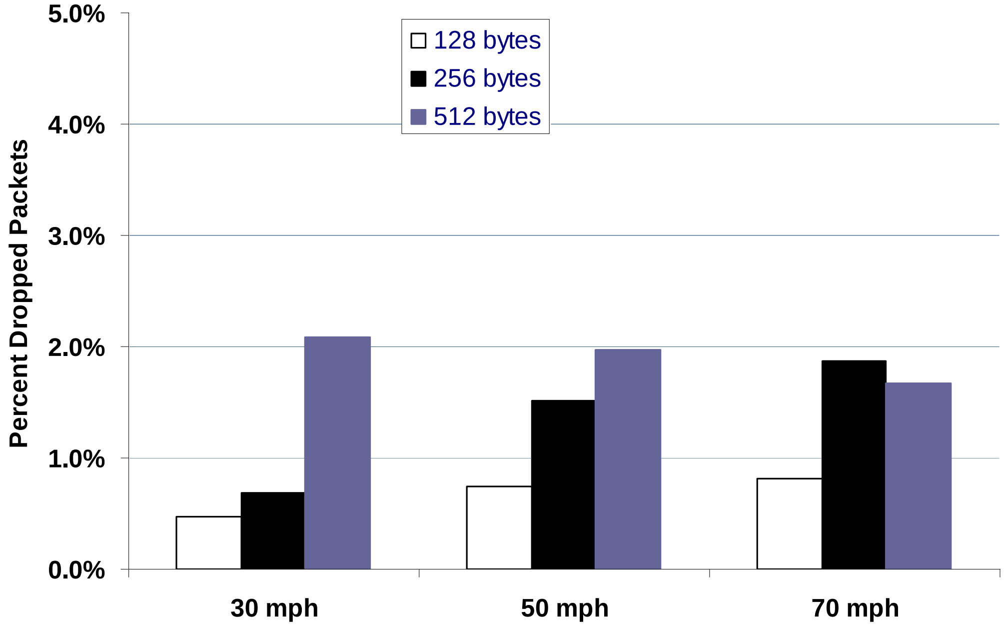

Figure 101. Dropped packets as a function of speed and packet size for the dynamic condition. (1 mph = 1.6 km/h)

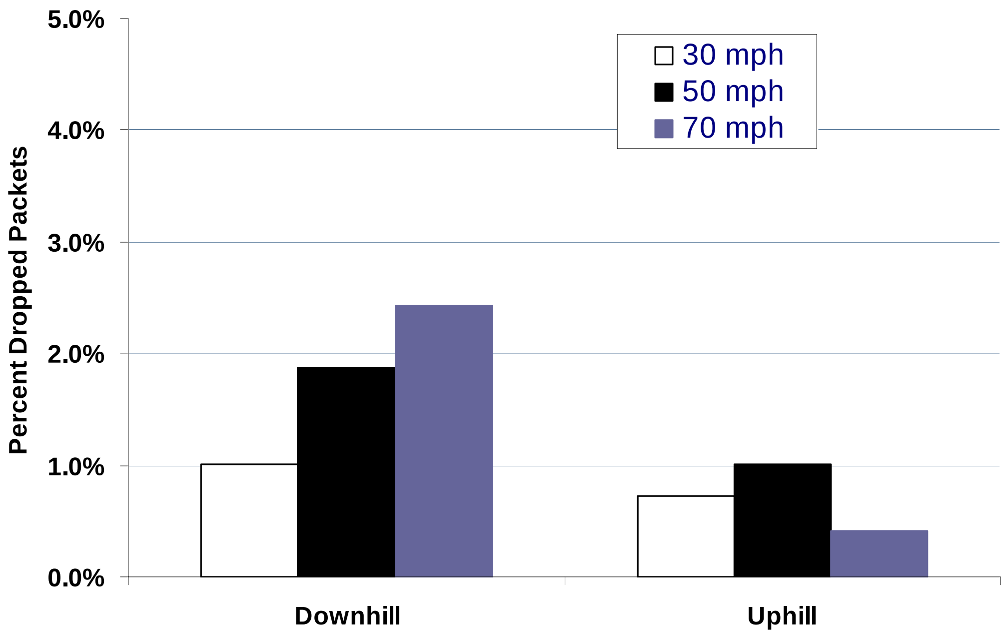

Figure 102. Dropped packets as a function of speed and approach for the dynamic condition. (1 mph = 1.6 km/h)

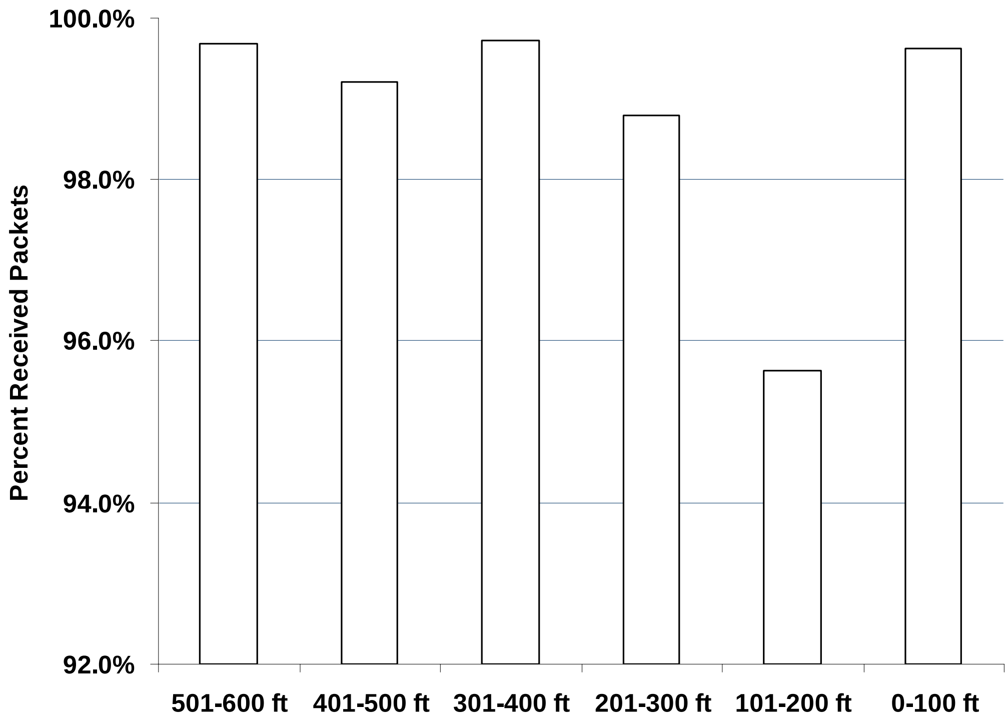

Figure 103. Dropped packets as a function of distance for the dynamic condition. (1 mph = 1.6 km/h)

Latency Test

For the uphill approach, a total of 1,960 packets were sent, with 99.90 percent of those packets being successfully received. The resultant latency was 0.005 s. Similar results were observed for the downhill approach, where 2,091 packets were sent, 99.86 percent received, and the associated latency was 0.002 s.

Implications

The first generation simulated DSRC system proved capable of achieving acceptable levels of performance. In general, the system allowed for the successful transmission of more than 95 percent of the packets broadcasted. This was observed across a range of speeds and distances and proved fairly independent of antenna approach direction. The system does exhibit, however, some dead-spot behavior that should be addressed in future prototypes. The applicability of this system to IDS depends on the final specifications of IDS systems. However, it is likely that DSRC technology will be sufficient to perform the IDS system communication function.

Near the end of the IDS project VTTI had the opportunity to acquire a set of the second generation DSRC radios. The same set of communications tests were conducted to see if the deficiencies identified above were addressed and to verify that no new limitations had inadvertently accompanied the updated system. These tests are discussed in the next section.

Second Generation DSRC Radios

The second generation radios operated using the 802.11a band (5.8 GHz) and were contained in a smaller, more elegant, and user friendly package. These radios are capable of achieving a 10 megabit-per-second data transmission rate. In bench-testing the second generation DSRC radios it was found that 100 percent of transmitted packets were successfully received. It was hypothesized that this was due to inherent error recovery within the radio hardware. This hypothesis was confirmed when it was discovered that the radios employed the Transmission Control Protocol/Internet Protocol (TCP/IP) instead of the User Datagram Protocol (UDP) employed in the first generation radios. TCP/IP contains error recovery algorithms, whereas UDP does not.

The bench test results were confirmed via dynamic test-track evaluation at up to 112.7 km/h (70 mph). A set of tests identical to those described for the fist generation system were replicated for the second generation system. No packets were lost during these tests, which marked a substantial improvement over the first generation system. Thus, the results of these tests are not discussed further in this report, as no data loss was observed across the range of conditions studied.

The main problem with a protocol that employs error recovery algorithms can be its increase in latency. That is, all of the data are transmitted appropriately, but new data may be backlogged while this correct transmission occurs. Given the use of TCP/IP (which includes error recovery algorithms) in the second generation radios, static latency tests were conducted to consider the extent of the latency problem; these results are reported below.

Methods

The latency test followed the protocol used in testing the first generation radios. Full 512-byte messages were sent with the vehicle located at 182.9 m (600 ft) from the stop bar in both uphill and downhill approaches. In each case, latency was measured and averaged over more than 1,800 packet transmissions.

Results

From the uphill approach, a total of 1,803 packets were sent, with a single packet lost within the 100ms pre-set maximum for message arrival (as determined by the 10 Hz data transmission rate). The average latency was 15.9 ms, with a maximum single-packet latency of 35.0 ms. Similar results were observed for the downhill approach. In this condition, 1,804 packets were sent, with no lost packets. The average latency was 15.8 ms, with a maximum single-packet latency of 27.0 ms.

Implications

The updates to these radios have fixed the problems observed during testing of the first generation radios, but at the expense of a slight increase in the latency of the message. The packet tests demonstrated a zero packet loss across approach speeds. Thus, the TCP/IP protocol and new hardware configuration provide an extremely reliable communications platform. The cost of this enhanced reliability is additional 10 ms latency over its predecessor. However, the overall lag is still relatively small, and should not prevent use of the technology to perform the IDS communications function. The DSRC system should be field tested at a variety of intersection sites to verify reliability in the presence of traffic and other line-of-site obstacles.

System Integration – Obtaining Signal State

The trade-off analysis indicated that standard controller technology should be tested for use in IDS, because it is the only Commercial Off-the-Shelf (COTS) technology to provide intersection state. Note that the system integration function goes beyond intersection state, including other hardware (i.e., algorithm computations). However, these supporting hardware were not tested as part of this project, as they employ commonly used and widely available computing technology. Instead, resources were directed toward a detailed evaluation of intersection controllers, since they represent a key element of the system integration function whose performance had not been tested in the IDS context.

For the purpose of these tests, VTTI obtained two signal controllers, each of which used a unique, independent communication protocol. The communication protocol is an essential element in these tests, as it represents the only way to directly query current state from the controller. Other approaches to obtaining signal phase and/or timing would bypass the controller. These approaches might be feasible in the future, but the focus of this effort was to test the feasibility of currently available technology that is already widely accepted by traffic engineers.

The two controllers obtained by VTTI were an Eagle 2070 using NTCIP for communications and a NEMA-type EPAC controller using ECOM for communications (ECOM is the name for the proprietary communications protocol developed by Eagle). These controllers are pictured in Figure 104.

Figure 104. Eagle ECOM (left) and 2070 (right) controllers.

Methods

The tests were conducted within the laboratory. Originally, more comprehensive test-track evaluations of these controllers were planned, but were not performed given the insufficient performance levels observed during bench testing. However, one should not infer that existing controller technology provides no functionality in this realm. Indeed, an Eagle 2070 controller was successfully used by the project team as the intersection state source for a number of technology demonstrations. The main difference between these demonstrations and the real-world is that an IDS system would be expected to have much higher performance requirements from an intersection state source than can be met by current signal controller technology.

The bench tests were conducted with controllers programmed on a single-ring configuration with an actuated recall to aid the experimenter in triggering signal changes when necessary. VTTI created custom software to assist the experimenter in determining any errors and information latencies, as well as to aid in the visualization of the intersection phase map (Figure 105). Controller performance, specifically its latency, was observed through a series of simulations.

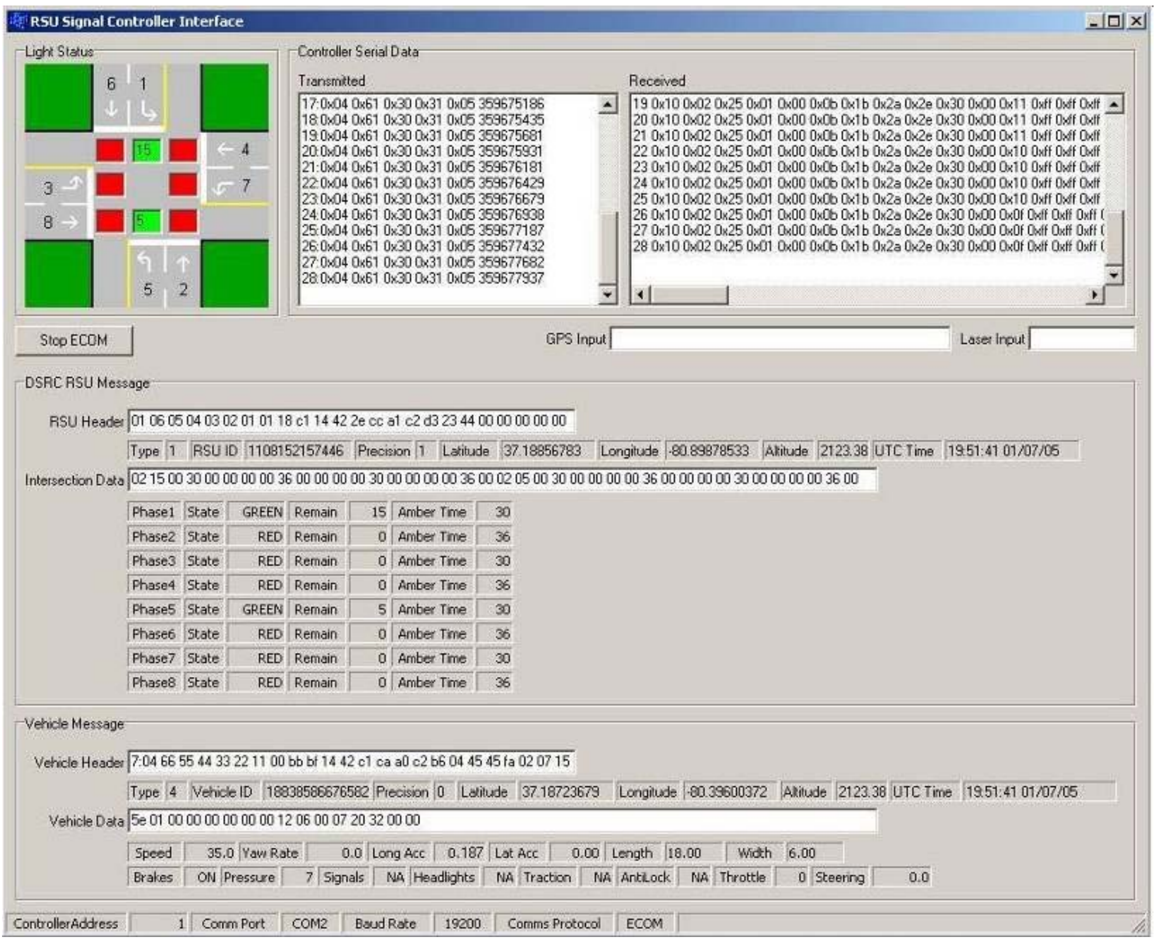

Figure 105. Custom software used in the controller tests.

Results

NTCIP, which has the advantage of being a widely accepted standard, showed latencies in the range of 0.8 s. This range is too large to support an IDS implementation. Furthermore, the protocol did not support the reporting of time left in phase.

The Eagle ECOM protocol exhibited lower latency (~0.1 s) than NTCIP. Furthermore, it included signal timing information in its response message, including time remaining in the phase, amber timings, and next phase indication. However, the remaining time in phase was reported only to a whole second.

Implications

None of the protocols tested are likely to be viable options for supporting an IDS implementation. NTCIP was not designed to support real-time polling, and consequently exhibited large latency levels. Furthermore, the protocol does not provide information that is likely to be essential for IDS applications (such as time left in phase). Another potential problem is that the repetitive polling that might be needed by an IDS system may interfere with existing traffic management programs, given the limited processing capabilities that are typically available in controllers using this protocol.

The ECOM protocol exhibited lower latencies than NTCIP and provided additional information in its message that may be required by an IDS system. However, the reporting precision was too low to allow the system to properly support the IDS function. However, it is possible that further development of this protocol would result in a viable intersection state provider technology. This, however, would not solve the problem of access to the protocol. Currently, the ECOM protocol is proprietary and not available for controllers that are not manufactured by Eagle.

Overall, these protocols and their associated controllers appear incapable of supporting IDS system in their current form. The trade-off analyses (see the Trade-Off Analyses section) indicated a number of alternative technologies, not currently available, which might properly support the IDS function. In particular VTTI envisions the use of a “phase sniffer” to support IDS functionality until an IDS enabled traffic controller is developed. The phase sniffer would monitor the inductance of the signal head power leads. This provides real-time status information on the signal state. The sniffer would then need to match this information with a signal program obtained either through the controller interface or through a learning algorithm. The sniffer could then provide both the current signal phase as well as the time left for a phase change (at a minimum the amber to red phase countdown, as other phase lengths would be more difficult to obtain for actuated signals). Future research should be directed toward the development and testing of sniffers and/or advanced traffic controllers. This research should be a priority since accurate signal phase and timing is paramount to overall system performance.

ALGORITHM DEVELOPMENT

Early in the design process, it became apparent that the warning algorithm of an IDS system must warn potential violators in enough time for the driver to choose and carry out a course of action. Thus, a system that can discriminate potential violators must take into account several dynamic factors, such as the actual time to relay the message to the target, driver recognition and response time, signal phase and timing, and the time necessary to stop once a decision is made. Reviews of the literature on past efforts of a similar nature allowed for the generation of a series of algorithms that considered these factors.

While the literature review provided estimates of driver kinematic behavior during intersection approaches, essential for algorithm development, it also highlighted the need for test-track studies that provided data to test the effectiveness of these algorithms and fill in knowledge gaps on driver behavior under certain conditions. These data were collected during the human factors tests discussed in the previous section. This section discusses how these data were used to determine and compare the effectiveness of the alternative algorithms.

Point Detection Algorithm

Overview

Recall that baseline data were collected during the initial human factors experiments to understand drivers' braking profiles. The initial approach undertaken for algorithm development was to use those data to identify specific points at which violating drivers could be differentiated from compliant drivers. Making an assessment at a specific point permits the use of readily available point detection sensors (i.e., loop-detectors). It was hypothesized that the range-rate distributions of compliant and violating drivers diverged at some point upstream of the intersection (Figure 106). It was hoped that this critical point of separation would occur sufficiently upstream to provide violating drivers time to respond to a warning without inappropriately warning compliant drivers.

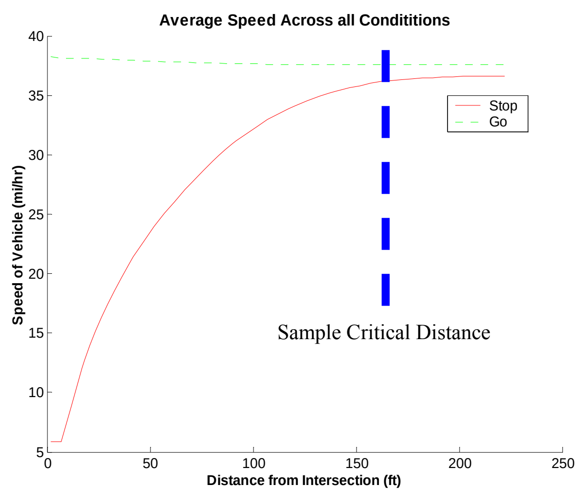

Figure 106. Range-rate distribution for violators and non-violators. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The problem of locating the critical point is much like a controls problem using signal detection theory. Depending on the location of the critical point, there will be a certain percentage of correctly identified violator (hits) and correctly identified compliant drivers (correct rejections). However, there will also be violators who were not warned (misses) and compliant drivers who were incorrectly warned (false alarms). This relationship is demonstrated by the normal curves for violator and compliant drivers (Figure 107).

A miss represents the condition in which a violating driver was not warned and inappropriately entered the intersection. It is assumed that if a violator who had received a warning could have modified his/her behavior and avoided the violation. Thus, an IDS system should minimize the number of misses, as they have a high probability of causing a conflict. Therefore, to control the number of allowable misses, alpha values of 0.2, 0.1, 0.05, and 0.01

were selected. The alpha value correlates to correctly identifying violators 80, 90, 95, and 99 percent of the time, respectively. While setting alpha controls the percentage of misses, the number of false alarms will vary as a function of the warning distance.

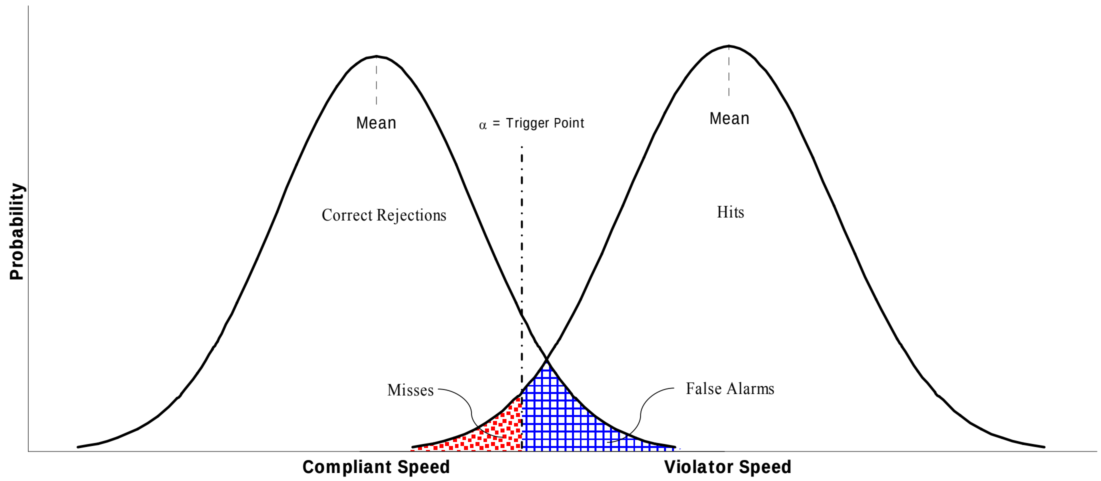

Figure 107. Probability distribution for rate of violator and compliant drivers at critical point.

If a critical warning distance is selected very close to the intersection, the two normal curves will not overlap, and there will be no false alarms or misses. However, the alarm would be too late for the driver to perceive, react, and stop. As distance from the intersection increases, the curves will move toward each other, and overlap will increase until the two are completely confounded. The percentage of false alarms will rise with increasing overlap. From signal detection theory, it is known that false alarms create problems such as decreased user confidence and annoyance. Consequently, there is a tradeoff between the number of false alarms and maximizing the distance to the critical point (e.g., false alarms increase with increasing warning distance). Determining the percentage of acceptable false alarms is not the goal of this section. Rather, the output of this analysis is a plot of false alarms versus distance for each of the alpha values. This analysis was completed for both 56.3 km/h (35 mph) and 72.4 km/h (45 mph) baseline datasets. For the interested reader, the details of the protocol and the full results used to determine the feasibility of a point detection algorithm are discussed in Appendix F.

Summary of Results for Point Detection

Across both speeds tested, several factors have been shown to negatively affect single point detection such that it does not appear feasible. An unacceptable number of misses or false alarms will occur when allowing for sufficient stopping distance. The excessive number of false alarms and misses cannot be compensated even if drivers are permitted to violate at the beginning of the signal phase change when the probability of a SCP crash is very low (i.e., a crash-level warning rather than violation-level warning).

There is a relationship between speed and warning location that cannot be accounted for with single-point detection. A speeding driver must be warned much earlier than a non-speeding driver. The range-rate profile of the non-speeding and speeding drivers deviate from compliant drivers at different distances and thus require different critical points. This indicates that point detection and the associated range-rate algorithm is not a viable option for IDS systems.

However, the results of the point detection analysis demonstrate that the critical point was not static. Instead, the point moved depending on a variety of factors such as travel speed and phase change distance. Furthermore, other variables such as acceleration that could augment the threat assessment cannot be measured at a single point. Thus, it was determined that vehicle information must be measured either at multiple points or continuously. As such, additional analyses for both detection frameworks were undertaken. The next section discusses the results of these analyses.

Continuous Detection

Overview

Continuous and multi-point detection permits the use of a variety of rather complex algorithms that consider an assortment of vehicle dynamic variables. Thus, several algorithms were developed and tested using the intersection approach data from the human factors baseline tests. The approaches from this data set were fed into algorithms either continuously or at certain discrete points. The performance of each algorithm was then assessed and compared based on the number of hits, misses, correct rejections, and false alarms. All of these four outcomes have important implications for defining algorithm performance:

- Hits – the algorithm correctly identified a violator (provided a warning)
- Correct Rejections – the algorithm correctly identified a non-violator (no warning)
- False Alarms – the algorithm classified a non-violator as a violator (provided a warning)
- Misses – the algorithms classified a violator as a non-violator (no warning)

In addition to these performance metrics, each of the algorithms was evaluated using two distinct levels of warnings. The first level (Level 1) consisted of a violation warning where the vehicle is warned if: (1) its range (R, in feet) is more than or equal to the remaining amber time (*Amber*, which is 0 if the light is red and infinite if the light is green) multiplied by the vehicle's velocity (V, in feet/sec) and (2) the vehicle's dynamic characteristics cross a pre-specified warning threshold.

The second level of warning (Level 2) consists of a crash warning. In this case, the vehicle is warned if it is forecast to be in a region of conflict with other traffic given its present range and range rate. Thus, Level 2 warnings would be presented less frequently than Level 1 warnings. For more information on the derivation of the Level 2 warning refer to Appendix G.

Seven different algorithm alternatives (Table 59) were considered in the search for an algorithm that closely modeled the data obtained in three separate experiments. The three experiments were:

- 56.3 km/h (35 mph) IDS: Previously discussed in this subtask. Included intersection approaches at 56.3 km/h with systematically varied phase-change distance and driver state (baseline, simulated distraction, and aggressive). Only trials from baseline drivers were considered for the calculation of false alarms, but trials from all drivers were considered for the calculation of misses.

- 72.4 km/h (45 mph) IDS: Previously discussed in this subtask. Included intersection approaches at 72.4 km/h with systematically varied phase change distance and driver state (baseline, simulated distraction, and aggressive). Only trials from baseline drivers were considered for the calculation of false alarms, but trials from all drivers were considered for the calculation of misses.
- ICAV (Lee et al, 2005): Included intersection approaches at 56.3 km/h and 72.4 km/h with systematically varied driver last-second braking behavior (normal or hard) and traffic device (signal or stop sign). Only trials from drivers using normal, last-second braking were considered for the calculation of false alarms, but trials from all drivers were considered for the calculation of misses.

Table 59. Algorithm alternatives considered.

Algorithm	Description
Case 1: Basic kinematics, no deceleration	Based on assumptions of constant deceleration and reaction time. Vehicle's range and range rate were the only inputs. Algorithm shut off if vehicle speed dropped below 24.1 km/h (15 mph).
Case 2: Basic kinematics, deceleration	Based on assumptions of constant deceleration, reaction time, and deceleration level that represented braking. Vehicle's range, range rate, and longitudinal acceleration were the only inputs. Algorithm shut off if vehicle speed dropped below 24.1 km/h (15 mph) or if the deceleration level that represented braking was exceeded.
Case 3: Parameterized kinematics, deceleration	Based on assumptions of constant reaction time, a coefficient and exponent that modify the contribution of vehicle speed to determination of the threshold, and deceleration level that represented braking. Vehicle's range, range rate, and longitudinal acceleration were the only inputs. Algorithm shut off if vehicle speed dropped below 24.1 km/h (15 mph) or if the deceleration level that represented braking was exceeded.
Case 4: TTI	Based on assumptions of constant time-to-intersection (TTI) and deceleration level that represented braking. Vehicle's range, range rate, and longitudinal acceleration were the only inputs. Algorithm shut off if vehicle speed dropped below 24.1 km/h (15 mph) or if the deceleration level that represented braking was exceeded.
Case 5: Dual threshold	Based on assumptions of constant deceleration, reaction time, and deceleration level that represented braking. Vehicle's range, range rate, and longitudinal acceleration were the only inputs. Algorithm shut off if vehicle speed dropped below 24.1 km/h (15 mph). The algorithm also shut down if the deceleration level that represented braking was exceeded **and** the vehicle's range vs. range rate profile did not exceed a secondary, more aggressive, threshold.
Case 6: CAMP Inverse TTI	Based on the Collision Avoidance Metrics Partnership (CAMP) inverse time-to-collision approach. Vehicle's range, range rate, and longitudinal acceleration were the only inputs. Algorithm shut off if vehicle speed dropped below 24.1 km/h (15 mph) or if the deceleration level that represented braking was exceeded.
Case 7: Point detection of acceleration	Based on point detection, assuming various individual detector distances from the intersection and minimum deceleration thresholds. Vehicle's range and acceleration at a single point in the approach were the only inputs. Algorithm shut off if vehicle speed dropped below 24.1 km/h (15 mph). Note that this was done for computational efficiency, since the constraint would not be applicable in real life.

Each individual approach recorded in the above experiments was passed to each of the algorithms in a pseudo-real time simulation. The frequency of hits, misses, false alarms, and correct rejections were then counted and used to determine the level of performance. For the interested reader, the details of the protocol to determine the feasibility of a continuous detection algorithm are discussed in Appendix G.

Summary of Results for Continuous Detection

Table 60 summarizes the results in terms of the optimum alternative found for each algorithm approach. A description of special cases (e.g., alternative minimums, minimization of a single criterion) is included. Note the Level 1 and Level 2 optimums for a given algorithm do not necessarily occur with the same parameters. Also, while the parameter combinations displayed optimize false alarm and miss rates for each algorithm model, the resulting warning thresholds may not be inherently ideal. For this reason, the parameter combinations used in this section should be considered as starting points for human factors experiments testing their efficacy. The results of such experiments, as applied to the evolution of these algorithms, are discussed in later sections of this report.

Observation of the table leads to some conclusions regarding the usefulness and applicability of the various algorithm options. It is easy to eliminate the single-point detection option discussed at the opening of this section; even when misses and false alarms are balanced, the number of each is too large for the algorithm to be effective. The basic kinematics (without deceleration) algorithm and the TTI algorithm can be eliminated based on their high rate of false alarms when compared with other options. This leaves the remaining five algorithms for consideration: Basic kinematics (with deceleration), Parameterized kinematics, Dual threshold; CAMP Inverse TTI; and Point Detection of Acceleration.

The next section of the document addresses the use of multi-point detection in an IDS system. Multi-point detection systems use several single-point detectors at specified locations. It is a compromise between the insufficient single-point detection scheme and the potentially costly continuous detection scheme. The usefulness of the technique is explored by determining areas of the intersection where sensor location becomes very important in providing a timely and accurate warning.

Table 60. Algorithm alternatives considered.

Algorithm	'Optimum' – Level 1	'Optimum' – Level 2	Special Considerations
Case 1: Basic kinematics, no deceleration	29.49% FA, 4.76% M, 0.86 g max observed deceleration (0.5 sec RT, 0.5 g constant deceleration)	4.11% FA, 16.67% M, 0.83 g max observed deceleration (0.5 sec RT, 0.75 g constant deceleration)	Misses remain constant across parameter changes
Case 2: Basic kinematics, deceleration	0% FA, 14.29% M, 0.75 g max observed deceleration (0.6 sec RT, 0.55 g constant deceleration)	0% FA, 16.67% M, 0.59 g max observed deceleration (0.6 sec RT, 0.55 g constant deceleration)	Alternative parameter combinations available with slightly increased percentage of misses and/or max observed deceleration
Case 3: Parameterized kinematics, deceleration	1.84% FA, 14.29% M, 0.79 g max observed deceleration (0.21 coefficient, 1.45 exponent)	1.83% FA, 16.67% M, 0.76 g max observed deceleration (0.21 coefficient, 1.45 exponent)	
Case 4: TTI	20.51% FA, 20.63% M, 0.88 g max observed deceleration (+1.4 Adjustment)	4.57% FA, 16.67% M, 0.37 g max observed deceleration (+2.0 Adjustment)	Using the +1.4 Adjustment would result in 11.19% FA for level 2
Case 5: Dual threshold	0.92% FA, 7.94% M, 0.80 g max observed, deceleration (1.5 sec RT, 0.75 g max constant deceleration)	0% FA, 16.67% M, 0.79 g max observed deceleration (1.4 sec RT, 0.75 g constant deceleration)	Level 2 FA rise to 0.23 % if the level 1 optimum is used.
Case 6: CAMP Inverse TTI	1.84% FA, 14.29% M, 0.64 g max observed deceleration (x=0.95, 0.5 sec RT)	1.83% FA, 16.67% M, 0.62 g max observed deceleration (x=0.95, 0.5 sec RT)	
Case 7: Point detection of acceleration	6.68% FA, 17.46% M, 0.55 g max observed deceleration (75% of distance, -0.07 acceleration threshold)	2.05% FA, 16.67% M, 0.47 g max observed deceleration (75% of distance, -0.05 acceleration threshold)	Level 2 FA rise to 5.94% if the level 1 optimum is used. These optimums minimize M, as minimal FA required M=100%. The results show what was believed to be the most reasonable compromise.

Multi-Point Detection

Overview

Multipoint detection is essentially low resolution continuous detection system over a limited range of the intersection approach. In an actual IDS system multi-point detection is a series of point-sensors located at discrete distances within the warning range (i.e., five sensors spaced 5 m apart between 30 to 55 m from the intersection). To determine the location and performance of a multi-point detection system, the previous "best" algorithms were tested again at specific points representing the sensor locations. The sensor locations were determined by inspection of the area in which the warning would go off with continuous detection. Virtual sensors were then placed within this region and evaluated across five of the spacing schemes. Finally, the data from the studies described in the continuous detection section were fed into the point sensors and then provided to the algorithm. This determined the optimal sensor spacing and permitted a comparison of multipoint to continuous detection. For the interested reader, the details of the protocol to determine the feasibility of a multi-point detection algorithm are discussed in Appendix H.

Summary of Results for Multipoint Detection

The performance of multi-point detection algorithms was often comparable to that of continuous detection algorithms. However, there were also instances in which multi-point detection performance suffered due to an insufficient number of available detectors or inter-detector spacing that was too large. The main conclusion is that continuous detection should be used whenever feasible. However, when continuous detection is not possible, multi-point detection might be considered an option to provide the vehicle kinematics data to a threat assessment algorithm. In any case, further research is needed for a much larger number of intersection approaches representing a more diverse set of environmental and roadway conditions. This will aid in determining whether multi-point detection can address special cases (e.g., speeding) that were not available in the dataset used and which would be addressed by a continuous detection scheme.

Algorithm Development Findings

In general, the results of this algorithm comparison process indicate that single-point detection is not a feasible detection alternative for IDS. Continuous detection and/or a number of carefully located point detectors are feasible alternatives worthy of further testing. There are a number of violation detection algorithms that appear to perform at similar levels, and these are all worthy of further consideration.

Considering the near equal performance of five algorithm alternatives, the question becomes how to subject these algorithms to further testing to determine the final algorithm. A logical step is to test the algorithms using more data to increase the sample size and to provide a larger range of possible approaches (e.g., phase-change distances, speeds, weather). These data should be naturalistic in nature, representative of the real-world where drivers in a variety of environmental conditions. This baseline data collection process would place data collection equipment at intersections to reliably detect violations, near-violations, and legal crossings. At the same time, the process would allow for complete characterization of the intersection environment (e.g., traffic, signal phase and timing). The different algorithms would then be overlaid on these data and adjusted so that they perform the best job possible in differentiating violators from compliant drivers.

The results of the human factors tests, however, must also be considered in this process. During algorithm development we must not only differentiate between violators and compliant drivers, but also be able to warn the violating driver early enough in their approach to permit a safe and controlled stop. This information would not be available from further baseline data analysis (as described in this section) because baseline drivers who violate did not receive any warnings. Obtaining this information would only be possible through human factors tests that determine the too-late point as a function of the DII in use.

Obtaining this information from a small set of DIIs was the focus of a subset of the human factors tests discussed in the previous section. However, none of the DIIs were particularly effective in alerting the driver prior to the point where triggering the warning would results in a large number of false alarms. Furthermore, at distances when some DIIs did perform adequately, the algorithms had a difficult time discriminating violator from compliant drivers. As indicated in the surface plot figures shown earlier, even the best algorithms produce over 30 percent false alarm rates at the 53 m optimized stop sign plus strobe DII

The main conclusion from these findings is that, although the capability to detect a violator fairly reliably is available (as shown in this section), there are currently no DIIs capable of coercing stopping behavior from that driver after that determination has been reliably made. Thus, if further research is desired, the baseline data collection should be accompanied by further driver interface development efforts that would ultimately result in a warning that is effective in coercing drivers to stop without resulting in a large percentage of nuisance alarms. However, the reader is cautioned that a substantial improvement is required indicating large improvements in the DII are needed.

CONCLUSIONS

The previous sections present the different efforts undertaken as part of the IDS project, which were meant to explore a number of issues related to the design and development of IDS systems to address the SCP intersection crash problem. The tasks were performed using a top-down approach, where system functions were first identified. Increasingly specific tests and experiments were then conducted to determine the feasibility of IDS from both a technological and a human factors perspective. The details of these tests and some of their implications have been discussed in previous sections, but it is also necessary to analyze these results based on their importance at a system level.

The first major effort for this project was the analysis of existing literature on past research related to the IDS function. Highlights of this review include:

- Intersection crashes represent a large proportion of the total number of crashes in the United States, including fatal crashes.
- A large proportion of these intersection crashes occur in SCP configurations, mainly due to signal and stop-sign violations.
- The intersection approach requires a series of driver behaviors of varying complexity, the sequence and timing of which might be affected by factors such as driver distraction.
- Breakdowns in these behaviors lead to violations and, consequently, SCP crashes. IDS countermeasures need to address and correct these breakdowns early enough in the intersection approach to provide the driver with sufficient time to react appropriately

The literature review process was followed by a systematic evaluation of the IDS functions and the technologies to perform these functions. Some of these technologies were tested, characterized, and/or used within an instrumented test track to determine the feasibility of employing them within IDS systems, either fully infrastructure-based or in an infrastructure cooperative fashion. When necessary, distinctions are made between signalized and stop-controlled intersections. The following subsections highlight the findings from the systematic evaluation for each function.

Vehicle Sensing

The trade-off study indicates radar as the infrastructure-based sensing technology with highest potential for IDS applications. The test-track evaluations of this technology show that it is feasible to use the technology, but several caveats exist. First, the usefulness will depend on the system specifications. While radar is not as accurate as in-vehicle sensing technologies (e.g., DGPS), its accuracy might still be sufficient. Second, the most promising radar technology tested will need to undergo further development before it is ready for deployment. This includes enhancements such as real-time processing, weatherproof enclosures, and a tracking algorithm. Third, the radar performance needs to be validated in real-world conditions. While tests on the Smart Road simulated some of the traffic patterns that can be problematic in the real-world, the Smart Road still represents a highly controlled environment. It is possible that radar performance could be substantially degraded under the variable conditions that occur in the real-world, especially in cluttered and traffic-dense urban environments. Thus, feasible radar technology needs to be developed further, perhaps with the intersection application as a design goal.

Additional work in radar testing by other organizations (e.g. from the University of Minnesota) suggests that arrays of radars may be built that could result in substantial improvements in detection performance over a single radar, assuming sufficient data processing power is available to combine the different radar tracks in real time. Nonetheless, it should be noted that thus far these efforts chain and fuse the data from multiple radars together for research purposes only. From a state DOT perspective, widespread implementation of such a solution in the deployment of IDS systems is very unlikely given complex installation and maintenance issues. It is also possible that radar technology could be augmented via other sensing technologies, although this possibility was not tested. However, it is clear that further development is needed in vehicle sensing to achieve FOT-readiness of this function.

System Integration – Intersection State

While the trade-off study indicated a number of technologies that could feasibly perform the intersection state function, only standard signal controllers were currently available and were thus tested. Test results show that standard signal controller technology will likely be insufficient for support of the IDS function. In the near term, the only other technology that could acceptably perform this function would be a phase sniffer. The development of this device is quite feasible; in fact, a prototype version was developed at VTTI towards the end of the project. Since the device is a prototype at this point in time, its performance was not formally tested; however, as a prototype, it can be reconfigured to comply with any foreseeable requirements from future IDS systems.

The use of a phase sniffer will likely have to be combined with periodic readings of the intersection timing program, since by itself, the sniffer does not receive information on the remaining length of a phase. With an intersection timing program, a sniffer device can be designed to countdown times parallel to the controller and thus provide the warning algorithm with a complete set of intersection state information at the required update rate. Alternatively, a basic sniffer device may be programmed to learn the yellow phase duration for the different traffic control rings upon startup and periodically check for changes. These two approaches are interchangeable as it pertains to the application tested in this investigation.

For a near-term FOT, this device would have to undergo further development and testing. For longer term IDS deployment, it is possible that advanced traffic controllers will support the IDS function, thus restricting the need for sniffer technology to intersections with legacy traffic control devices.

Communications

During the project, two generations of DSRC prototype technology were tested. The second generation proved to be more robust than the first generation, and, although higher latencies were detected for the second generation system, these were not large enough to affect the feasibility of the technology for an IDS system. Thus, the second generation system appears to be sufficient for an IDS application.

There are, however, several communications issues that need to be addressed prior to an FOT or deployment. First, the message set needs to be standardized to ensure cross-platform operation. Second, security overhead must be developed and allocated. Given the safety implications, it is important that the communications content not be accessed by any outside party (i.e., hackers). Third, the system has to be tested in a real-world environment, where outside factors may affect signal strength and reception and where the presence of a multitude of these radios may cause interference issues. The Vehicle Safety Communication (VSC) group at CAMP has performed some of this research, but further testing should be performed strictly on the intersection application to avoid any unintended effects that may hinder FOT or future deployment of IDS.

Algorithm and DII

The technology development and evaluation process was supplemented by human factors tests which determined DII and algorithm performance. Unfortunately, inadequate levels of performance were observed across the warning interfaces tested as part of the human factors research efforts. Thus, providing an effective infrastructure-based warning appears infeasible at this point. Further efforts could be directed toward alternative technologies that were not tested given their low implementation potential if deemed important by state DOTs. At this point, in-vehicle warnings appear to represent the best warning interface option.

The human factors tests aided in the development of algorithm alternatives to control the triggering process for warnings. Some of these algorithms registered relatively low levels of nuisance and missed alarms, which are important considerations. However, further development is needed before they can be employed in an FOT, specifically in two main areas. First, it is important to better define the "too-early" boundaries, since they are essential in the prediction of the number of nuisance alarms that will be presented. While estimates of these boundaries were obtained during the initial set of too-early tests, these tests were run within a controlled road environment. To obtain too-early curves that are truly representative of the driving population, it is necessary to unobtrusively collect baseline data at live intersections. In addition to allowing for the generation of these too-early curves, the baseline data collection process would also serve to indicate special conditions and exceptions that should be considered in an algorithm and to "bench-test" potential algorithm timing curves by overlaying them on these data.

This last point leads to the second algorithm development area, which is the development of those timing curves. As has been stressed in past sections of this report, the optimal timing for a warning, or the point where the largest number of drivers is addressed while creating the minimum number of nuisance alarms possible, is a function of the interface used. Thus, the development in this area entails determining, as a function of warning interface, the optimal algorithm. Baseline data are useful in one aspect of this task: determining the number of nuisance alarms. However, nuisance alarms represent only half of the problem, since late alarms must also be avoided. Thus, determining the late alarms will also have to be an integral part of the development of the timing curves. Additional experiments on the Smart Road and in the real-world, in which drivers are exposed to the warning under surprise conditions, will be necessary in addressing the late alarm issue.

These two algorithm development areas, that is, the definition of the "too-early" boundaries and the development of timing curves, need to consider the limitations of various sensing instrument arrangements that may be incorporated into the infrastructure. Infrastructure-based vehicle sensing devices can be configured as either single-point (vehicle speed and position at one static location during the approach), multi-point (vehicle speed and position at several static locations during the approach), and continuous (vehicle speed and position updates available throughout the approach, limited only by the sampling rate used). The results of simulations performed during the algorithm comparison process indicate that single-point detection is not a feasible detection alternative for IDS. Continuous detection and/or multi-point detection are feasible alternatives worthy of further testing.

Implications for System Design and Development

The research effort and findings summarized above represent a large wealth of knowledge that can be applied to the development of performance specifications for cooperative IDS. Originally, the goal of the project was to develop performance specifications that applied to Infrastructure-Only systems and to Infrastructure-Cooperative systems. Obtaining performance specifications for the infrastructure-only case was not possible due to the ineffectiveness of the DIIs tested in eliciting driver compliance with the warning. The overall performance of any IDS system will depend on the human response to it. If the warning interface used to communicate with the driver is ineffective, then so is the system, regardless of the degree of technological accuracy and reliability that is built in. The human factors tests indicated that there was no infrastructure-based interface among those tested that elicited the intended stopping behavior in a reliable and timely fashion. This in turn hinders the development of performance specifications for the infrastructure-only case, as these are directly related to the type of warning, and more specifically, to the timing at which this warning is presented. Since no acceptable timing (a timing that elicited a stopping behavior on drivers while avoiding a large number of nuisance alarms) could be found, the development of performance specifications was not possible for Infrastructure-Only systems.

However, specification for an infrastructure-cooperative system for which an in-vehicle warning is provided was possible, in cooperation with the ICAV project (Lee et al., 2005). These specifications include the vehicle positioning, algorithm, and intersection state functions, which could be performed solely by the infrastructure; the communications function, which establishes a link between the vehicle and the infrastructure, and the DVI. Tables 61 through 64 present these performance specifications assuming a combined visual and auditory DVI. These specifications were meant to be technology independent, implying that any technology, infrastructure or in-vehicle, which meets the requirements is a candidate technology for inclusion in a prototype system. For a detailed derivation of the specifications the reader is referred to the ICAV final report (Lee et al., 2005). Note that these specifications pertain to an auditory "STOP" plus visual stop sign in-vehicle warning. The specifications assume that drivers violating the intersection within the first second of the red phase would not receive a warning (referred to in the table headings as a '1.0 s too-early time shift').

Table 61. Minimum communication specifications for the "STOP" plus stop-sign warning assuming a 1.0 s too-early time shift.

Specification Type	Minimum Requirement
Minimum Communication Range	Speed Dependent: $Range_{\min} = \frac{V_0^2}{2 \cdot g \cdot RDP}$ i.e., 147 m (424 ft) @ 25 m/s (55 mph) where: *V* is typical intersection approach velocity, and *RDP* is required deceleration parameter, an assumed deceleration rate representing the behavior of an average attentive driver performing a very gradual stop to the intersection stop bar. Assumed to be 0.215 g in the example, based on ICAV research
Update Rate and packet reliability	4Hz with zero dropped packets, 7 Hz with one dropped packet, or 10 Hz with two dropped packets
Data latency	0.05 s assuming a 10 Hz update rate. At most, half of the period for the update rate that is selected. Latencies higher than the requirement would prevent accurate data synchronization.
Packet Size	256 bytes. Initial testing at VTTI showed major performance degradation when packet size increased from 256 to 512 bytes; therefore, VTTI currently recommends a packet structure of up to 256 bytes.
Content of data stream	Will include, at a minimum, signal phase and timing and stop bar locations. The content may include but is not limited to: traffic signal phase/timing, intersection geometry, security information, weather/road surface conditions, adjacent traffic kinematics, and GPS correction information. The content of the data stream will not be determined by tests but by the needs of the final threat assessment algorithm.
Security	While developing security requirements is outside the scope of this project, the communications subsystem needs to be 'hack proof' to maintain a high level of public safety and public trust in the technology.

*Note: All requirements are assuming an otherwise perfectly performing system.

Table 62. Vehicle speed sensing requirements for the "STOP" auditory plus stop-sign visual warning assuming a 1.0 s too-early time shift.

Specification Type		Minimum Requirement
Speed	Maximum Speed	112.7 km/h (70 mph) This has been the assumed upper limit for all tests and is considered a maximum limit speed for intersection approaches
	Minimum Speed	24.1 km/h (15 mph) To prevent false alarms in slow-moving traffic, this has been the assumed lower limit for all tests and is considered a minimum limit speed for intersection approaches.
	Accuracy	± 4% of the speed traveled. This equates to ±1.6 km/h (±1 mph) in the worst case speed of 40.2 km/h (25 mph) Derived from the detuning tests assuming the worst-case 25 mph condition
	Update Rate	Minimum of 3 Hz This requirement is based on the inverse of the time required for the vehicle to accelerate or decelerate beyond the allowable speed error magnitude defined above. The smallest accuracy occurred for the 40.3 km/h (25 mph) speed. If a 0.1 g acceleration input is assumed, then 0.45 s are required to reduce vehicle speed by the 1.6 km/h (1 mph) specified by the speed accuracy requirement. These 0.45 s represent a minimum update rate of 2.2 Hz, which is rounded up to 3 Hz.
	Data latency	At most, half of the period for the update rate that is selected. This equates to 0.17 s at an assumed update rate of 3Hz. Latencies higher than the requirement would prevent accurate data synchronization.

*Note: All requirements are assuming an otherwise perfectly performing system.

Table 63. Vehicle position sensing requirements for the "STOP" auditory plus stop-sign visual warning assuming a 1.0 s too-early time shift.

Specification Type		Minimum Requirement
Vehicle Position	Longitudinal Accuracy	Less than ±1.31 m (4.30 ft)
	Lateral Accuracy	Less than 5 m (16.4 ft) if lane-level accuracy is not needed. If lane-level accuracy is required, then tests conducted to date indicate that 1.75 m (5.75 ft) accuracy is needed for a 3.7 m (12 ft) lane. Thus, the required accuracy is also approximately half the width of the lane.
	Update Rate	At least 9 Hz The distance traveled during an update cycle must not exceed the required longitudinal accuracy specified above. Considering this limitation the specified update rate to maintain a 1.31 m positional accuracy is 9 Hz.
	Data Latency	At most, half of the period for the update rate that is selected. For a 9 Hz system this equates to 0.06 s Latencies higher than the requirement would prevent accurate data synchronization.

*Note: All requirements are assuming an otherwise perfectly performing system.

Table 64. ICAV computations specifications for the "STOP" auditory plus stop-sign visual warning assuming a 1.0 s too-early time shift.

Specification Type	Minimum Requirement
Update Rate	10 Hz Specification is set to the maximum update rate suggested in the requirements for its input subsystems, in this case the update rate necessary for accurate positioning as described above.
Latency	0.05 s At most, half of the period for the update rate that is selected. Latencies higher than the requirement would prevent accurate data synchronization.
Warning Onset Timing Equation	WDP = 0.28 g Determined as the mid-point of the interval defined by the empirically-obtained warning threshold and the nuisance alarm limit. WDP stands for Warning Deceleration Parameter and is an acceleration-based representation of the nominal timing at which the warning should be provided.
False Alarm Rate	2%
Miss Rate	Zero

RECOMMENDATIONS

Several recommendations are possible based on the results documented in this report:

1. *If it is determined that an infrastructure-based vehicle sensing method is preferable for a cooperative IDS, further development of cooperative vehicle sensing technology is needed.* There are currently no commercial-off-the-shelf components that comply with the minimum performance specifications that are within a reasonable cost. Federal coordination with vendors of vehicle sensing technologies is necessary for this development.

2. *There are currently no commercial-off-the-shelf components that provide timely intersection state function information. Federal coordination with vendors of signal controllers is necessary for the development of this system component.*

3. *Baseline intersection approach data need to be collected to assist in algorithm development and to further understand intersection approach behavior in naturalistic settings and in conditions and environments that cannot be readily simulated on a test track.* This effort could be supported through a combined federal, state, and industry effort; however, state involvement would be mandatory since equipping live intersections is necessary.

4. *A coordinated effort should be directed toward interacting and encouraging the standards development process so that cooperative IDS technologies are included in future standards.* This effort would most efficiently be supported through a combined federal, state, and industry effort.

5. *Once prototype cooperative IDS systems are available, they should be evaluated in a FOT so that their effectiveness can be estimated and any unintended consequences identified and addressed*. This effort would most efficiently be supported through a combined federal, state, and industry effort.

6. *Given the results of this project, work on an infrastructure-only violation warning system should be suspended until suitable DII alternatives become available.* Most of the findings indicate that an infrastructure-only violation warning system will only address a marginal portion of the target crash population. At present, efforts should be concentrated on developing a cooperative system that has demonstrated considerable potential. If a suitable DII technology is developed, the results of the cooperative work will be directly applicable to an infrastructure-only violation warning system. For instance, the live intersection data collection experiment is not dependent on the interface location. The results of these and other projects could highlight new algorithm and interface alternatives, which may make an infrastructure-only violation warning system a viable option.

BENEFITS AND COSTS ASSESSMENT

Given that the infrastructure-only systems tested as part of this investigation do not appear to be feasible due to DII ineffectiveness, this section refers to an infrastructure-cooperative system. From the perspective of a department of transportation, the main cost of this system lies with the instrumentation and maintenance of additional equipment at the intersection. This additional equipment will likely include a number of vehicle sensing technologies, communications equipment, and equipment to interface with the signal controller to obtain signal state. The equipment costs should be small relative to the total cost of an intersection, on the order of less than 10 percent of the overall cost. Maintenance costs should also be relatively small but will undoubtedly add to their current level, as additional equipment is added to the intersection.

The primary purpose of an IDS system is to mitigate crashes, thus reducing the societal cost resulting from injury, fatality, and property damage conflicts. Consequently, an appropriate measure of effectiveness for IDS is the reduction of crashes and their associated cost implications. Note that these costs do not include expenses associated with instrumenting vehicles and/or intersections. These implementation costs are not precisely defined at this point given that these IDS systems are still at their initial developmental stages. A formal benefits and costs assessment would need to consider these implementation costs, and thus, by only considering societal cost, this benefit analysis is preliminary in nature and will likely require further refinement. The ICAV report by Lee et al. (2005) identified the addressable crash population and determined a cost per crash figure. The authors determined benefit from the monetary gain to society resulting from a reduction in crashes based on information from the General Estimates System analyzed by Blincoe et al. (2002). Calculations were based on costs associated with medical expenses, emergency services, market productivity, household productivity, insurance administration, workplace cost, legal costs, travel delay, and property damage; however, they did not include pain and suffering or other intangible costs. Therefore, the results will provide information on only economic feasibility and do not consider the individual value of saving a life.

Lee et al. (2005) calculated the costs resulting from both injuries and property damage. The analysis showed costs of $47,024,403,000 for the 1,667,000 Crossing-Path (CP) crashes identified for the year 2000. 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-crash cost 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 related crashes. Table 5 shows costs for the 1,667,000 CP crash types with a further breakdown of SCP (property damage only, injury (including fatal injuries), and unknown injury crashes are combined for this list since the per-crash cost is a combined figure).

It is expected that the system would primarily address drivers who violate due to distraction. For the 126,000 cited SCP crashes due to distraction, the potential benefit in 2000 dollars would be approximately $3.5 billion per year. If the higher target number of 242,000 cited SCP crashes (without regard to distraction) is used, the potential benefit rises to approximately $6.8 billion per year. The SCP crash problem is thus significant, and countermeasures designed to prevent intersection violations have the potential to save lives, health, property, and other resources in a meaningful way.

Table 65. Estimated target crash benefit (based on 2000 GES figures).

Characteristic	Crashes/Year	Benefit/Year
Total	6,389,000	$180,227,301,000
Crossing Path (CP)	1,667,000	$47,024,403,000
Straight Crossing Path (SCP)	542,000	$15,289,278,000
SCP Signalized	190,000	$5,359,710,000
SCP Signalized Cited	86,000	$2,425,974,000
SCP Signalized/Cited/Distraction	45,000	$1,269,405,000
SCP Stop Sign	347,000	$9,788,523,000
SCP Stop Sign Cited (est.)	156,000	$4,400,604,000
SCP Stop Sign/Cited/Dist. (est.)	81,000	$2,284,929,000
All SCP Cited	242,000	$6,826,578,000
All SCP with Distraction Cited	126,000	$3,554,334,000

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APPENDICES

Appendix A. Sensing Trade-Off Study Results

Infrastructure-based

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
Radar: Doppler	Uses radar reflections from the target vehicle to measure speed directly.	• Long range • Can track multiple vehicles	• It cannot measure position or acceleration directly. • Can be susceptible to inclement weather conditions. • The presence of stationary vehicles cannot be detected. • Large targets can be "preferred" over smaller, closer vehicles • Sensitive to periodic calibration and alignment.	**Speed** • Maximum Detection Range - < 304.8 m (1000 ft) • Maximum Speed – 134.1 m/s (300 mph) • Minimum Speed – 0.4 m/s (1 mph) • Accuracy - <2 percent of nominal speed • Update Rate – <10 Hz • Data latency - <0.05 s	Not suitable considering that frequency-modulated technology does give position information.
Radar: Frequency Modulated	Uses radar return from the vehicle of interest to detect vehicle position and speed.	• Reliably detects slow and standing objects/vehicles. • Long range • Can track multiple vehicles	• Closely spaced cars may not be discriminated. • Large targets can be "preferred" over smaller, closer vehicles. • This device cannot measure acceleration directly. • Sensitive to periodic calibration and alignment.	**Position** • Maximum Detection Range - < 152.4 m (500 ft) • Longitudinal Accuracy – < 1.0 m (3.28 ft) • Update Rate – <10 Hz • Data latency - <0.05 s • Lateral Accuracy - < 1 m (3.28 ft) **Speed** • Maximum Detection Range - < 152.4 m (500 ft) • Maximum Speed - < 44.7 m/s (100 mph) • Minimum Speed – < 0.3	Complies with both speed and position requirements. Considered a potential IDS technology.

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
				m/s (0.6 mph) • Accuracy - < 0.1 m/s (0.3 mph) (<1.2 percent of nominal speed @ 11.2 m/s (25 mph)) • Update Rate – <10 Hz • Data latency - <0.05 s	
Acoustic: Ultrasonic	Emits pulses of ultrasonic sound energy and measures the time for the signal to return to the device. The energy is reflected from a passing vehicle back to the device and can be used to measure vehicle position and speed.	• Reliably detects slow and standing objects/vehicles.	• Low range (≤ 12.2 m (40 ft) • Substantial signal degradation in sub-optimum environment conditions • The speed accuracy is too low to comply with the requirement • No tracking function is possible with a single device. • Cannot measure acceleration directly.	**Position** • Maximum Detection Range - < 12.2 m (40 ft) • Longitudinal Accuracy – < 1.8 m (6 ft) • Update Rate – <10 Hz • Data latency - <0.05 s • Lateral Accuracy - < 1.8 m (6 ft) **Speed** • Maximum Detection Range - < 12.2 m (40 ft) • Maximum Speed - < 33.5 m/s (75 mph) • Minimum Speed – < 1.1 m/s (2.5 mph) • Accuracy - <10 percent of nominal speed • Update Rate – <10 Hz • Data latency - <0.05 s	Gives position to the required level, but does not comply with the speed requirements.
Acoustic: Passive	Utilizes an array of microphones aimed at the traffic stream and collects information based on the noise made by the vehicles passing over the	• It can reliably detect slow and standing objects/vehicles.	• No tracking function is possible with a single device. • Cannot measure acceleration directly. • Low range (≤ 9.1 m (30 ft)	**Position** • Maximum Detection Range - < 9.1 m (30 ft) • Longitudinal Accuracy – < 1.8 m (6 ft) • Update Rate – <10 Hz • Data latency – <0.05 s	Gives position to the required level, but does not comply with the speed requirements.

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
	sensor range		• Substantial signal degradation without optimum environmental conditions	• Lat Accuracy – <1.8 m (6 ft) **Speed** • Maximum Detection Range - < 9.1 m (30 ft) • Maximum Speed - < 33.5 m/s (75 mph) • Minimum Speed – 0 m/s • Accuracy - <16 percent of nominal speed • Update Rate – <10 Hz • Data latency - <0.05 s	
Infrared: Active	Detect the presence of vehicles by emitting laser beam(s) at the road surface and measuring the time for the reflected signal to return to the sensor.	• Reliably detects slow and standing objects/vehicles.	• Precipitation, fog, and shadowing reduce signal return, lowering range and accuracy. • Direct sunlight interferes with detection. • Large targets can be "preferred" over smaller, closer vehicles. • Acceleration is not measured • No tracking function is possible with a single device.	**Position** • Maximum Detection Range - < 7.62 m (25 ft) • Longitudinal Accuracy – < 1.2 m (4 ft) • Update Rate – <10 Hz • Data latency - <0.05 s • Lateral Accuracy - < 1.2 m (4 ft) **Speed** • Maximum Detection Range - < 7.62 m (25 ft) • Maximum Speed - < 55.9 m/s (125 mph) • Minimum Speed – 0 m/s (0 mph) • Accuracy - <10 percent of nominal speed • Update Rate – <10 Hz • Data latency - <0.05 s	Gives position to the required level, but does not comply with the speed requirements.
Infrared: Passive	Detects the presence of vehicles by measuring the		• No tracking function is possible with a single	**Position** • Maximum Detection	Gives position to the required level, but does

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
	infrared energy radiating from the detection zone. A vehicle will always have a temperature contrast to the background environment. The infrared energy naturally emanating from the road surface is compared to the energy radiating when a vehicle is present.		device. • Acceleration data are not measured directly. • Precipitation and high temperatures significantly lower the accuracy. • Low range, 19.8 m (65 ft)	Range - < 19.8 m (65 ft) • Longitudinal Accuracy – Not available • Update Rate – <10 Hz • Data latency - <0.05 s • Lateral Accuracy - Not available **Speed** • Maximum Detection Range - < 19.8 m (65 ft) • Maximum Speed – Not available • Minimum Speed – 0 m/s (0 mph) • Accuracy - <10 percent of nominal speed • Update Rate – <10 Hz • Data latency - <0.05 s	not comply with the speed requirements.
Magnetic: Active (Loop Detectors)	When a vehicle travels over the detector, it creates a change in current due to the generation of an induced voltage.	• Already installed in a large number of intersections. • Unaffected by weather conditions	• Acceleration cannot be directly detected. • Can be susceptible to interference from other loops • No tracking function is possible with a single device.	**Position** • Maximum Detection Range – < 1.8 m (6 ft) • Longitudinal Accuracy – Varies depending on loop construction and amplifier settings • Update Rate – <10 Hz • Data latency - <0.05 sec • Lateral Accuracy - Varies depending on loop construction and amplifier settings **Speed** • Maximum Detection Range - < 1.8 m (6 ft) • Maximum Speed – 35.8	Complies with speed and position requirements. Considered a potential technology for IDS.

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
				m/s (80 mph) • Minimum Speed – 0 m/s (0 mph) • Accuracy - <5 percent of nominal speed (assuming a particular vehicle class) • Update Rate – <10 Hz • Data latency - <0.05 s	
Magnetic: Passive	Unlike conventional area loops, these are small tubes which can be inserted into drilled holes or conduit under the roadbed. Newer technology (i.e., microloops) allows alternate methods of installation, for example, under bridge decks.	• Flexibility of installation.	• Acceleration cannot be directly detected. • No tracking function is possible with a single device.	**Position** • Maximum Detection Range – < 1.8 m (6 ft) • Longitudinal Accuracy – Varies depending on detector arrangement • Update Rate – <10 Hz • Data latency - <0.05 sec • Lateral Accuracy - Varies depending on detector arrangement **Speed** • Maximum Detection Range - < 1.8 m (6 ft) • Maximum Speed – 35.8 m/s (80 mph) • Minimum Speed – 1.3-2.2 m/s (3-5 mph) • Accuracy - <5 percent of nominal speed (assuming a particular vehicle class) • Update Rate – <10 Hz • Data latency - <0.05 s	Complies with speed and position requirements. Considered a potential technology for IDS.
Laser	Measures the reflection of a laser beam off the vehicle.	• Long range • Can track multiple vehicles	• Does not measure acceleration directly. • Precipitation and fog	**Position** • Maximum Detection Range – < 1219.2 m (4000 ft)	Although technology meets speed and position requirements, is not dependable

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
			reduce range and accuracy. • Direct sunlight interferes with detection. • Periodic lens cleaning might be required. • Requires careful alignment during installation	• Longitudinal Accuracy – < 0.3 m (1 ft) • Update Rate – <100 Hz • Data latency - <0.01 s • Lateral Accuracy - < 0.3 m (1 ft), if properly aligned **Speed** • Maximum Detection Range - < 1219.2 m (4000 ft) • Maximum Speed – <134.1 m/s (300 mph) • Minimum Speed – 0.4 m/s (1 mph) • Accuracy - <0.9 m/s (2 mph) (<8 percent of nominal speed @ 11.2 m/s (25 mph)) • Update Rate – <100 Hz • Data latency - <0.01 s	during poor weather conditions.
Piezoelectric	Detectors gather data by converting mechanical energy into electrical energy, i.e., a voltage, which sets off the controller.	• Flexibility of installation	• Does not measure acceleration directly. • Low signal power • No tracking function is possible with a single device.	**Position** • Maximum Detection Range – Inadequate due to low signal power • Longitudinal Accuracy – < 1 meter • Update Rate – <10 Hz • Data latency – <0.05 s • Lateral Accuracy - < 1 meter **Speed** • Maximum Detection Range – Inadequate due to low signal power • Maximum Speed – >24.6 m/s (55 mph)	Does not comply with speed and position requirements due to low signal power, which creates an inadequate range.

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
				• Minimum Speed – >0.4 m/s (1 mph) (will not detect stationary vehicles) • Update Rate – <10 Hz • Data latency - <0.05 s	
Video	Video image detection uses a microprocessor to analyze the video image input from a camera. Two techniques, trip line and tracking, are used to record traffic data. Trip line techniques monitor specific zones on the roadway to detect the presence of a vehicle. Video tracking techniques employ algorithms to identify and track vehicles as they pass through the field of view.	• Can track multiple vehicles. • The technology is increasing in its installed base. • Video can cover a relatively wide area.	• Acceleration cannot be measured directly. • Dust, rain, snow, ice, and condensation can obscure the lens and impair or disable operation. • Headlight glare, wet pavement glare, and direct sunlight can interfere with functioning. • High winds can degrade software scene interpretation and resulting data reliability. • Accuracy can be dependent on mounting height and the use of dedicated poles.	**Position** • Maximum Detection Range - < 45.7 m (150 ft) • Longitudinal Accuracy – < 1.5 m (5 ft) • Update Rate – <10 Hz • Data latency - <0.05 s • Lateral Accuracy - < 1.5 m (5 ft) **Speed** • Maximum Detection Range - < 45.7 m (150 ft) • Maximum Speed - < 67.1 m/s (150 mph) • Minimum Speed – < 0 m/s (0 mph) • Accuracy - <5 percent • Update Rate – <10 Hz • Data latency - <0.05 s	Potential technology for IDS.

Vehicle-Based

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
GPS: Standard	A worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. This equipment can be used to characterize the position and movement of ground-based devices, including vehicles.	They are robust to changes in weather and environmental conditions	• The GPS unit requires a clear view to the sky that allows its antenna to 'see' some satellites. • Can vary in accuracy as satellites are acquired or dropped from its internal calculations. • Satellite signal is subject to interference. • Does not directly measure acceleration. • Requires an accurate map database.	**Position** • Maximum Detection Range – Not applicable, the technology moves with the car • Longitudinal Accuracy – < 15.2 m (50 ft) • Update Rate – <1 Hz • Data latency - <0.50 s • Lateral Accuracy - < 15.2 m (50 ft) **Speed** • Maximum Detection Range - < Not applicable, the technology moves with the car • Maximum Speed - < 44.7 m/s (100 mph) • Minimum Speed – 0 m/s (0 mph) • Accuracy - < 0.1 m/s (0.22 mph) (0.8% of nominal speed @ 11.2 m/s (25 mph)) • Update Rate – <1 Hz • Data latency - <0.50 s	The technology does not comply with minimum requirements for position and speed detection, so it would not be useful for this application by itself.
GPS: Differential (DGPS)	DGPS uses data from a receiver that is placed at a known location to collect data from the receiver that is at the unknown location. If performed in real time, the corrections are	They are robust to changes in weather and environmental conditions	• The GPS unit requires a clear view to the sky that allows its antenna to 'see' some satellites. • Can vary in accuracy as satellites are acquired or dropped from its internal	**Position** • Maximum Detection Range – Not applicable, the technology moves with the car • Longitudinal Accuracy – < 0.3 m (1 ft)	Suitable to support human factors tests.

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
	transmitted to the unknown location receiver via a radio-frequency link.		calculations. • Satellite signal is subject to interference. • Does not directly measure acceleration. • Requires an accurate map database.	• Update Rate – <20 Hz • Data latency - <0.05 s • Lateral Accuracy - < 0.3 m (1 ft) **Speed** • Maximum Detection Range - Not applicable, the technology moves with the car • Maximum Speed - < 44.7 m/s (100 mph) • Minimum Speed – 0 m/s (0 mph) • Accuracy - < 0.04 m/s (0.10 mph) (0.4% of nominal speed @ 11.2 m/s (25 mph)) • Update Rate – <20 Hz • Data latency - <0.05 s	
GPS with INS	Measures the vehicle's inertial properties to increase the accuracy of the GPS signal and to supplant the GPS signal when enough satellites are not visible by the vehicle antennas.	They are robust to changes in weather and environmental conditions Supports a completely vehicle-based solution for stop-controlled intersections	• Currently, an extremely expensive technology that is not likely to be acceptable to the automotive manufacturers. • Requires an accurate map database.	**Position** • Maximum Detection Range – Not applicable, the technology moves with the car • Longitudinal Accuracy – < 0.3 m (1 ft) • Update Rate – <100 Hz • Data lat - <0.005 s • Lateral Accuracy - < 0.3 m (1 ft) **Speed** • Maximum Detection Range - Not applicable, the technology moves with the car	Although this technology meets all of the requirements, the current cost makes this technology infeasible.

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
				• Maximum Speed - < 44.7 m/s (100 mph) • Minimum Speed – 0 m/s (0 mph) • Accuracy - < 0.04 m/s (0.10 mph) (0.4 percent of nominal speed @ 11.2 m/s (25 mph)) • Update Rate – <100 Hz • Data latency - <0.005 s **Acceleration** • Maximum Detection Range - Not applicable, the technology moves with the car • Maximum Acceleration - < ±50 *g* • Accuracy - < 0.01 *g* • Update Rate – <100 Hz • Data latency - <0.005 s	
Machine Vision	Takes an image and breaks it into pixels. It then looks for contrast differences between the pixels to form edges. Using the edges, shapes are built, which can be compared to a known shape. Such a system would need a camera mounted within the vehicle focused at a considerable distance ahead of the vehicle. For optimal benefit, the camera should have a	Supports a completely vehicle-based solution for stop-controlled intersections.	Would require a camera system that would, in theory, only work for stop-controlled intersections.	Not known at this time.	Not known at this time.

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
	color capability to recognize sign color. At night, adequate light from the headlights would be necessary to activate the retro-reflective paint.				
In-Vehicle Network	Data on vehicle speed and acceleration (in some cases) can be found within the range of measures that is already monitored in a vehicle and available in its in-vehicle network. This functionality can be provided as part of the ECU or as a DSP.	Already in vehicles. If the information available on the current in-vehicle network does not provide the necessary performance, it is probable that auto manufacturers could upgrade the system to provide these data.	Does not measure position.	Specifications likely change depending on the automotive manufacturer.	Suitable to support human factors tests.
Accelerometer	Converts the effects of mechanical motion into an electrical signal that is proportional to the acceleration value of the motion.	One of the few devices that measures acceleration directly.	Vehicle position and speed are not directly measured by this device.	**Acceleration** • Maximum Detection Range - Not applicable, the technology moves with the car • Maximum Acceleration - < ±2 *g* • Accuracy - < 0.002 *g* • Update Rate – < 60 Hz • Data latency - <0.01 s	Suitable to support human factors tests.
RFID	A reader-tag combination of devices that communicate with each other. At its most basic, the tags are attached to the devices that are of interest, and, via an antenna,	Very inexpensive single point detection that could be used in concert with other technologies to determine speed and acceleration. Can be made to identify	Provides single point detection. May be subject to interference based on the radio frequency technology.	To be determined based upon further evaluation.	Potential technology for IDS.

Technology	Description	Capabilities/Advantages	Limitations	Specifications	Suitability
	communicate with an interrogating device (reader) which can obtain information on the tagged device's position, physical characteristics, or any other information that is encoded within the tag.	specific vehicles.			

Appendix B1: The Dula Dangerous Driving Index

Please answer each of the following items as honestly as possible. Please read each item carefully and then circle the answer you choose on the form. If none of the choices seem to be your ideal answer, then select the answer that comes closest. THERE ARE NO RIGHT OR WRONG ANSWERS. Select your answers quickly and do not spend too much time analyzing your answers. If you change an answer, erase the first one as well.

I drive when I am angry or upset.

A. Never B. Rarely C. Sometimes D. Often E. Always

I lose my temper when driving.

A. Never B. Rarely C. Sometimes D. Often E. Always

I consider the actions of other drivers to be inappropriate or "stupid"

A. Never B. Rarely C. Sometimes D. Often E. Always

I flash my headlights when I am annoyed by another driver.

A. Never B. Rarely C. Sometimes D. Often E. Always

I make rude gestures (e.g., giving "the finger"; yelling curse words) toward drivers who annoy me.

A. Never B. Rarely C. Sometimes D. Often E. Always

I verbally insult drivers who annoy me.

A. Never B. Rarely C. Sometimes D. Often E. Always

I deliberately use my car/truck to block drivers who tailgate me.

A. Never B. Rarely C. Sometimes D. Often E. Always

I would tailgate a driver who annoys me.

A. Never B. Rarely C. Sometimes D. Often E. Always

I "drag race" other drivers at stop lights to get out front.

A. Never B. Rarely C. Sometimes D. Often E. Always

I will illegally pass a car/truck that is going too slowly.

A. Never B. Rarely C. Sometimes D. Often E. Always

I feel it is my right to strike back in some way, if I feel another driver has been aggressive toward me.

A. Never B. Rarely C. Sometimes D. Often E. Always

When I get stuck in a traffic jam I get very irritated.

A. Never B. Rarely C. Sometimes D. Often E. Always

I will race a slow moving train to a railroad crossing.

A. Never B. Rarely C. Sometimes D. Often E. Always

I will weave in and out of slower traffic

A. Never B. Rarely C. Sometimes D. Often E. Always

I will drive if I am only <u>mildly</u> intoxicated or bussed.

A. Never B. Rarely C. Sometimes D. Often E. Always

When someone cuts me off, I feel I should punish him/her

A. Never B. Rarely C. Sometimes D. Often E. Always

I get impatient and/or upset when I fall behind schedule when I am driving.

A. Never B. Rarely C. Sometimes D. Often E. Always

Passengers in my car/truck tell me to calm down.

A. Never B. Rarely C. Sometimes D. Often E. Always

I get irritated when a car/truck in front of me slows down for no reason.

A. Never B. Rarely C. Sometimes D. Often E. Always

I will cross double yellow lines to see if I can pass a slow moving car/truck.

A. Never B. Rarely C. Sometimes D. Often E. Always

I feel it is my right to get where I need to go as quickly as possible.

A. Never B. Rarely C. Sometimes D. Often E. Always

I feel that <u>passive</u> drives should learn how to drive or stay home.

A. Never B. Rarely C. Sometimes D. Often E. Always

I will drive in the shoulder lane or median to get around a traffic jam.

A. Never B. Rarely C. Sometimes D. Often E. Always

When passing a car/tuck on a 2-lane road, I will barely miss on-coming cars.

A. Never B. Rarely C. Sometimes D. Often E. Always

I will drive when I am drunk.

A. Never B. Rarely C. Sometimes D. Often E. Always

I feel that I may lose my temper if I have to confront another driver.

A. Never B. Rarely C. Sometimes D. Often E. Always

I consider myself to be a risk-taker.

A. Never B. Rarely C. Sometimes D. Often E. Always

I feel that most traffic "laws" could be considered as suggestions.

A. Never B. Rarely C. Sometimes D. Often E. Always

Appendix B2: Driver Stress Inventory

Please answer the following questions on the basis of your usual or typical feelings about driving. Each question asks you to answer according to how strongly you agree with one or other of two alternative answers. Please read each of the two alternatives carefully before answering. To answer, mark the horizontal line at the point which expresses your answer most accurately. Be sure to answer all the questions, even if some of them don't seem to apply to you very well: guess as best you can if need be.

Example: Are you a confident driver?

The more confident you are, the closer to the 'very much' alternative you should mark your cross.

1. Does it worry you to drive in bad weather?

very much 0 1 2 3 4 5 6 7 8 9 10 not at all

2. I am disturbed by thoughts of having an accident or the car breaking down

very rarely 0 1 2 3 4 5 6 7 8 9 10 very often

3. Do you lose your temper when another driver does something silly?

not at all 0 1 2 3 4 5 6 7 8 9 10 very much

4. Do you think you have enough experience and training to deal with risky situations on the road safely?

not at all 0 1 2 3 4 5 6 7 8 9 10 very much

5. I find myself worrying about my mistakes and the things I do badly when driving

very rarely 0 1 2 3 4 5 6 7 8 9 10 very often

6. I would like to risk my life as a racing driver

not at all 0 1 2 3 4 5 6 7 8 9 10 very much

7. My driving would be worse than usual in an unfamiliar rental car

not at all 0 1 2 3 4 5 6 7 8 9 10 very much

8. I sometimes like to frighten myself a little while driving

very much 0 1 2 3 4 5 6 7 8 9 10 not at all

9. I get a real thrill out of driving fast

very much 0 1 2 3 4 5 6 7 8 9 10 not at all

10. I make a point of carefully checking every side road I pass for emerging vehicles

very much 0 1 2 3 4 5 6 7 8 9 10 not at all

11. Driving brings out the worst in people

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

12. Do you think it is worthwhile taking risks on the road?

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

13. At times, I feel like I really dislike other drivers who cause problems for me

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

14. Advice on driving from a passenger is generally:

useful	0	1	2	3	4	5	6	7	8	9	10	unnecessary

15. I like to raise my adrenaline levels while driving

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

16. It's important to show other drivers that they can't take advantage of you

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

17. Do you feel confident in your ability to avoid an accident?

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

18. Do you usually make an effort to look for potential hazards when driving?

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

19. Other drivers are generally to blame for any difficulties I have on the road

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

20. I would enjoy driving a sports car on a road with no speed-limit

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

21. Do you find it difficult to control your temper when driving?

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

22. When driving on an unfamiliar road do you become more tense than usual?

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

23. I make a special effort to be alert even on roads I know well

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

24. I enjoy the sensation of accelerating rapidly

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

25. If I make a minor mistake when driving, I feel it's something I should be concerned about

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

26. I always keep an eye on parked cars in case somebody gets out of them, or there are pedestrians behind them

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

27. I feel more anxious than usual when I have a passenger in the car

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

28. I become annoyed if another car follows very close behind mine for some distance

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

29. I make an effort to see what's happening on the road a long way ahead of me

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

30. I try very hard to look out for hazards even when it's not strictly necessary

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

31. Are you usually patient during the rush hour?

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

32. When you pass another vehicle do you feel in command of the situation?

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

33. When you pass another vehicle do you feel tense or nervous?

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

34. Does it annoy you to drive behind a slow moving vehicle?

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

35. When you're in a hurry, other drivers usually get in your way

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

36. When I come to negotiate a difficult stretch of road, I am on the alert

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

37. Do you feel more anxious than usual when driving in heavy traffic?

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

38. I enjoy cornering at high speed

not at all	0	1	2	3	4	5	6	7	8	9	10	very much

39. Are you annoyed when the traffic lights change to red when you approach them?

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

40. Does driving usually make you feel aggressive?

very much	0	1	2	3	4	5	6	7	8	9	10	not at all

41. Think about how you feel when you have to drive for several hours, with few or no breaks from driving.

How do your feelings change during the course of the drive?

More uncomfortable physically (e.g., headache or muscle pains)	0	1	2	3	4	5	6	7	8	9	10	No change
More drowsy or sleepy	0	1	2	3	4	5	6	7	8	9	10	No change
Maintain speed of reaction	0	1	2	3	4	5	6	7	8	9	10	Reactions to other traffic increasingly slow
Maintain attention to road signs	0	1	2	3	4	5	6	7	8	9	10	Become increasingly inattentive to road signs
Normal vision	0	1	2	3	4	5	6	7	8	9	10	Vision becomes less clear
Increasingly difficult to judge your speed	0	1	2	3	4	5	6	7	8	9	10	Normal judgment of speed
Interest in driving does not change	0	1	2	3	4	5	6	7	8	9	10	Increasingly bored and fed-up
Passing become increasingly risky and dangerous	0	1	2	3	4	5	6	7	8	9	10	No change

---

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a) b) c) d) e) f) g) h)

Appendix C: Questionnaire on Warning

The true purpose of this research is to evaluate intersection violation warnings. One aspect of the research project deals with how people might respond to such a warning the first time they encounter it. To do this, we needed to create a situation where you were presented with the warning while not looking at the road in front of you. If you had been looking directly at the road, you might have seen the light turn red and the data would not have been as useful. There was no "correct" or "incorrect" information in the data that you provided. We needed to compare your response to others who were presented with the same situation. All known precautions were taken to ensure your complete safety throughout this session and during the presentation of the scenario. Let the experimenter know at this time if you would like further explanation before completing this questionnaire.

Questionnaire

There is no "correct," "incorrect," or expected way for you to respond.

Please **circle one number** that most closely corresponds to your experience during this stop.

---

1. I expected this event at the time it occurred.

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

---

2. What do you think about the timing of the warning?

Very Early	1	2	3	4	5	6	7	Very Late

---

3. How comfortable was the stop you just made?

Very Uncomfortable	1	2	3	4	5	6	7	Very Comfortable

---

4. Please rate your level of vehicle control during the stop you just made.

Very Much In Control	1	2	3	4	5	6	7	Very Much Out of Control

---

5. Please rate your feeling of safety during the stop.

Very Safe	1	2	3	4	5	6	7	Very Unsafe

---

6. Did you notice anything as you were approaching the intersection?

____

Weather behind sign:
__ Clear __ Partly Cloudy __ Mostly Cloudy __ Cloudy __ Sun directly behind the sign

Clouds (if any) were:
__ White __ Gray

Ambient Light Measurement (from POV):
____

The true purpose of this research is to evaluate intersection violation warnings. An intersection violation warning would detect a vehicle that is likely to run the red and warn that driver such that a collision could be avoided. One aspect of the research project deals with how people might respond to such a warning the first time they encounter it. To do this, we needed to create a situation where you were presented with the warning while not looking at the road in front of you. If you had been looking directly at the road, you might have seen the light turn red and the data would not have been as useful. There was no "correct" or "incorrect" information in the data that you provided. We needed to compare your response to others who were presented with the same situation. All known precautions were taken to ensure your complete safety throughout this session and during the presentation of the scenario. Let the experimenter know at this time if you would like further explanation before completing this questionnaire.

Questionnaire

There is no "correct," "incorrect," or expected way for you to respond.

Please **circle one number** that most closely corresponds to your experience during this stop.

---

1. I expected this event at the time it occurred.

Strongly Disagree	1	2	3	4	5	6	7	Strongly Agree

---

2. What do you think about the timing of the warning?

Very Early	1	2	3	4	5	6	7	Very Late

---

3. Why did you decide not to stop?

---

4. If I had decided to stop the car it would have been:

Not At All Difficult	1	2	3	4	5	6	7	Very Difficult

---

5. Please rate your feeling of safety as you crossed the intersection

Very Safe	1	2	3	4	5	6	7	Very Unsafe

---

6. Did you notice anything as you were approaching the intersection?

Weather behind sign:
__ Clear __ Partly Cloudy __ Mostly Cloudy __ Cloudy __ Sun directly behind the sign

Clouds (if any) were:
__ White __ Gray

Ambient Light Measurement (from POV):
____

Appendix D. Distribution of Participants who Performed the DII Effectiveness Tests.

Table D-1. Participants used for too-late test with no warning (baseline group) at 56.3 km/h (35 mph) using standardized occlusion goggles protocol with an amber light at occlusion clearing.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
53.3 m (175 ft)	16	4 OM 4 OF 4 YM 4 YF	2	**18 (18 total)**
Total	**16**	**4 OM 4 OF 4 m 4 YF**	**2 (11% unusable)**	**18**

Table D-2. Participants used for too-late test with the LED stop sign plus strobes + low-fidelity rumble strip simulation at 56.3 km/h (35 mph) using standardized occlusion goggles protocol with an amber light at occlusion clearing.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
44.2 m (145 ft)	3	1 OM 0 OF 0 YM 2 YF	0	**3 (3 total)**
Total	**3**	**1 OM 0 OF 0 m 2 YF**	**0 (0% unusable)**	**3**

Note: this DII was run as a pilot test to verify that all systems were operational and that the protocol was working as intended. Hence, no full groups were run for it.

Table D-3. Participants used for too-late test with the LED stop sign plus strobes at 56.3 km/h (35 mph) using standardized occlusion goggles protocol with an amber light at occlusion clearing.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
32.0 m (105 ft)	7	2 OM 1 OF 2 YM 2 YF	1	**8 (8 total)**
41.1 m (135 ft)	4	0 OM 0 OF 2 YM 2 YF	1	**5 (13 total)**
47.2 m (155 ft)	2	0 OM 0 OF 2 YM 0 YF	0	**2 (15 total)**
50.3 m (165 ft)	2	0 OM 0 OF 0 YM 2 YF	0	**2 (17 total)**
51.8 m (170 ft)	5	2 OM 0 OF 2 YM 1 YF	0	**5 (22 total)**
53.3 m (175 ft)	17	4 OM 4 OF 5 YM 4 YF	7	**24 (46 total)**
Total	**37**	**8 OM 5 OF 13 YM 11 YF**	**9 (20% unusable)**	**46**

Note: this DII terminated at 175 ft because it became optimal at that point (note this distance also represents the too-early boundary).

Table D-4. Participants used for too-late test with the LED stop sign plus strobes + traffic clearing lights (TCLs) at 56.3 km/h (35 mph) using standardized occlusion goggles protocol with an amber light at occlusion clearing.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
42.7 m (140 ft)	3	0 OM 0 OF 1 YM 2 YF	0	**3 (3 total)**
44.2 m (145 ft)	2	1 OM 0 OF 1 YM 0 YF	1	**3 (6 total)**
45.7 m (150 ft)	4	2 OM 0 OF 2 YM 0 YF	2	**6 (12 total)**
47.2 m (155 ft)	1	1 OM 0 OF 0 YM 0 YF	0	**1 (13 total)**
48.8 m (160 ft)	5	1 OM 2 OF 0 YM 2 YF	0	**5 (18 total)**
50.3 m (165 ft)	1	0 OM 0 OF 0 YM 1 YF	1	**2 (20 total)**
51.8 m (170 ft)	2	2 OM 0 OF 0 YM 0 YF	0	**2 (22 total)**
53.3 m (175 ft)	16	4 OM 4 OF 4 YM 4 YF	6	**22 (44 total)**
Total	**34**	**11 OM 6 OF 8 m 9 YF**	**10 (23% unusable)**	**44**

Note: this DII terminated at 175 ft because it reached the too-early boundary without resulting in 100 percent compliance.

Table D-5. Participants used for too-late test with the dual flashing red at 56.3 km/h (35 mph) using standardized occlusion goggles protocol with an amber light at occlusion clearing.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
47.2 m (155 ft)	1	0 OM 0 OF 0 YM 1 YF	0	**1 (1 total)**
50.3 m (165 ft)	6	2 OM 3 OF 0 YM 1 YF	3	**9 (10 total)**
53.3 m (175 ft)	16	4 OM 4 OF 4 YM 4 YF	5	**21 (31 total)**
Total	**23**	**6 OM 7 OF 4 m 6 YF**	**8 (26% unusable)**	**31**

Note: this DII terminated at 175 ft because it reached the too-early boundary without resulting in 100 percent compliance.

Table D-6. Participants used for too-late test with the high-fidelity rumble strip simulation at 56.3 km/h (35 mph) using standardized occlusion goggles protocol with an amber light at occlusion clearing.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
47.2 m (155 ft)	1	0 OM 0 OF 0 YM 1 YF	0	**1 (1 total)**
50.3 m (165 ft)	1	1 OM 0 OF 0 YM 0 YF	0	**1 (2 total)**
53.3 m (175 ft)	16	4 OM 4 OF 4 YM 4 YF	5	**21 (23 total)**
Total	**18**	**5 OM 4 OF 4 m 5 YF**	**5 (22% unusable)**	**23**

Note: this DII terminated at 175 ft because it reached the too-early boundary without resulting in 100 percent compliance.

Table D-7. Participants used for too-late test with no warning (baseline group) at 56.3 km/h (35 mph) using standardized occlusion goggles protocol with a red light at occlusion clearing.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
32.0 m (105 ft)	9	2 OM 2 OF 2 YM 3 YF	2	**11 (11 total)**
41.1 m (135 ft)	8	2 OM 2 OF 2 YM 2 YF	4	**12 (23 total)**
47.2 m (155 ft)	8	2 OM 2 OF 2 YM 2 YF	2	**10 (33 total)**
53.3 m (175 ft)	8	2 OM 2 OF 2 YM 2 YF	4	**12 (45 total)**
Total	**33**	**8 OM 8 OF 8 m 9 YF**	**12 (27% unusable)**	**45**

Table D-8. Participants used for too-late test with the LED stop sign plus strobes at 56.3 km/h (35 mph) using standardized occlusion goggles protocol with a red light at occlusion clearing.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
32.0 m (105 ft)	8	2 OM 2 OF 2 YM 2 YF	1	**9 (9 total)**
41.1 m (135 ft)	8	2 OM 2 OF 2 YM 2 YF	5	**13 (22 total)**
47.2 m (155 ft)	8	2 OM 2 OF 2 YM 2 YF	3	**11 (33 total)**
53.3 m (175 ft)	8	2 OM 2 OF 2 YM 2 YF	2	**10 (43 total)**
Total	**32**	**8 OM 8 OF 8 m 8 YF**	**11 (26% unusable)**	**43**

Table D-9. Participants used for too-late test with the high-fidelity rumble strip simulation at 56.3 km/h (35 mph) using standardized occlusion goggles protocol with a red light at occlusion clearing.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
32.0 m (105 ft)	8	2 OM 2 OF 2 YM 2 YF	5	**13 (13 total)**
41.1 m (135 ft)	8	2 OM 2 OF 2 YM 2 YF	4	**12 (25 total)**
47.2 m (155 ft)	8	2 OM 2 OF 2 YM 2 YF	3	**11 (36 total)**
53.3 m (175 ft)	8	2 OM 2 OF 2 YM 2 YF	6	**14 (50 total)**
Total	**32**	**8 OM 8 OF 8 m 8 YF**	**18 (36% unusable)**	**50**

Table D-10. Participants used for stop sign tests at 56.3 km/h (35 mph) using standardized occlusion goggles protocol.

Distance Tested:	Participants with Usable Data	Age/Gender Distribution	Participants with Unusable Data	Total Participants Run
32.0 m (105 ft) Warning	8	2 OM 2 OF 2 YM 2 YF	2	**10 (10 total)**
41.1 m (135 ft) Baseline	8	2 OM 2 OF 2 YM 2 YF	0	**8 (18 total)**
41.1 m (135 ft) Warning	8	2 OM 2 OF 2 YM 2 YF	2	**10 (28 total)**
47.2 m (155 ft) Baseline	8	2 OM 2 OF 2 YM 2 YF	1	**9 (37 total)**
47.2 m (155 ft) Warning	8	2 OM 2 OF 2 YM 2 YF	2	**10 (47 total)**
53.3 m (175 ft) Baseline	8	2 OM 2 OF 2 YM 2 YF	0	**8 (55 total)**
53.3 m (175 ft) Warning	6	2 OM 2 OF 1 YM 1 YF	3	**9 (64 total)**
Total	**54**	**14 OM 14 OF 13 m 13 YF**	**10 (16% unusable)**	**64**

Appendix E: Subjective Questionnaire Results from On-Road Studies

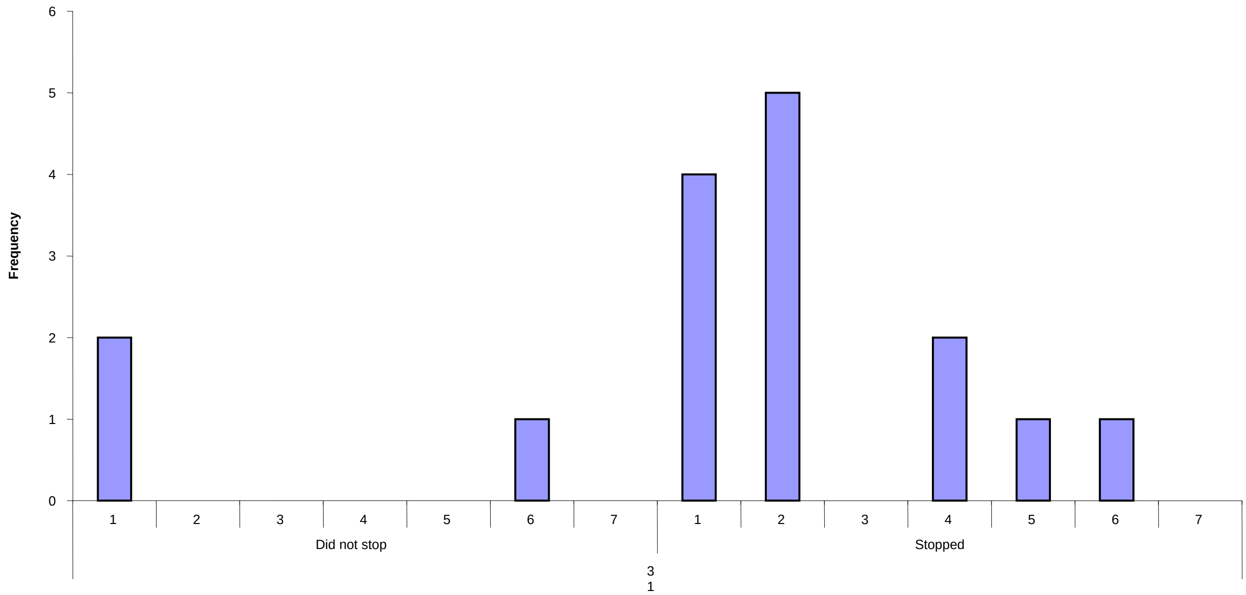

Figure E-1. Baseline, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

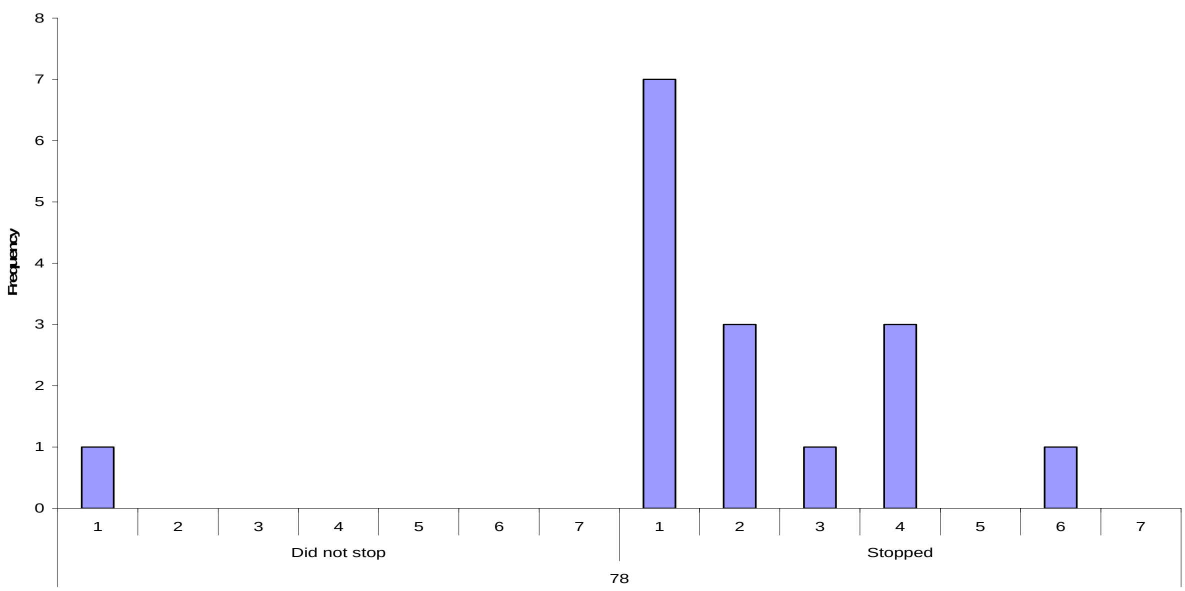

Figure E-2. “STOP” LED sign plus strobes plus TCLs, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

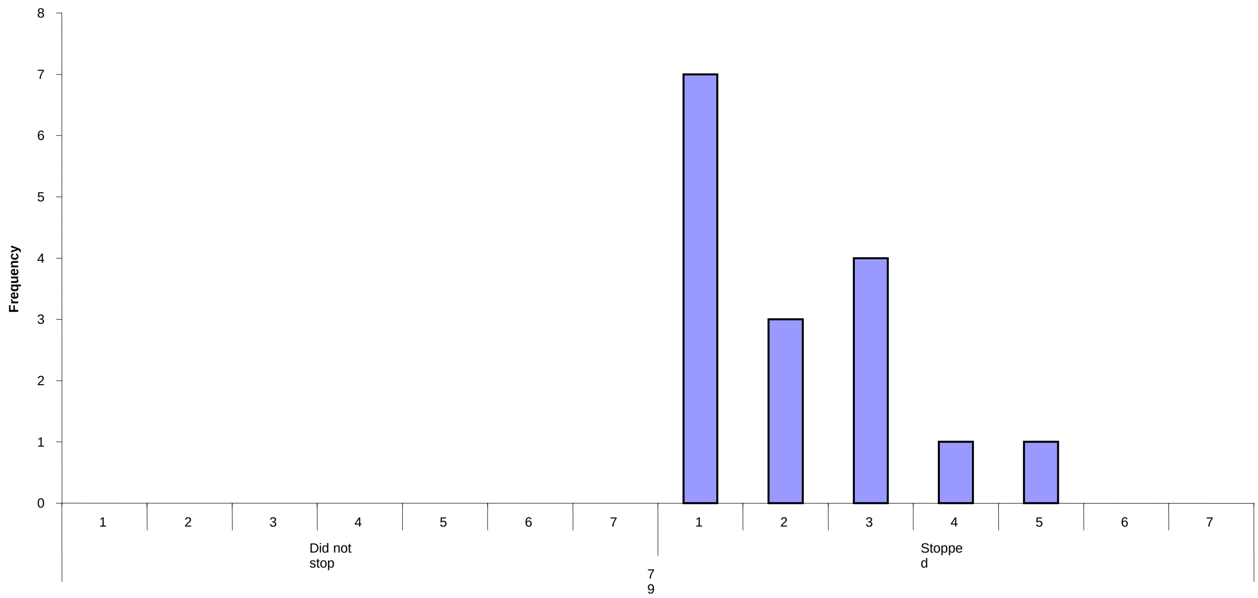

Figure E-3. "STOP" LED sign plus strobes, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

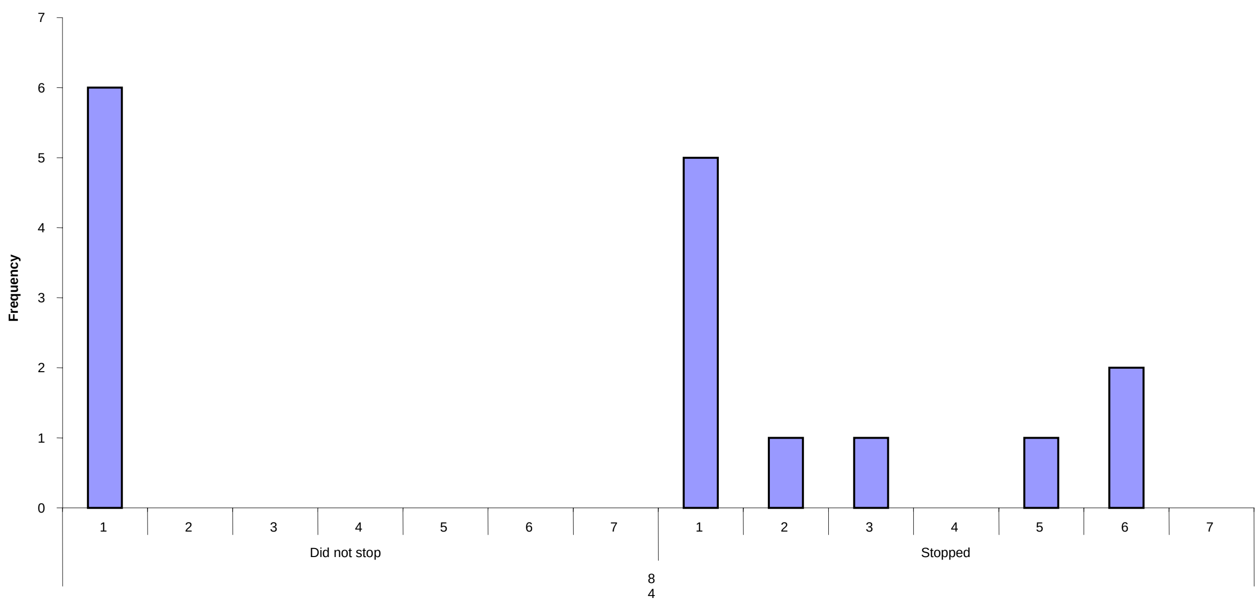

Figure E-4. Dual flashing red, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

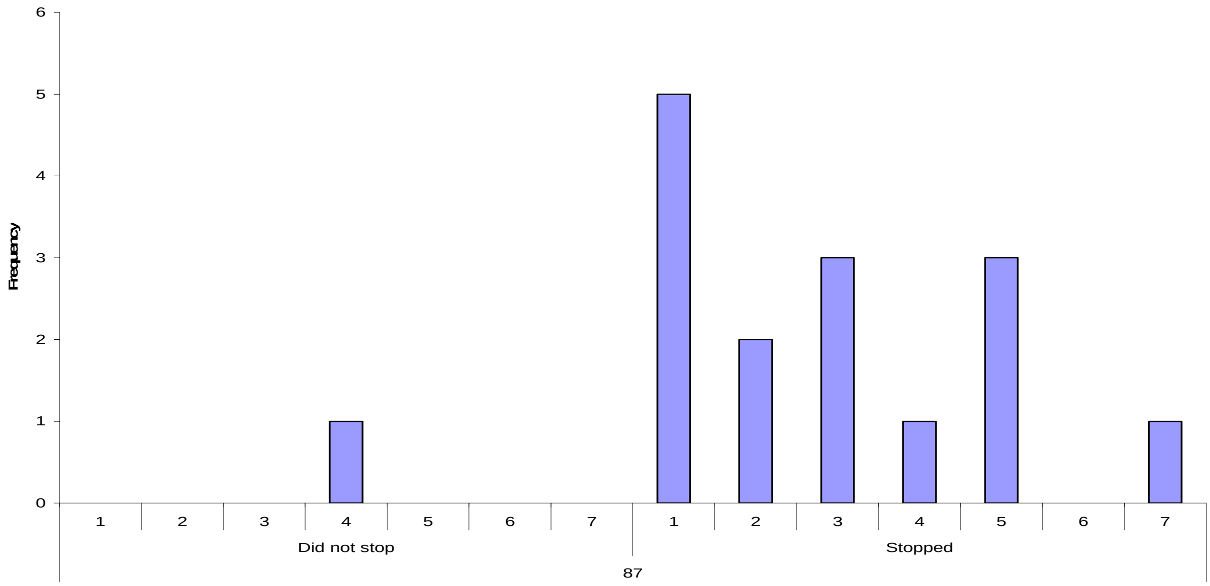

Figure E-5. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

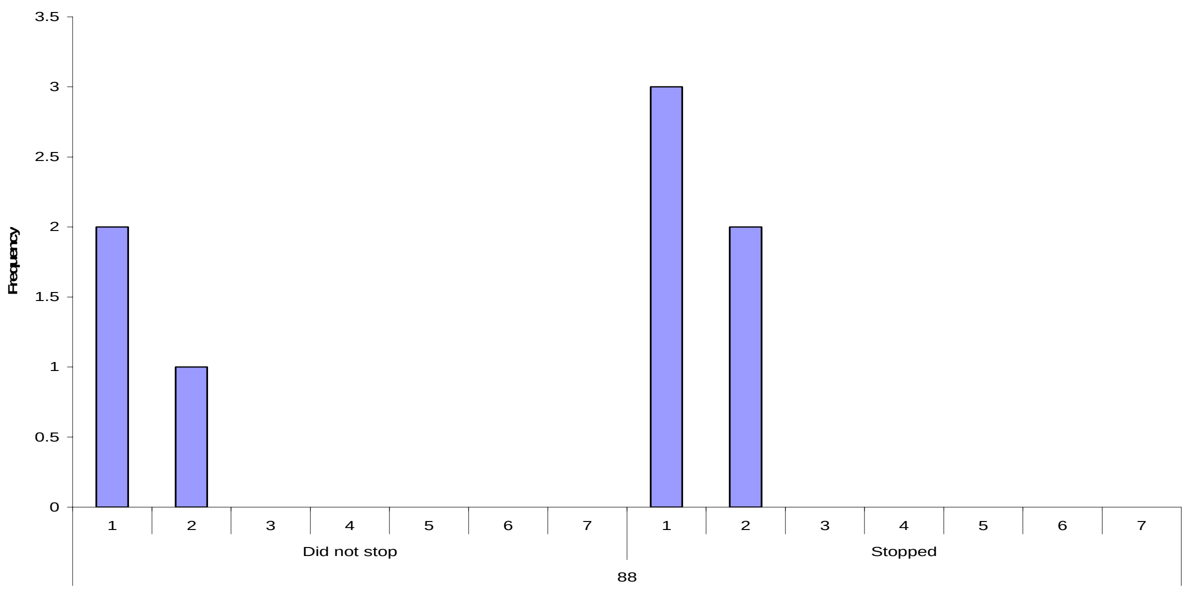

Figure E-6. Baseline, 35 mph, 2.65-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

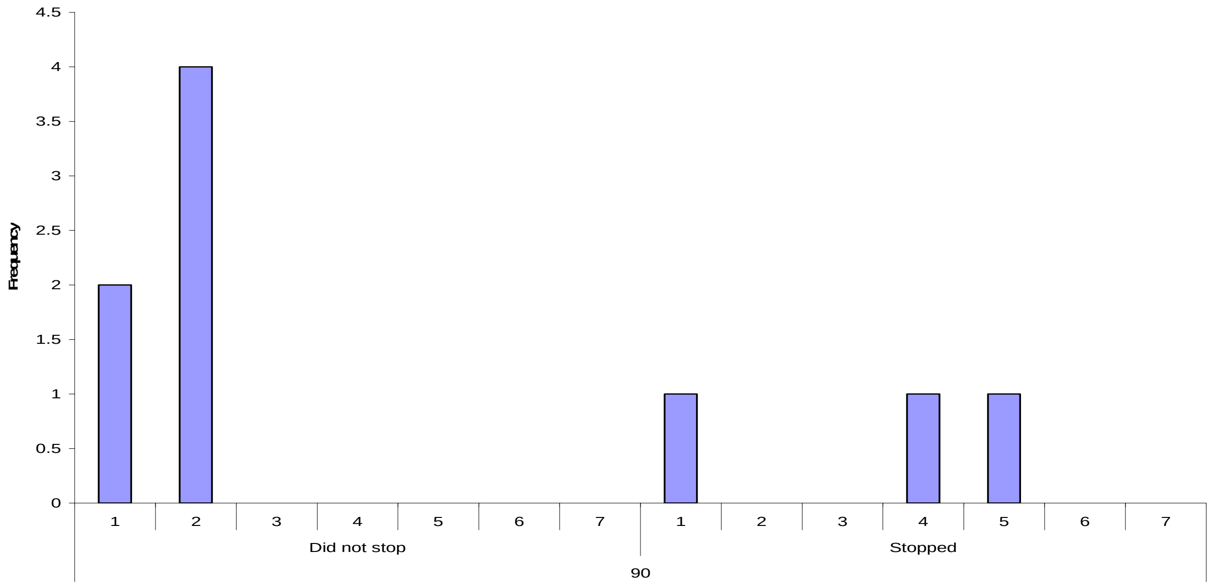

Figure E-7. Baseline, 35 mph, 2.03-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

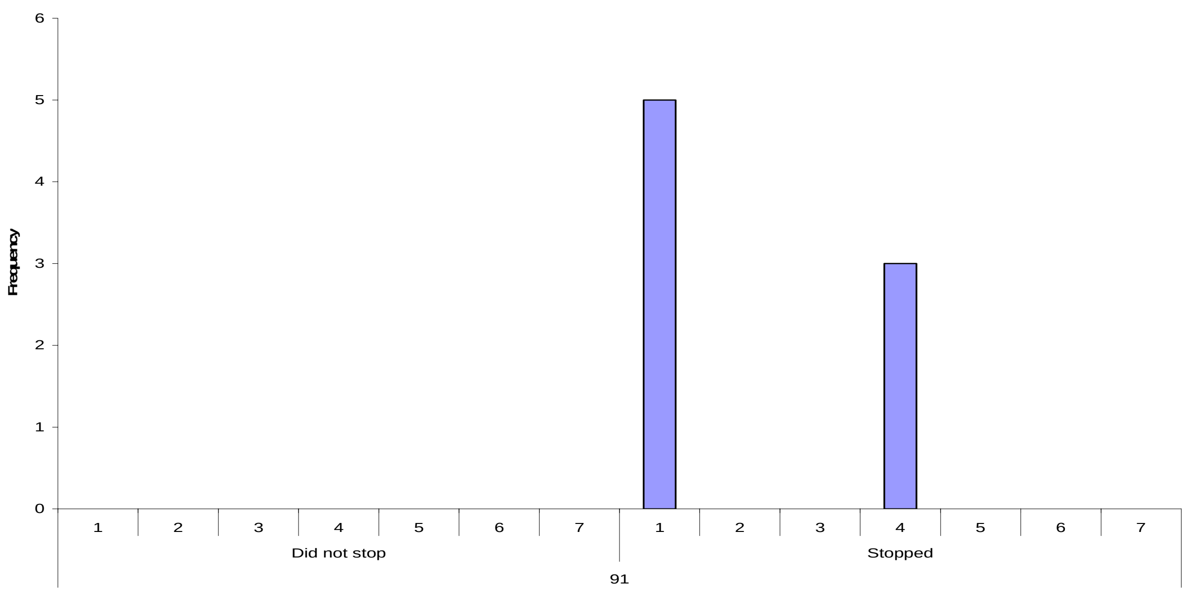

Figure E-8. Baseline, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

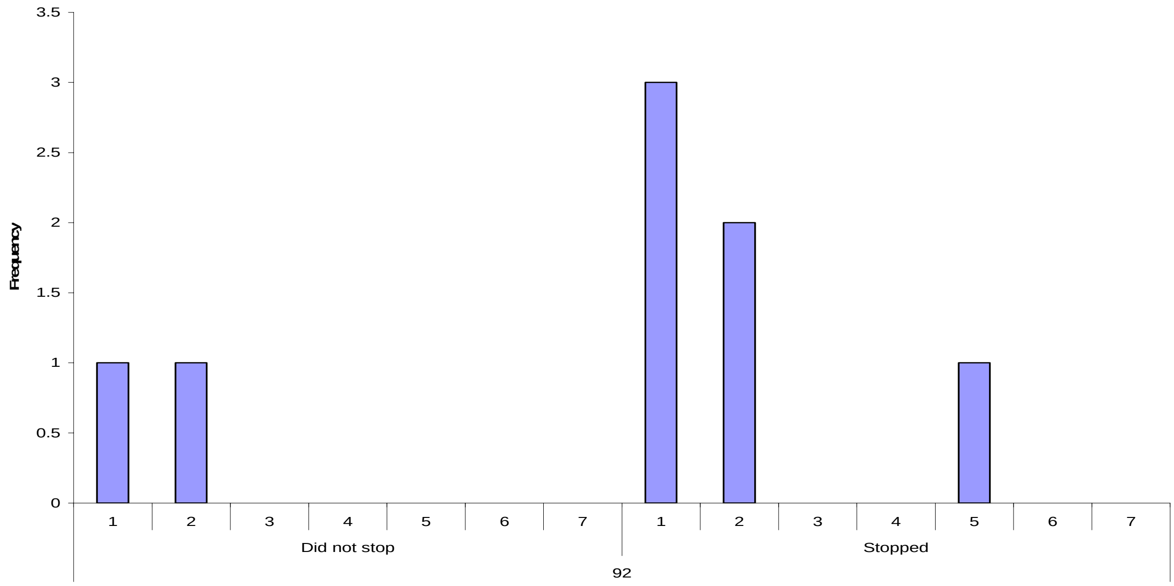

Figure E-9. Baseline, 35 mph, 3.02-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

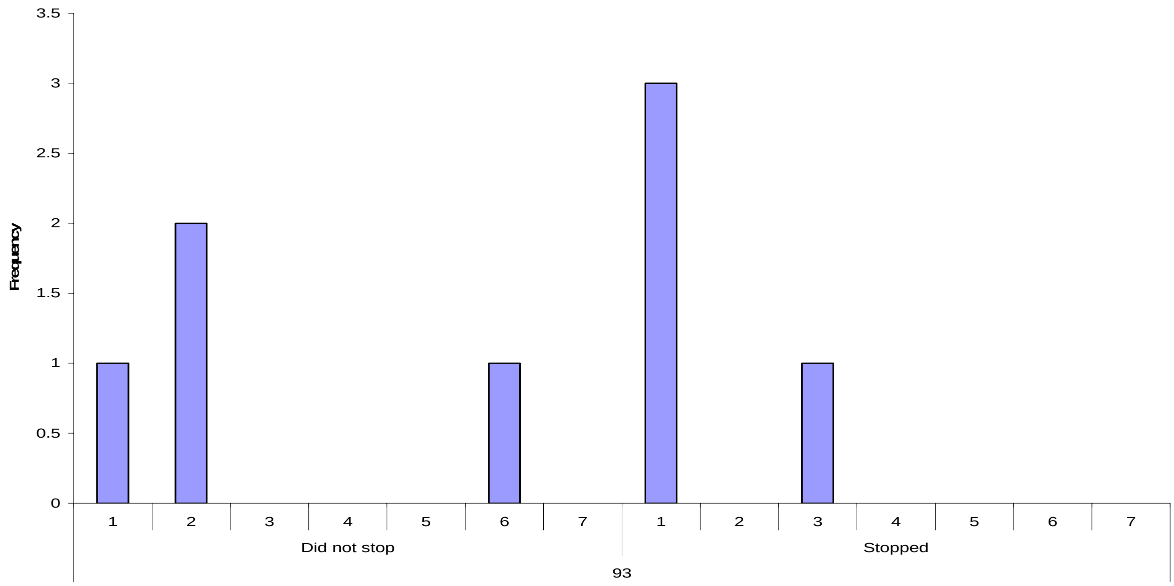

Figure E-10. Rumble strip simulation, 35 mph, 2.03-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

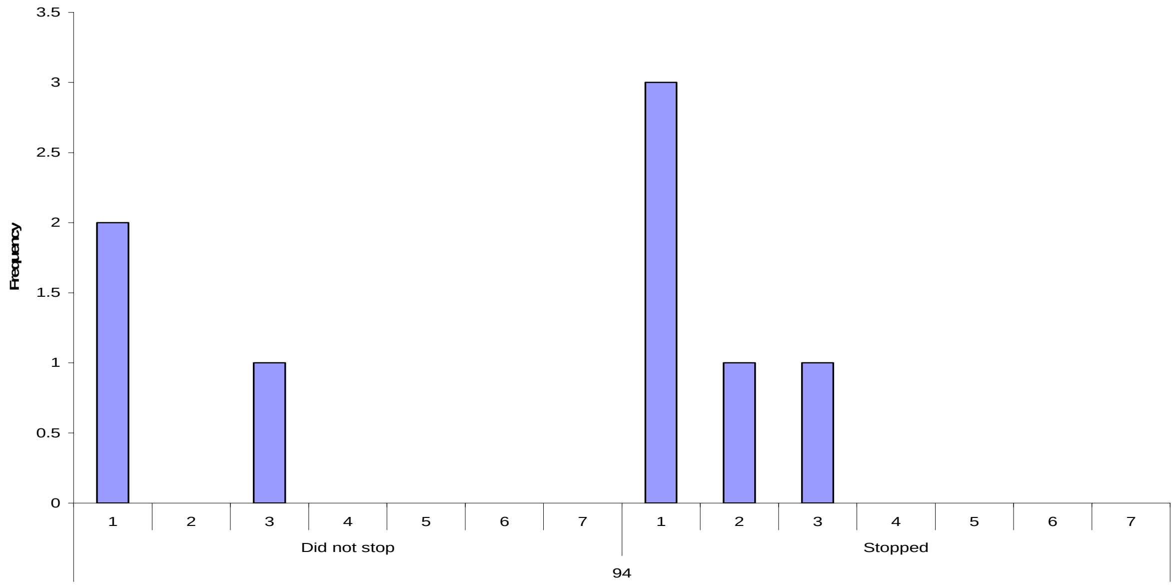

Figure E-11. Rumble strip simulation, 35 mph, 2.65-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

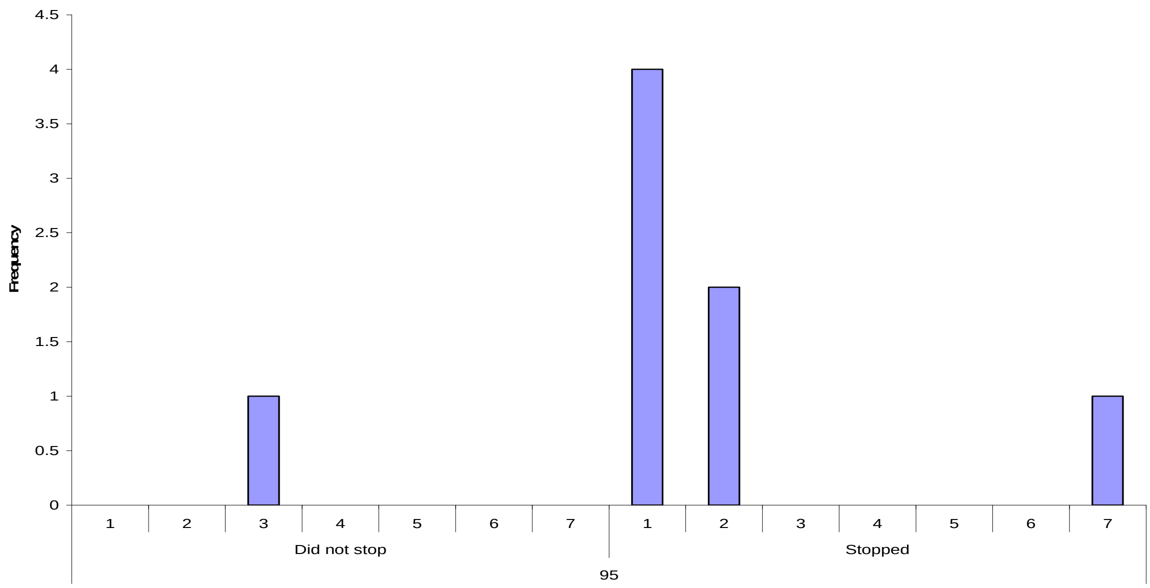

Figure E-12. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

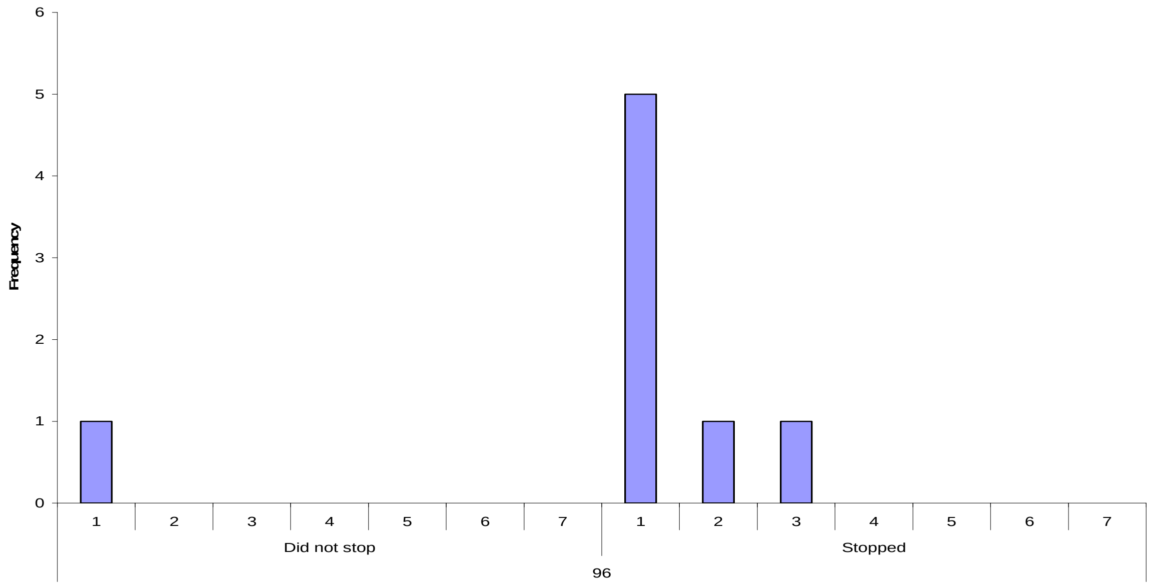

Figure E-13. Rumble strip simulation, 35 mph, 3.02-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

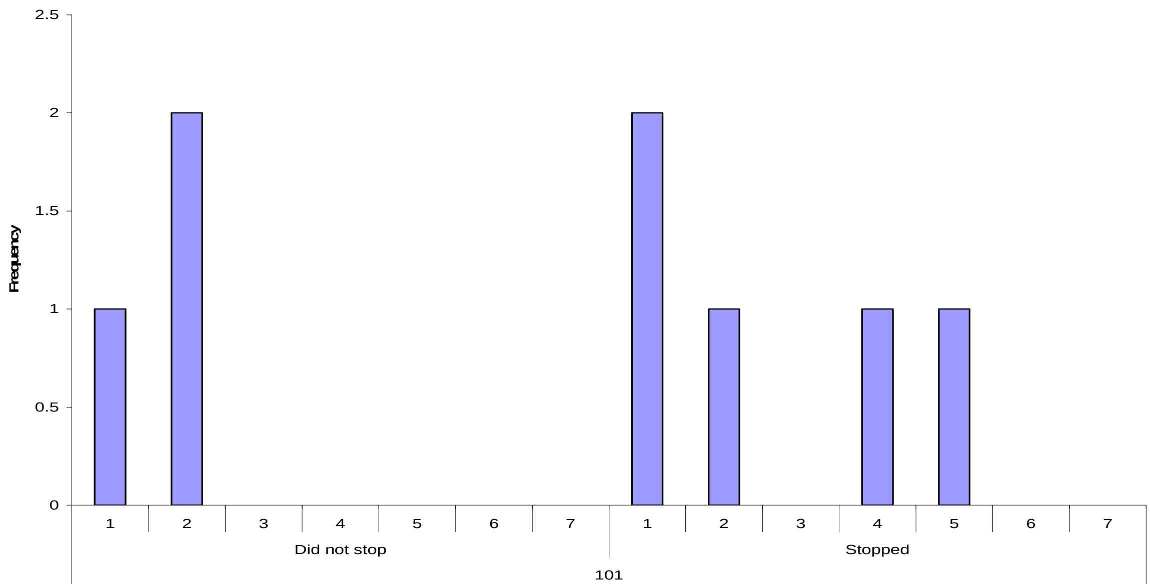

Figure E-14. "STOP" LED sign plus strobes, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

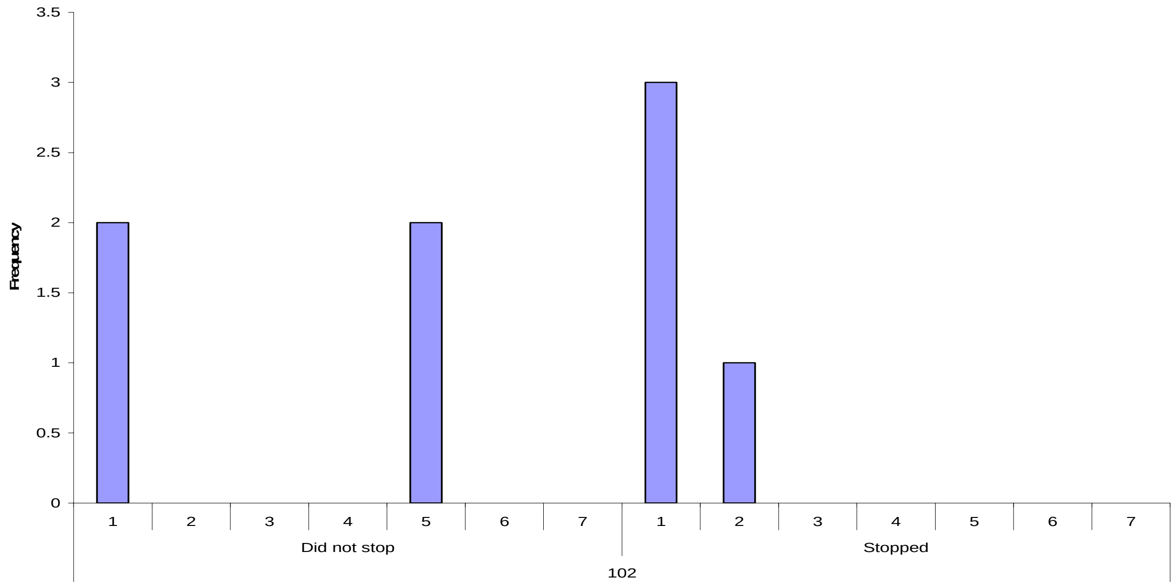

Figure E-15. "STOP" LED sign plus strobes, 35 mph, 2.03-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

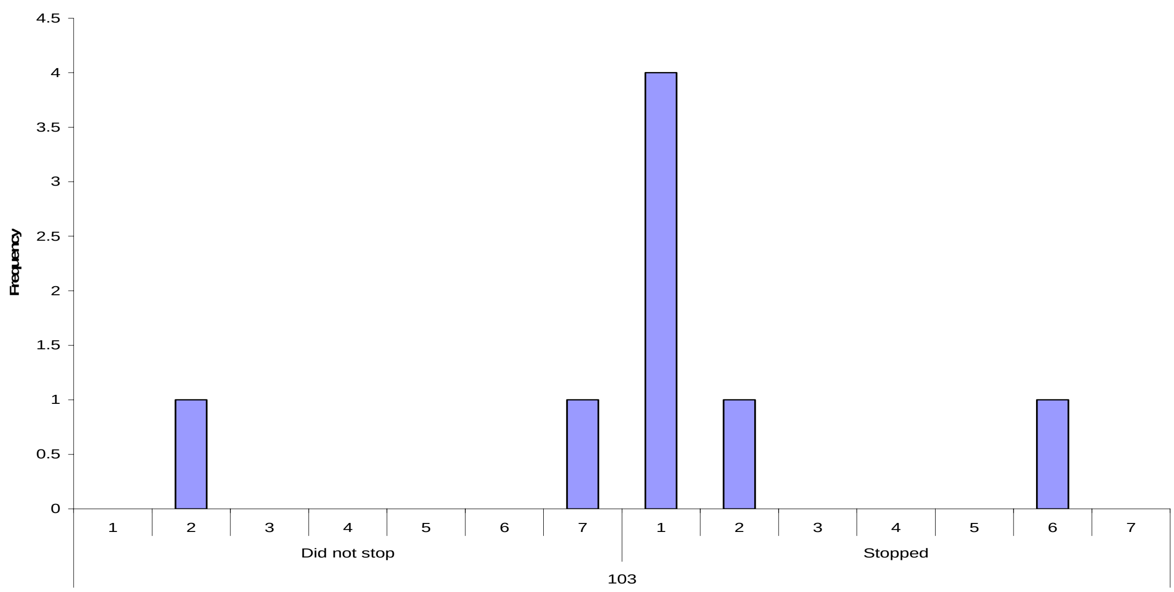

Figure E-16. "STOP" LED sign plus strobes, 35 mph, 2.65-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

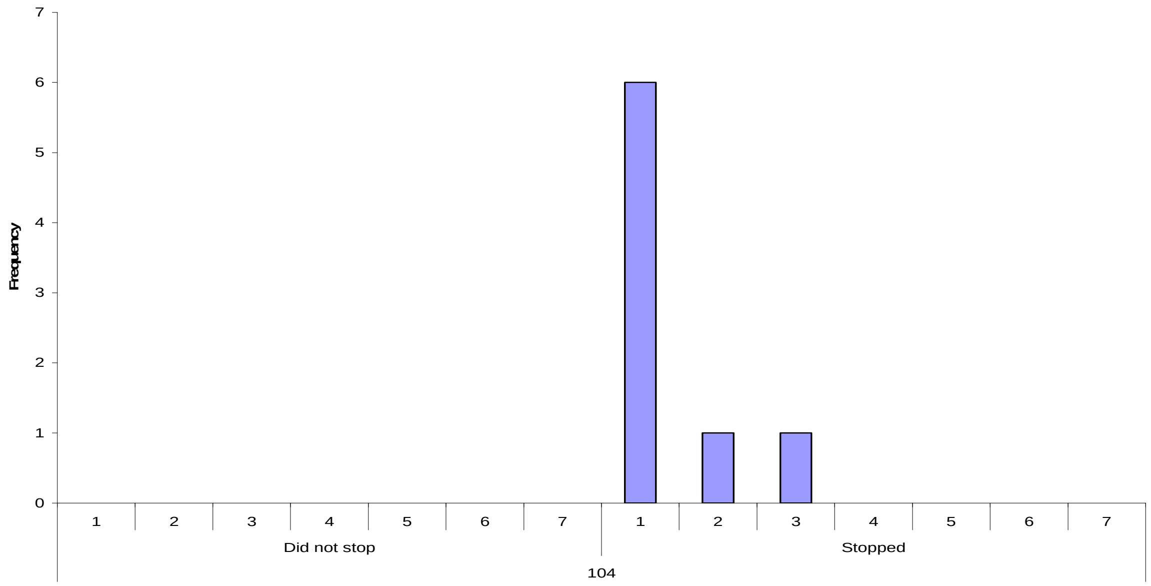

Figure E-17. "STOP" LED sign plus strobes, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

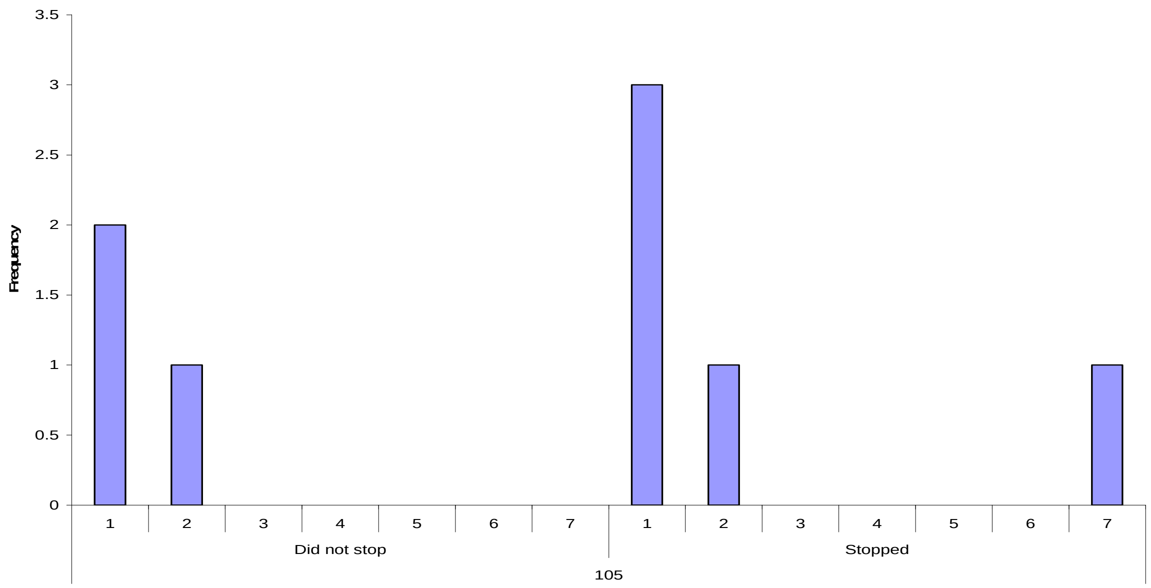

Figure E-18. LED-enhanced stop sign, 35 mph, 3.02-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

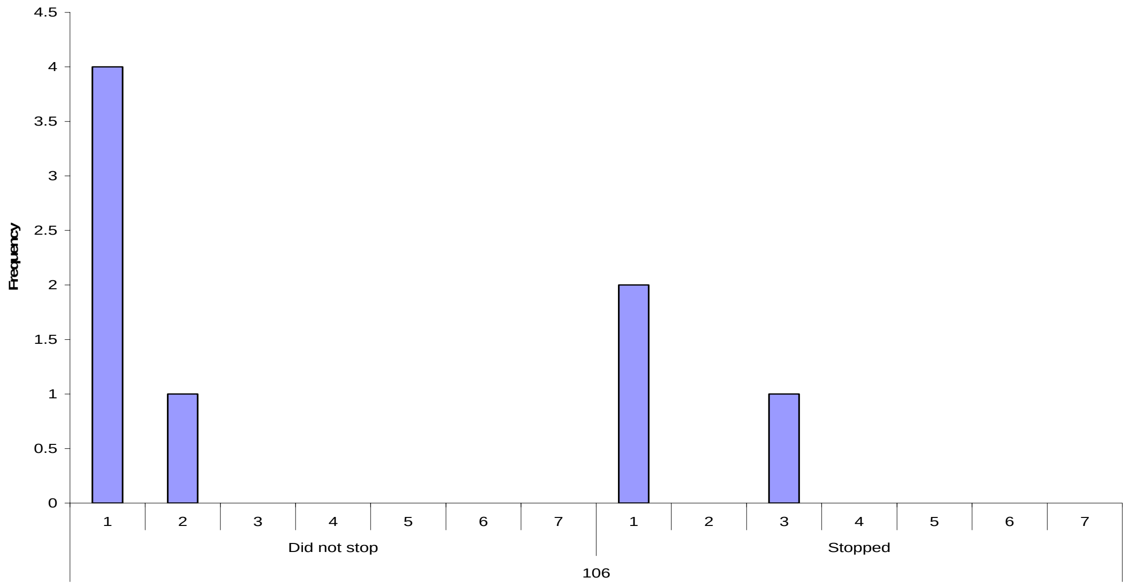

Figure E-19. Baseline, 35 mph, 3.02-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

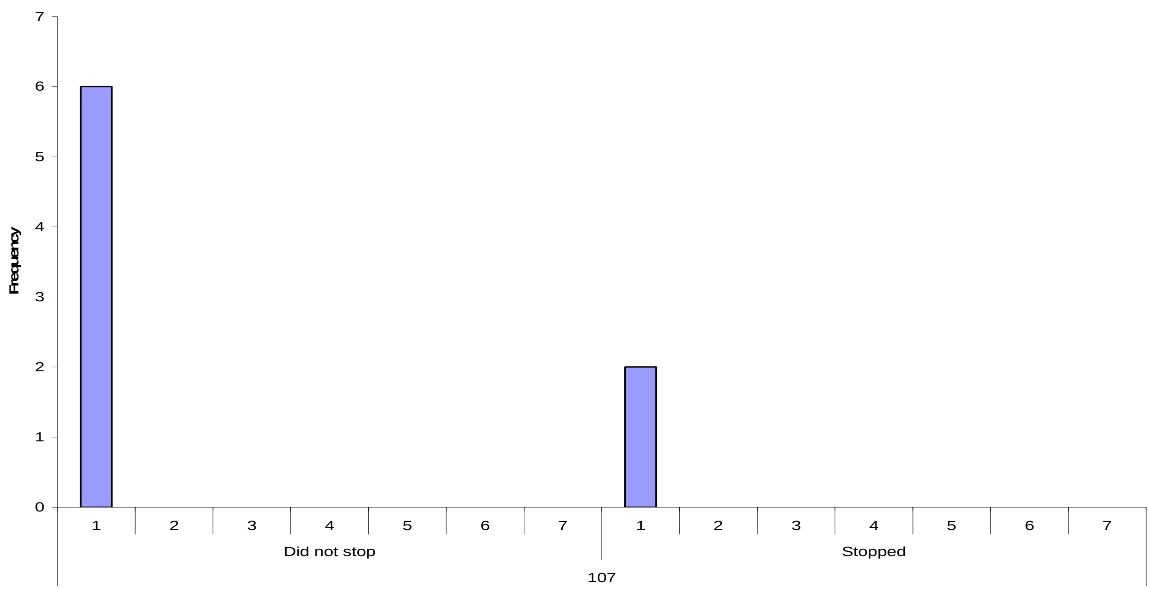

Figure E-20. LED-enhanced stop sign, 35 mph, 2.03-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

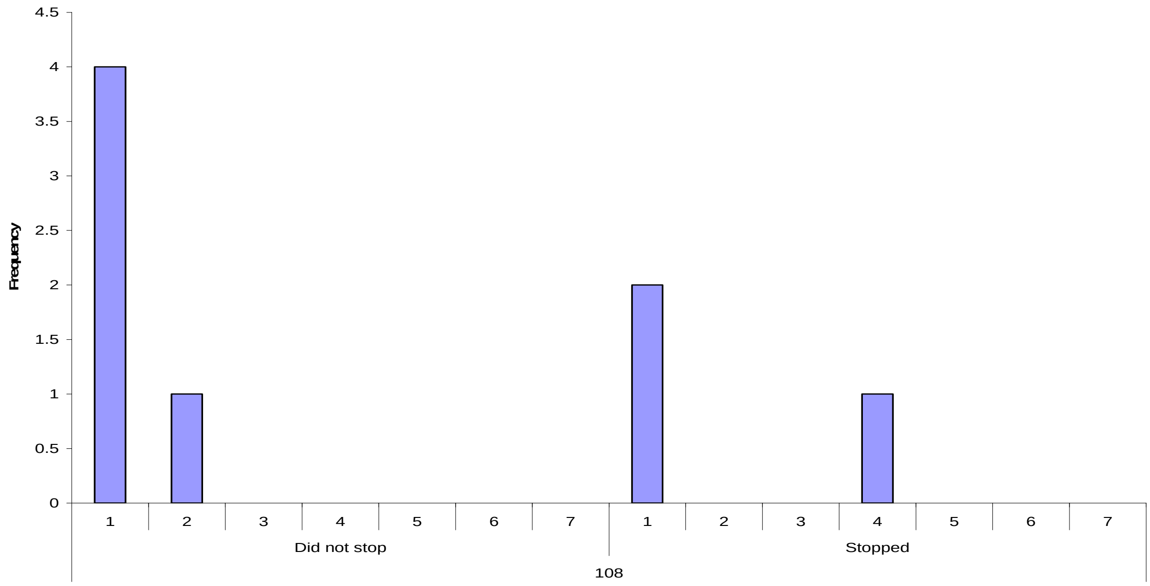

Figure E-21. LED-enhanced stop sign, 35 mph, 2.65-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

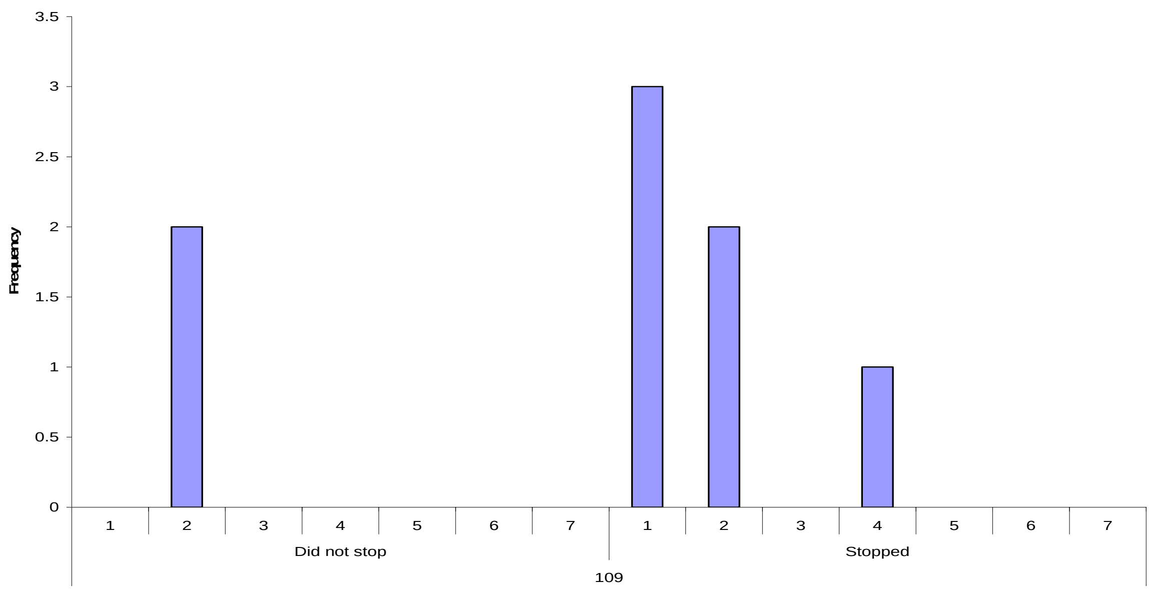

Figure E-22. Baseline, 35 mph, 2.65-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

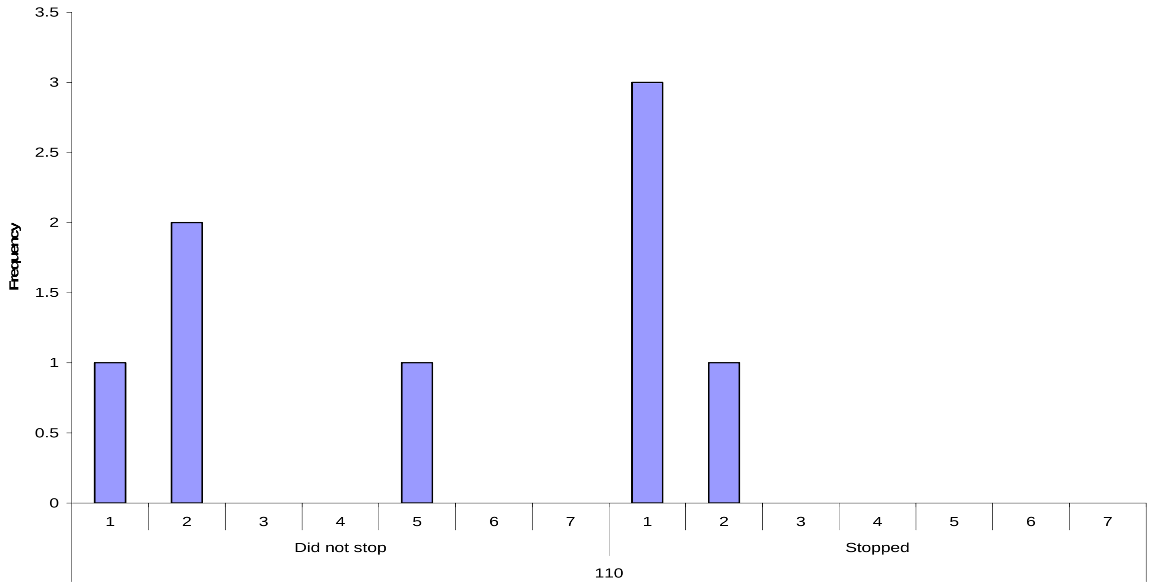

Figure E-23. Baseline, 35 mph, 3.41-second TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

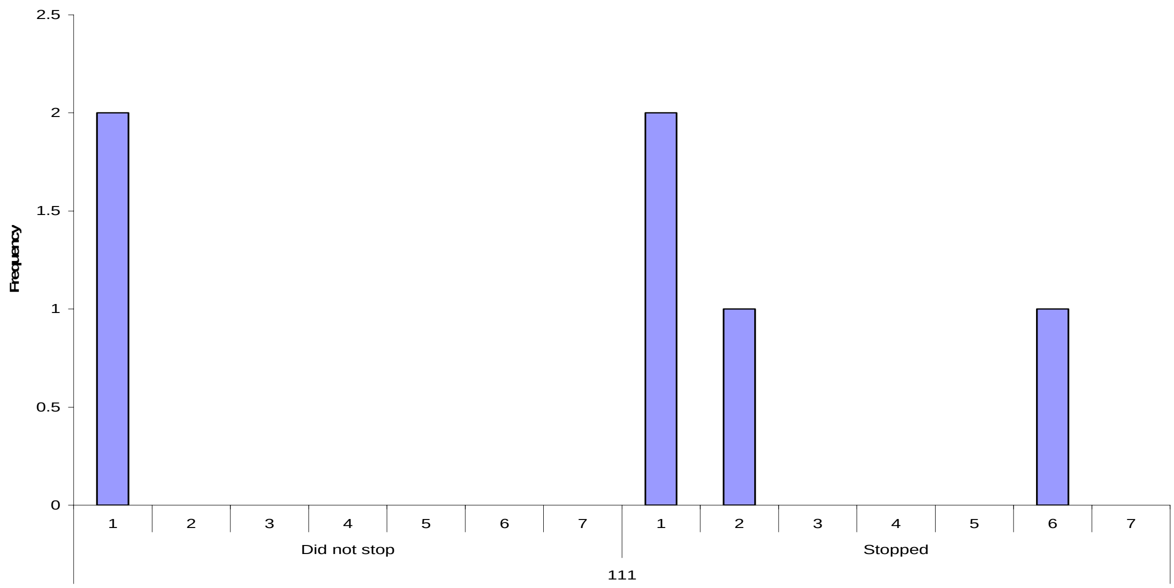

Figure E-24. LED-enhanced stop sign, 35 mph, 3.41-s TTI: Driver expectancy of the surprise event (1 = Strongly Disagree, 7 = Strongly Agree).

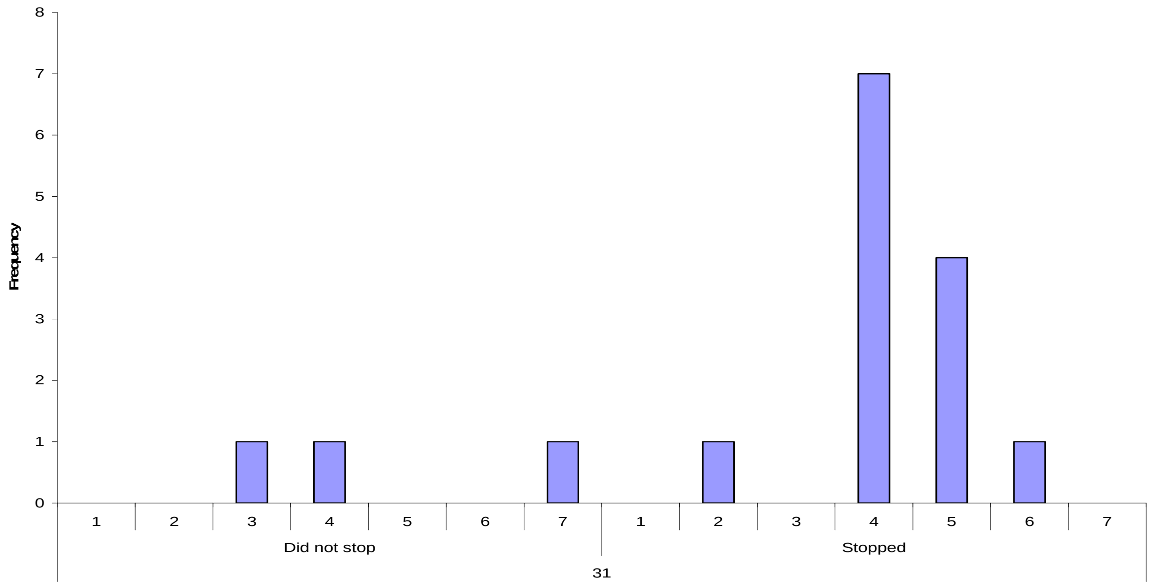

Figure E-25. Baseline, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

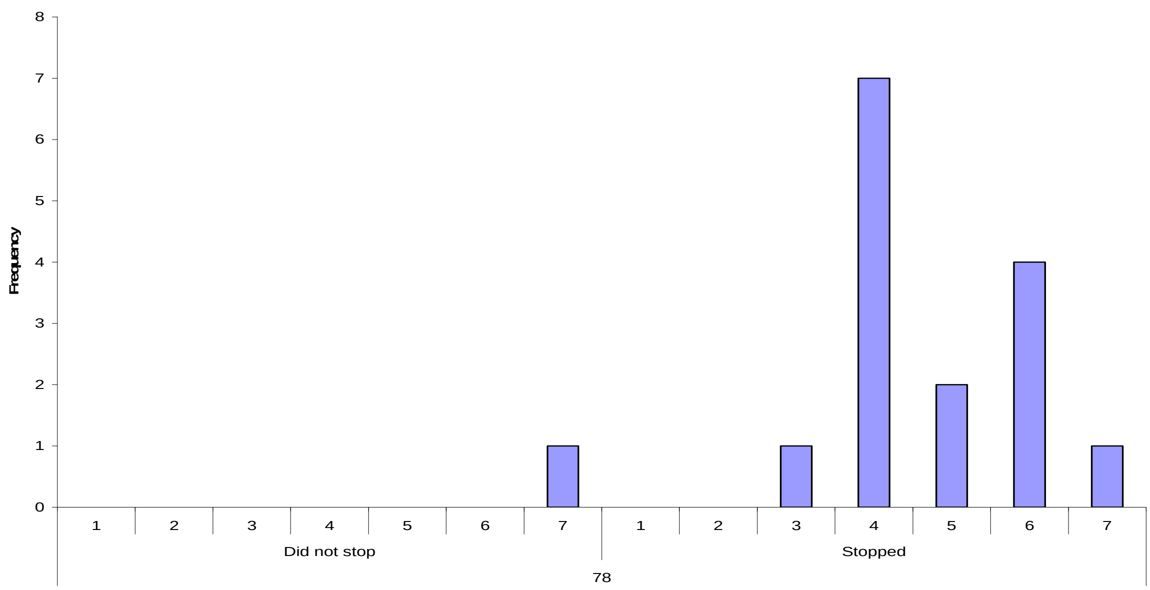

Figure E-26. "STOP" LED sign plus strobes plus TCLs, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

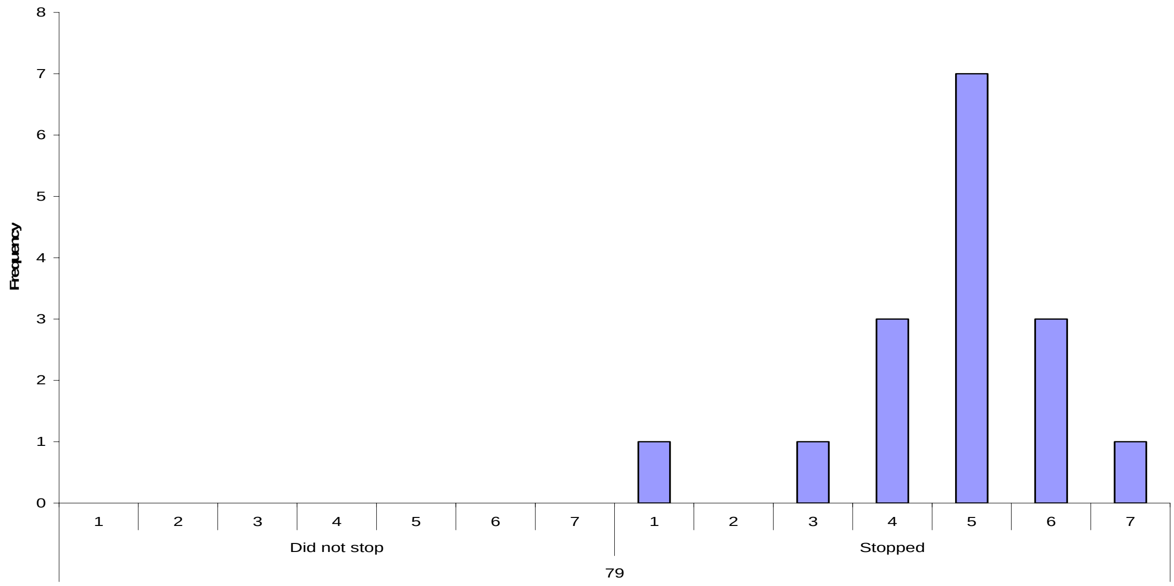

Figure E-27. "STOP" LED sign plus strobes plus TCLs, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

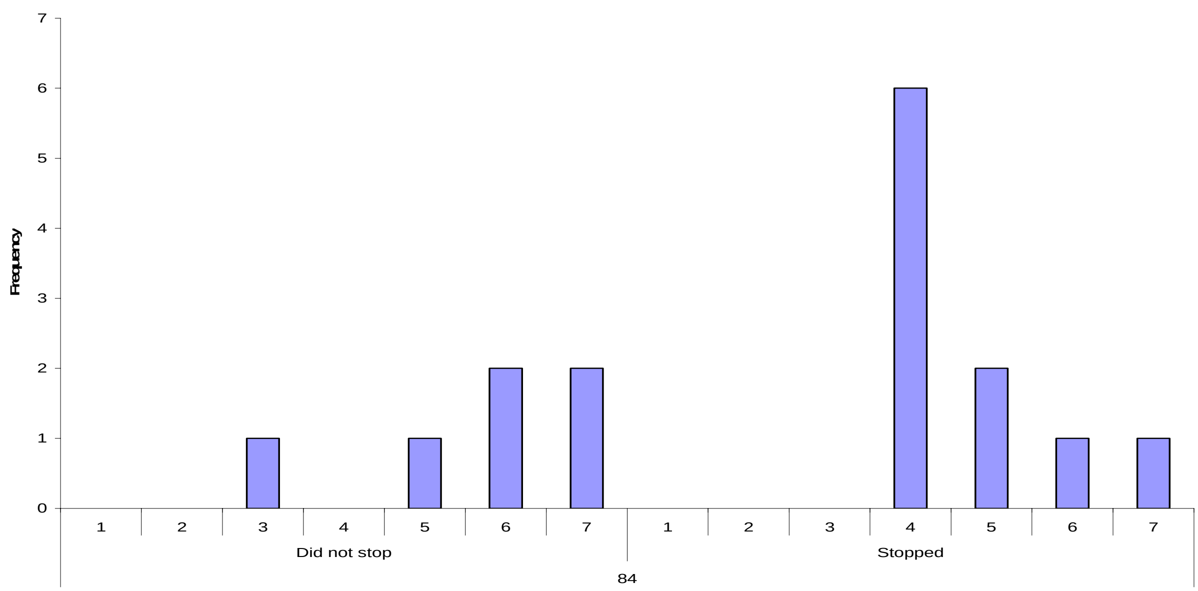

Figure E-28. Dual flashing red, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

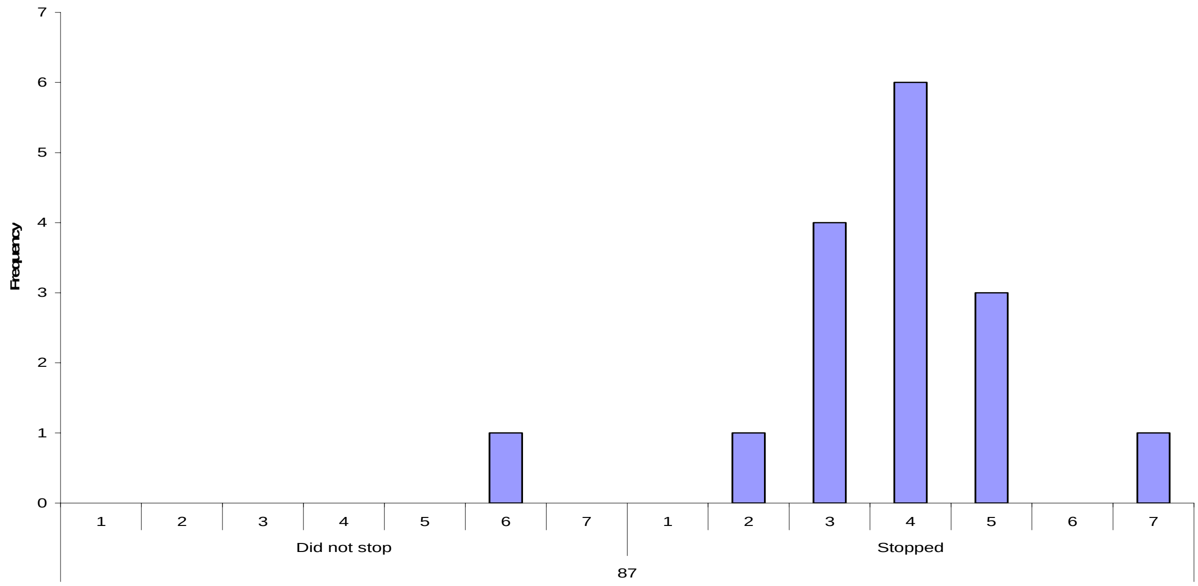

Figure E-29. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

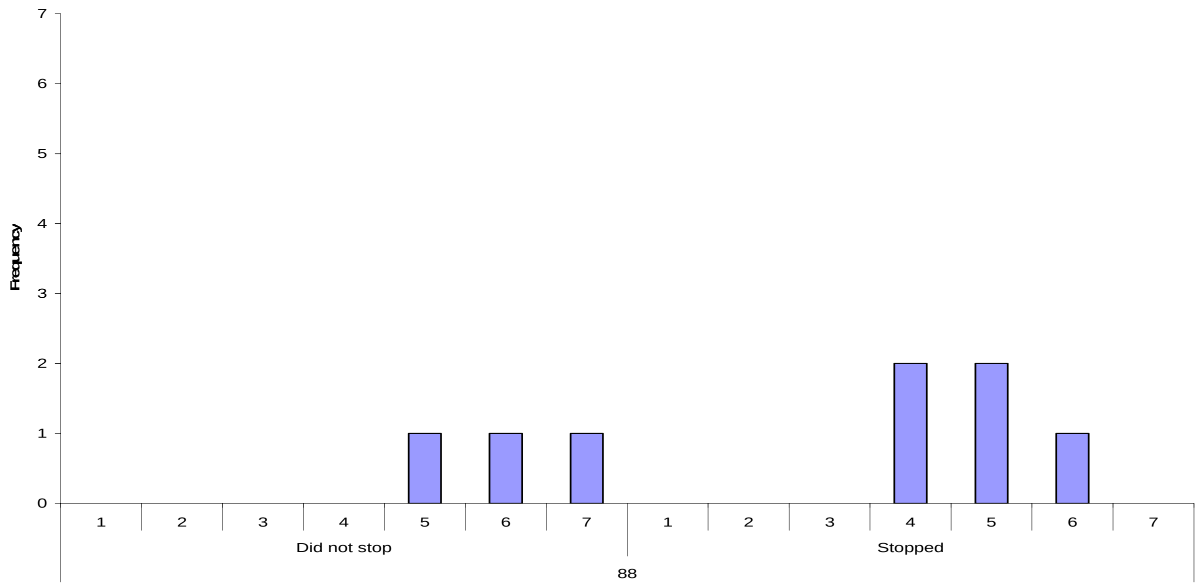

Figure E-30. Baseline, 35 mph, 2.65-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

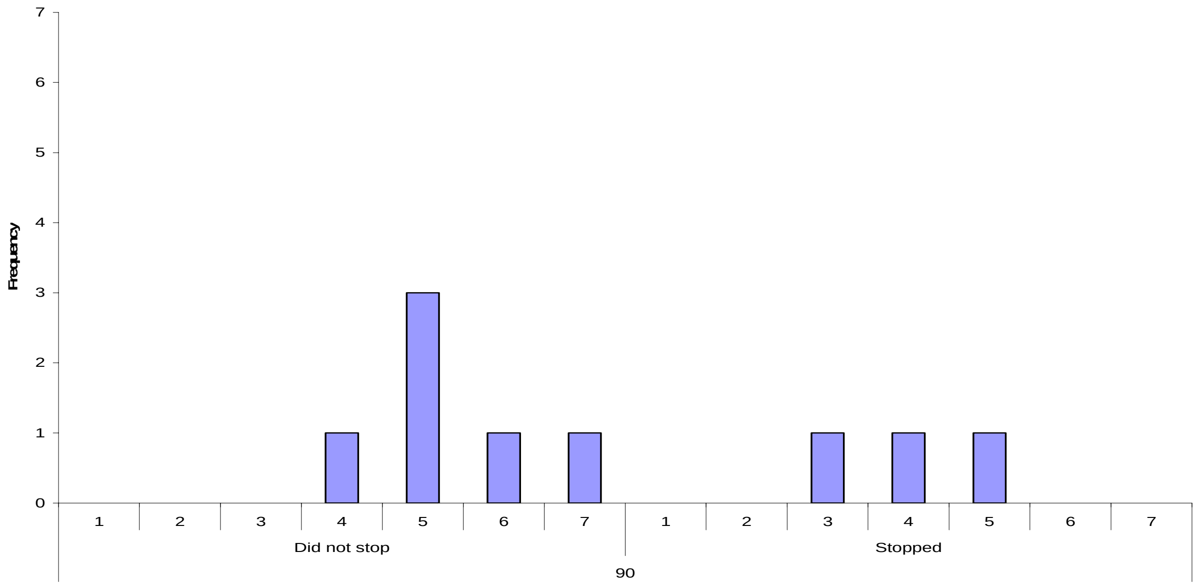

Figure E-31. Baseline, 35 mph, 2.03-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

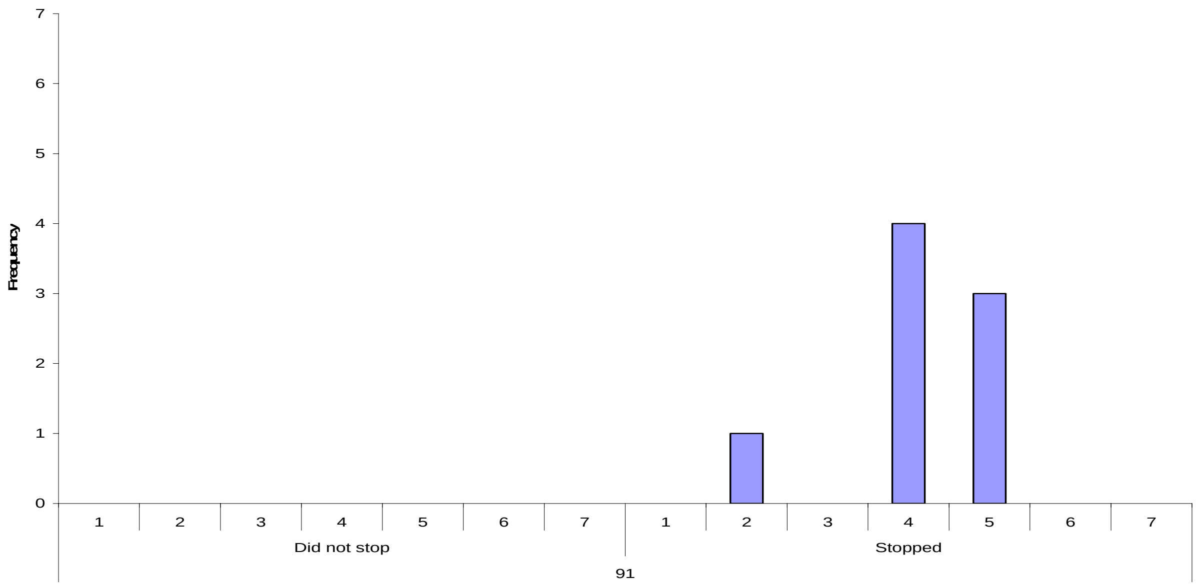

Figure E-32. Baseline, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

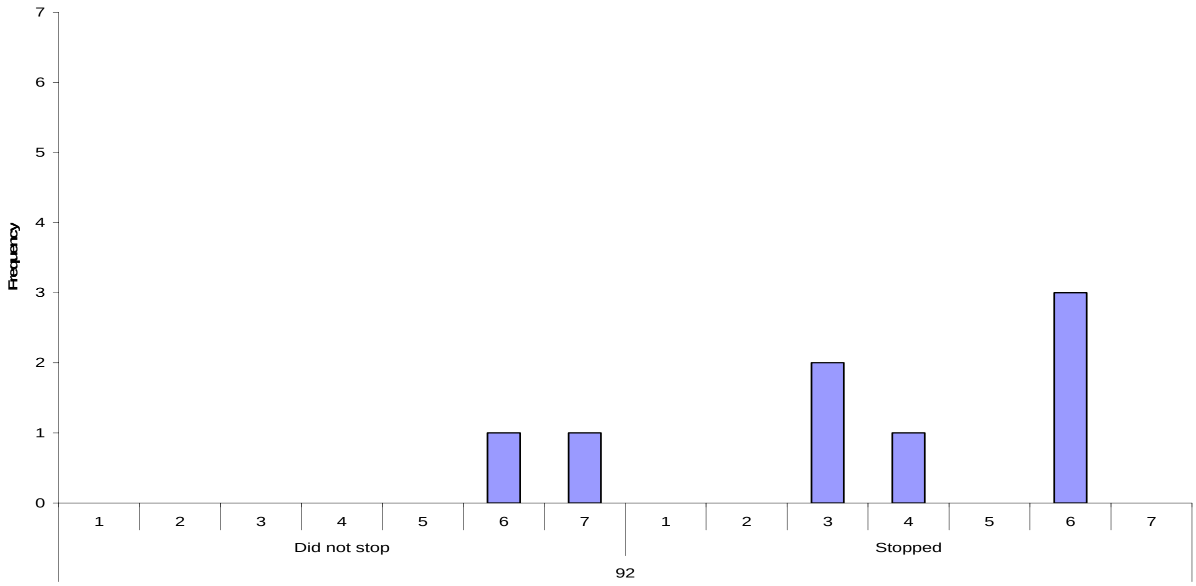

Figure E-33. Baseline, 35 mph, 3.02-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

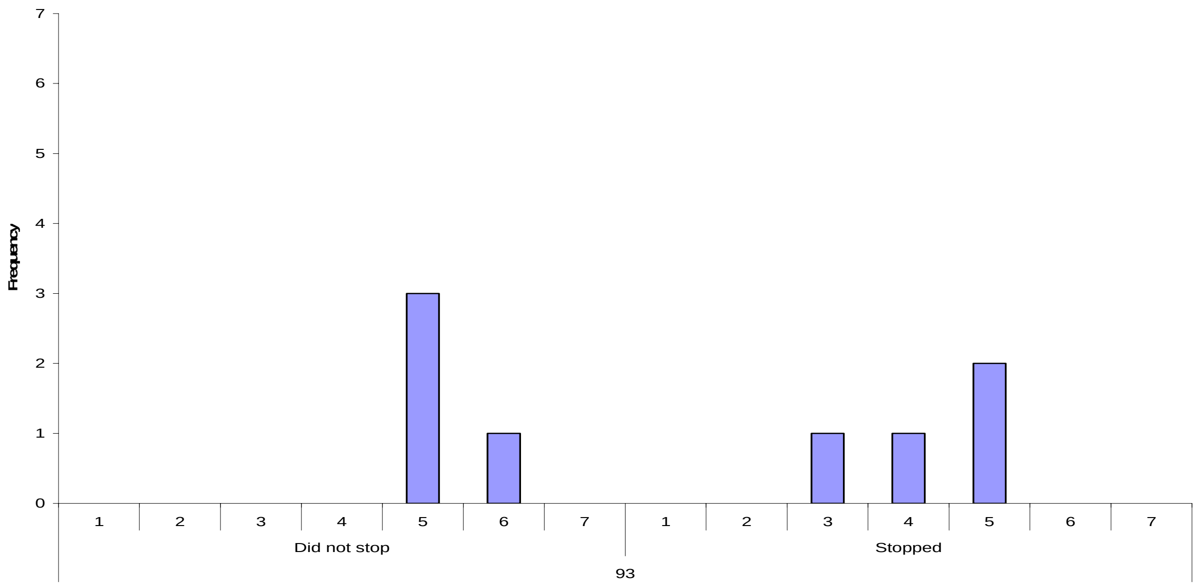

Figure E-34. Rumble strip simulation, 35 mph, 2.03-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

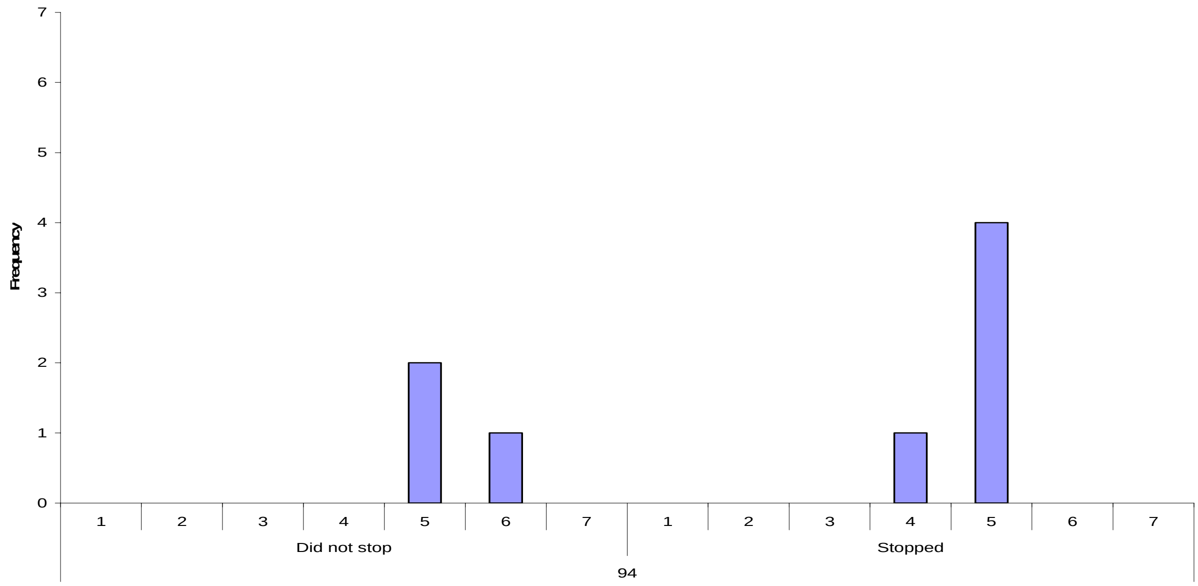

Figure E-35. Rumble strip simulation, 35 mph, 2.65-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

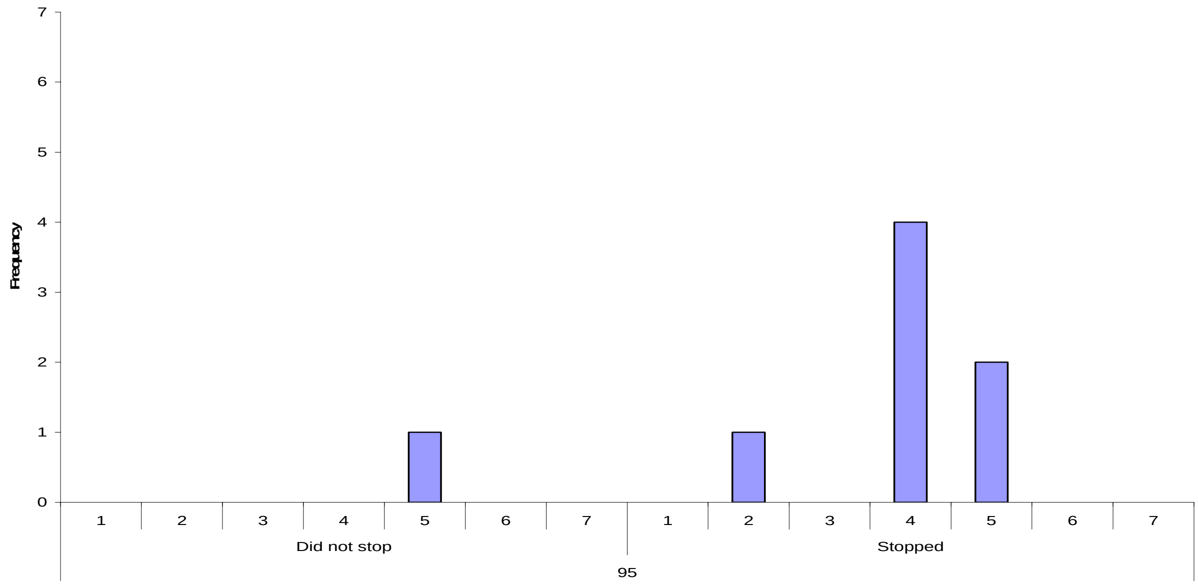

Figure E-36. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

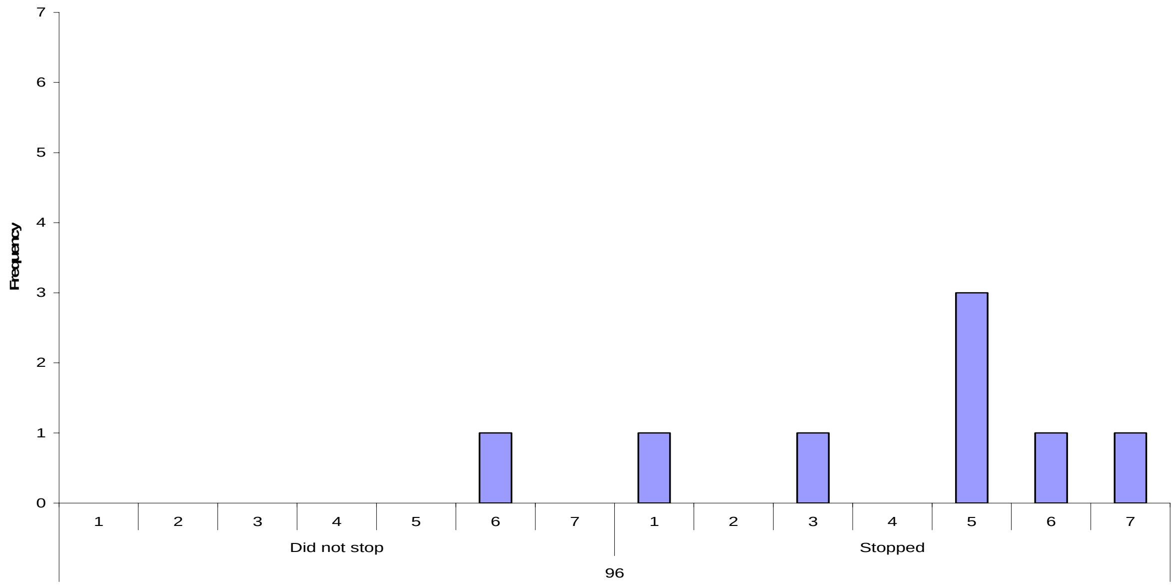

Figure E-37. Rumble strip simulation, 35 mph, 3.02-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

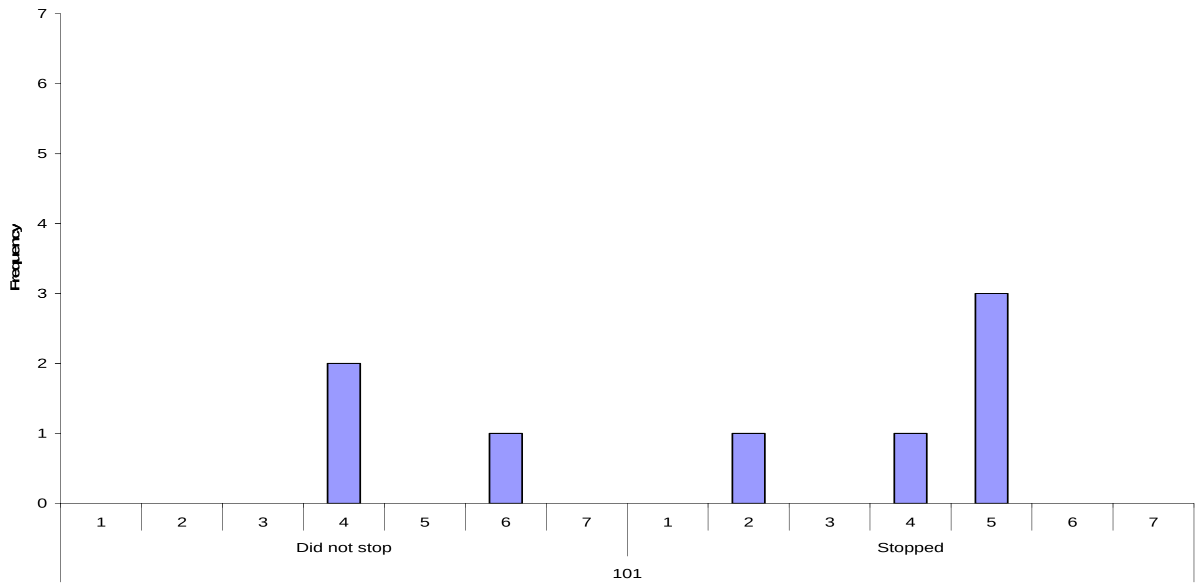

Figure E-38. "STOP" LED sign plus strobes, 35 mph, 3.02-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

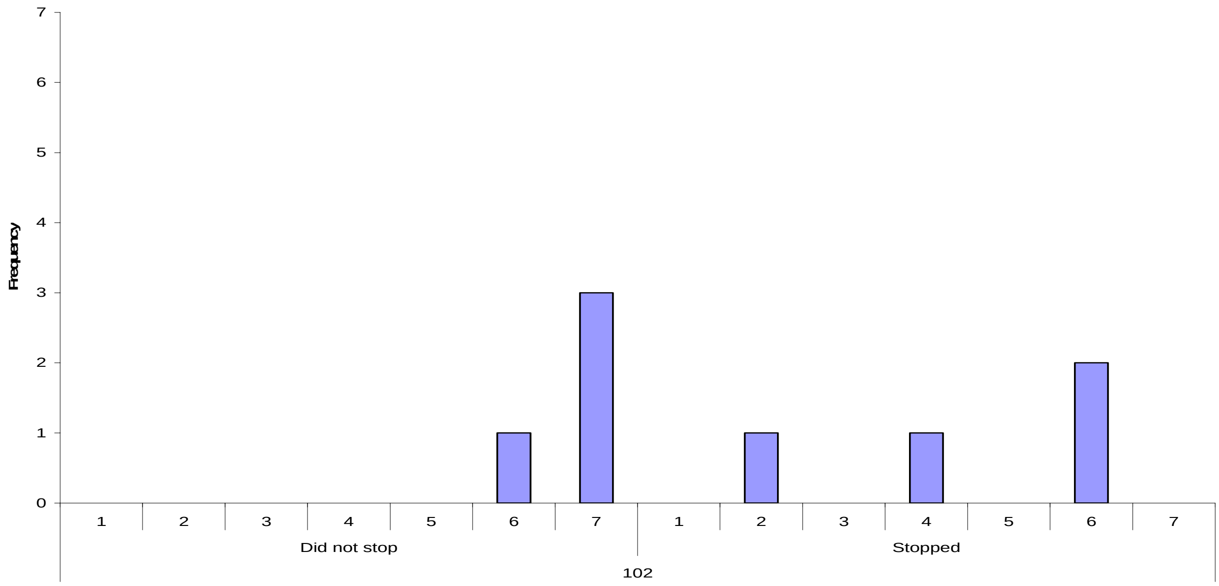

Figure E-39. "STOP" LED sign plus strobes, 35 mph, 2.03-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

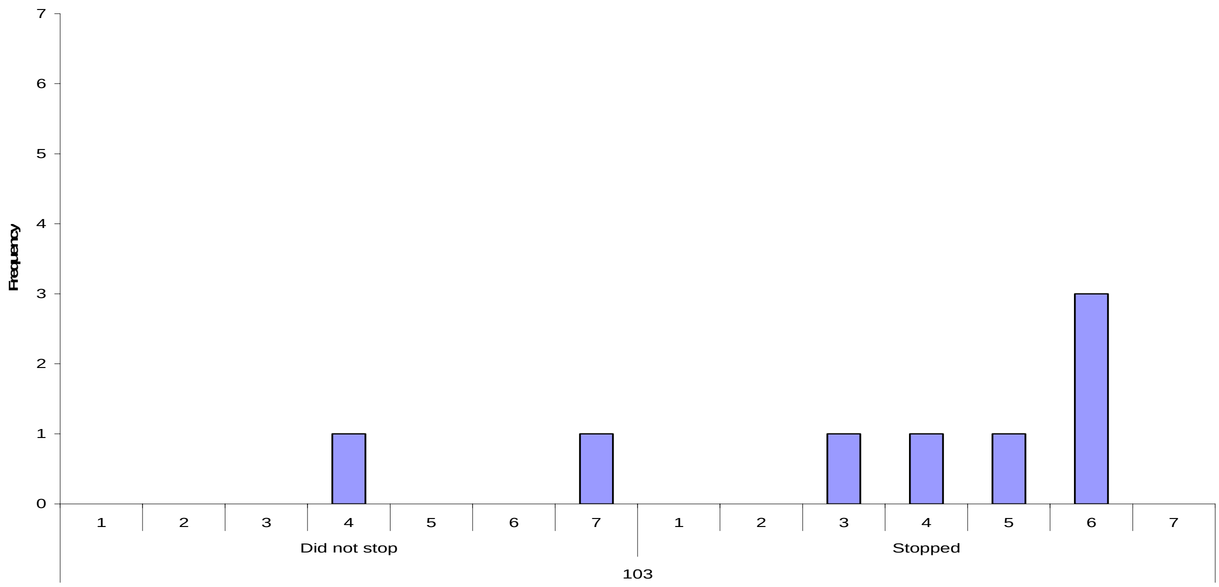

Figure E-40. "STOP" LED sign plus strobes, 35 mph, 2.65-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

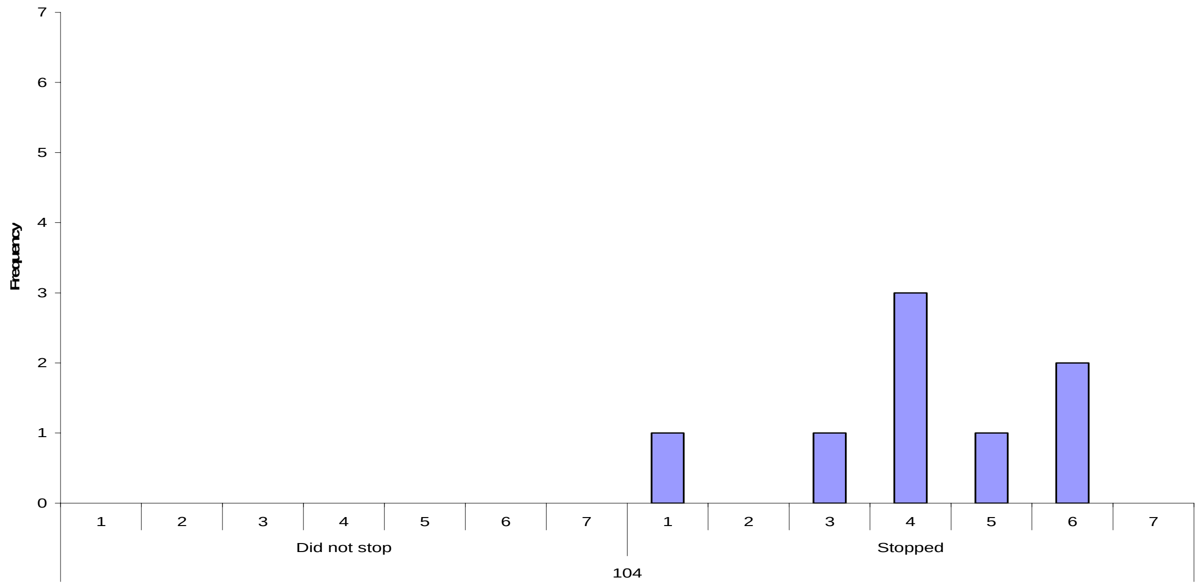

Figure E-41. "STOP" LED sign plus strobes, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

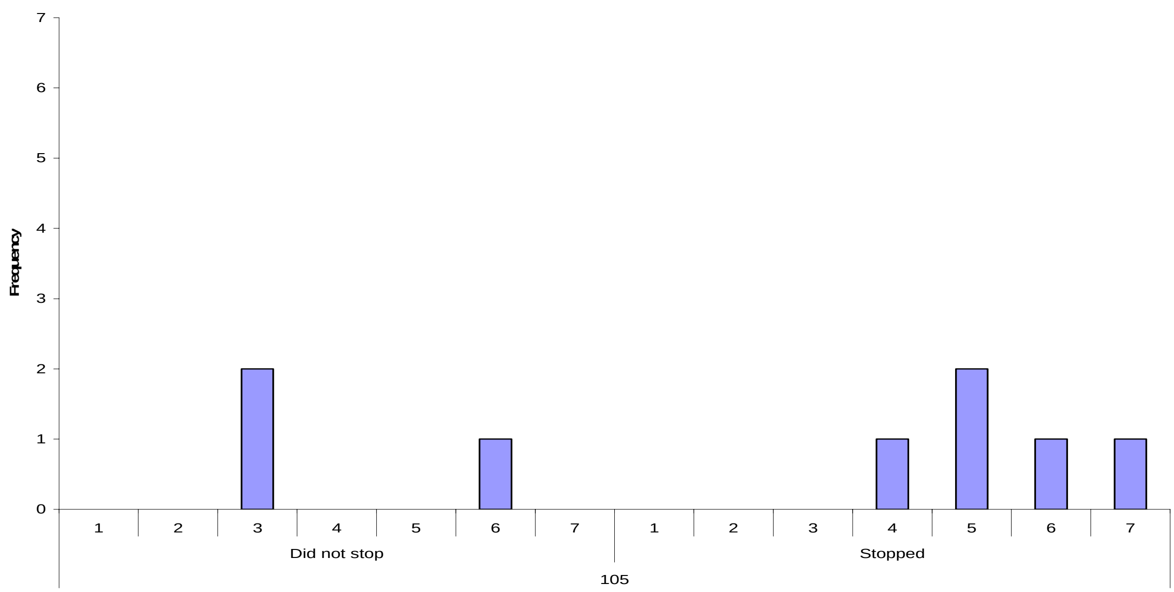

Figure E-42. LED-enhanced stop sign, 35 mph, 3.02-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

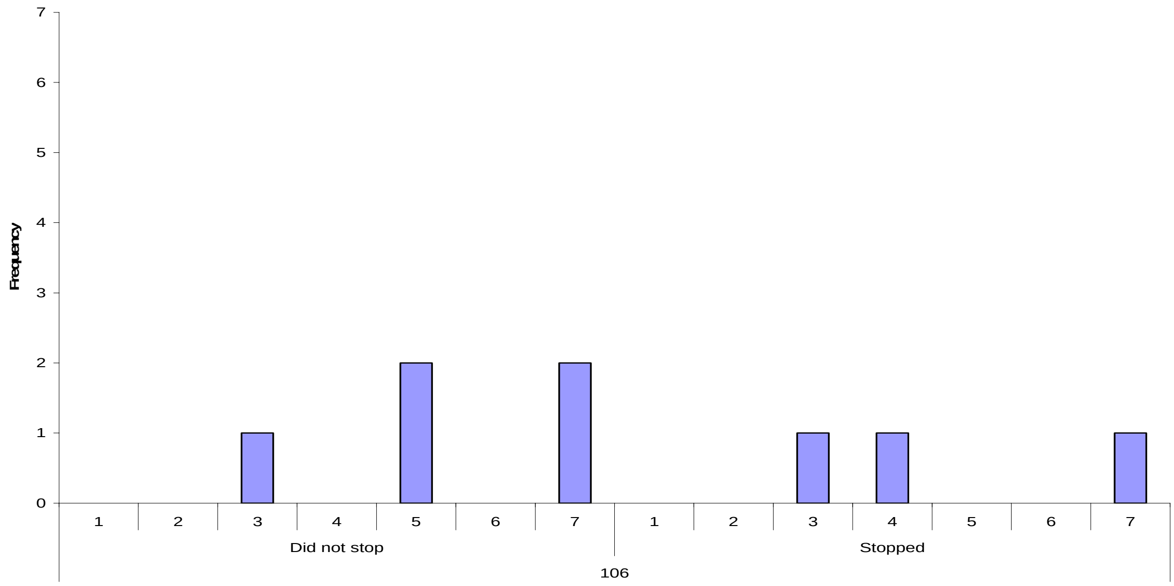

Figure E-43. Baseline, 35 mph, 3.02-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

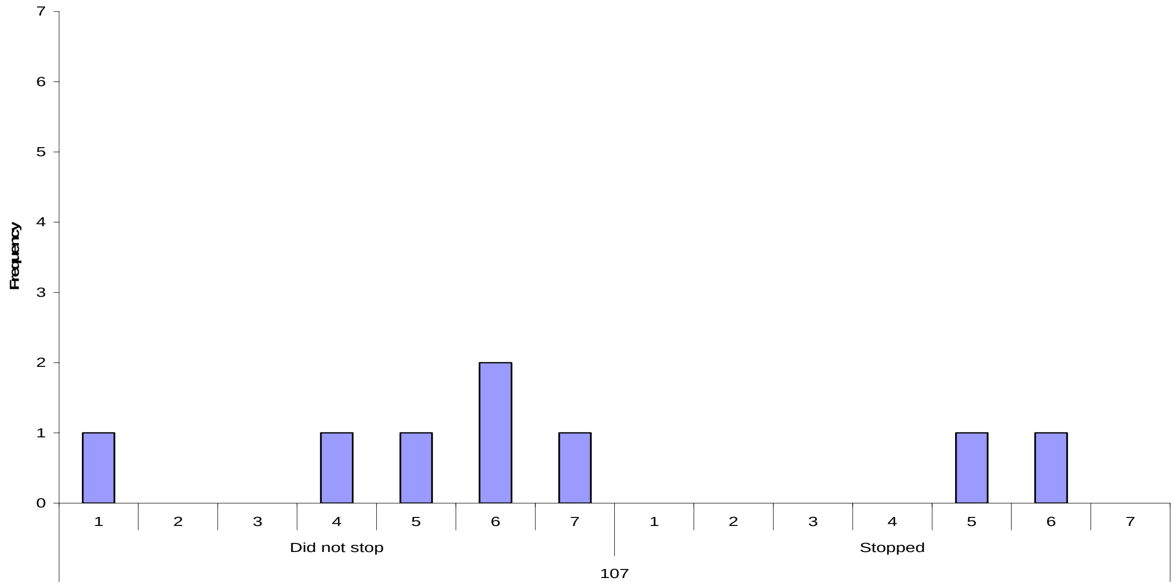

Figure E-44. LED-enhanced stop sign, 35 mph, 2.03-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

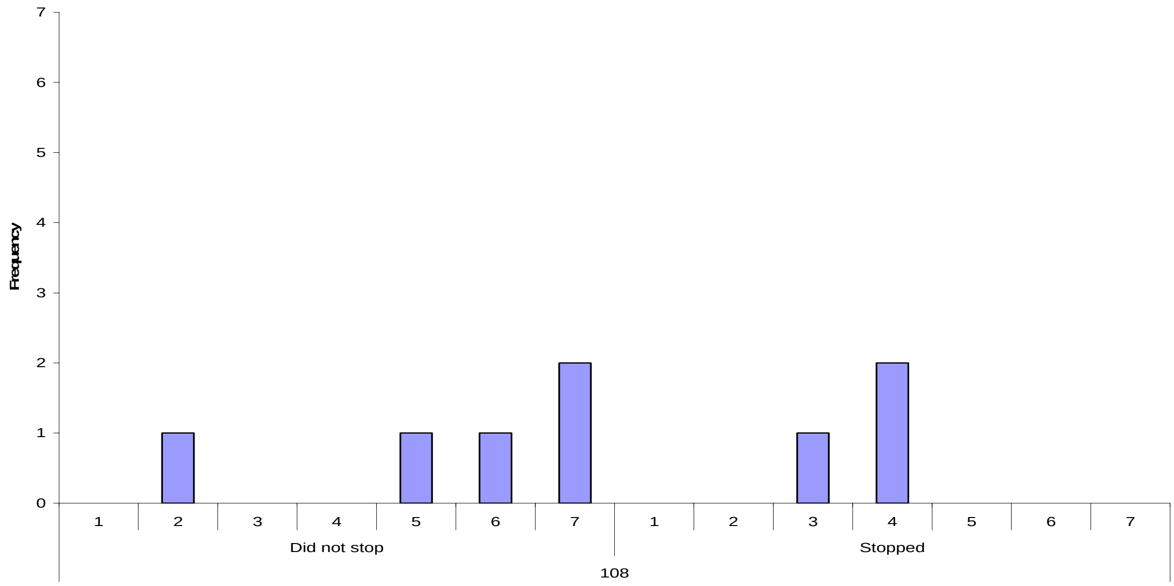

Figure E-45. LED-enhanced stop sign, 35 mph, 2.65-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

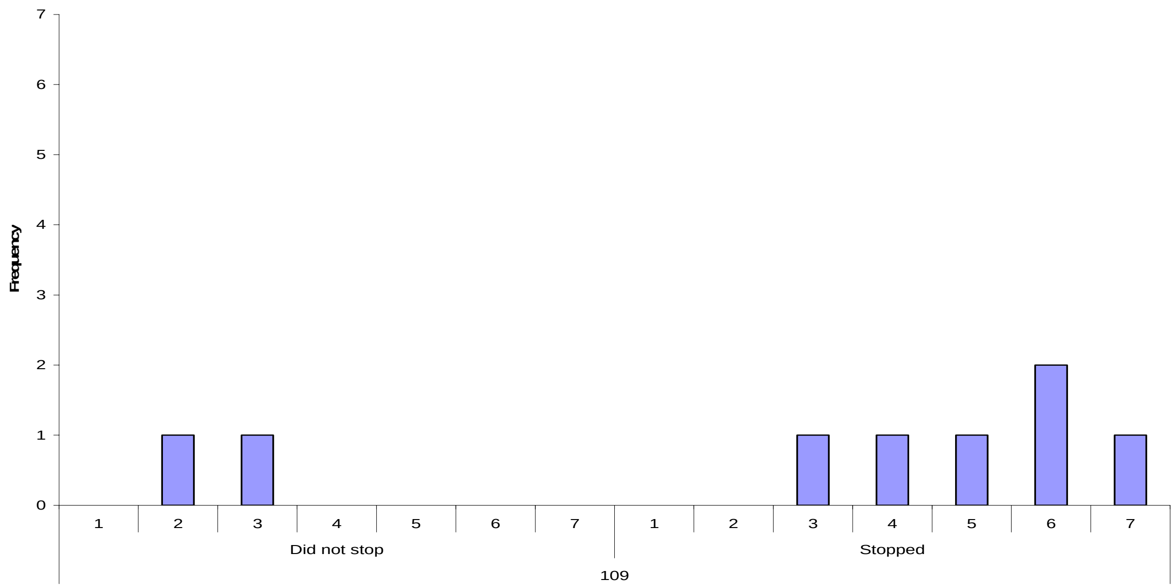

Figure E-46. Baseline, 35 mph, 2.65-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

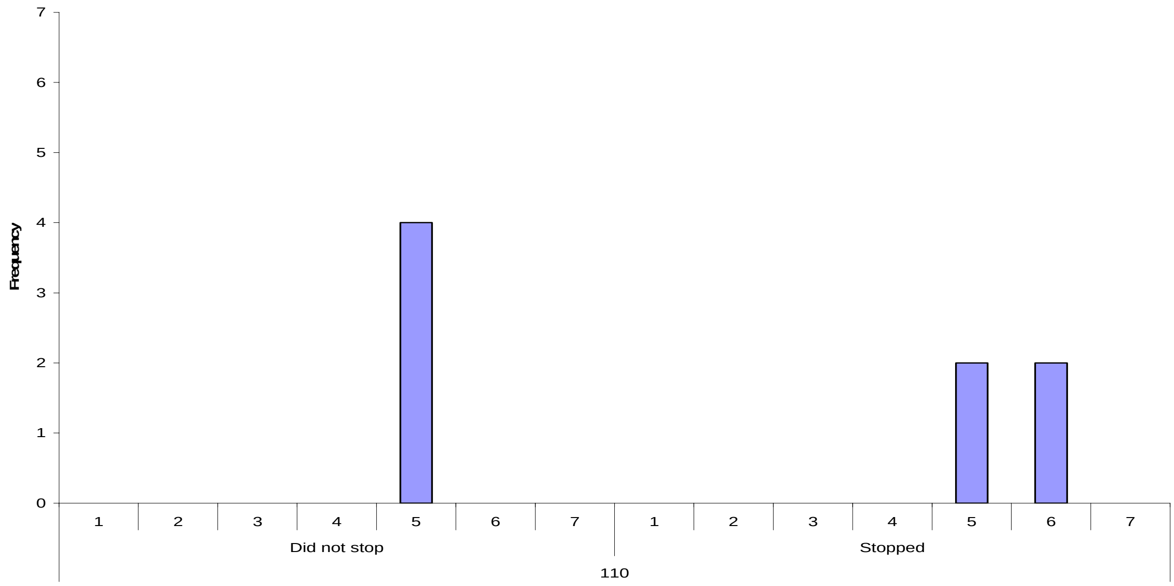

Figure E-47. Baseline, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

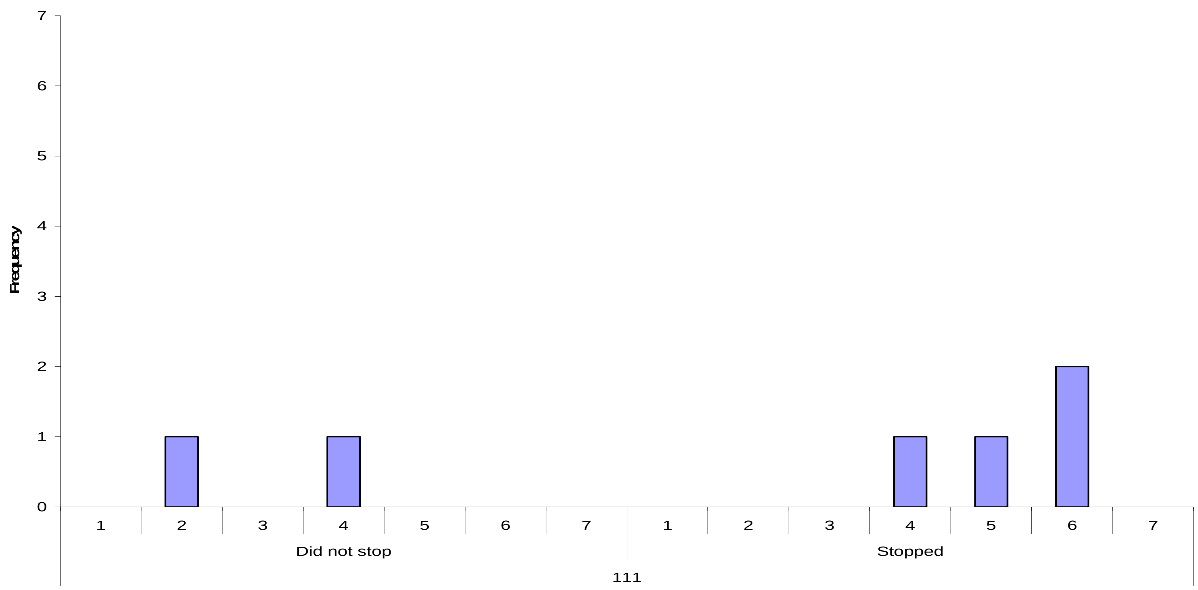

Figure E-48. LED-enhanced stop sign, 35 mph, 3.41-second TTI: Driver-perceived timing of the end of the occlusion for the surprise event (1 = Very Early, 7 = Very Late).

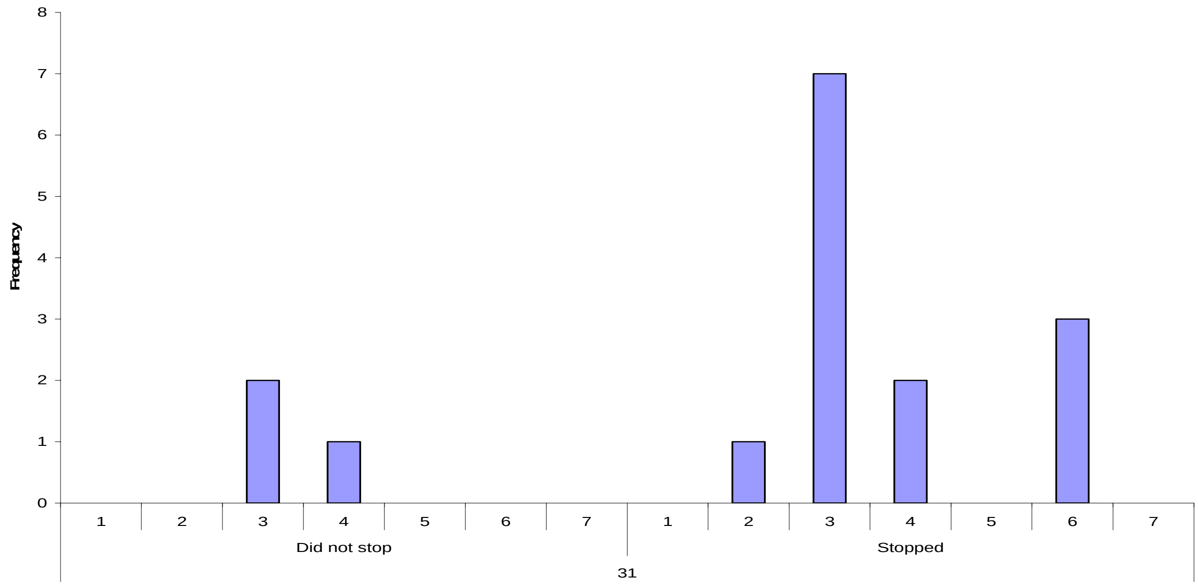

Figure E-49. Baseline, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

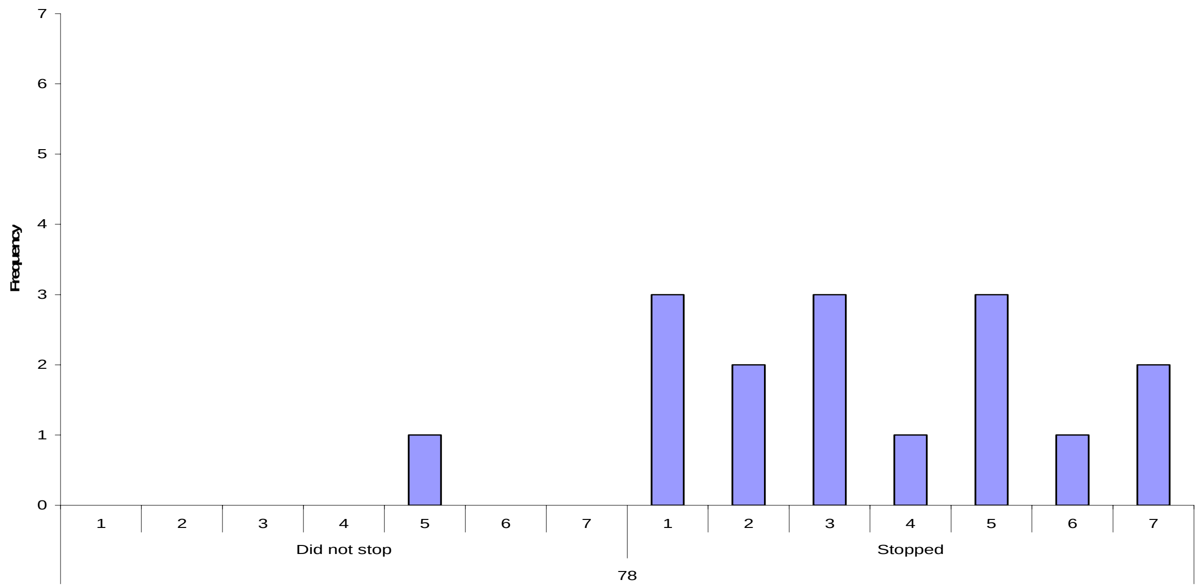

Figure E-50. "STOP" LED sign plus strobes plus TCLs, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

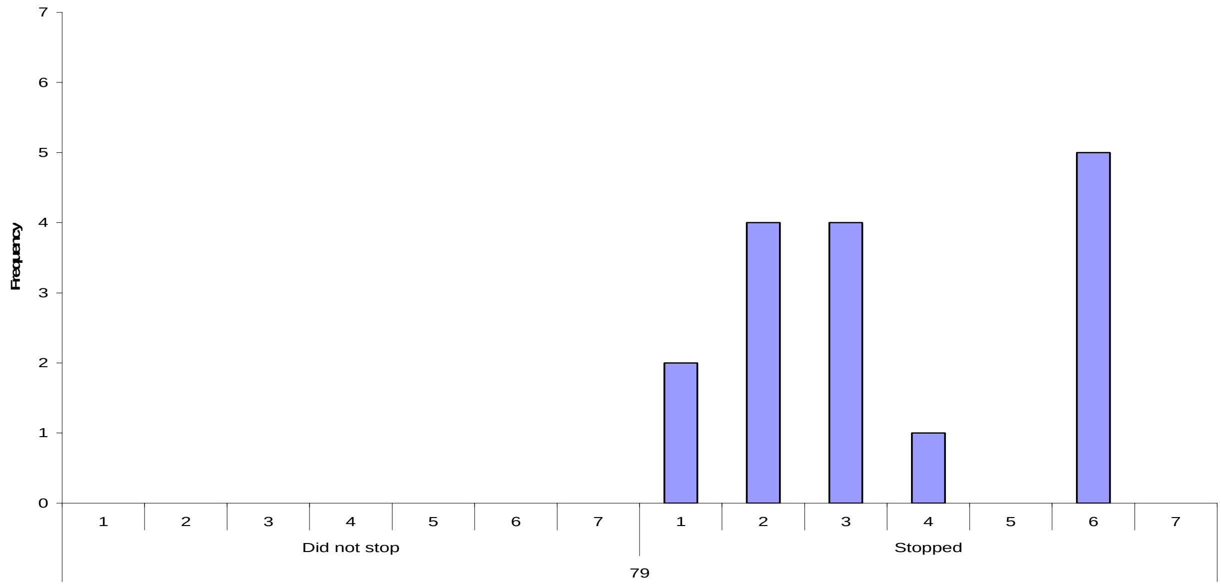

Figure E-51. "STOP" LED sign plus Strobes, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

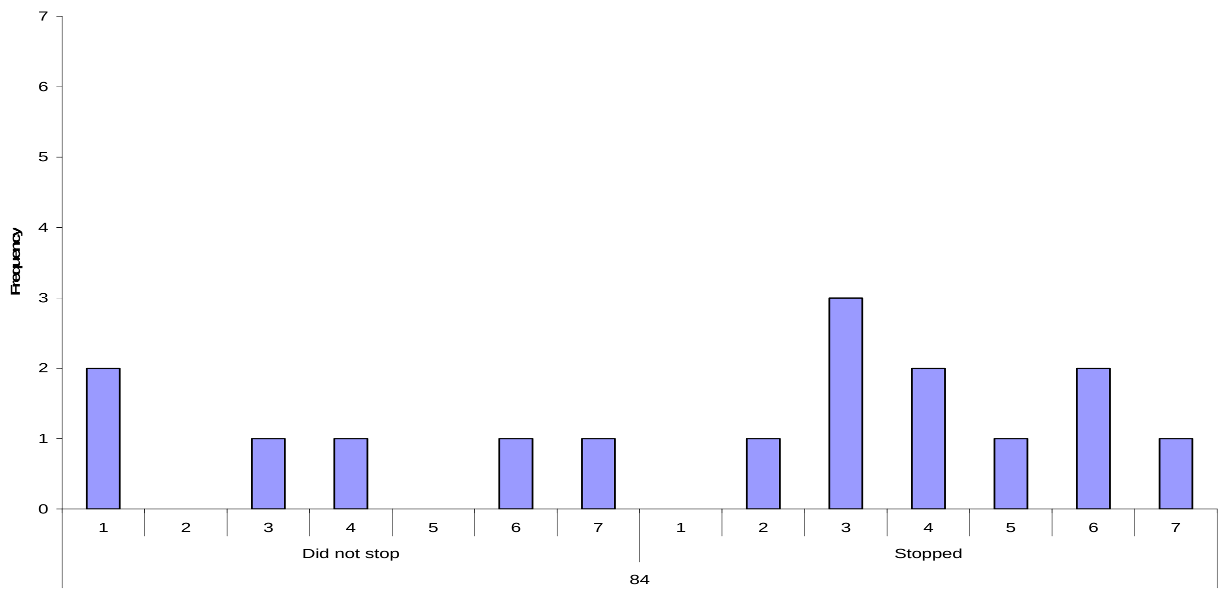

Figure E-52. Dual flashing red, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

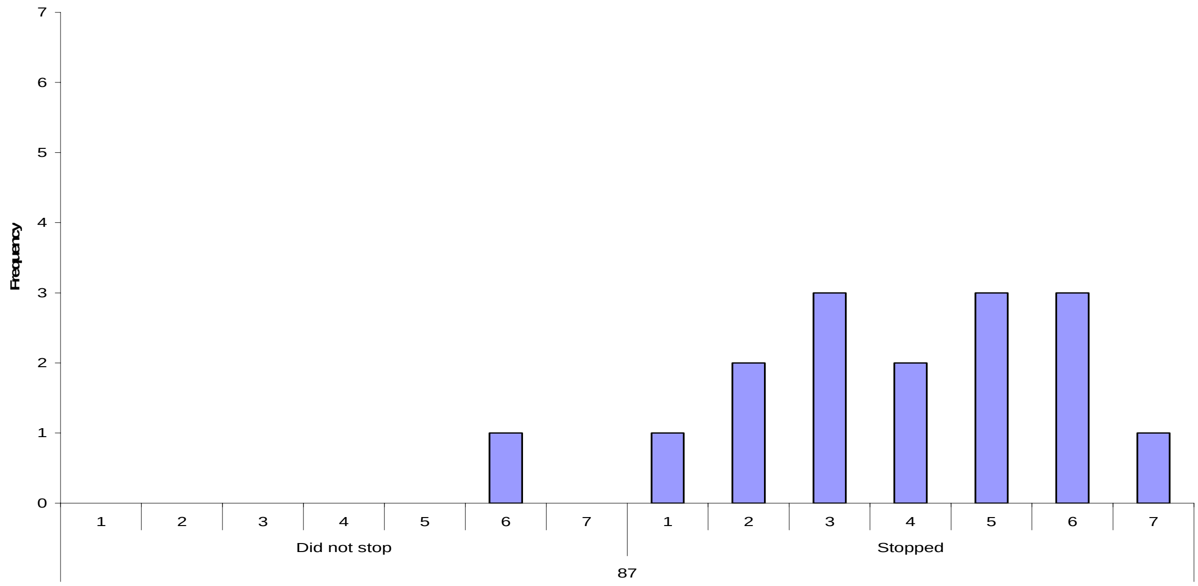

Figure E-53. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

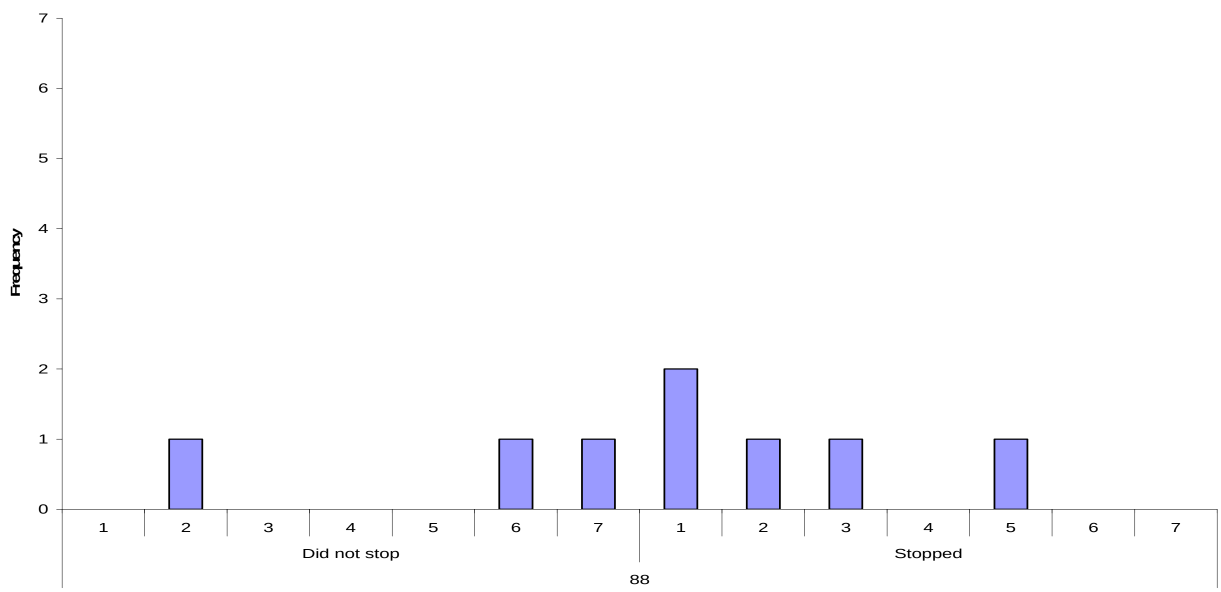

Figure E-54. Baseline, 35 mph, 2.65-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

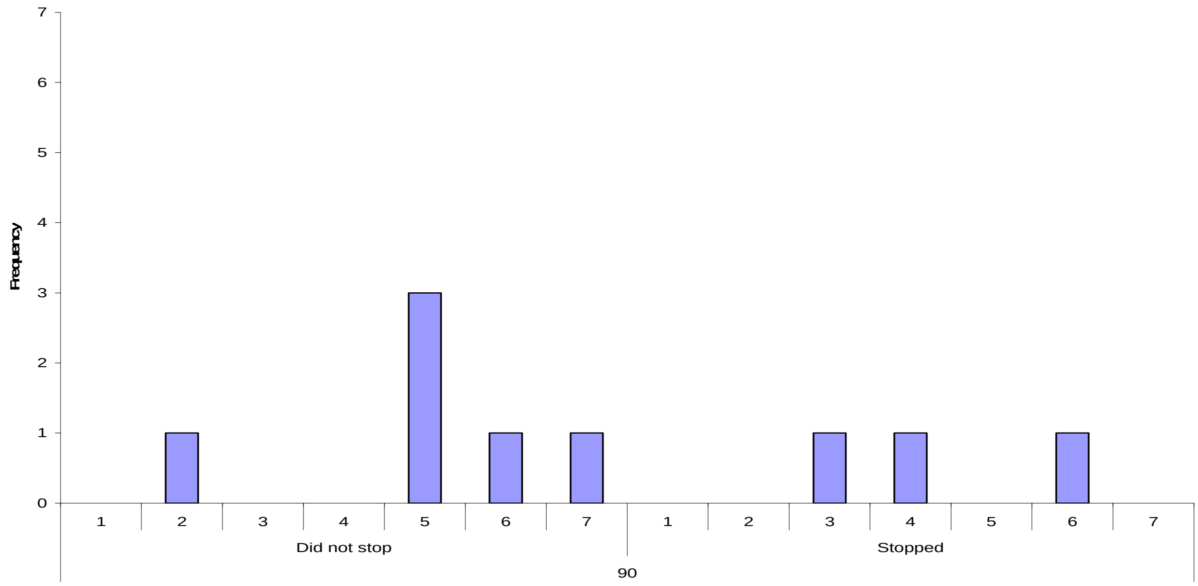

Figure E-55. Baseline, 35 mph, 2.03-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

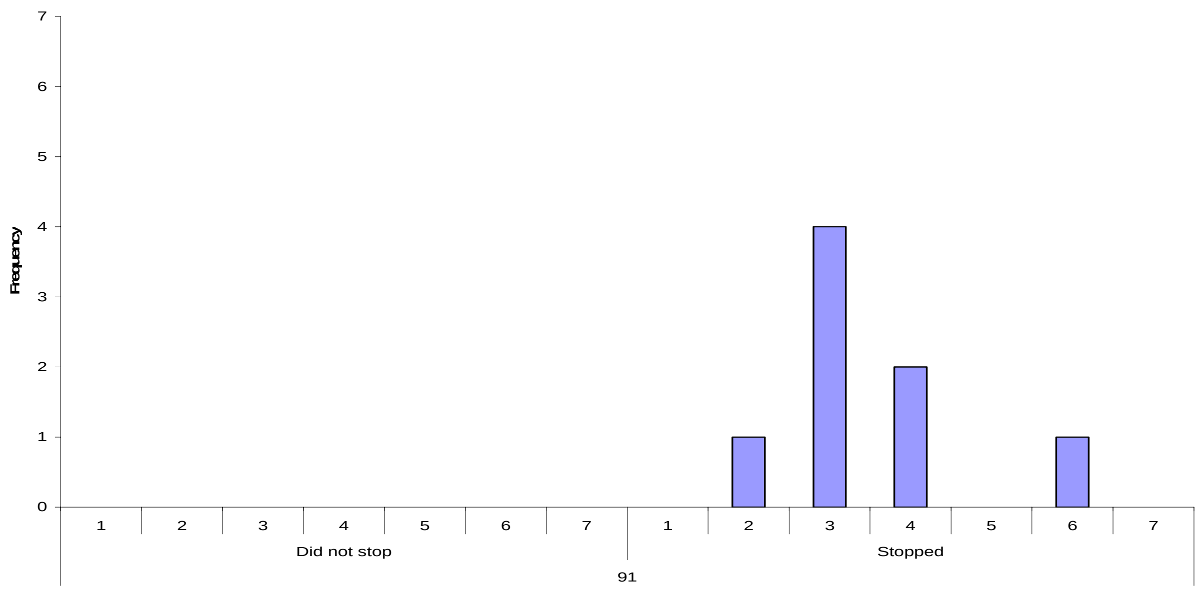

Figure E-56. Baseline, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

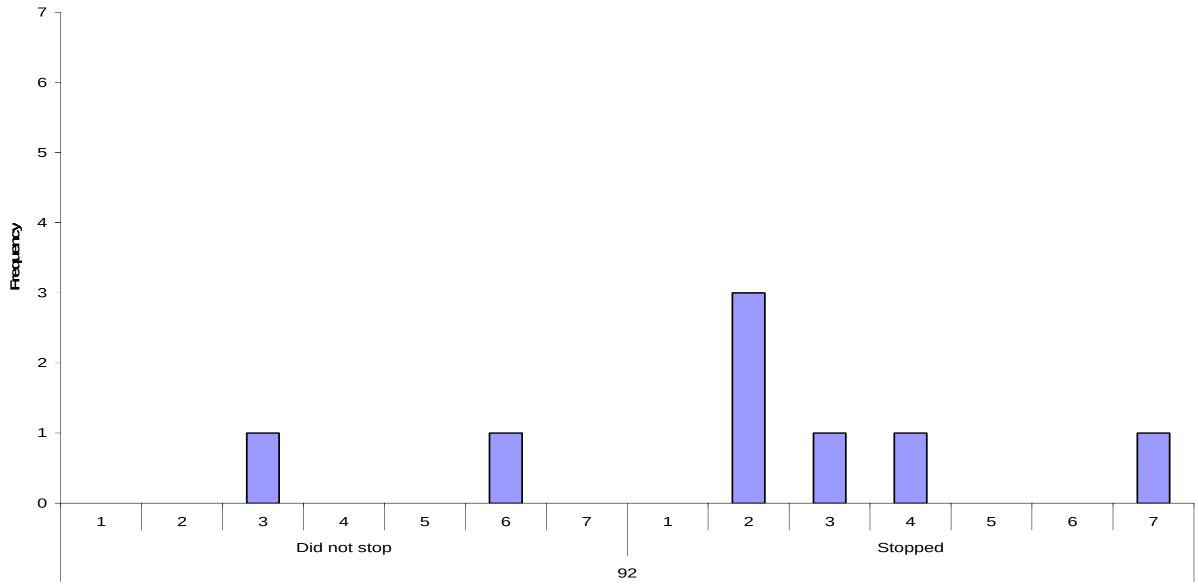

Figure E-57. Baseline, 35 mph, 3.02-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

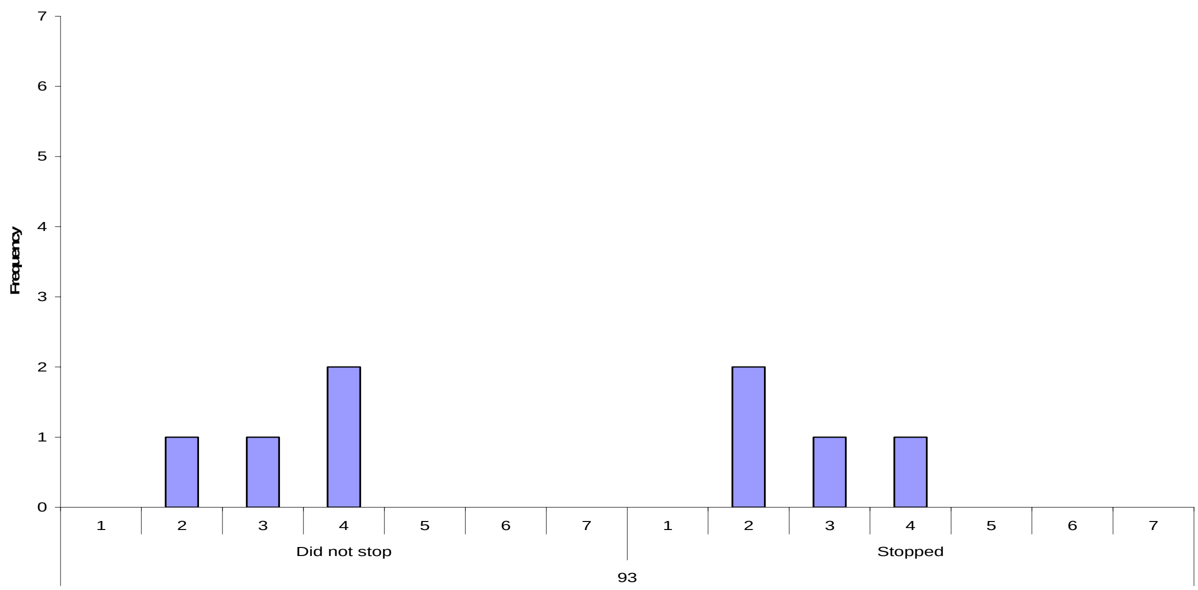

Figure E-58. Rumble strip simulation, 35 mph, 2.03-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

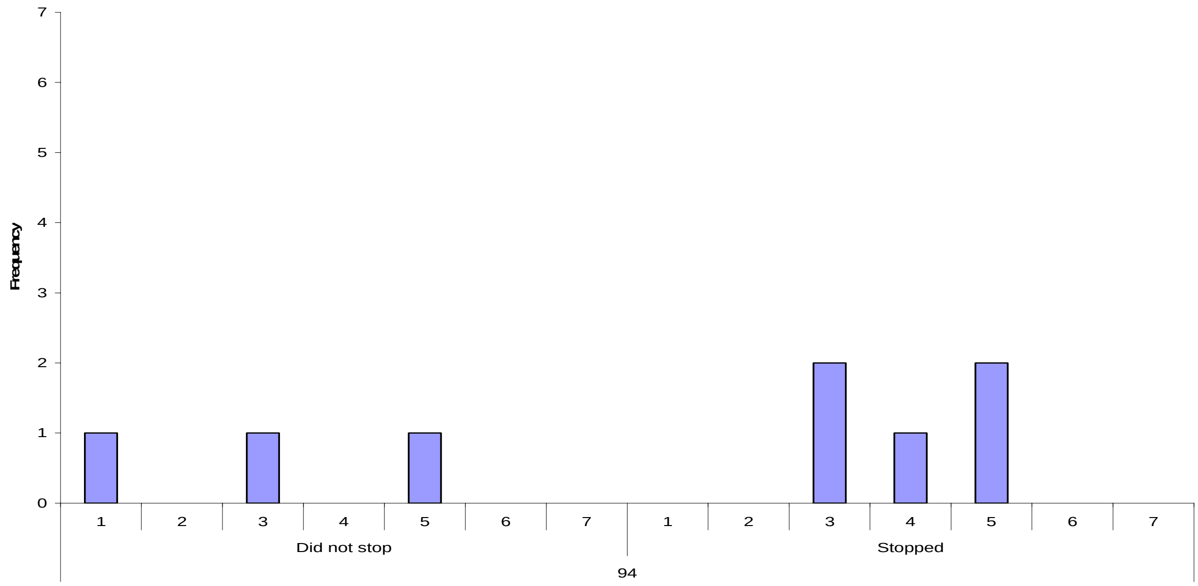

Figure E-59. Rumble strip simulation, 35 mph, 2.65-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

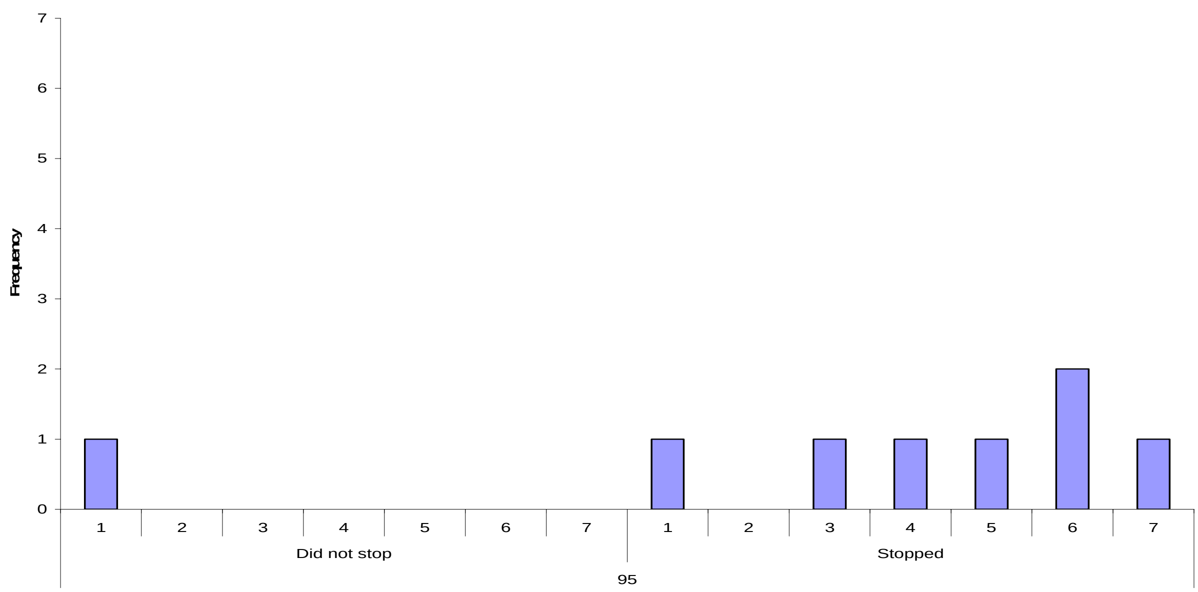

Figure E-60. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

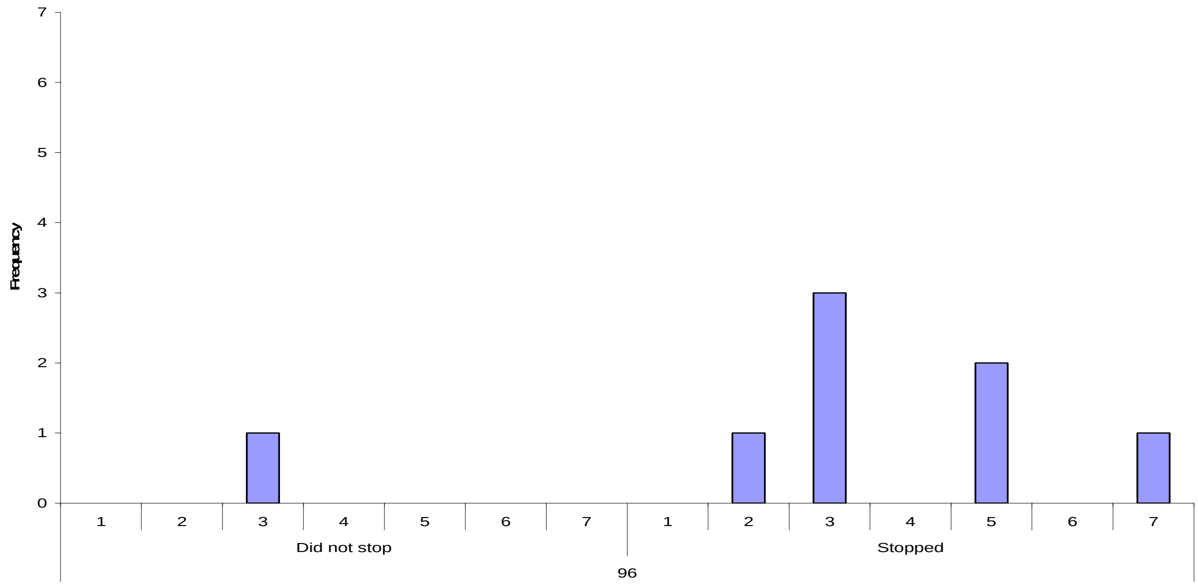

Figure E-61. Rumble strip simulation, 35 mph, 3.02-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

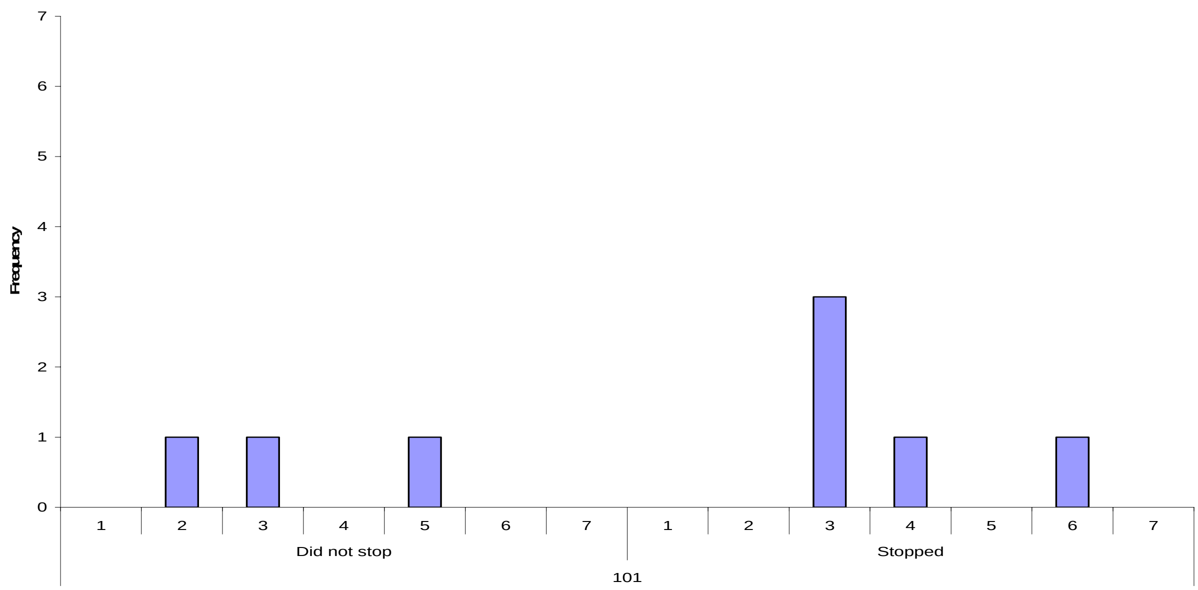

Figure E-62. "STOP" LED sign + Strobes, 35 mph, 3.02-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

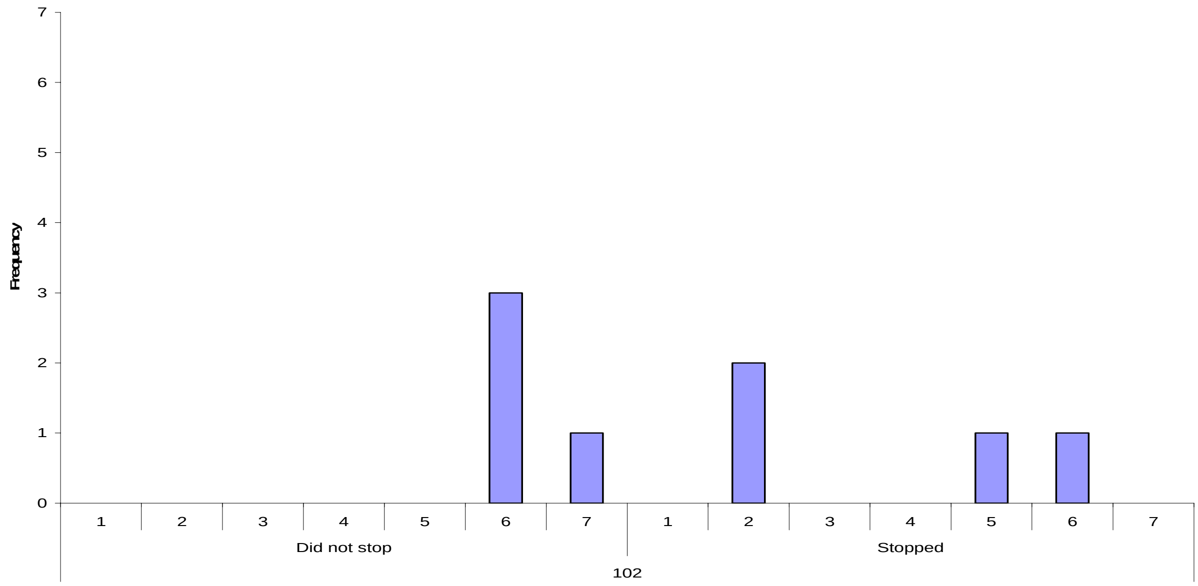

Figure E-63. "STOP" LED sign + Strobes, 35 mph, 2.03-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

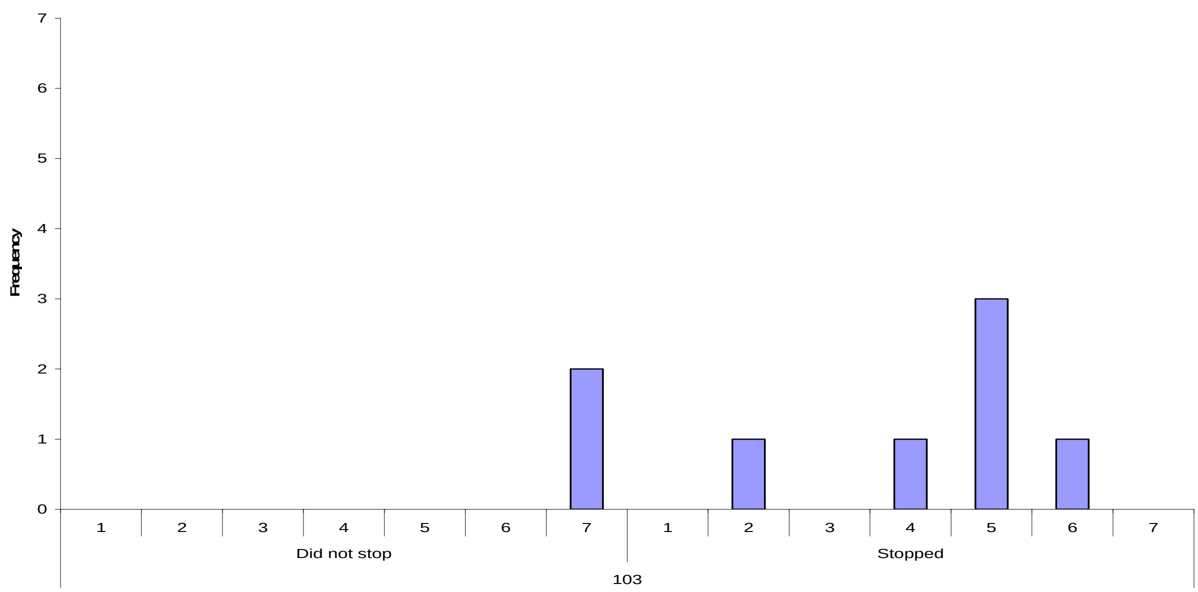

Figure E-64. "STOP" LED sign plus strobes, 35 mph, 2.65-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

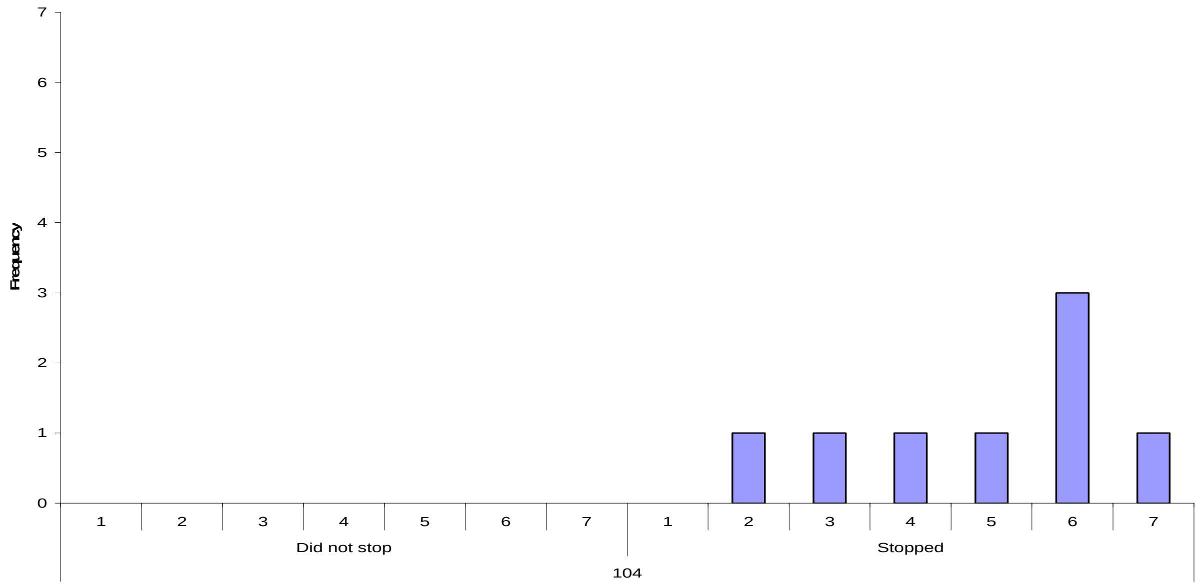

Figure E-65. "STOP" LED sign plus strobes, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

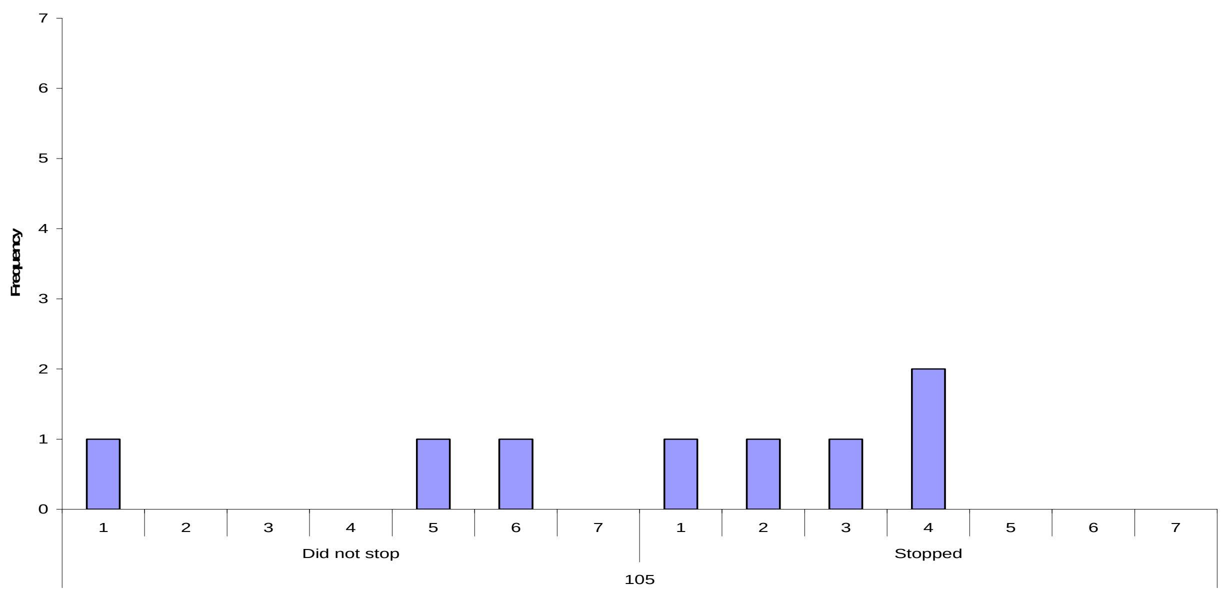

Figure E-66. LED-enhanced stop sign, 35 mph, 3.02-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

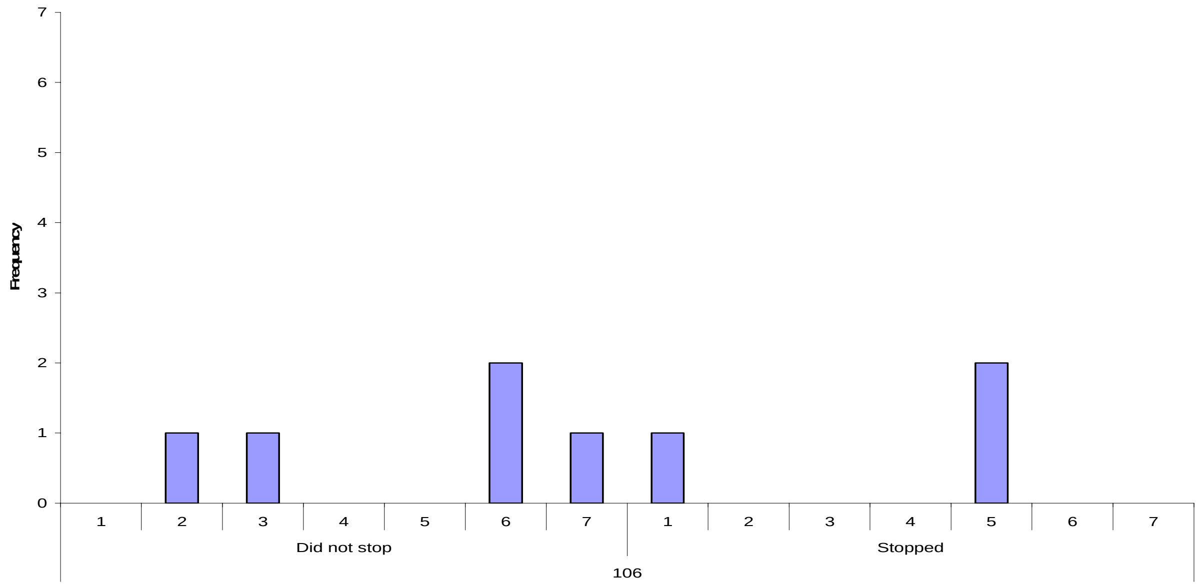

Figure E-67. Baseline, 35 mph, 3.02-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

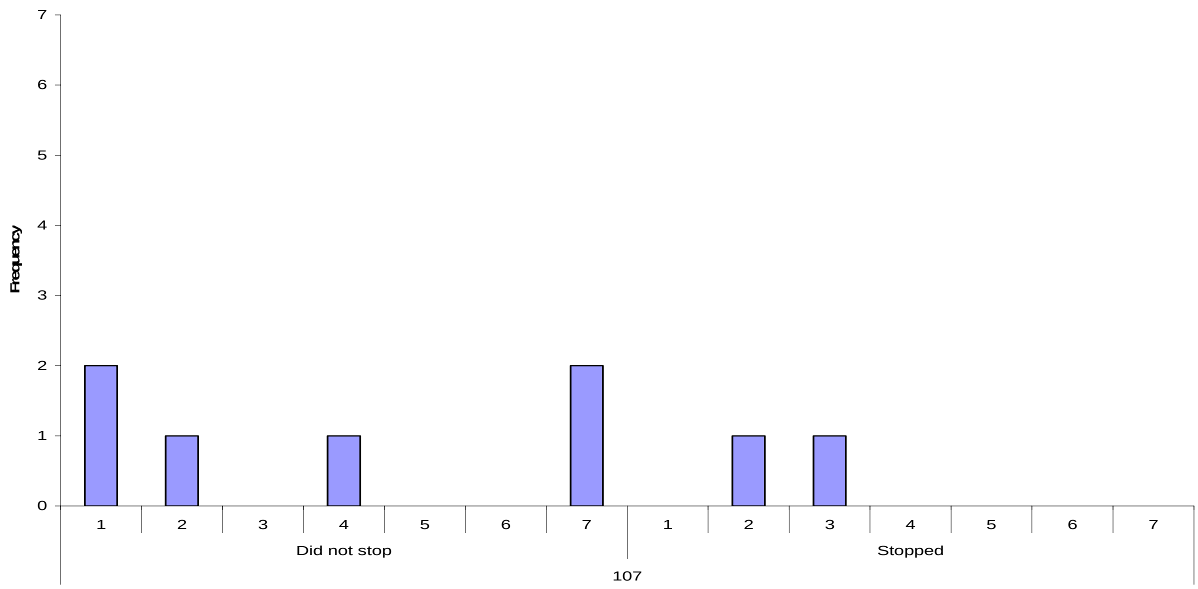

Figure E-68. LED-enhanced stop sign, 35 mph, 2.03-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

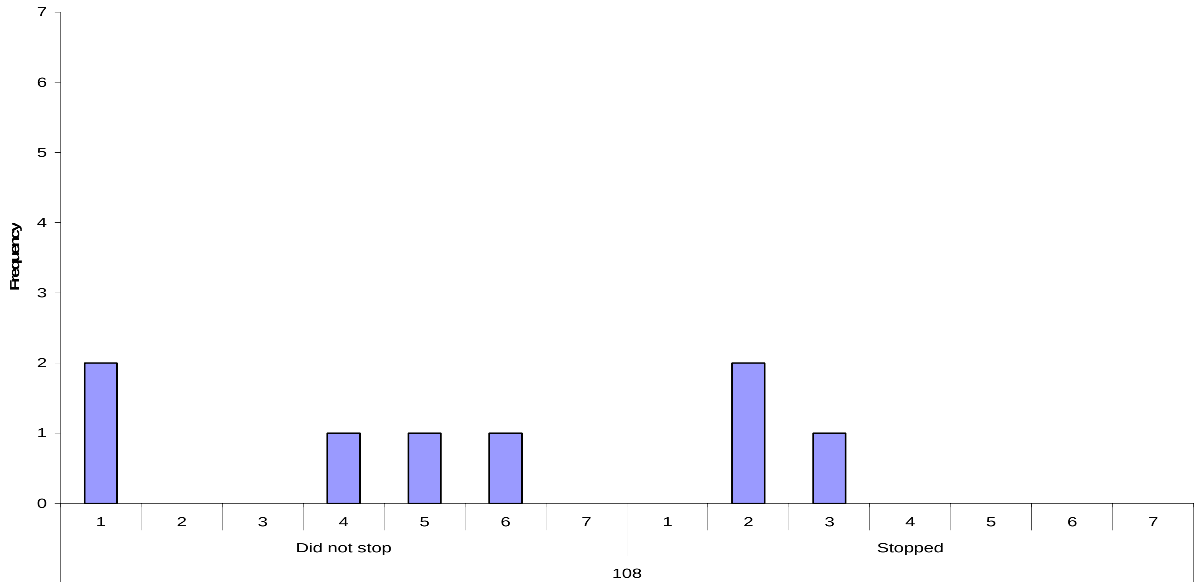

Figure E-69. LED-enhanced stop sign, 35 mph, 2.65-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

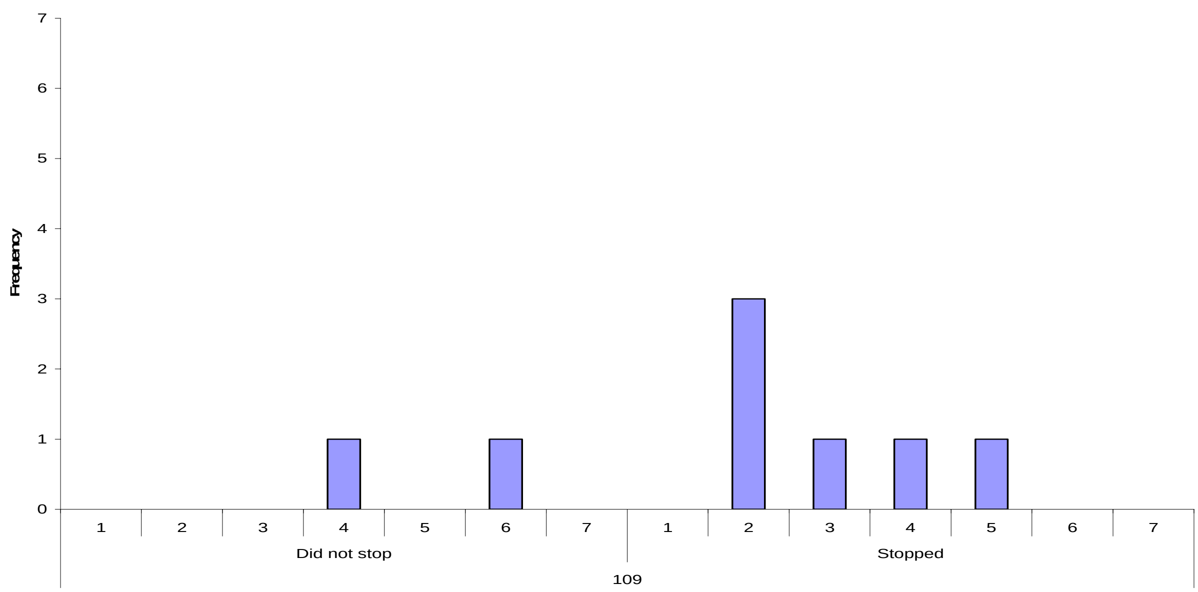

Figure E-70. Baseline, 35 mph, 2.65-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

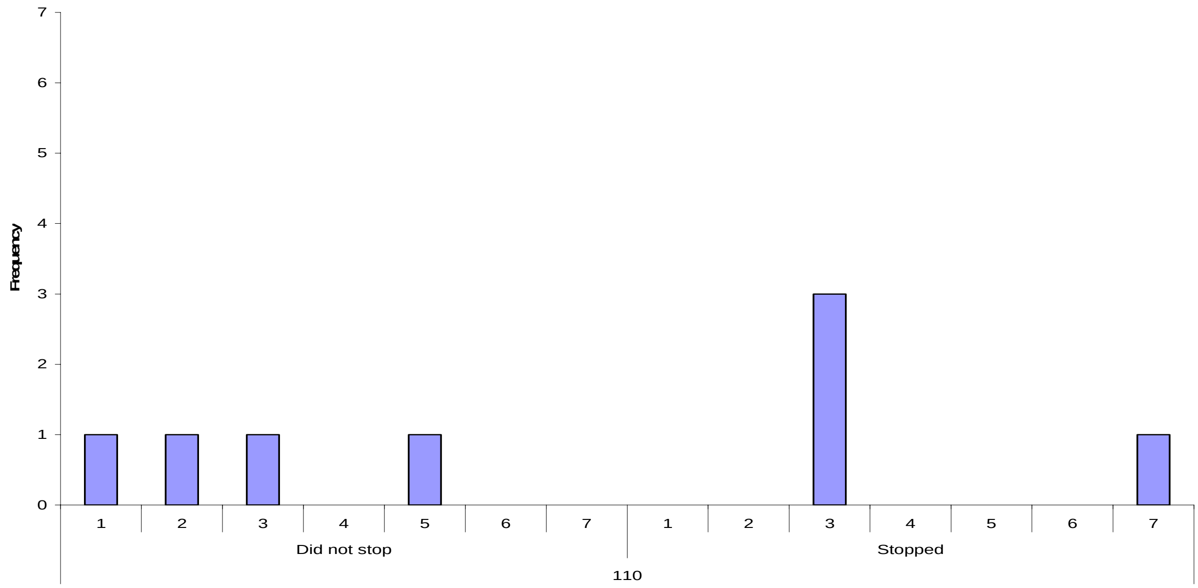

Figure E-71. Baseline, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

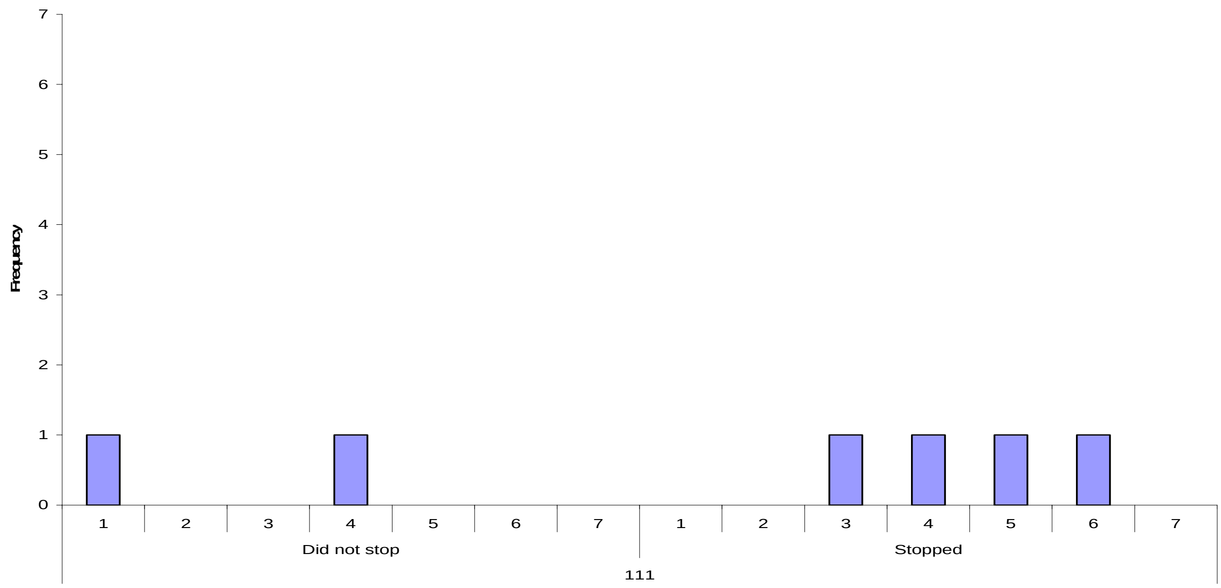

Figure E-72. LED-enhanced stop sign, 35 mph, 3.41-second TTI: Driver-perceived difficulty of stopping ("Did not Stop") and comfort of the stop ("Stop") during the surprise event (1 = Not At All Difficult or Very Uncomfortable, 7 = Very Difficult or Very Comfortable).

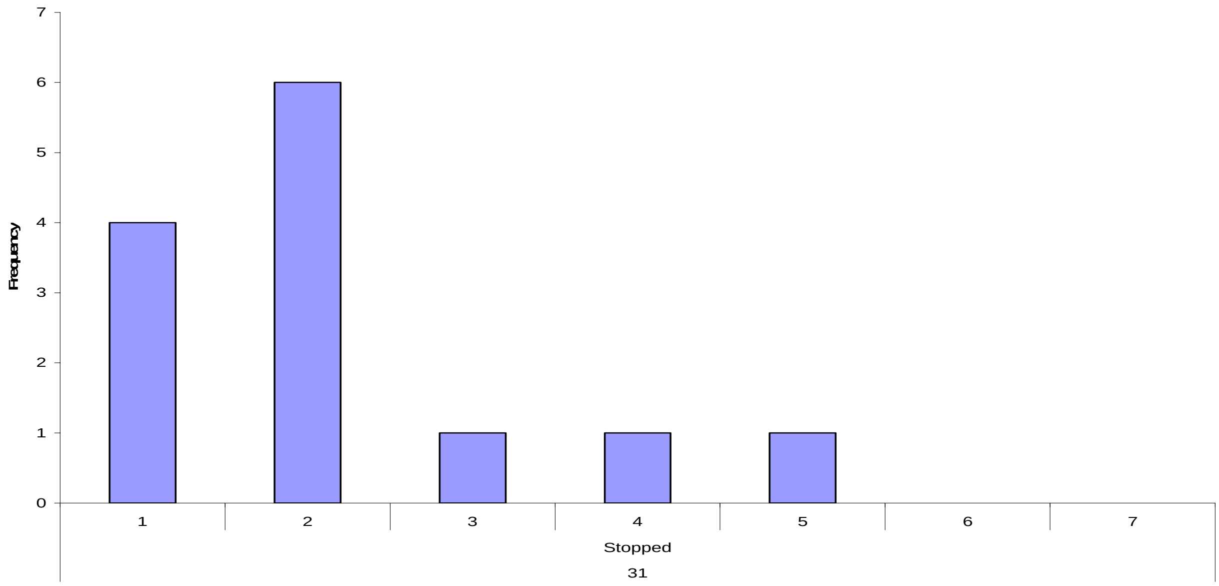

Figure E-73. Baseline, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

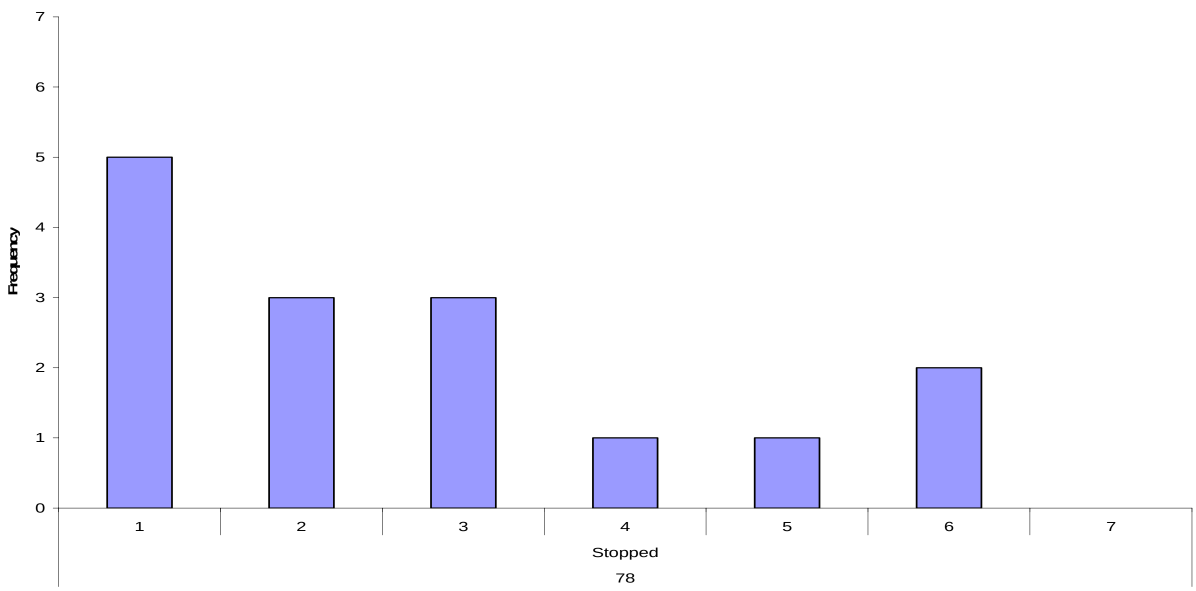

Figure E-74. "STOP" LED sign plus Strobes plus TCLs, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

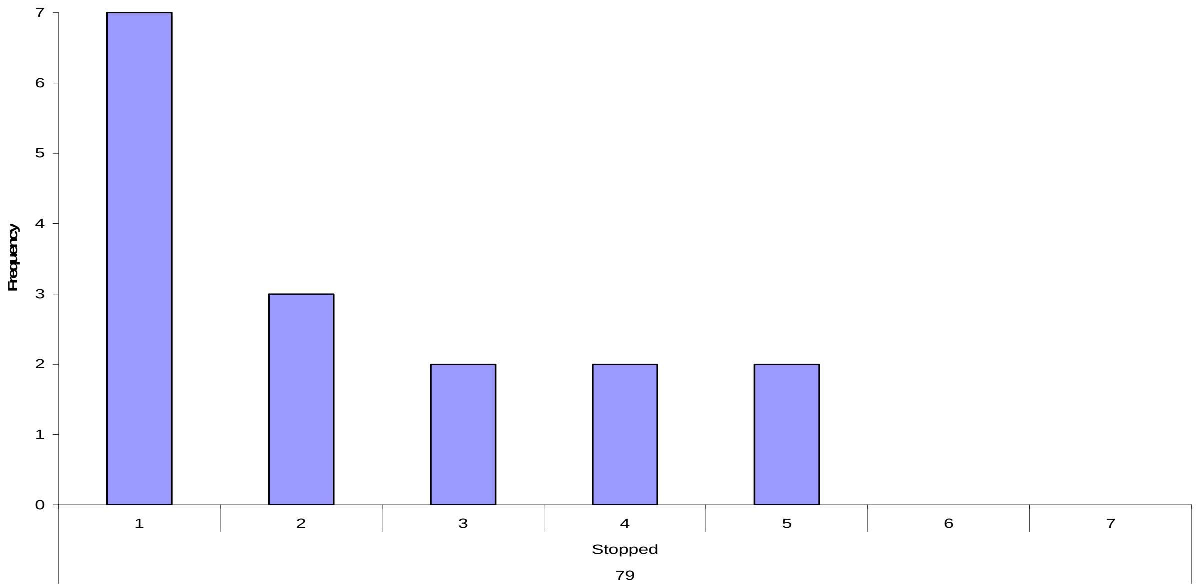

Figure E-75. "STOP" LED sign plus Strobes, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

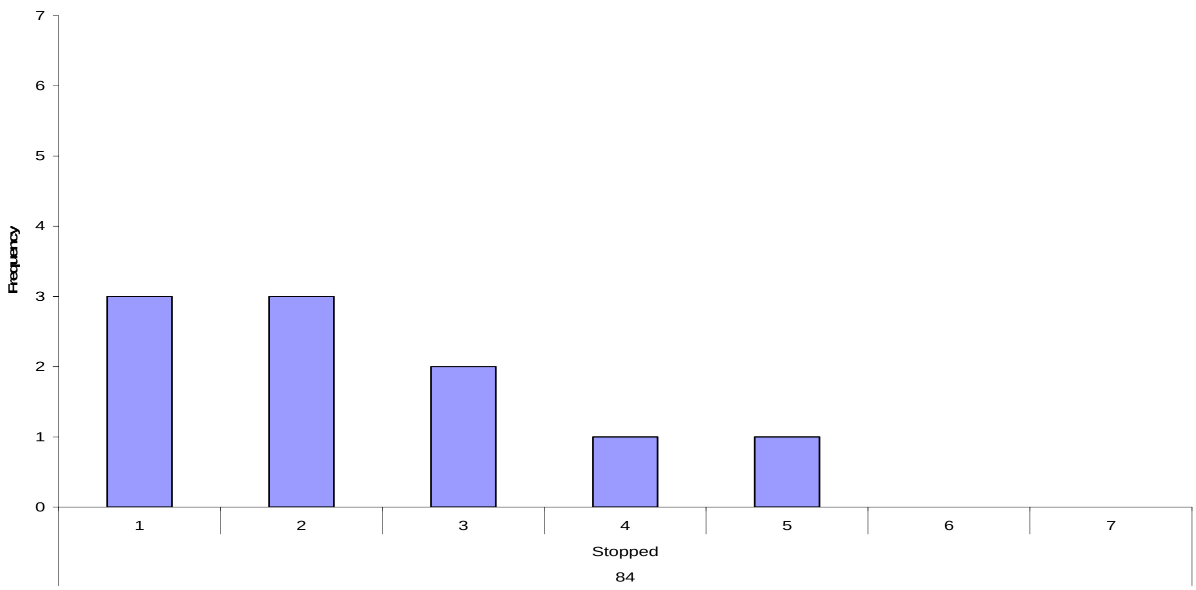

Figure E-76. Dual flashing red, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

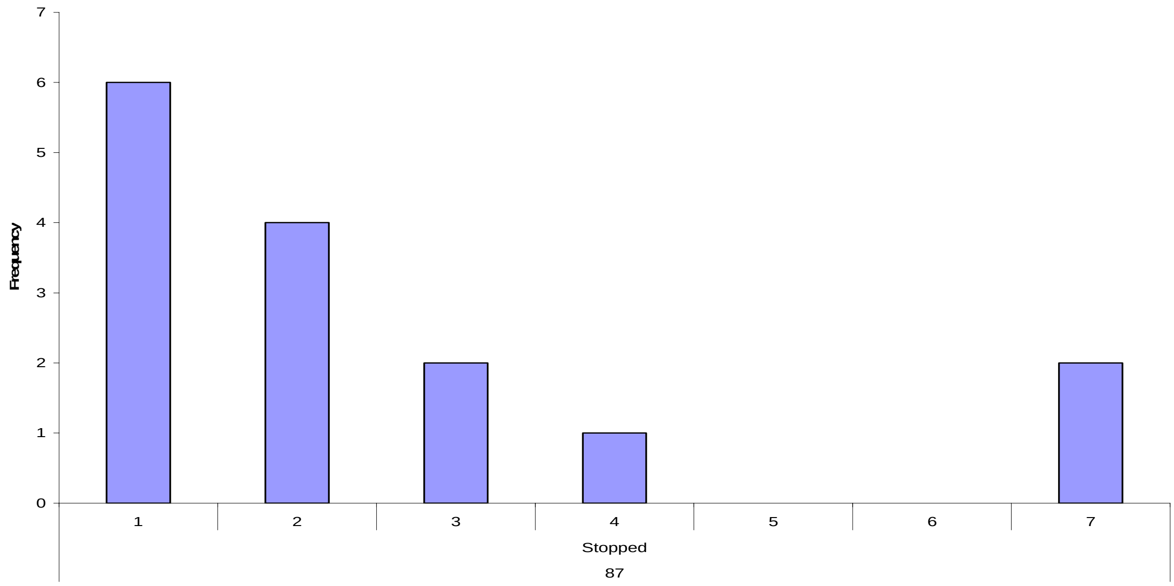

Figure E-77. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

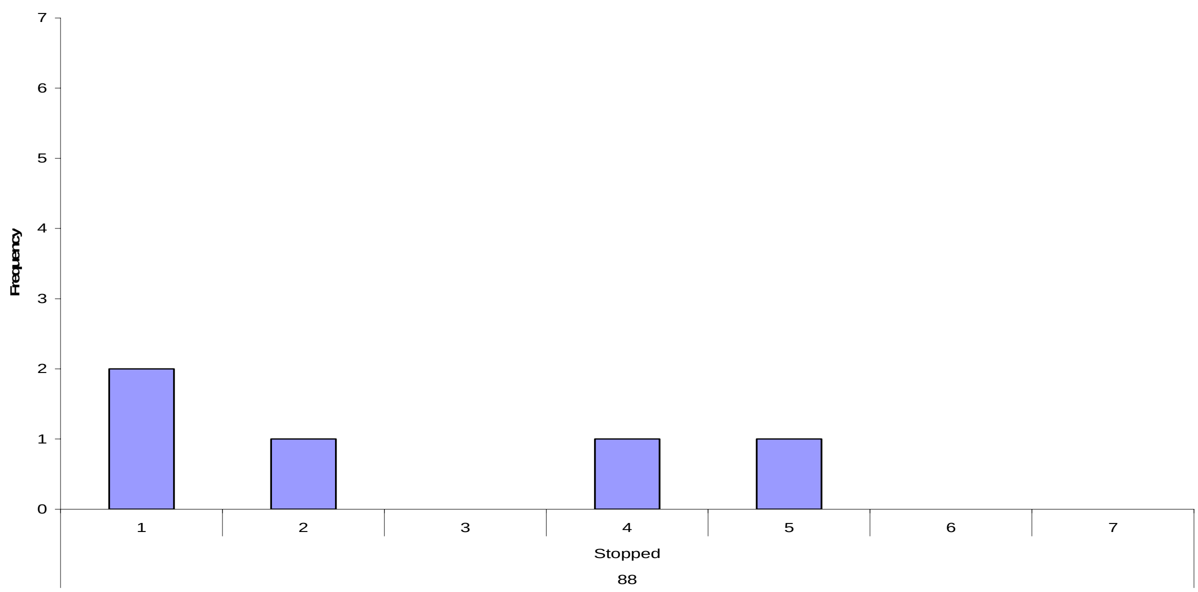

Figure E-78. Baseline, 35 mph, 2.65-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

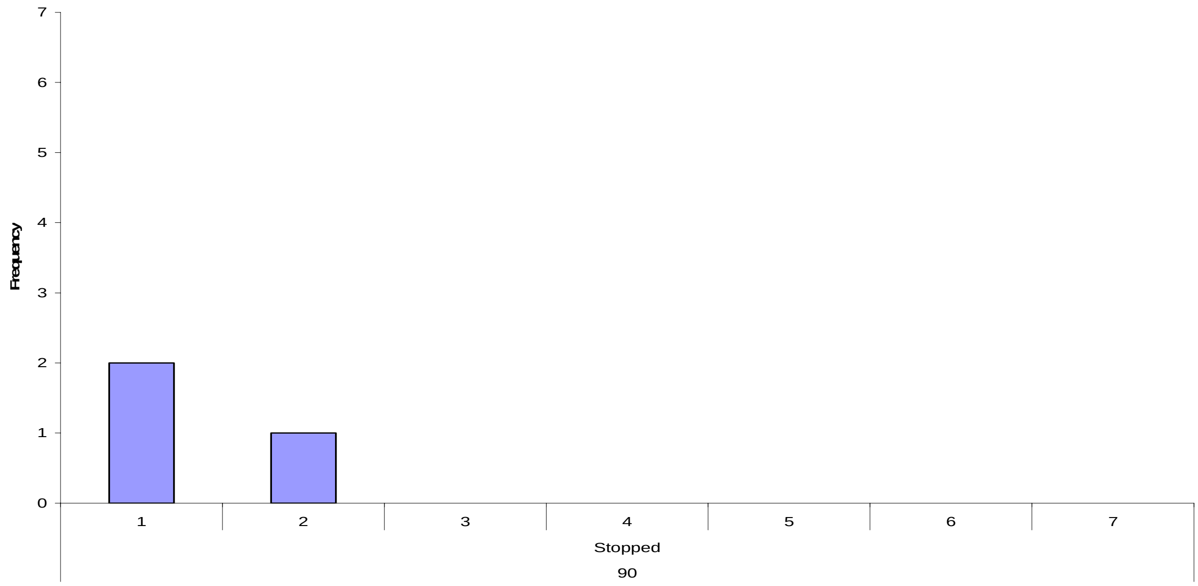

Figure E-79. Baseline, 35 mph, 2.03-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

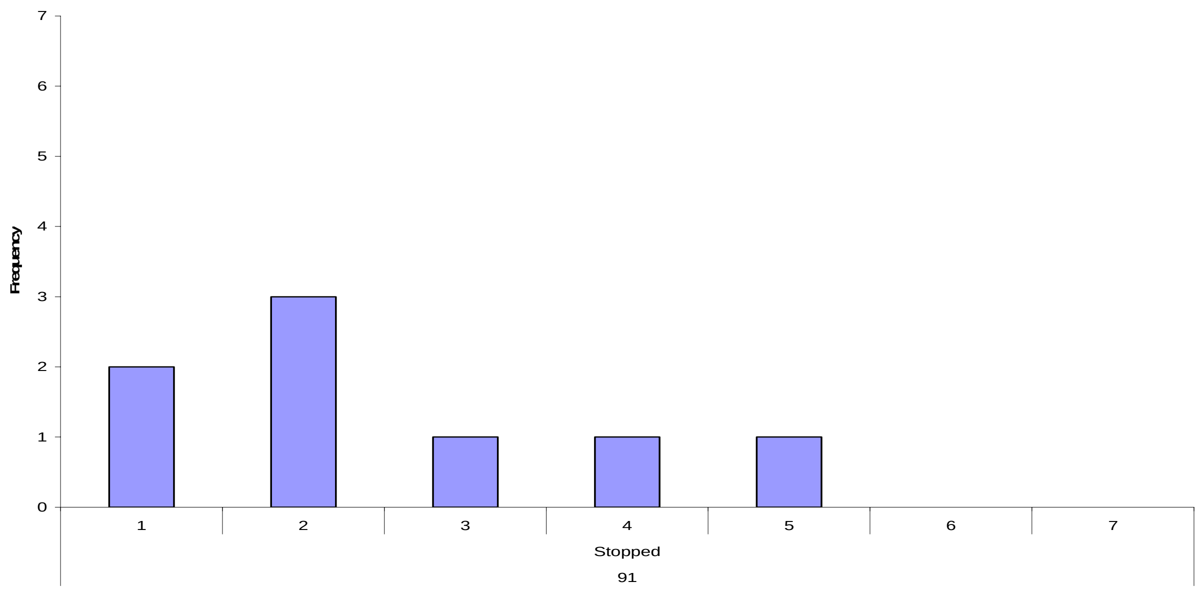

Figure E-80. Baseline, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

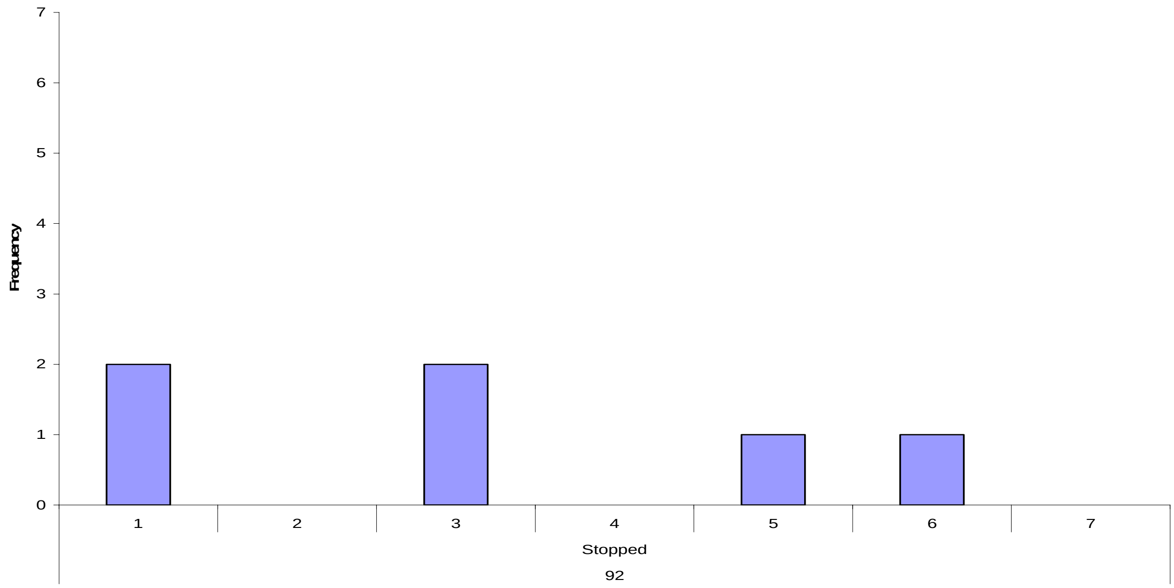

Figure E-81. Baseline, 35 mph, 3.02-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

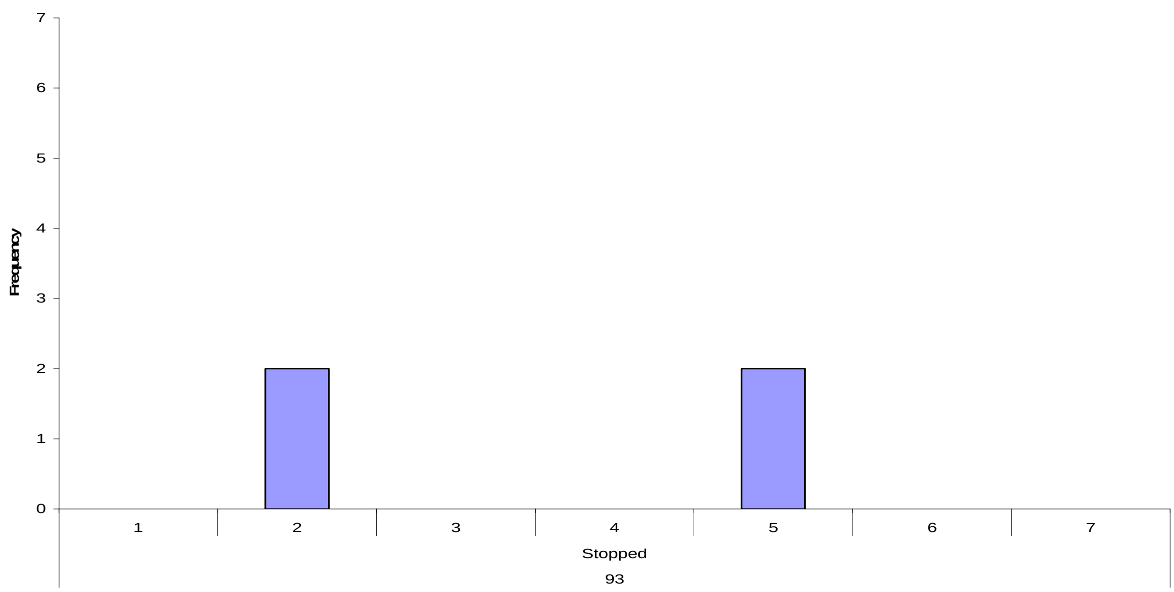

Figure E-82. Rumble strip simulation, 35 mph, 2.03-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

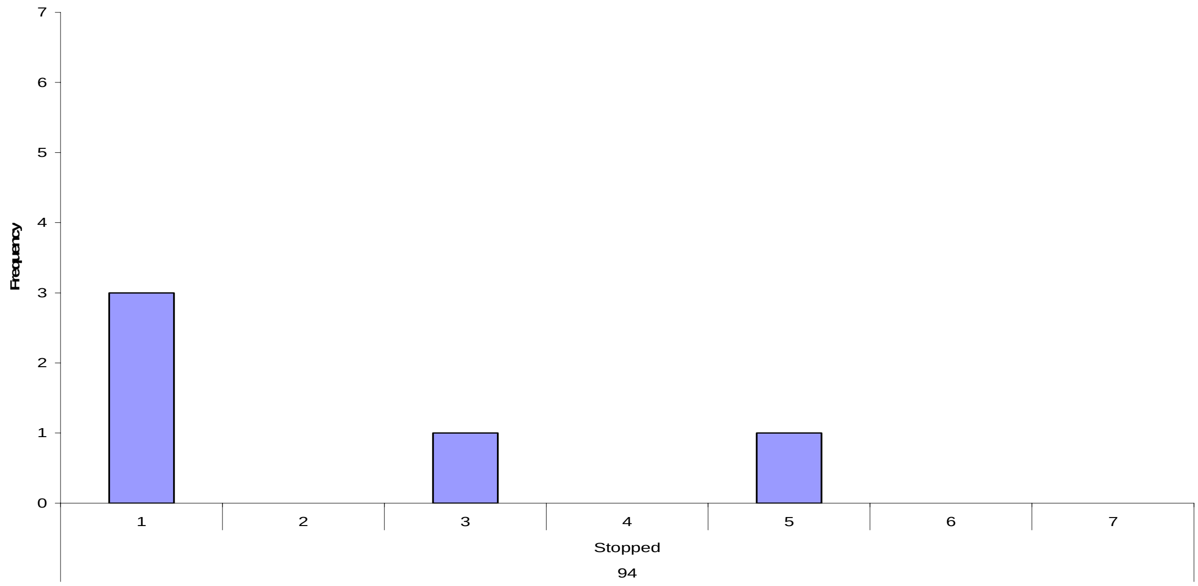

Figure E-83. Rumble strip simulation, 35 mph, 2.65-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

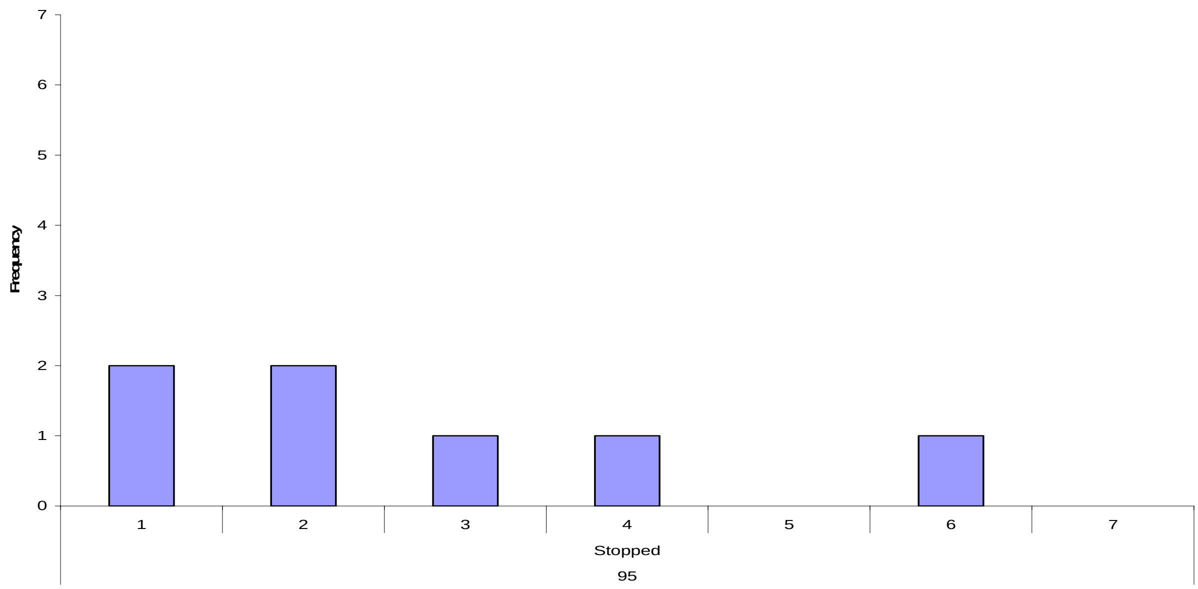

Figure E-84. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

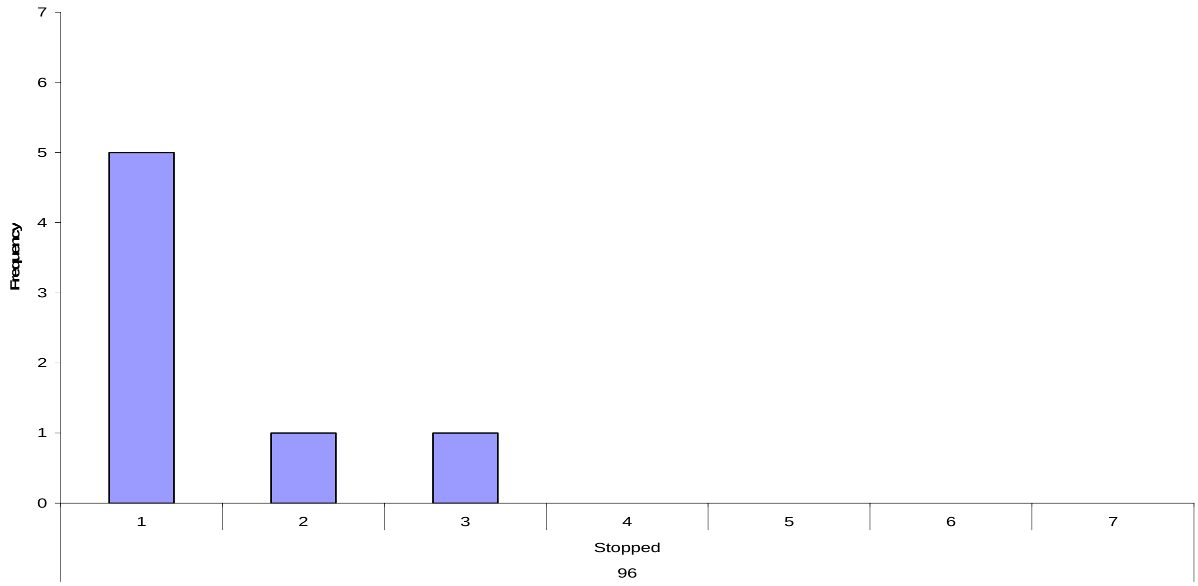

Figure E-85. Rumble strip simulation, 35 mph, 3.02-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

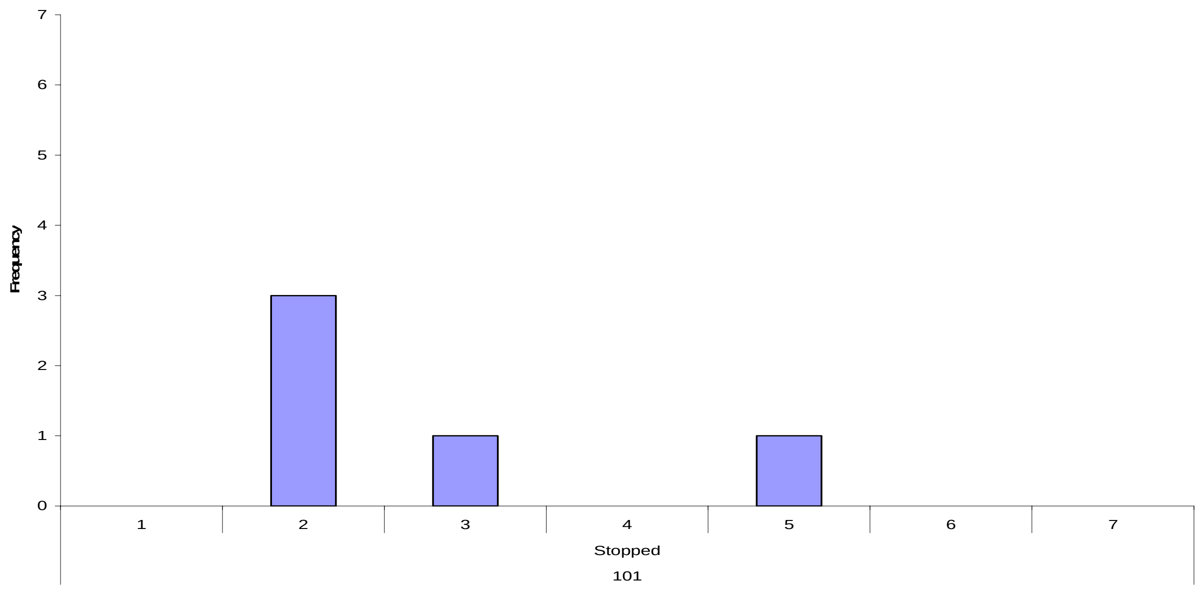

Figure E-86. "STOP" LED sign plus strobes, 35 mph, 3.02-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

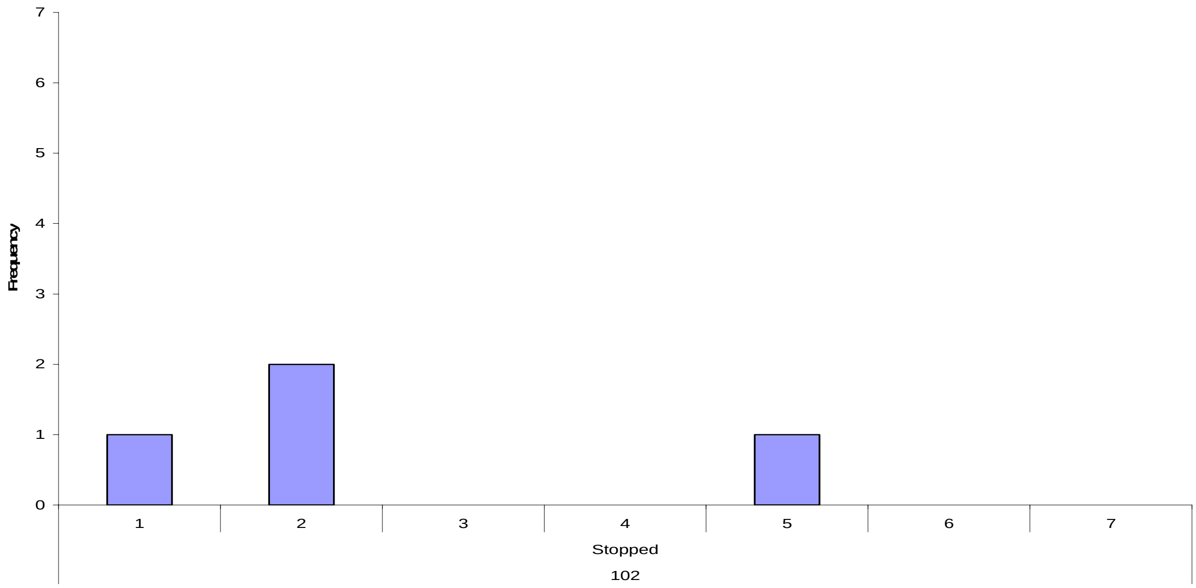

Figure E-87. "STOP" LED sign plus strobes, 35 mph, 2.03-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

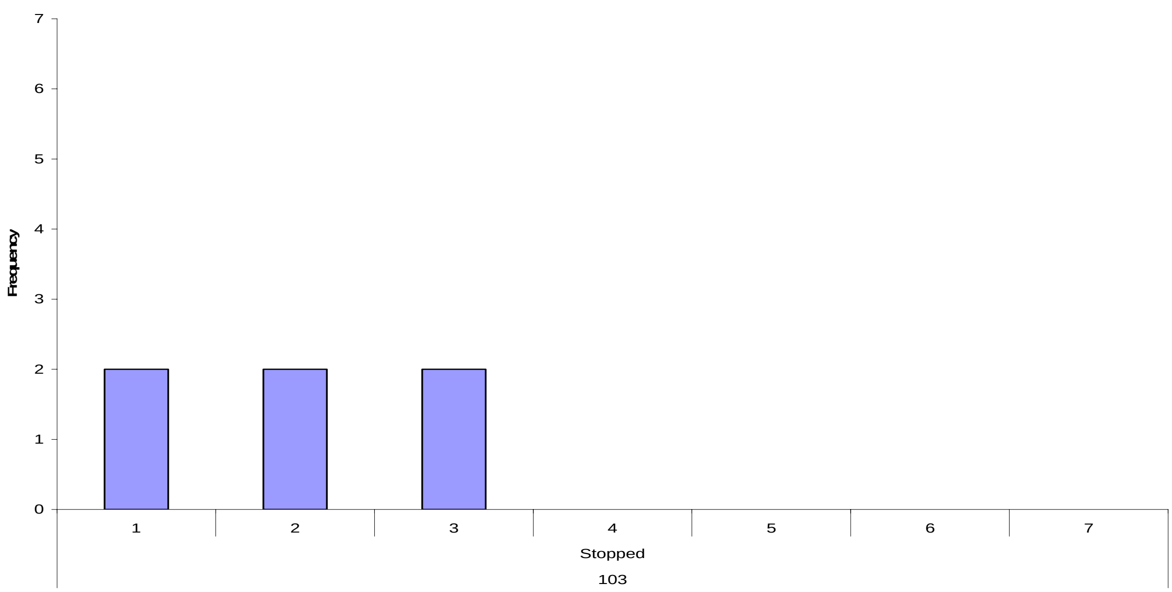

Figure E-88. "STOP" LED sign plus strobes, 35 mph, 2.65-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

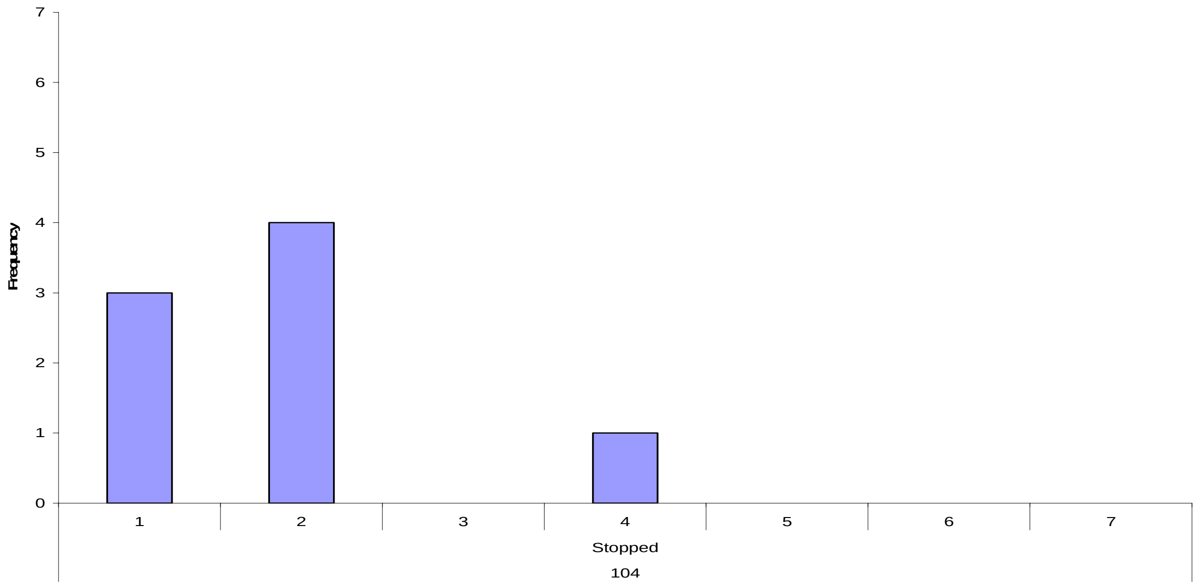

Figure E-89. "STOP" LED sign plus strobes, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

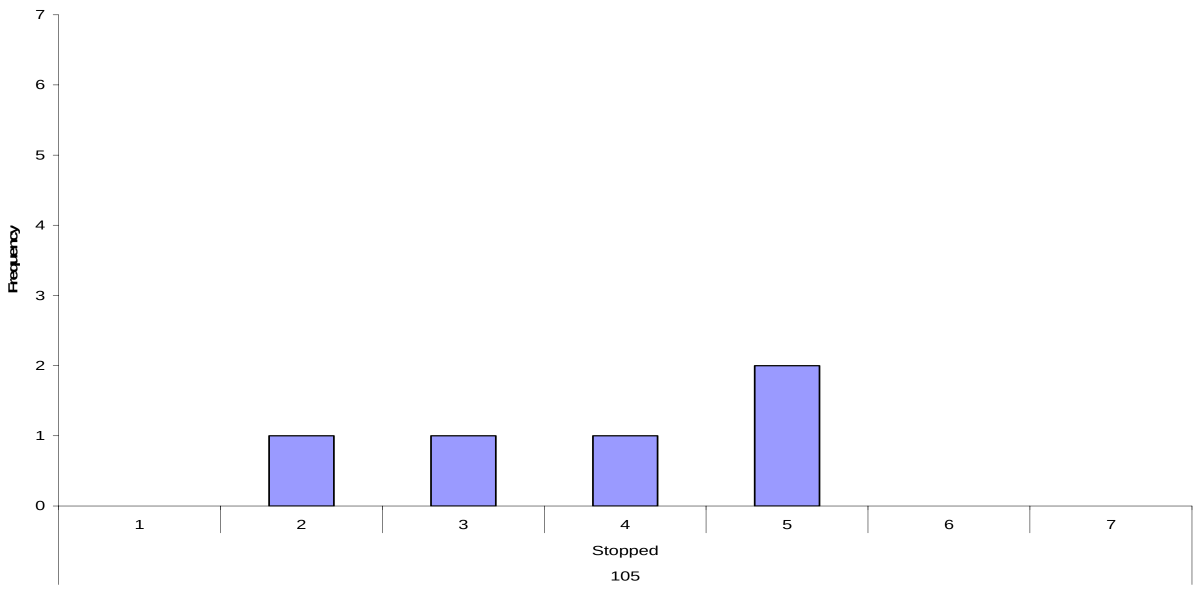

Figure E-90. LED-enhanced stop sign, 35 mph, 3.02-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

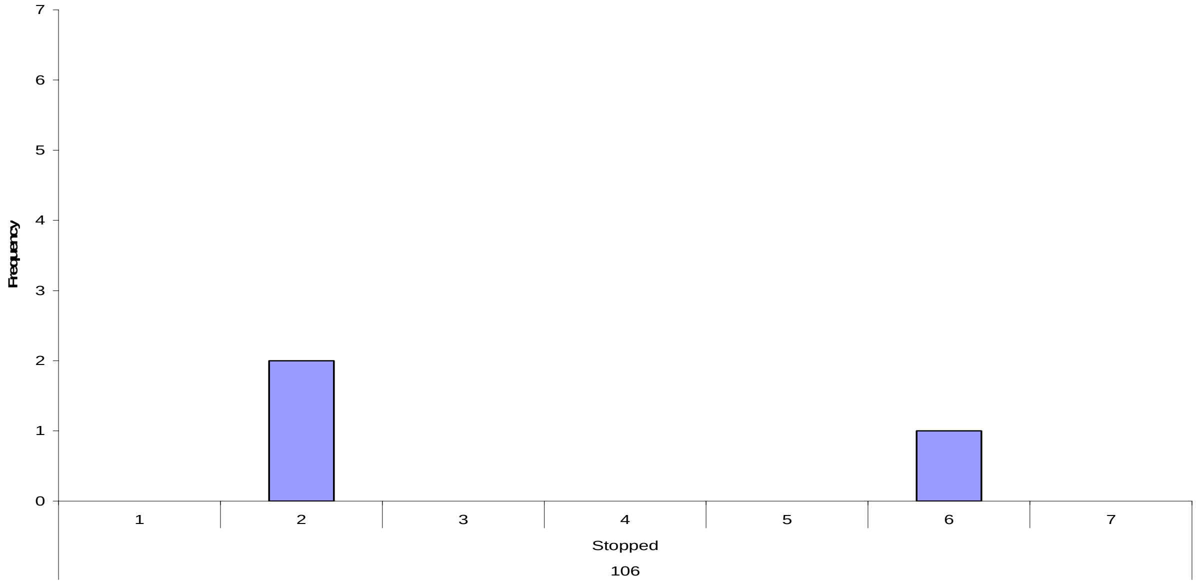

Figure E-91. Baseline, 35 mph, 3.02-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

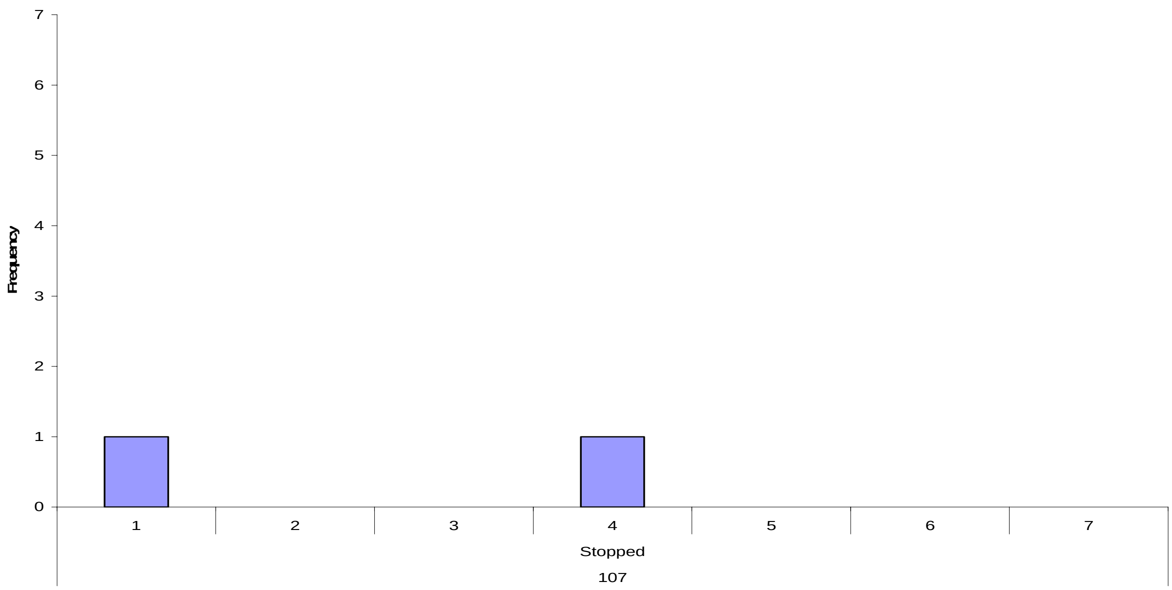

Figure E-92. LED-enhanced stop sign, 35 mph, 2.03-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

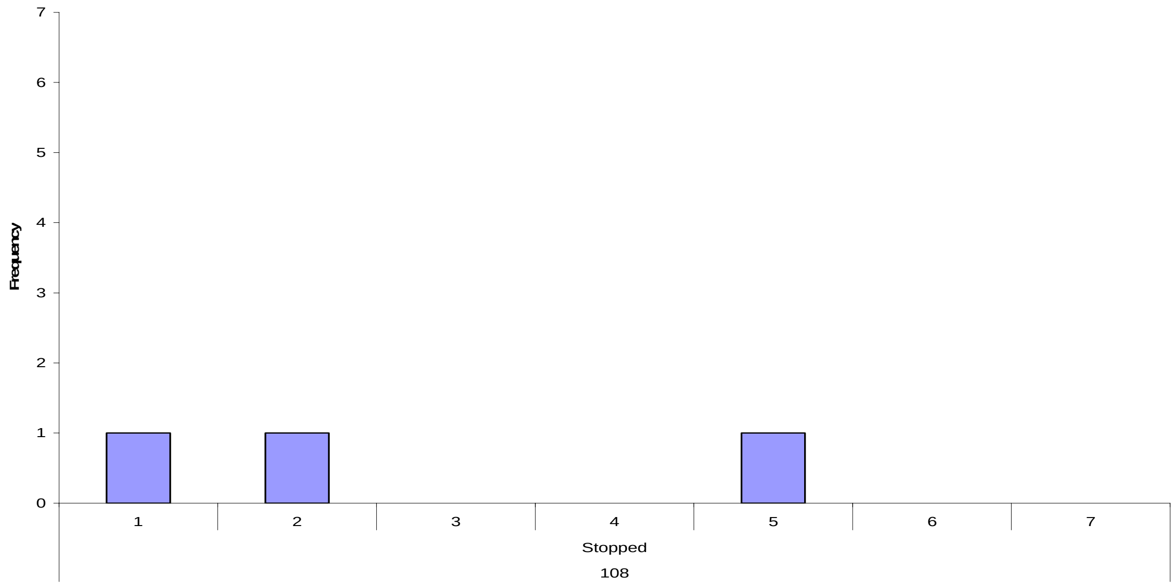

Figure E-93. LED-enhanced stop sign, 35 mph, 2.65-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

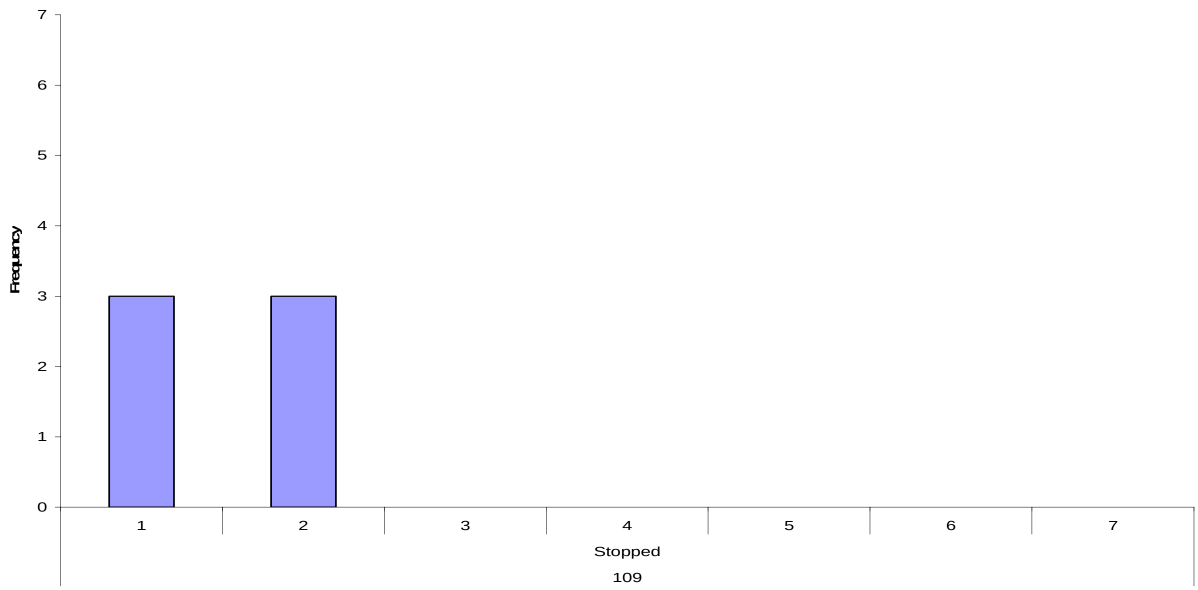

Figure E-94. Baseline, 35 mph, 2.65-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

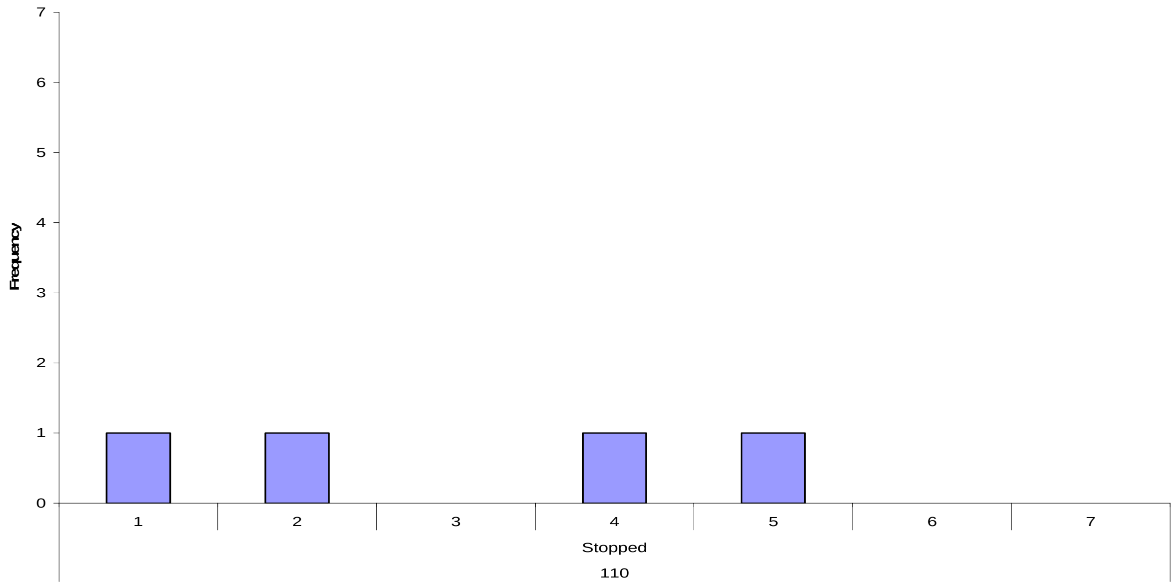

Figure E-95. Baseline, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

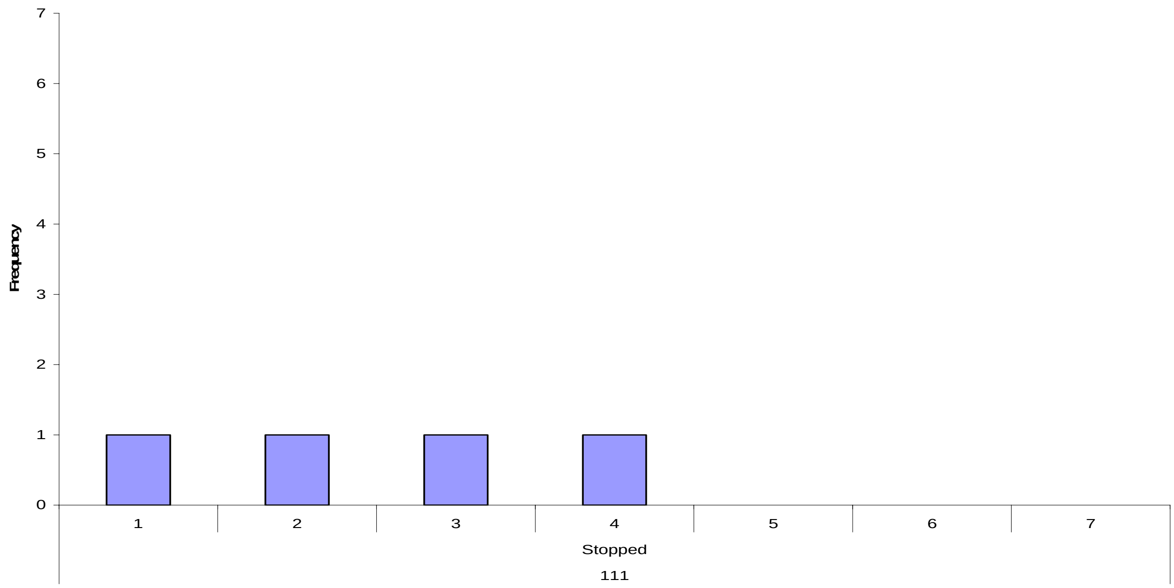

Figure E-96. LED-enhanced stop sign, 35 mph, 3.41-second TTI: Driver-perceived control during their stop (1 = Very Much in Control, 7 = Very Much Out of Control).

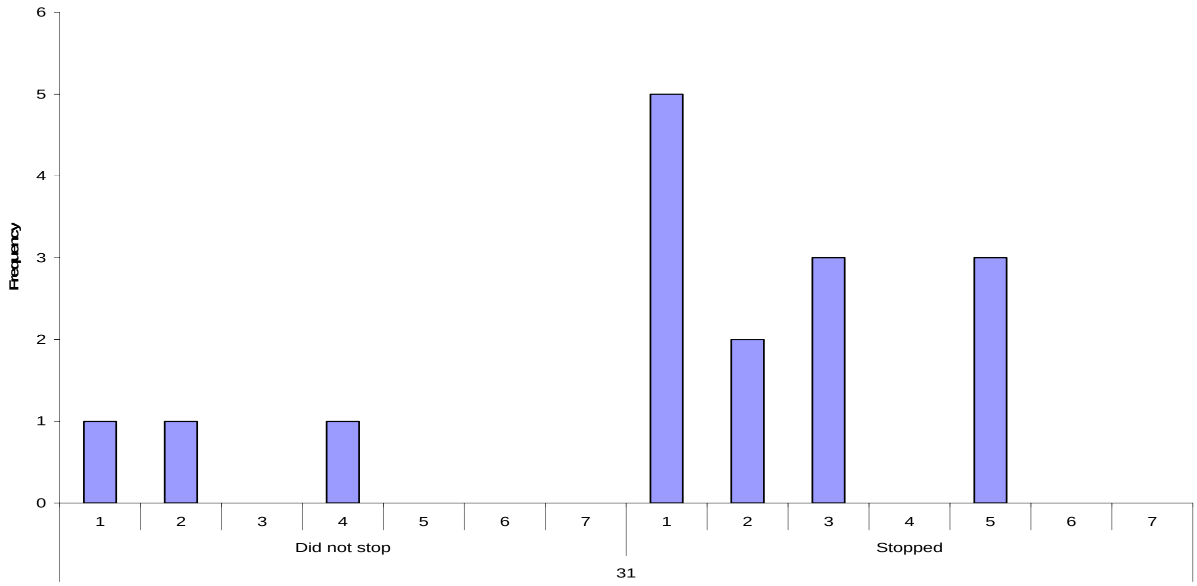

Figure E-97. Baseline, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

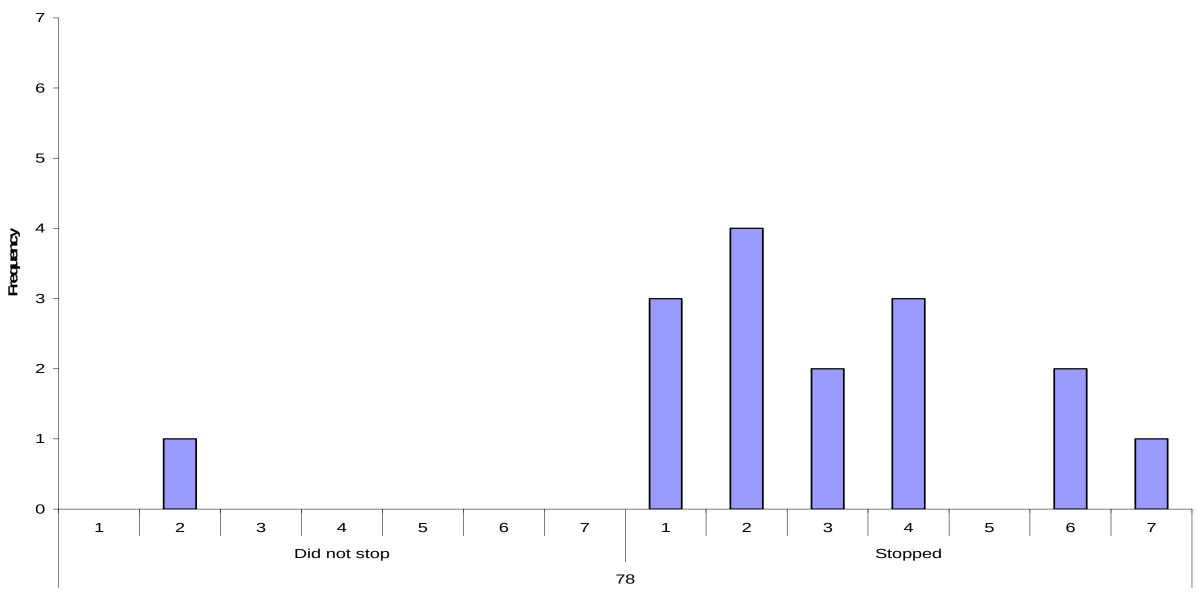

Figure E-98. "STOP" LED sign plus Strobes plus TCLs, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

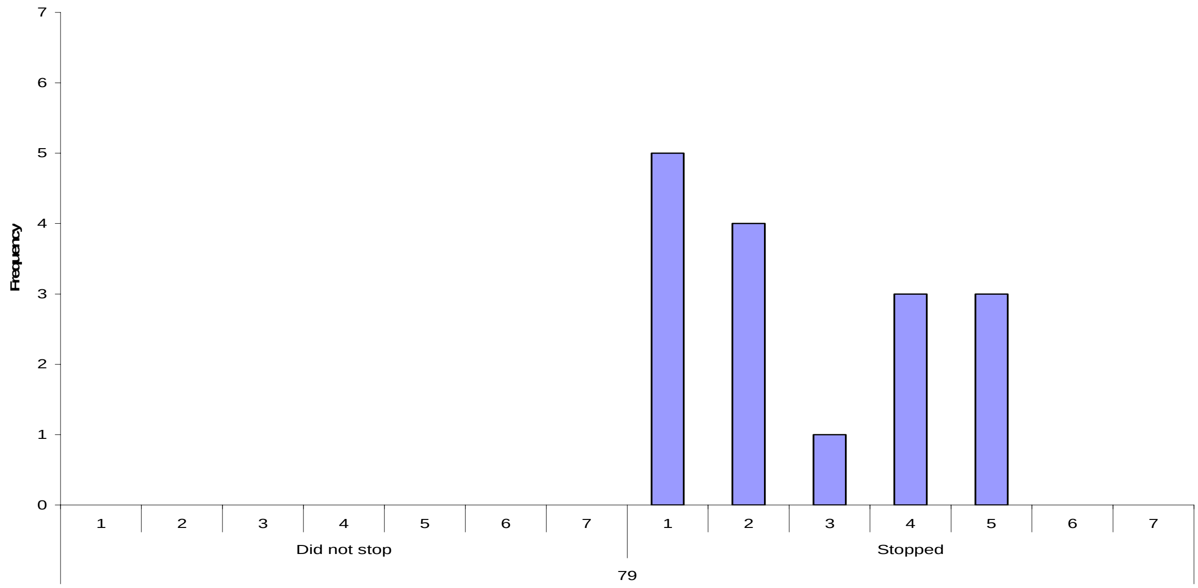

Figure E-99. “STOP” LED sign plus strobes, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

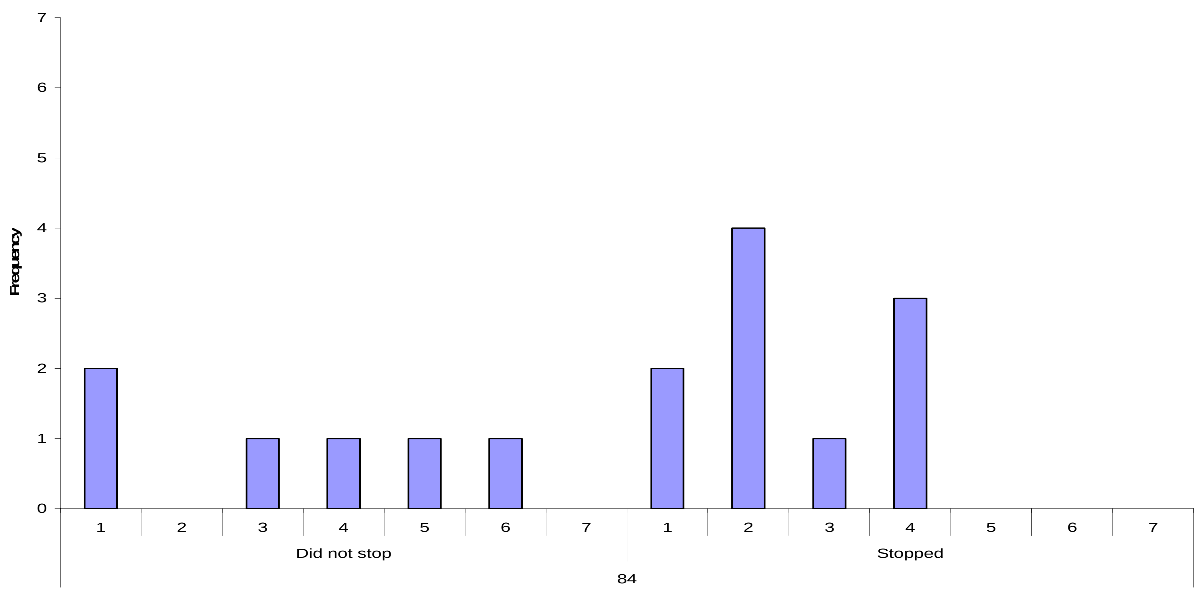

Figure E-100. Dual flashing red, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

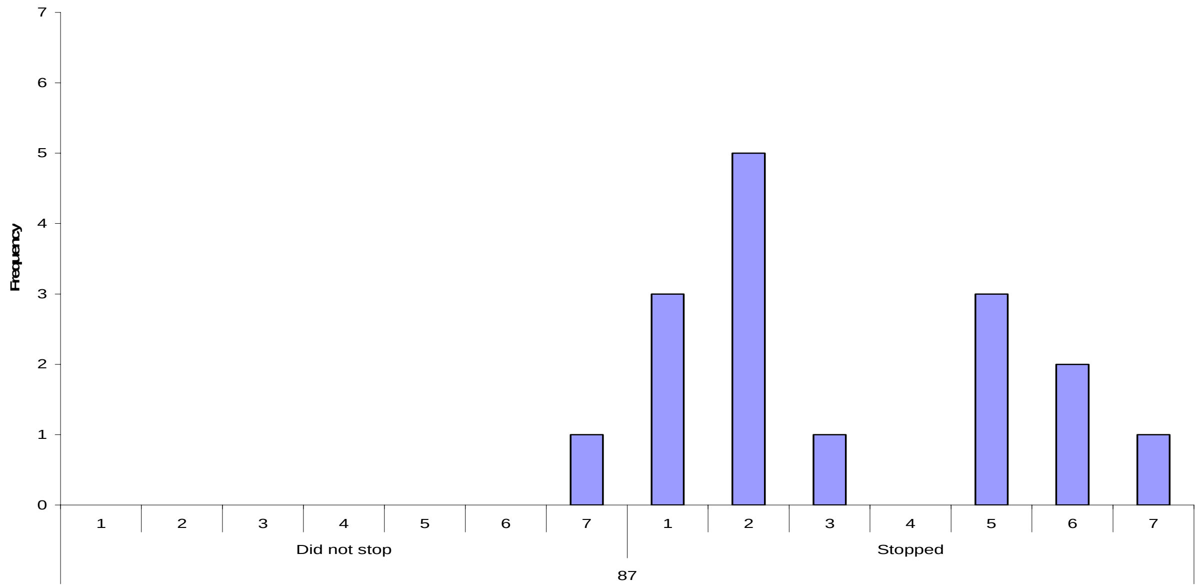

Figure E-101. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

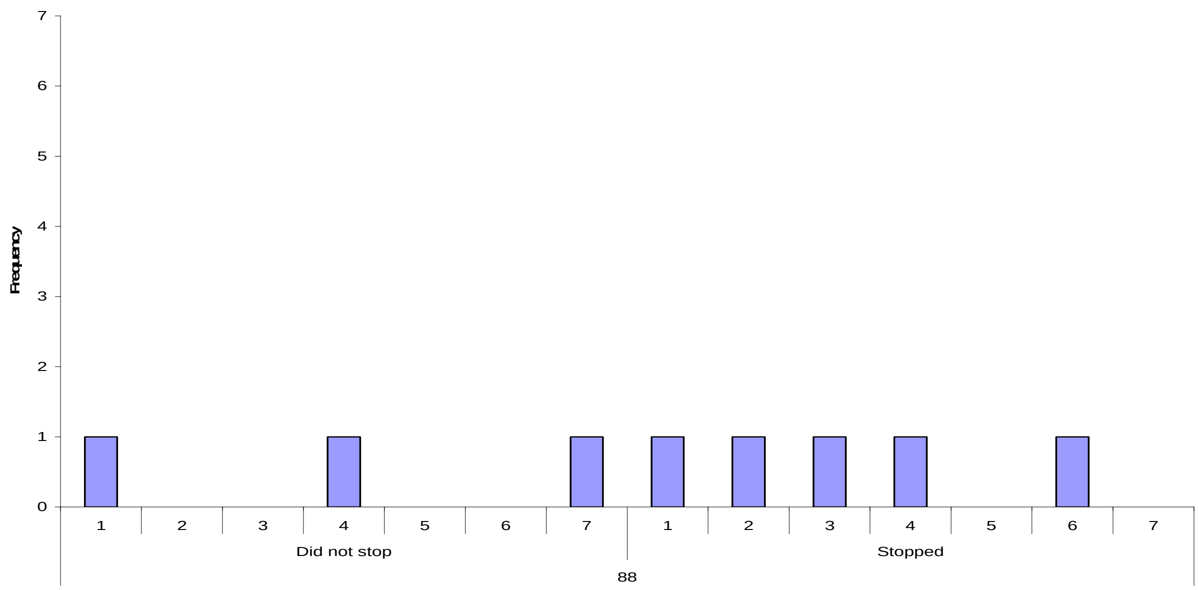

Figure E-102. Baseline, 35 mph, 2.65-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

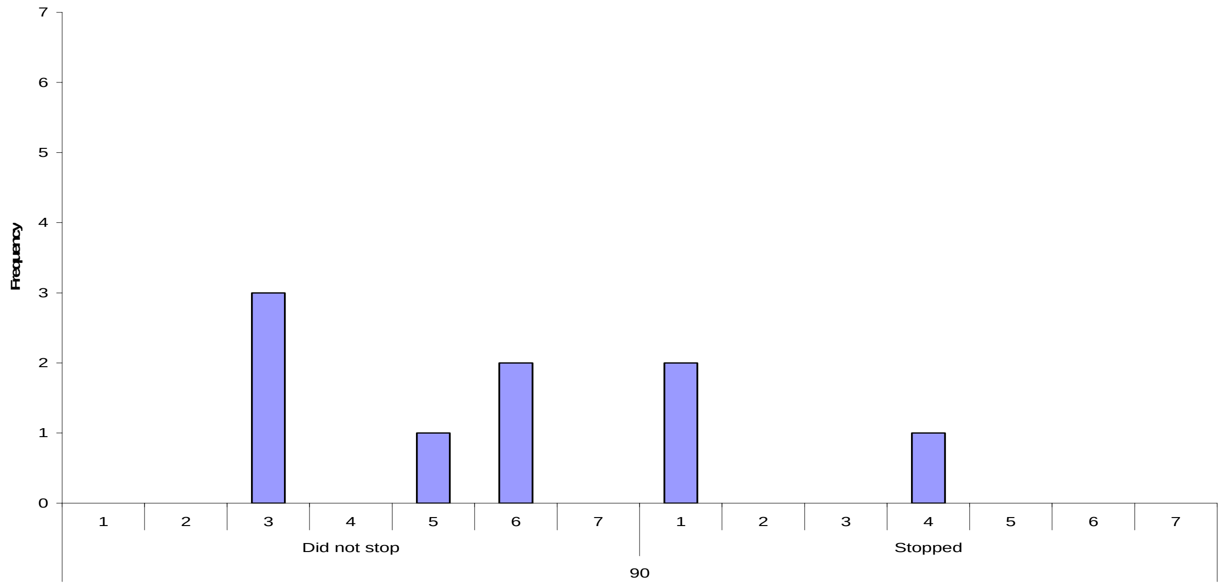

Figure E-103. Baseline, 35 mph, 2.03-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

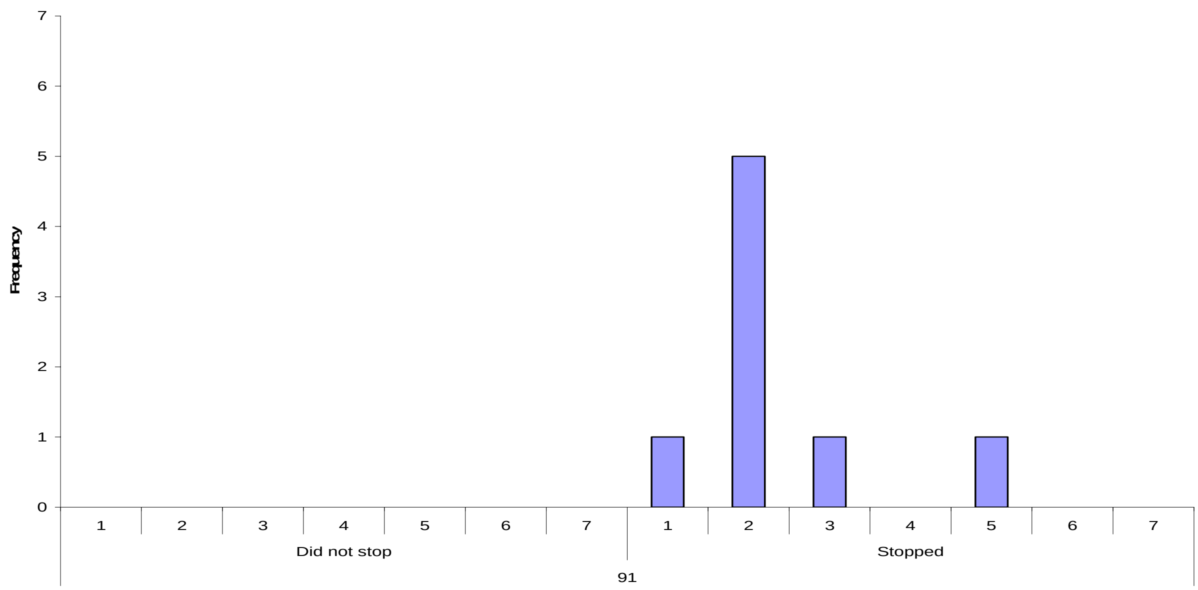

Figure E-104. Baseline, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

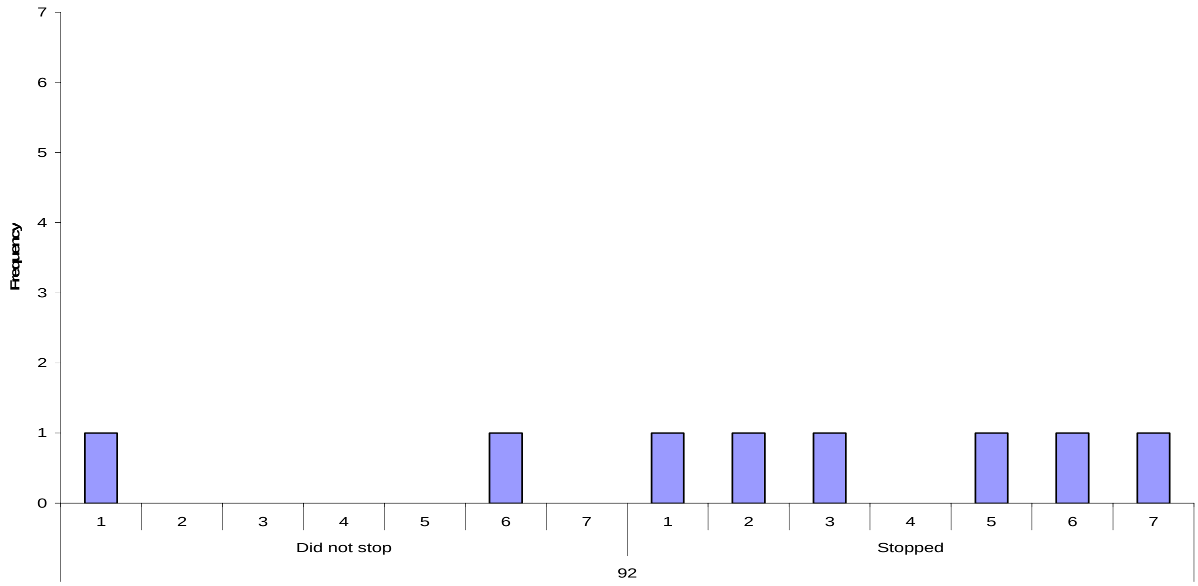

Figure E-105. Baseline, 35 mph, 3.02-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

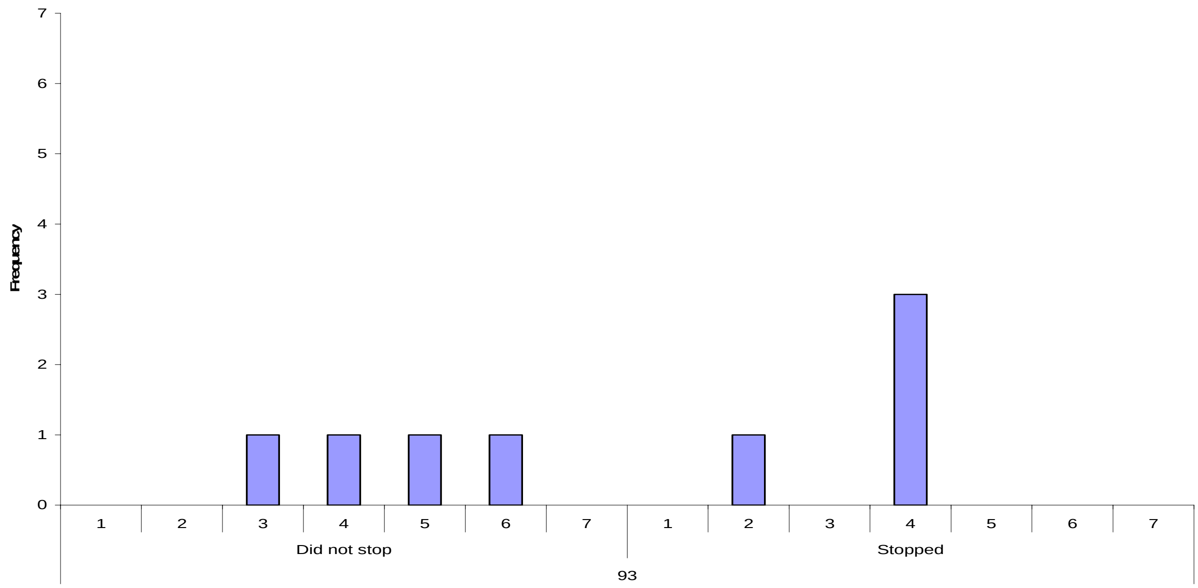

Figure E-106. Rumble strip simulation, 35 mph, 3.02-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

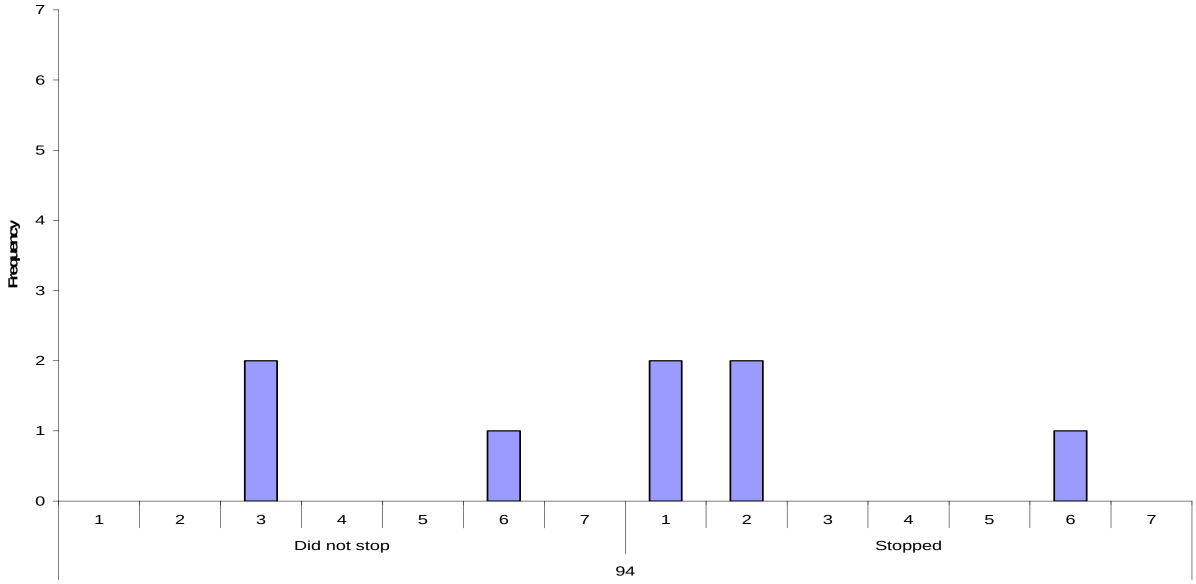

Figure E-107. Rumble strip simulation, 35 mph, 2.65-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

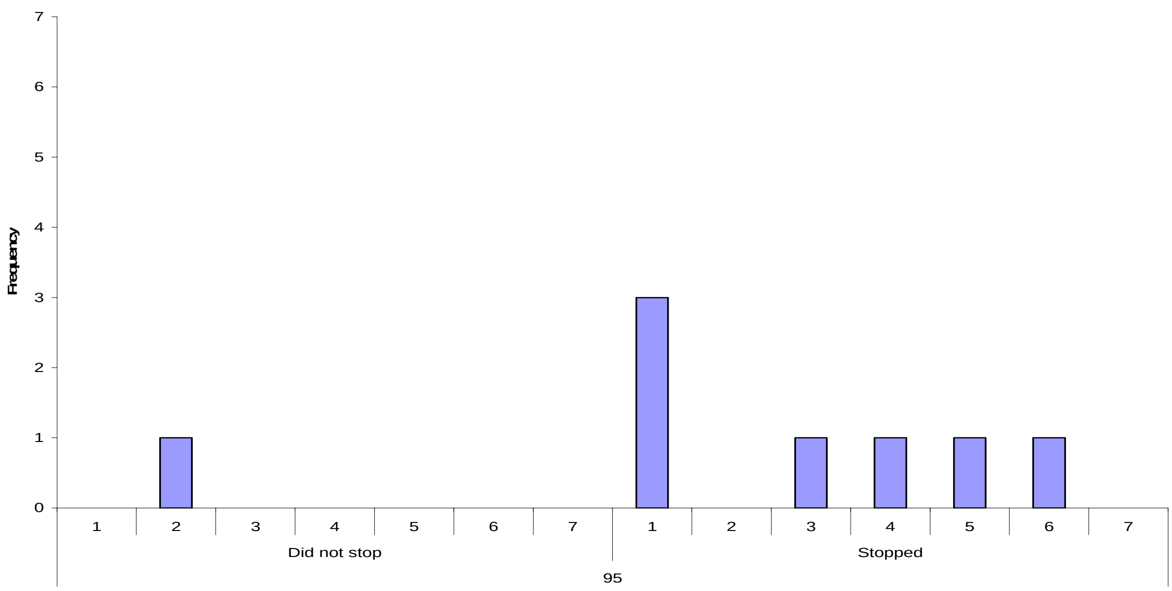

Figure E-108. Rumble strip simulation, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

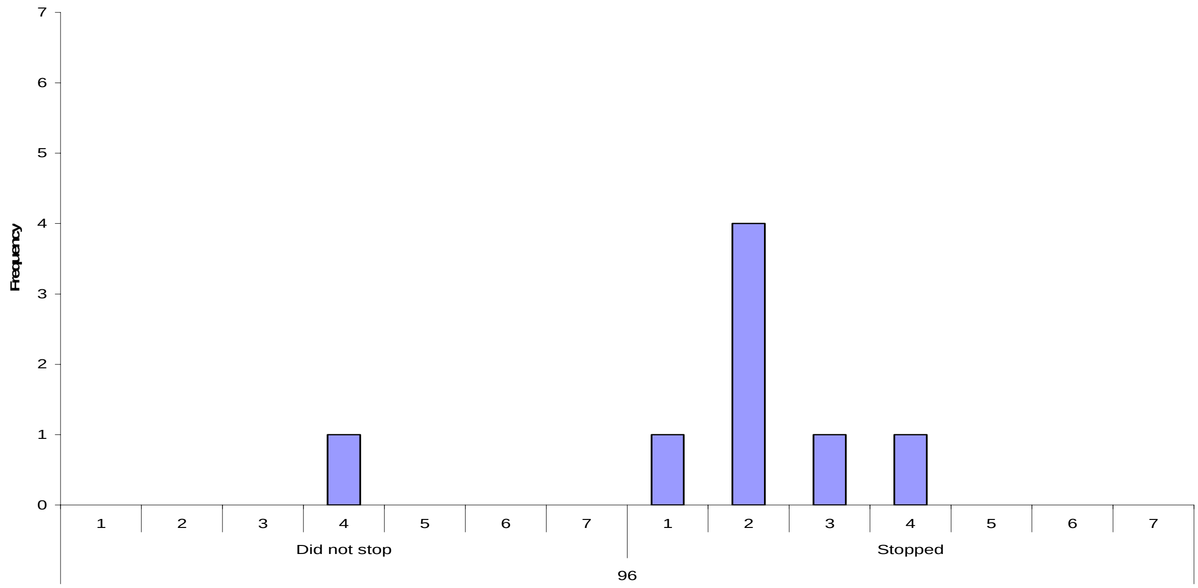

Figure E-109. Rumble strip simulation, 35 mph, 3.02-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

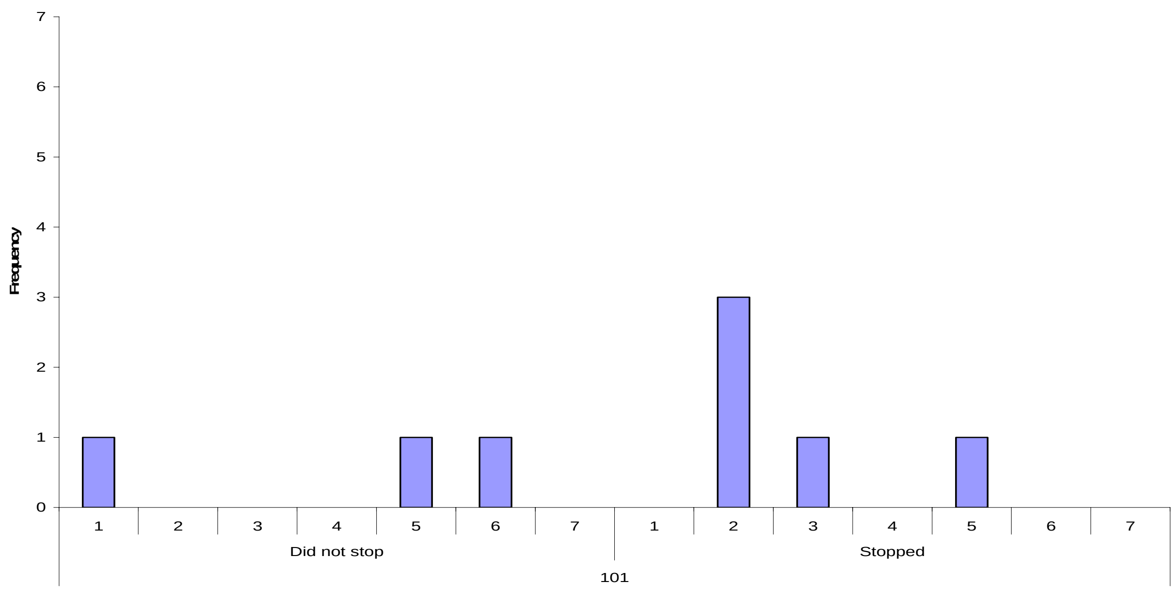

Figure E-110. "STOP" LED sign plus strobes, 35 mph, 3.02-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

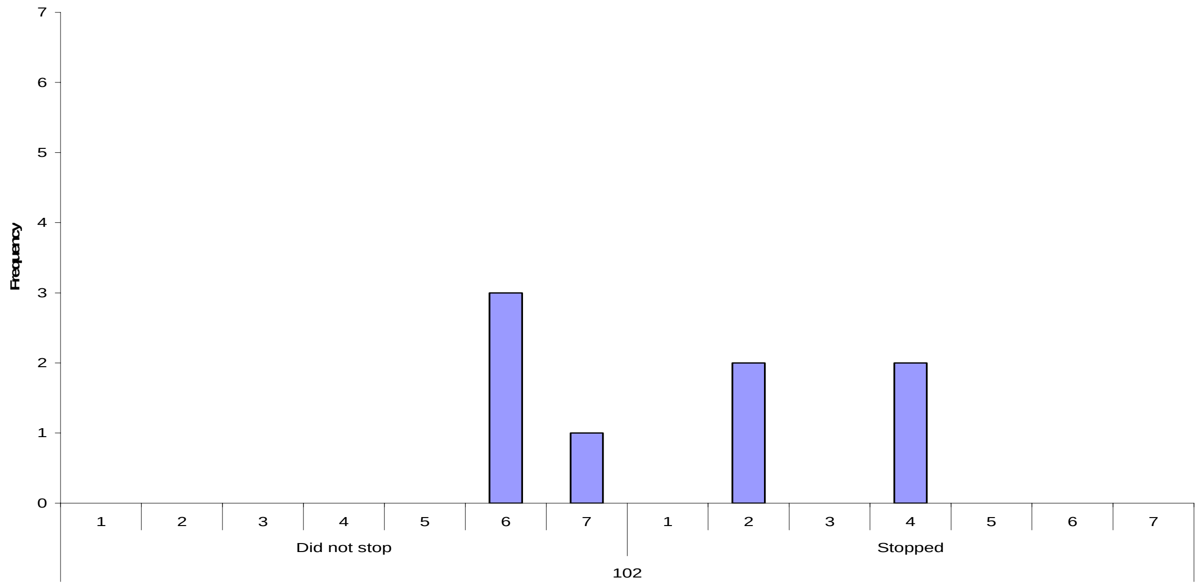

Figure E-111. "STOP" LED sign plus strobes, 35 mph, 2.03-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

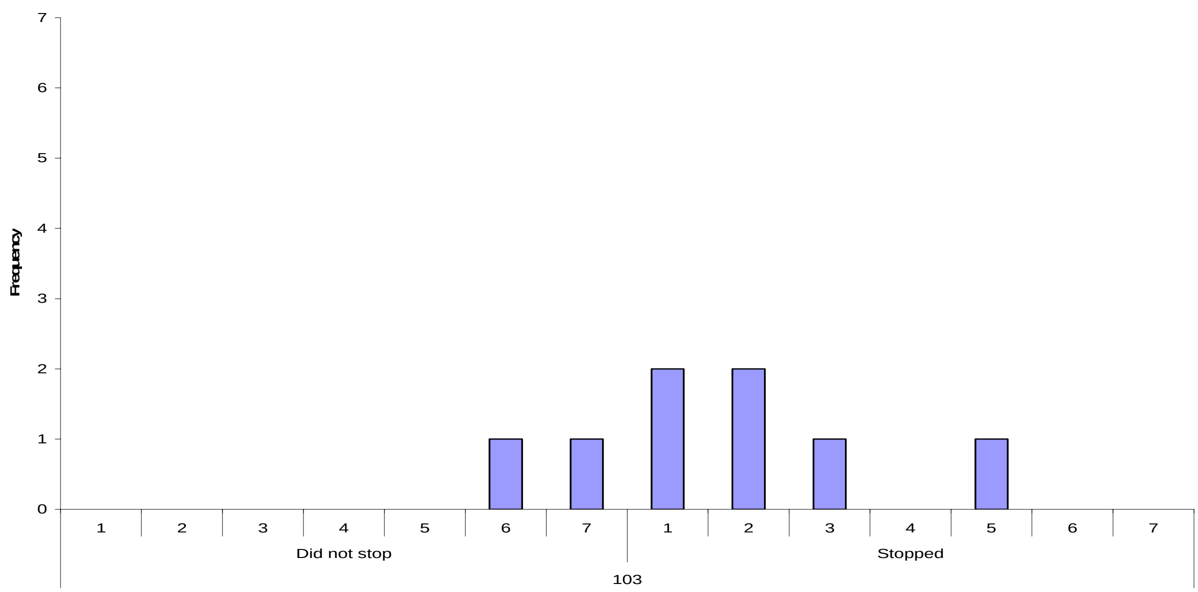

Figure E-112. "STOP" LED sign plus strobes, 35 mph, 2.65-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

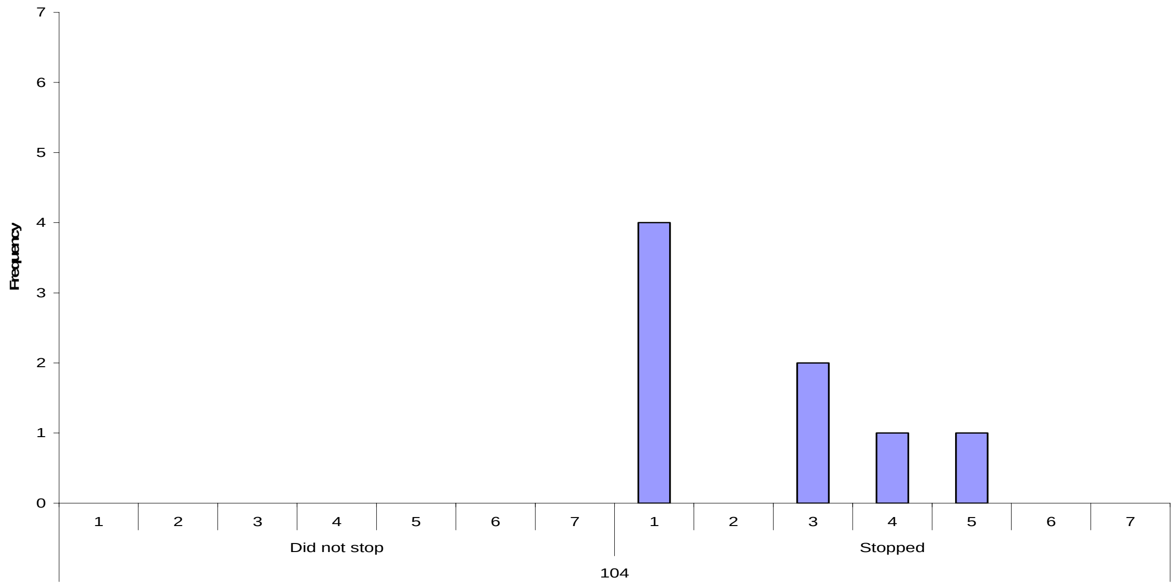

Figure E-113. "STOP" LED sign plus strobes, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

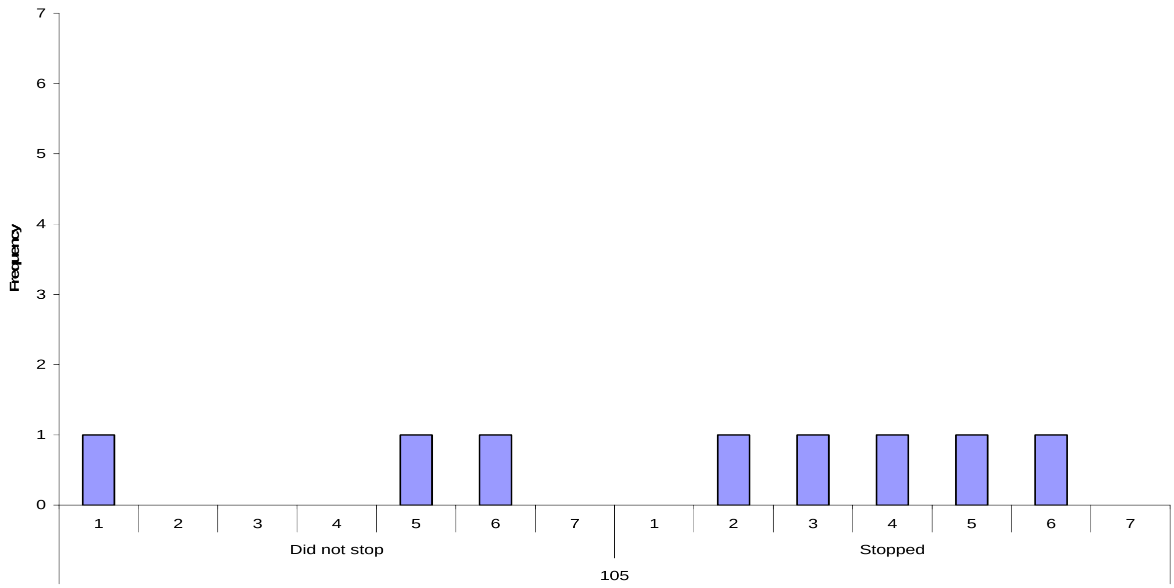

Figure E-114. LED-enhanced stop sign, 35 mph, 3.02-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

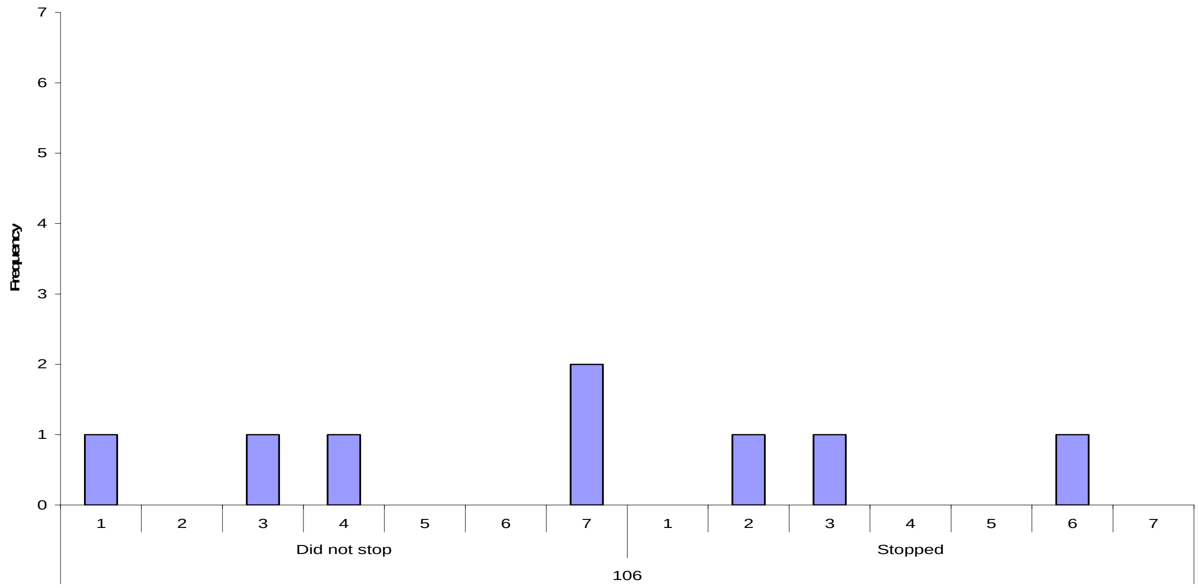

Figure E-115. Baseline, 35 mph, 3.02-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

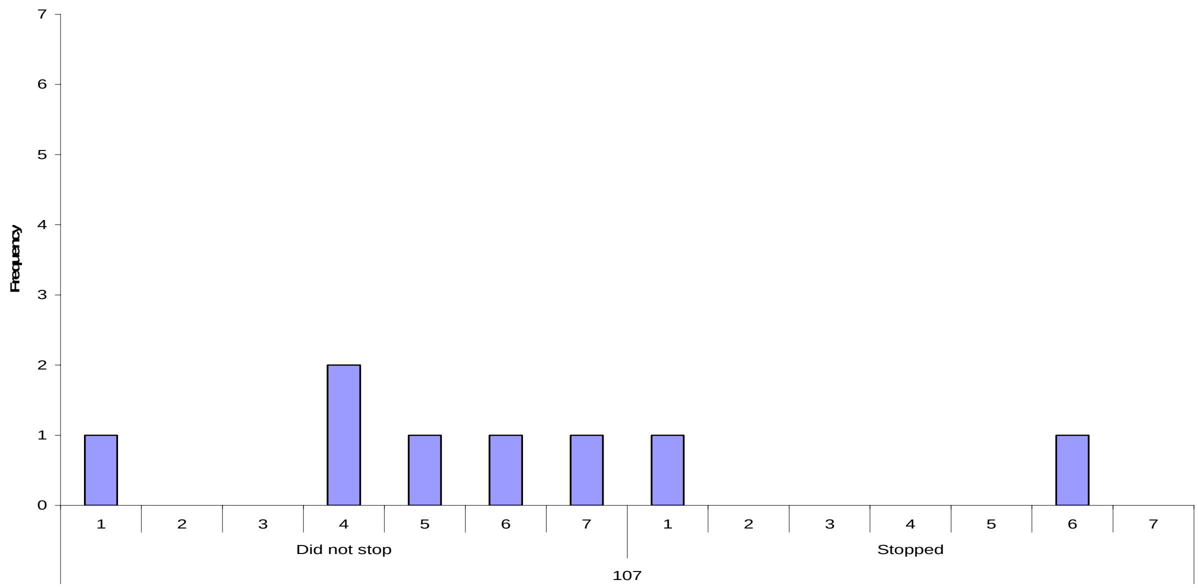

Figure E-116. LED-enhanced stop sign, 35 mph, 2.03-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

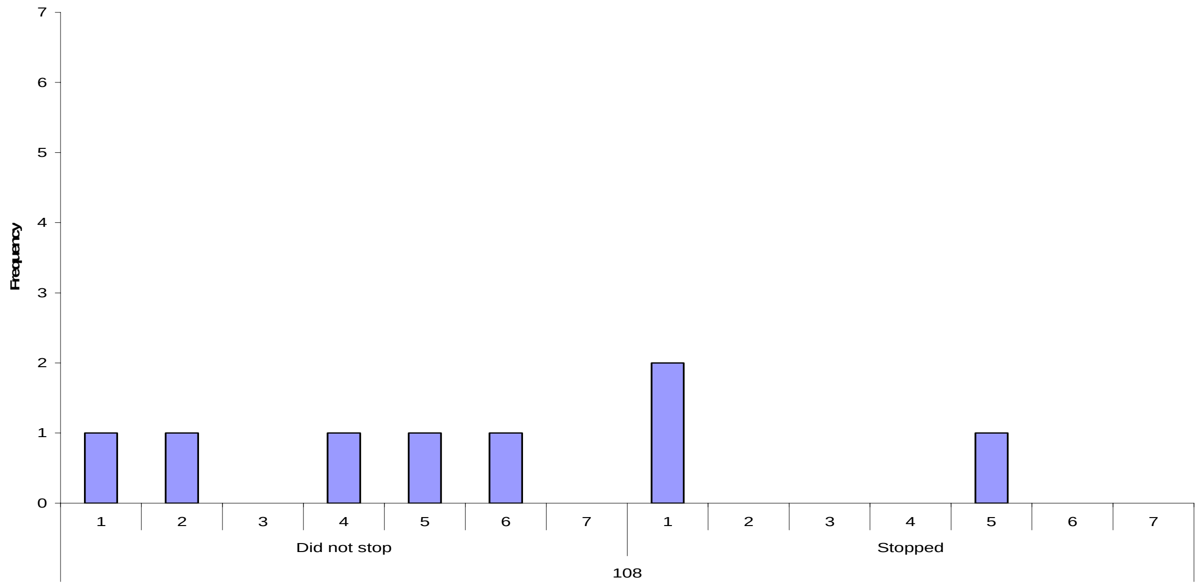

Figure E-117. LED-enhanced stop sign, 35 mph, 2.65-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

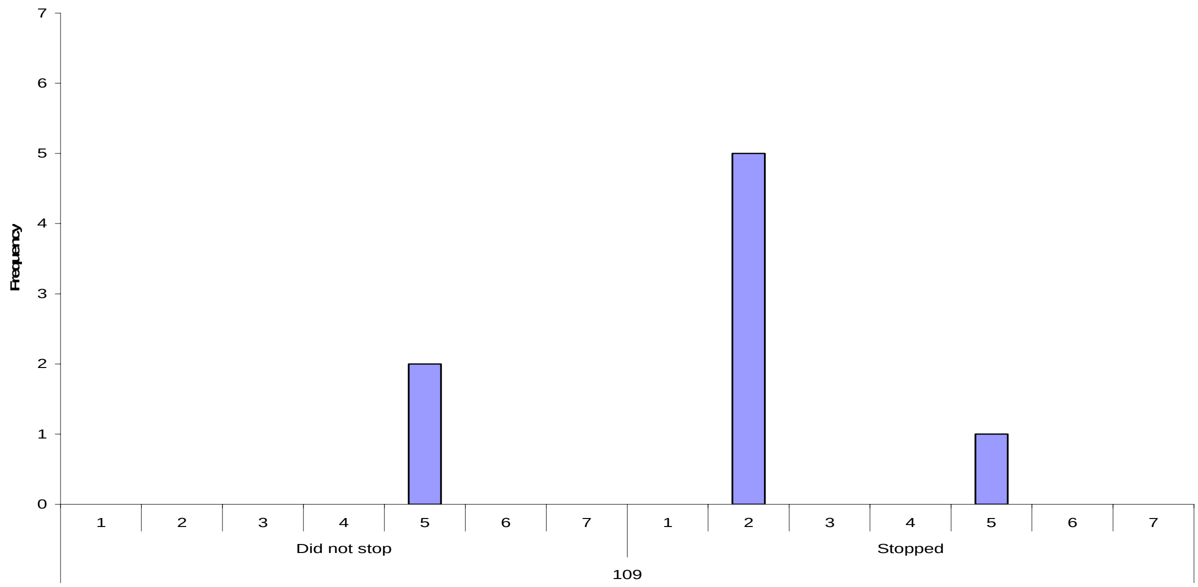

Figure E-118. Baseline, 35 mph, 2.65-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

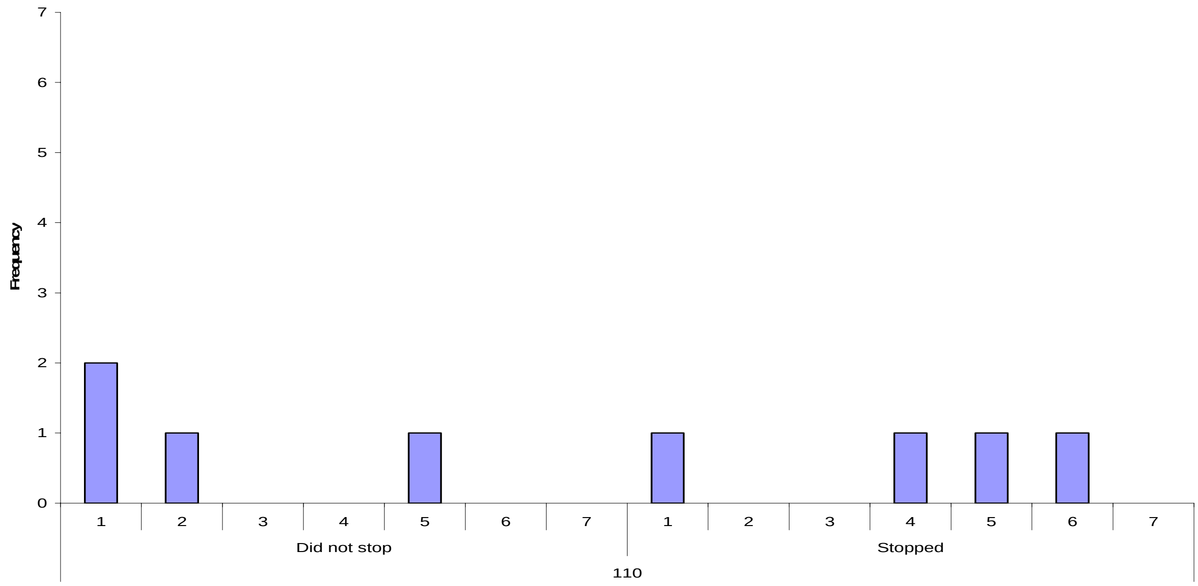

Figure E-119. Baseline, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

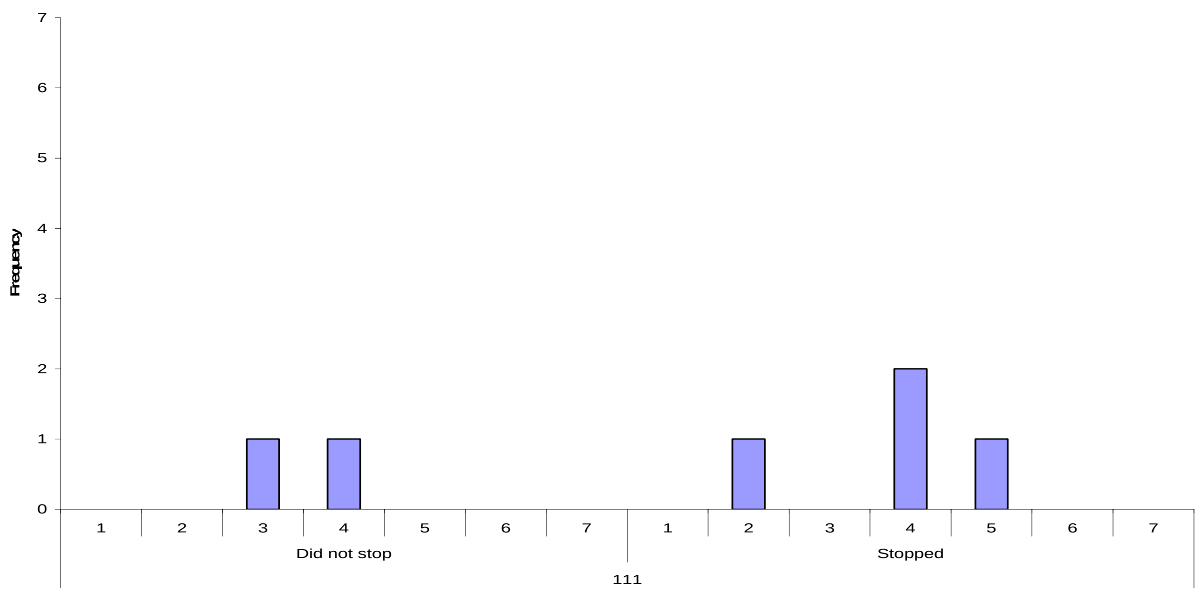

Figure E-120. LED-enhanced stop sign, 35 mph, 3.41-second TTI: Driver-perceived safety during the surprise event (1 = Very Safe, 7 = Very Unsafe).

Appendix F: Algorithm Single Point Detection

Single-point detection entails knowledge of a vehicle's position and speed at a discrete point in the intersection approach. The advantages of a single point detection algorithm would be its mathematical simplicity and its requirement of low complexity, widely available, sensing technology. For example, appropriately located loop detectors, which are used in the control of many intersections, might be able to provide the necessary data for a single point detection algorithm.

Those considerations prompted the use of the data obtained in the baseline human factors experiment in the development of point detection algorithms. The main goal in algorithm design was to minimize the number of both nuisance and missed alarms that were presented to drivers. The approach used was to overlay the different algorithm alternatives against available normal intersection approaches and determine the extent to which appropriate alarms were provided.

Algorithm Point Detection at 56.3 km/h (35 mph)

For the point-detection analysis, the critical point (or distance) was determined using an analysis of range and range rate data. The process started by determining the threshold speed. This speed represents a decision variable. Any driver traveling faster than the threshold speed at the detection point would be identified as a violator. Any driver below the threshold speed would be identified as a compliant driver.

All drivers that chose to go were separated from those who chose to stop. It was then assumed that all drivers that chose to go were violators. In other words, it is assumed that the approach profile of a violating driver is not different than the approach for a driver that decides to go. Average speed and corresponding confidence intervals were calculated by distance for drivers that opted to go. Thus, depending on the value of alpha, 80, 90, 95, or 99 percent of the drivers that chose to go will fall above the lower confidence interval (Figure F-1). Distance did not significantly affect the threshold speed. Thus, the speed trigger was calculated by averaging the lower confidence limit data across distance. This resulted in the trigger speeds as indicated in Table F-1 and overlaid on a scatter plot in Figure F-2.

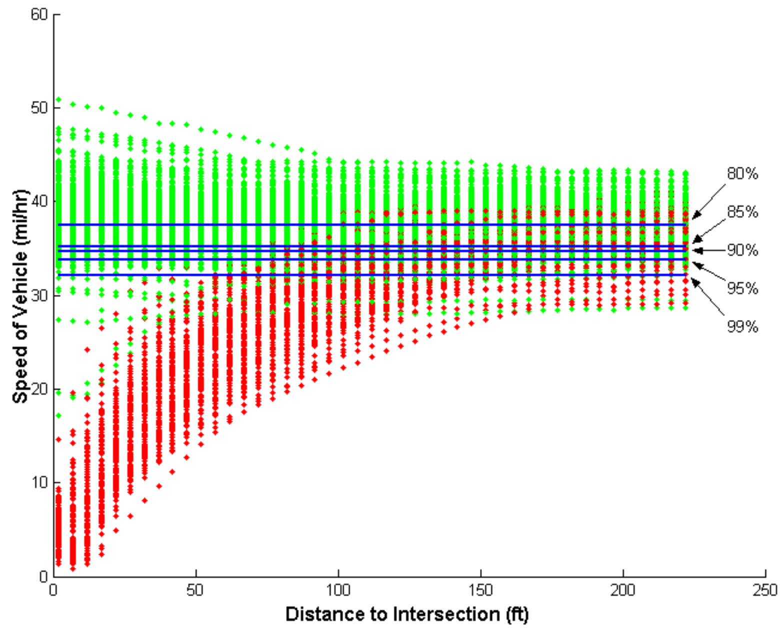

Figure F-1. Trigger speeds overlaid on scatter-plot of drivers who chose to go and drivers who chose to stop. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table F-1: Trigger speeds for five alpha levels.

Alpha	(1-Alpha) *100	Trigger Speed
0.2	80%	60.40 km/h (37.53 mph)
.15	85%	56.68 km/h (35.22 mph)
.1	90%	55.75 km/h (34.64 mph)
.05	95%	54.33 km/h (33.76 mph)
.01	99%	51.76 km/h (32.16 mph)

Each compliant driver that has a speed higher than the threshold speed at the detection point will receive a nuisance alarm. That is, the driver would have been alerted despite the fact that he or she would have stopped without the warning. For a given critical distance, the number of nuisance alarms is the sum of the compliant profiles lying above the threshold speed line. An assumption can be made to reduce the number of nuisance alarms that occur. The assumption involves ignoring any driver that can safely pass through the intersection if he or she simply maintains 56.3 km/h (35 mph). Safely passing through the intersection does not necessarily indicate that a violation did not occur. Rather, it indicates that ample time is available for a driver to clear the intersection before cross traffic has entered. This is referred to as a crash warning in this report and is less stringent than the violation level warning. Thus, for this analysis only intersection crossings in which the phase change initiated at the furthest distance (69.5 m, 228 ft) are considered.

Using the five threshold speeds (corresponds to alpha) the number of false alarms as a function of warning distance was plotted (Figure F-2). As expected, the number of false alarms increased with distance from the intersection and with increasing alpha (corresponding to higher threshold speeds).

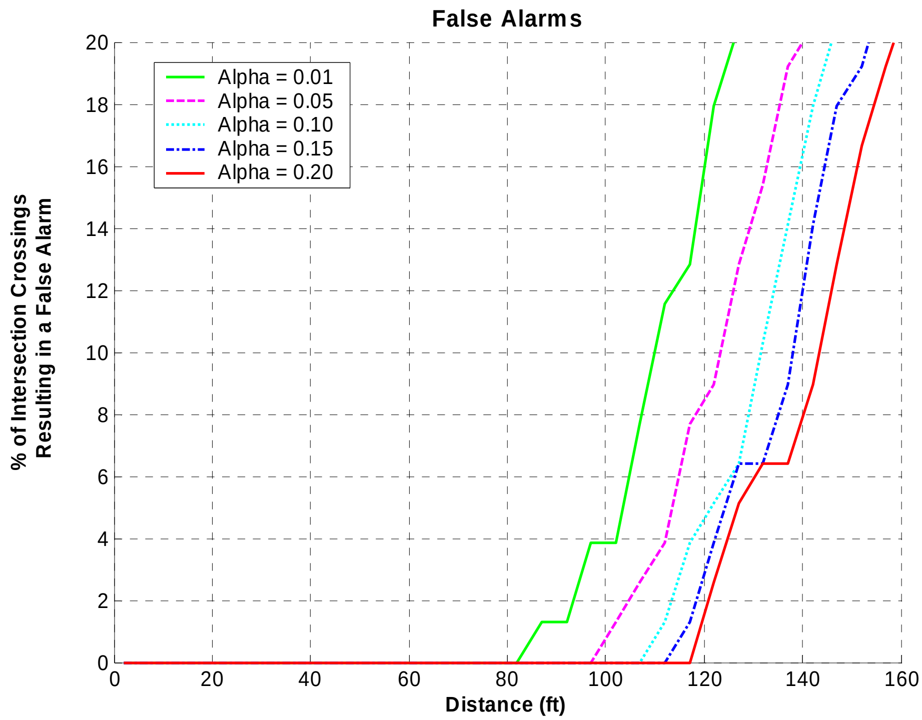

Figure F-2. The percentage of false alarms as a function of critical distance and alpha (corresponds to trigger speed) for baseline drivers only. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The above plot suggests that with an alpha value of 0.01 (51.5 km/h, 32 mph) a trigger distance set at 24.4 m (80 ft) is the furthest point from the intersection that will result in no false alarms. To consider the implications of setting the critical distance at 24.4 m a required braking rate plot is provided (Figure F-3). This plot was generated using the basic kinematics equations of motion assuming constant deceleration. It displays the average rate of deceleration required to stop depending on the distance at which the warning is initiated and assuming a 0.5-, 1-, or 1.5-second reaction time. At a trigger distance of 24.4 m an average deceleration rate of near 1 *g* is required to stop. Deceleration rates in this range will not be acceptable to drivers nor fall within the braking capacity of many vehicles. Consider that to avoid a crash the violating driver needs only to stop before entering the adjacent travel lane and not at the stop bar. Thus, an extra 9.1 m (30 ft) of stopping distance can be added. This provides 33.5 m (110 ft) of stopping distance rather than 24.4 m (80 ft), but corresponds to a still unrealistic 0.7 *g* assuming a 1-second reaction time.

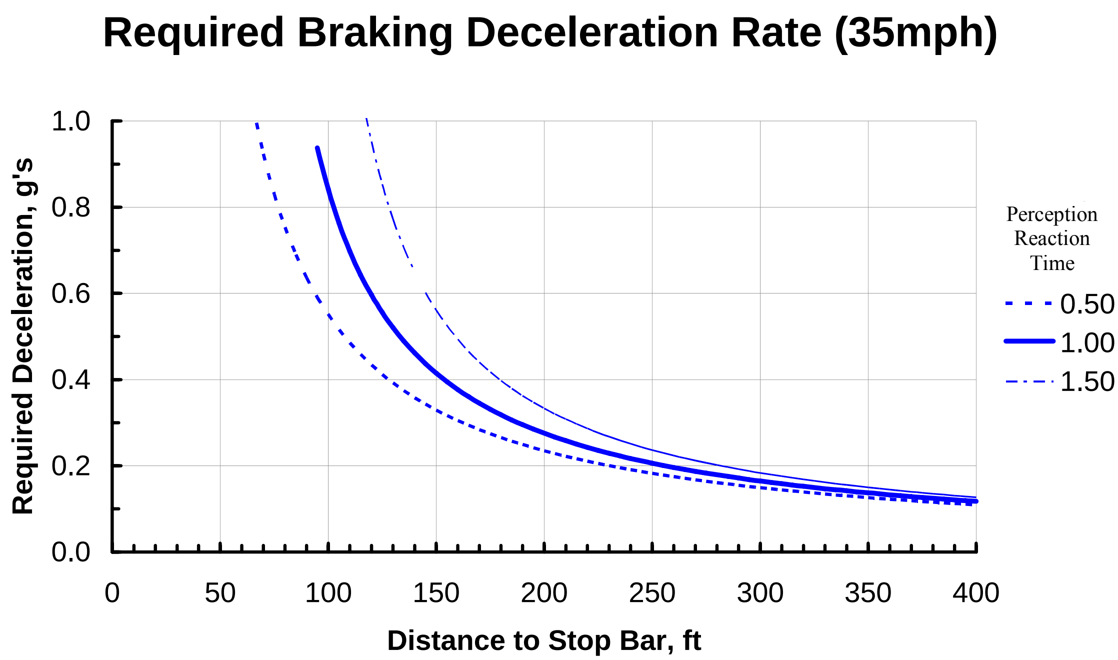

Figure F-3. Required deceleration rate as a function of distance at which the alarm is initiated for perception reaction times of .5, 1, and 1.5 s and assuming an initial speed of 35 mph. (Note: 1 ft = 0.305 m)

If it is decided that missing some violators is acceptable the trigger speed (alpha) can be increased. Or, if it is decided that a certain percentage of false alarms are acceptable the trigger distance can increase. For instance, if alpha is increased to 0.05 (54.7 km/h, 34 mph) and we accept a 2 percent false alarm rate, a triggering distance of 39.6 m (130 ft) is selected. With an assumed one second reaction time this corresponds to a 0.5 *g* average deceleration rate. The DII testing described in the DII Effectiveness Tests section of this report indicated that a 0.5 *g* deceleration rate is still unrealistic for a driver in response to the DII. To decrease the required deceleration further a higher number of misses can be permitted. However, continuing to increase alpha creates trigger speeds that exceed the speed limit. This would miss any driver that is not speeding; negating the safety enhancement for law-abiding drivers. Such an approach seems an unacceptable compromise. Thus, it would seam the only solution is to accept more false alarms. However, to reduce the required deceleration to 0.4 *g* would result in over 20 percent false alarms with a 5 percent miss rate. If speeding is considered, the problem is worse.

It is not unusual for drivers to exceed the posted speed limit in excess of 16.1 km/h (10 mph). Speeders can substantially impact the performance of a single-point detection intersection algorithm. For instance, in the last scenario described the critical distance was 39.6 m (130 ft) which corresponded to a 0.5 *g* average deceleration with an assumed one second reaction time. For the speeding driver, this once again corresponds to a 0.75 *g* deceleration. Yet the speeding driver represents the highest potential for severe injury and thus should not be disregarded.

Algorithm Point Detection at 72.4 km/h (45 mph)

For the 72.4-km/h case, the critical point was determined using an identical analysis of range and range rate as the one discussed in the previous section but for the 56.3-km/h case. All drivers that chose to go were separated from those who chose to stop. It was again assumed that all drivers that chose to go were violators. Average speed and confidence intervals were calculated as a function of distance for drivers that opted to go. Thus, depending on the value of alpha, 80, 90, 95, or 99 percent of the drivers that chose to go fell above the lower confidence interval. This resulted in the trigger speeds as indicated in Table F-2 and overlaid on a scatter plot in Figure F-4.

Table F-2: Trigger speeds for five alpha levels

Alpha	(1-Alpha) *100	Trigger Speed
0.2	80%	72.20 km/h (44.86 mph)
.15	85%	71.47 km/h (44.41 mph)
.1	90%	70.68 km/h (43.92 mph)
.05	95%	70.15 km/h (43.59 mph)
.01	99%	66.21 km/h (41.14 mph)

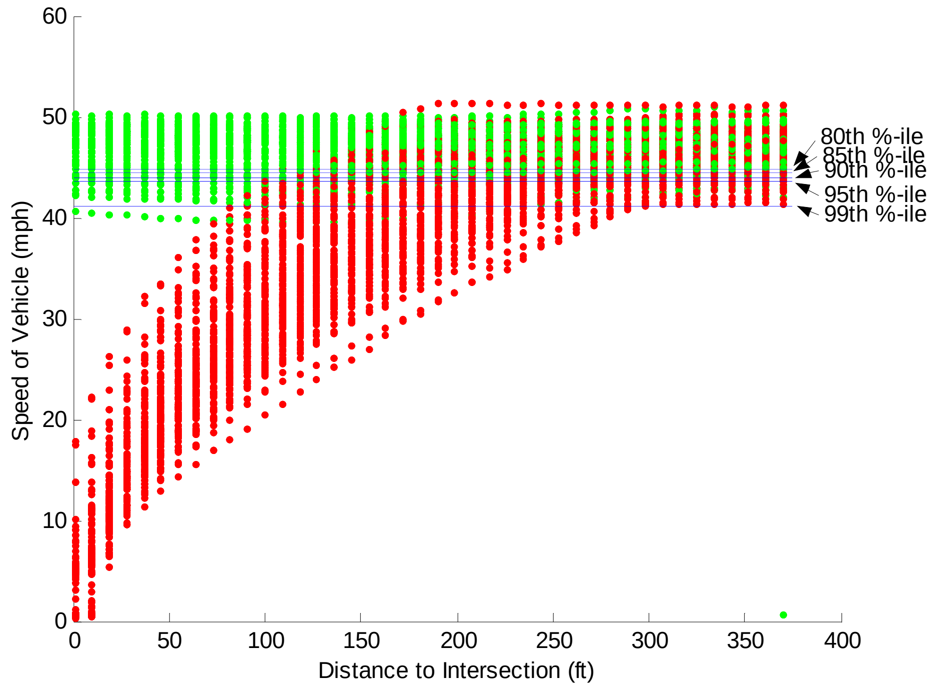

Figure F-4. Trigger speeds overlaid on scatter-plot of drivers who chose to go and drivers who chose to stop. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

As explained for the 56.3-km/h situation, when a compliant approach lies above the trigger line at the critical distance, a nuisance alarm has occurred. That is, the driver would have been alerted despite the fact that he or she would have stopped without the warning.

As before, for a given critical distance, the number of nuisance alarms is the sum of the stop profiles lying above the trigger line. The same assumptions can be made to reduce the number of nuisance alarms that occur. The first assumption is that a crash-level warning rather than violation warning meets the goals of IDS. Thus, for the nuisance alarm analysis only intersection crossings in which the phase change initiated at the farthest distances (>103.3 m, 339 ft) are considered. To enhance the visualization of the miss/false alarm relationship a three-dimensional plot is used (Figure F-5). The plot shows two surfaces, one representing the number of false alarms and the other the corresponding number of misses (corresponding to alpha). To determine effectiveness of a warning parameter select a critical distance and speed threshold and read the corresponding number of misses and false alarms. As expected, the number of nuisance alarms again increases with distance from the intersection.

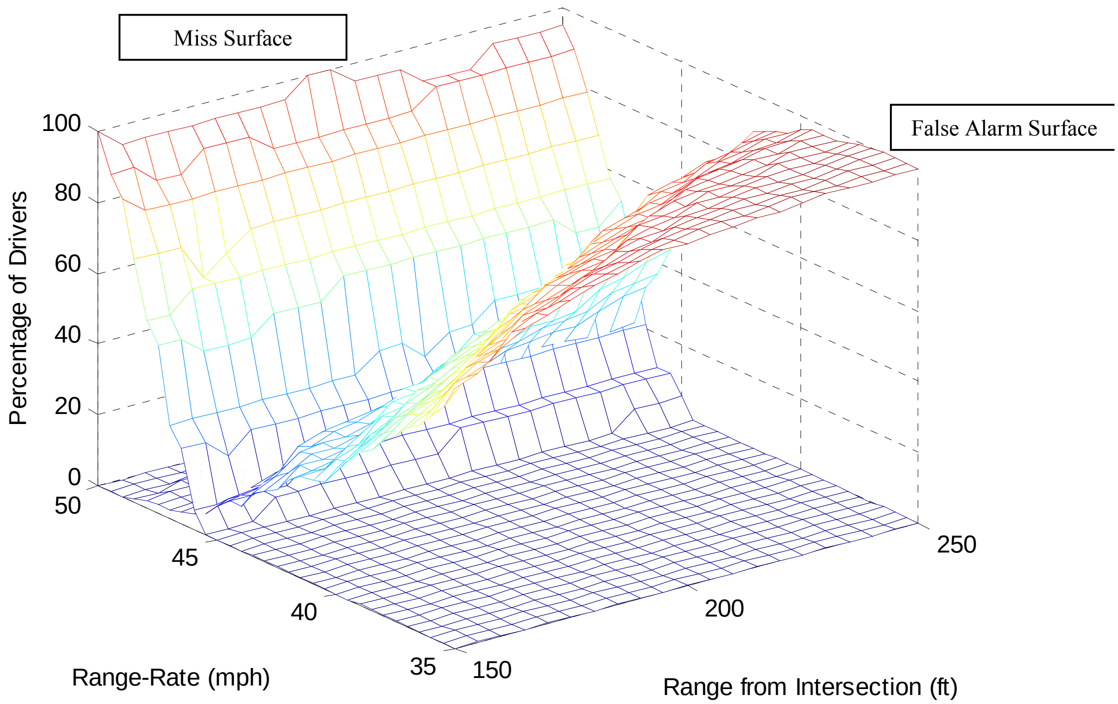

Figure F-5. The percentage of false alarms (curve that increases with range rate) and misses (curve that decreases with range rate) as a function of critical distance and threshold speed for all driver states. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The above plot suggests that an alpha value of ~0.05 (73.2 km/h, 45.5 mph) with a trigger distance set at 45.7 m (150 ft) would result in minimal nuisance alarms and fewest misses. Even at this point, however, ~23.3 percent of the drivers will receive nuisance alarms. To further consider the implications of setting the critical distance at 45.7 m a required braking rate plot is provided (Figure F-6). At a trigger distance of 45.7 m (150 ft) an average deceleration rate of ~0.6 *g* is required to stop. As determined in the DII testing deceleration rates in this range will not be acceptable to a large proportion of drivers and may not fall within the braking capacity of every vehicle under certain environmental conditions. If it is assumed that a driver will continue to stop after the stop bar has been crossed an additional 9.1 m (30 ft) can be added to the distance available for stopping. This provides 54.9 m (180 ft) of stopping distance rather than 45.7 m (150 ft), corresponding to a more realistic ~0.45 *g* stop. However, consider that even if drivers can be convinced to stop at 0.45 *g* there will still be a 23.3 percent false alarm rate.

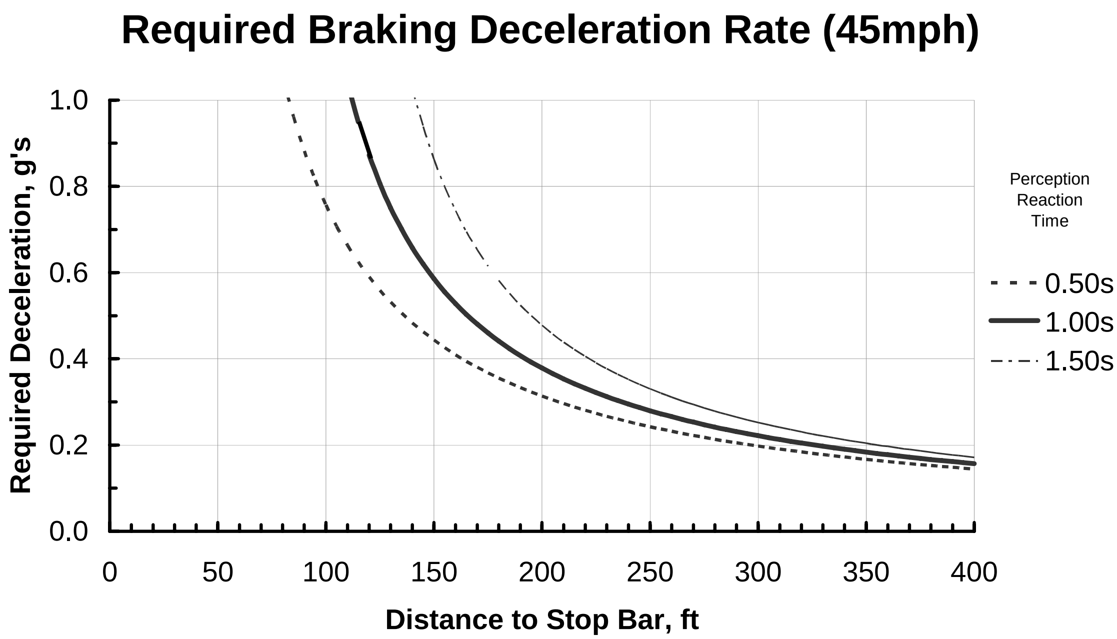

Figure F-6. Required deceleration rate as a function of distance at which the alarm is initiated for perception reaction times of .5, 1, and 1.5 s and assuming an initial speed of 72.4 km/h. (Note: 1 ft = 0.305 m)

If it is decided that missing some violators is acceptable (i.e., increasing alpha) the trigger speed can be increased. Or, if it is decided that a certain percentage of false alarms is acceptable, the trigger distance can increase. However, in any case it seams that either number of misses or the false alarms will be unacceptably high. This problem is again made worse when speeders are considered. For instance, in the last scenario described, the critical distance was 54.9 m which corresponded to a ~0.45 *g* average deceleration with an assumed 1-second reaction time. For the speeding driver, this scenario once again corresponds to an unrealistic 1.02 *g* deceleration.

Conclusion

The results suggest that, while technologically feasible, a single-point detection algorithm would provide inadequate performance for an IDS application. When either missed or nuisance alarms are minimized using this approach, the type of incorrect algorithm decision that was not minimized becomes unacceptably large. Attempts to trade-off these two types of incorrect alarms did not yield any acceptable balance. Thus, it appears that single point detection is not an acceptable approach to provide an IDS system designed to prevent SCP intersection crashes with warning decisions.

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Appendix G: Algorithm Continuous Detection

Algorithms that require continuous detection employ in their calculations information about a vehicle's position, speed, and/or acceleration throughout a range of the intersection approach. This information is provided to the algorithm at the sampling rate available for the sensing technology and this rate is not dependent on the location of any particular detector. Continuous detection algorithms can either use the time history of the approach in making their decision or simply use the vehicle's instant kinematics. In any case, the vehicle kinematics are compared against pre-established and kinematically variant warning thresholds. When the vehicle kinematics cross those thresholds, a warning is issued.

The number and shape of thresholds that can be used when continuous detection is available is infinite. However, based on reviews of the literature and knowledge of the kinematic characteristics of normal intersection approaches, they can be bound and a number of potential thresholds reduced. That process is the focus of this appendix, which was meant to determine, as a function of human behavior (e.g., reaction time) and/or vehicle kinematics (e.g., longitudinal acceleration), the algorithm settings that results in warning thresholds with low rates of nuisance and missed alarms.

The data obtained for the baseline human factors tests were used in testing the different algorithm approaches. Algorithm options were overlaid on these data to provide an indication of an appropriate alarm (for those approaches in which a warning was issued and which ultimately resulted in a violation or approaches in which no warning was issued and did not result in a violation), a nuisance alarm (when the driver stopped), or a missed alarm (for those approaches in which a violation was incurred but no warning was issued). These violation warnings are referred to in this section as Level 1 warnings.

Given that Level 1 warnings were expected to result in considerable numbers of nuisance alarms, an additional warning level (Level 2) was defined. Level 2 warnings would only be issued when a violation occurs late enough in the red phase that a crash is probable, given the presence of crossing traffic at the intersection. It was expected that Level 2 warnings would exhibit a much lower rate of nuisance alarms while still preventing crash situations. The discussion in this section is not directed towards advocating one approach over the other, but rather to consider and quantify the inherent trade-offs between a violation (Level 1) and crash (Level 2) warning.

The steps performed to determine the need for a Level 2 warning were:

1) The average speed at which a POV might enter the intersection (*avgVpov*) is calculated, based on a percentage (*perPOV*) of design speed (*VD*). Throughout this report, the percentage was assumed to be 75 percent, based on engineering judgment. Since the results of different experiments were used in this report, the design speed for each was considered to be the speed limit verbally provided to the participants of each experiment. In the equation below, the design speed could also be used without any percentage adjustment (i.e., *perPOV* = 100 percent), but the **average** speed of the POV is unlikely to

be that high, as it would require the POV to time the red-green phase change very accurately while approaching the intersection at the design speed (Equation G-1).

$$avgVpov = perPOV * VD \qquad \text{(G-1)}$$

2) Once the average speed of entering POVs is determined, the time it would take for a POV to be in the conflict area, after the red clearance time, is calculated for the far (*tfar*) and near (*tnear*) POV traffic lanes. The terms 'near' and 'far' refer to the lane from which the POV is entering from the SV's reference point. This calculation is based on *avgVpov* and assumptions for the car length (*L*) and the intersection's width (*W*) (Figure G-1). Throughout this report, *L* was assumed to be 6.1 m (20 ft) while *W* was assumed to be 18.3 m (60 ft), based on the values representative of the Smart Road intersection, on which these studies were performed. These values can be changed, as necessary, for each particular intersection (Equations G-2 and G-3).

$$tfar = \frac{\frac{1}{4} * W + \frac{1}{2} * L}{avgVpov} \qquad \text{(G-2)}$$

$$tnear = \frac{\frac{3}{4} * W + \frac{1}{2} * L}{avgVpov} \qquad \text{(G-3)}$$

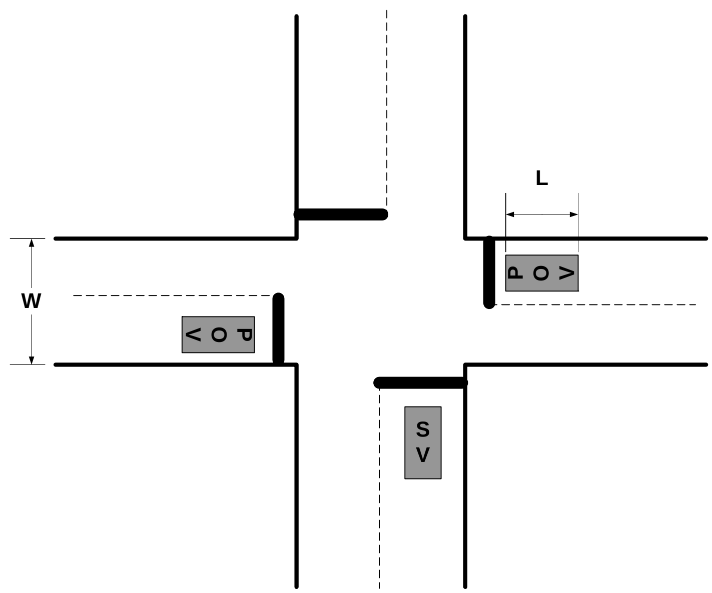


Figure G-1. Intersection schematic.

3) *Xc* values are calculated as the maximum distances from the stop bar at which the SV would have to be when the amber to all-red phase change occurs for the SV to be at risk of hitting the POV(s) in the far and near lanes once these POV(s) see an all-red-to-green phase change. Note that at the *Xc* distance the POV receives a red-to-all-red phase change, which is not necessarily apparent to the POV's driver. The variable a_{beat} in this case is in units of ft/s^2 and represents the level of acceleration achievable by a vehicle at

speed. The a_{beat} variable is applied to the SV and calculated from an empirical equation, also shown below. It would also be possible to make a more conservative assumption of no acceleration from the SV, which would result in smaller values for *Xc*. *RC* represents the red clearance time, in seconds, and was calculated to be ~1.8 s for the Smart Road intersection, based on the ITE equation (ITE 1991). Note that there is an implicit assumption contained in these equations that a collision occurs with the front bumper of the SV hitting the mid-side of the POV. A vehicle front corner-to-corner collision would reduce *tfar* and *tnear*, resulting in a more conservative estimate of crash risk. The extent of this reduction, however, depends on the characteristics of the intersection under design (Equations G-4 through G-6).

$$Xcfar = V*(RC+tfar) + \frac{a_{beat}*(RC+tfar)^2}{2} - \frac{3}{4}*W + \frac{1}{2}*L \qquad \text{(G-4)}$$

$$Xcnear = V*(RC+tnear) + \frac{a_{beat}*(RC+tnear)^2}{2} - \frac{1}{4}*W + \frac{1}{2}*L \qquad \text{(G-5)}$$

$$a_{beat} = 16 - 0.145*V \qquad \text{(G-6)}$$

4) The smaller of the *Xc* numbers (i.e., far or near) is selected, as a worst case, for use in determining the maximum range from the intersection at which the SV would have to be when an amber-red phase change occurred for the potential to exist for the issuance of a Level 2 warning (if necessary).
5) A check on the amber time remaining is performed. A Level 2 warning is necessary if: (1) the range, corrected by *Xc*, is more than or equal to the remaining amber time multiplied by the vehicle's velocity, and (2) the vehicle's dynamic characteristics exceed a pre-specified warning threshold. The equation assumes no acceleration from the SV to 'beat' the light until the amber time is consumed. Again, this results in a more conservative estimate of the need for a warning (Equation G-7).

$R - Xc \geq Amber*V$, **and**

Vehicle Characteristics < *Dynamic Threshold* (discussed in later sections) (G-7)

Seven different algorithms were developed and overlaid on the baseline data. These seven algorithms start with basic kinematics approaches and evolve into more complex relationships between the kinematics and human factors variables that were available.

Case 1: Basic Kinematics, No Deceleration

Algorithm constants for this case are the assumed constant deceleration rate (*a*, in *g*) and the assumed reaction time (*RT*, in s). Algorithm inputs are the vehicle's range (*R*, in ft) and range rate (*V*, in ft/s). Algorithm output is the required stopping distance for the vehicle (*Rw*). The minimum speed under which the algorithm operates is 24.1 km/h (15 mph) as seen in Equation G-8. **No assumptions are made, or information provided to the algorithm, with respect to the vehicle's deceleration or braking status (net deceleration of pedal position data).**

$$Rw = \frac{V^2}{2*32.174*a} + V*RT \qquad \text{(G-8)}$$

The result for *Rw* is then compared to the range of the vehicle, *R*. If a Level 1 or Level 2 warning is applicable (as described previously), it is presented only if (Equation G-9):

$$R \leq Rw \tag{G-9}$$

The two algorithm parameters, *a* and *RT*, were systematically varied between 0.25 and 0.75 *g* and 0.5 and 1.5 s, respectively. These limits were selected based on both reviews of the literature and engineering judgment, and produced considerable variation in the thresholds considered (Figure G-2).

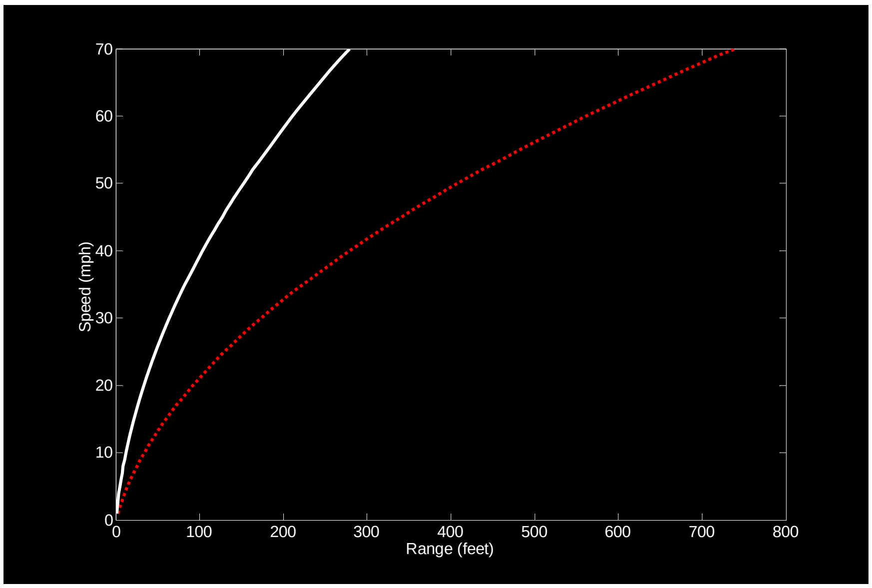


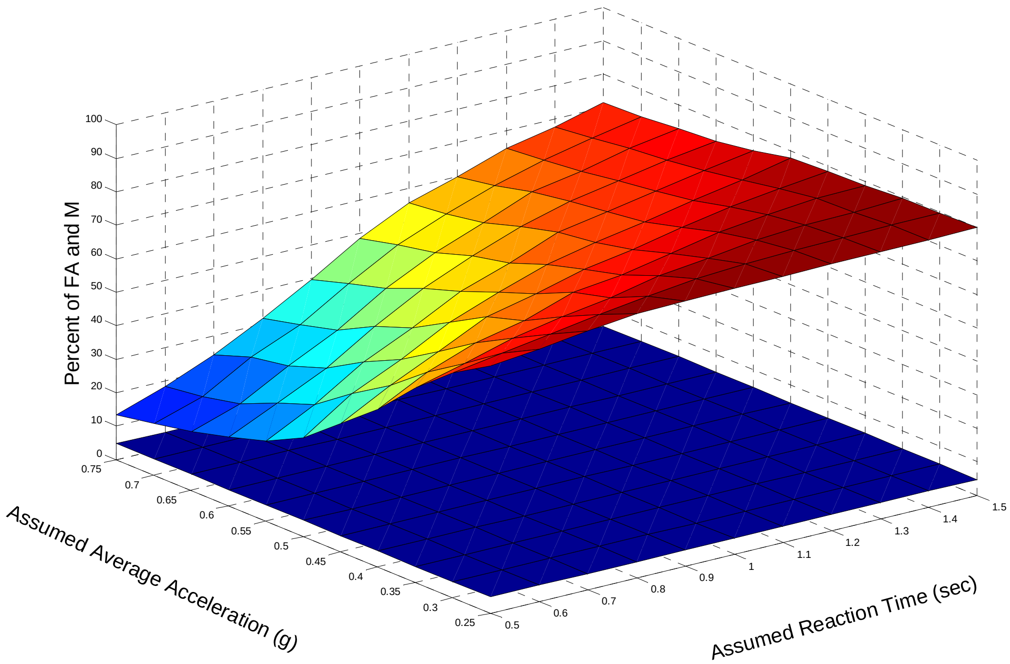
Figure G-2. Algorithm threshold limits. The dotted line represents a threshold assuming a 1.5-second reaction time and a 0.25 *g* constant deceleration level, the least aggressive threshold. The solid line represents a threshold assuming a 0.5-second reaction time and a 0.75 *g* constant deceleration level, the most aggressive threshold. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Using this algorithm, a large proportion of Level 1 and Level 2 false alarms, combined with few misses, occur (Figures G-3 and G-4). Three Level 1 misses (Figure G-5) occurred at 72.4 km/h (45 mph). Of these misses, two occurred at full speed and one while the driver was in the process of stopping. In the two violations at full speed, a violation is assigned due to the sampling rate (10 Hz). Both the intersection crossing and the end-of-the-amber countdown occur in the same sampling window, and, without interpolation, a violation has to be assumed. Closer inspection, however, shows that the crossings were legal, so these two instances can be considered correct rejections. In the third case, in which the participant chose to stop, the intersection crossing is legal (thus, the algorithm does not provide a warning), but the participant ends up stopping ~4.3 m (14 ft) into the intersection, and is correspondingly assigned a violation. This can also be classified as a correct rejection. This would effectively result in the elimination of all observed Level 1 misses and, as a result, an algorithm that would detect every violation in the datasets used. Despite these considerations, however, the “Miss” classification for these events was still retained to maintain a common basis of comparison against other algorithms. It was a concern that “nitpicking” through these events when various algorithms were being compared could introduce unwanted biases into the analysis.

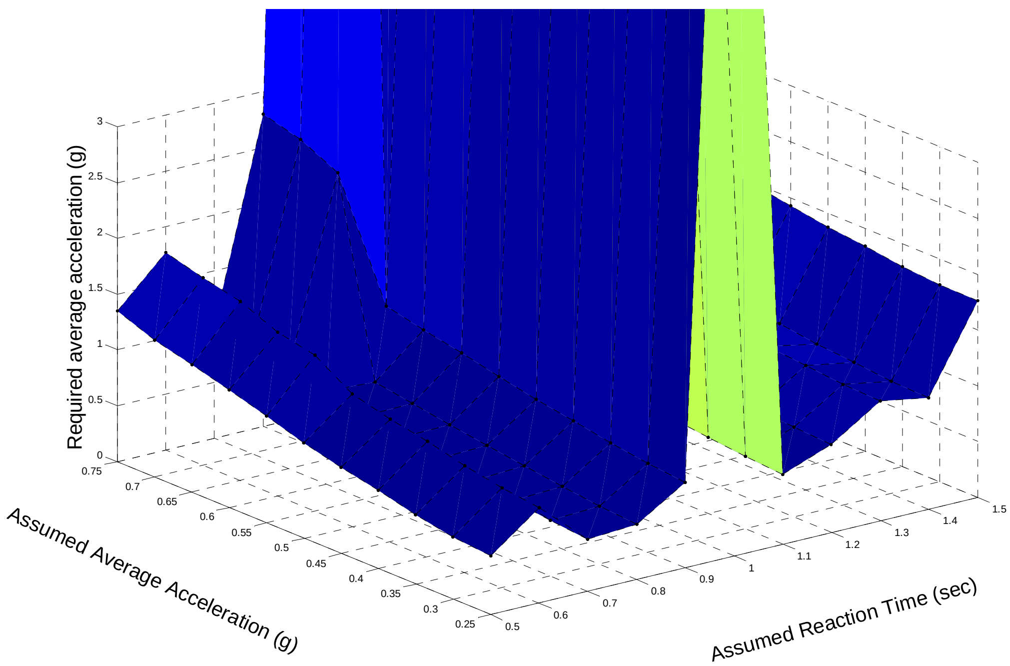
The Level 2 miss also occurred at 72.4 km/h (45 mph). In this case, the participant barely missed exiting the conflict zone due to a drop-off in the vehicle cruising speed. By the time the algorithm could have detected the possible conflict, the vehicle was already in the intersection (Figure G-6). Note the slight speed reduction in speed after the stop bar is crossed, which is barely large enough to prevent the vehicle from avoiding the conflict zone. This miss is retained as such, with the caveat that it is well within the error of the process to determine the need for a Level 2 warning, based on the number of assumptions that went into its creation.

Albeit the relative absence of misses in this algorithm, the number of false alarms for most parameter combinations is large. Level 1 false alarms range from a minimum of 13.36 percent to a maximum of 79.95 percent. Level 2 false alarms range from a minimum of 5.05 percent to a maximum of 71.79 percent. For the most part, these alarms seemed to be the result of the lack of a braking restriction. Warnings would have occurred when participants were in the act of braking, but were not braking hard enough to be within the algorithm threshold. These false alarms result in unrealistic required deceleration levels (> 0.9 *g*), since most of the false alarms were provided late in the approach. This 0.9 *g* limit is based on engineering judgment on constant vehicle braking capabilities and pilot trials on the Smart Road test track.

The large number of false alarms, combined with the unrealistic required deceleration levels, renders this algorithm approach infeasible. The effects of considering the apparent need for a braking restriction are explored in Case 2.

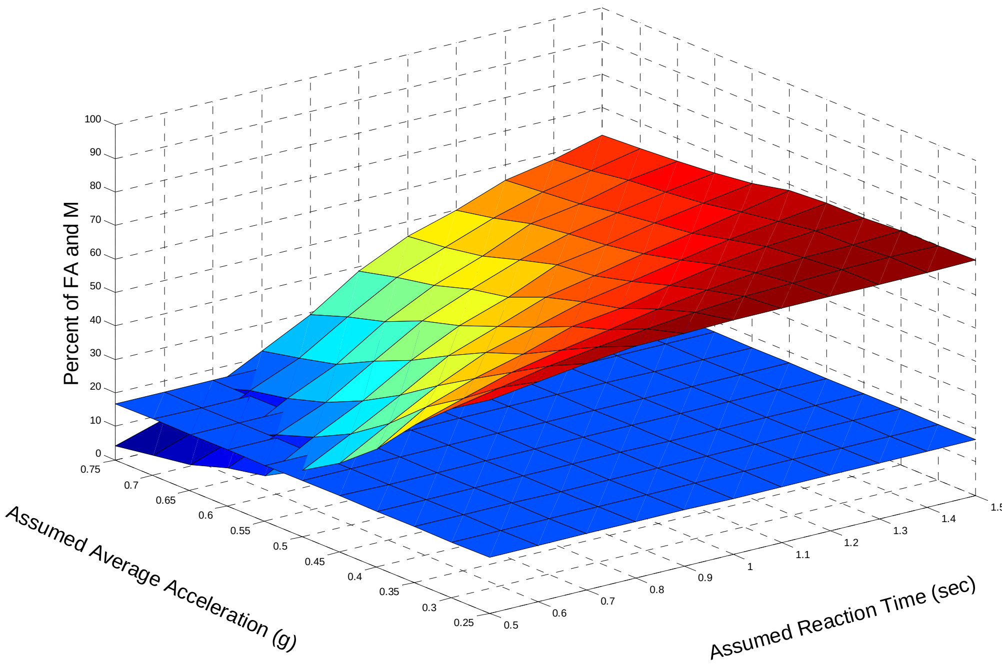


a)

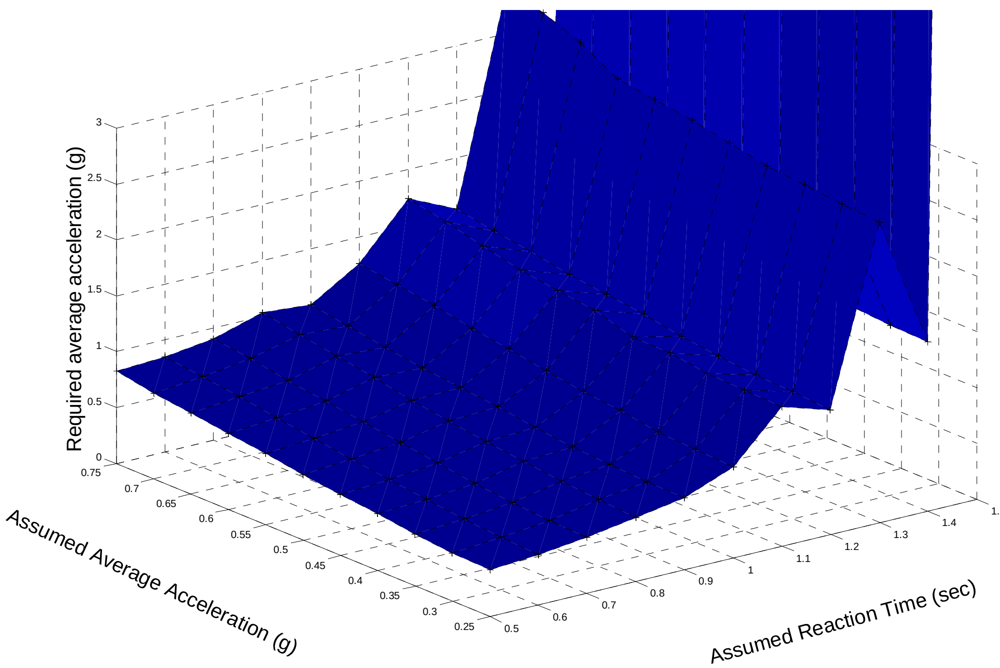


b)

Figure G-3. Level 1 false alarms (a, top surface), misses (a, bottom surface), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 1 algorithm.



a)



b)

Figure G-4. Level 2 false alarms (a, top surface), misses (a, flat surface), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 1 algorithm.

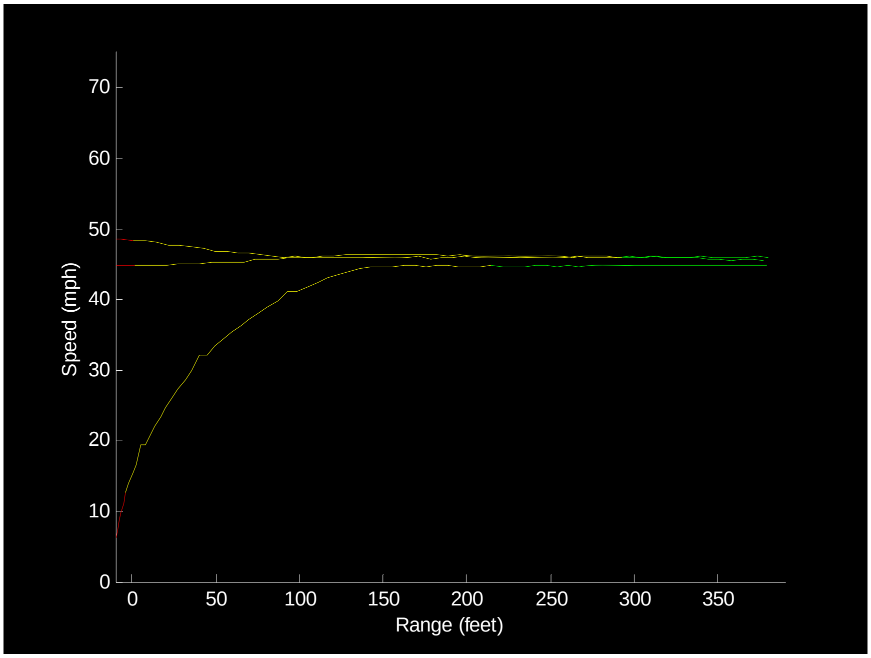


Figure G-5. Level 1 misses for the Case 1 algorithm. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

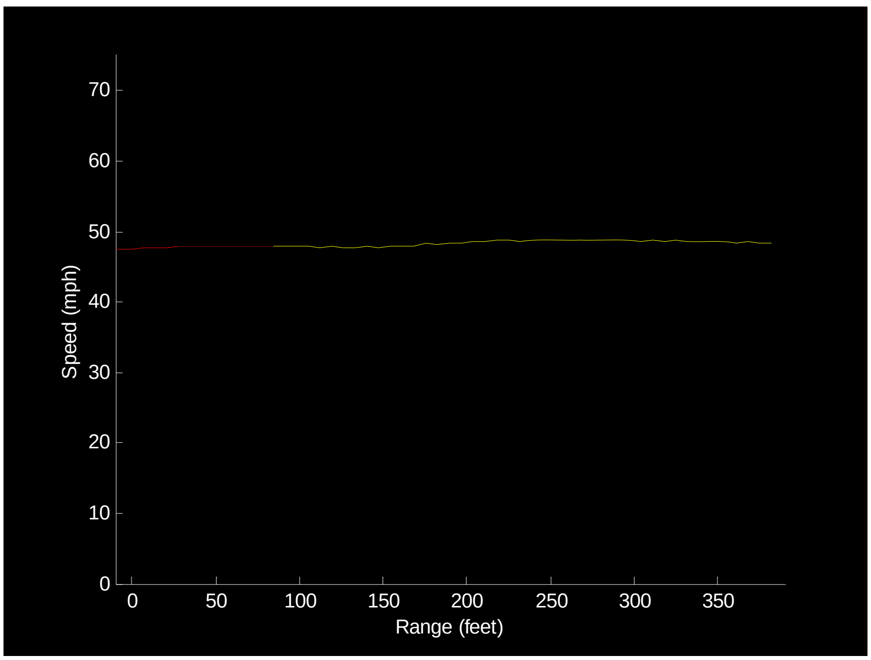


Figure G-6. Level 2 miss for the Case 1 algorithm. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

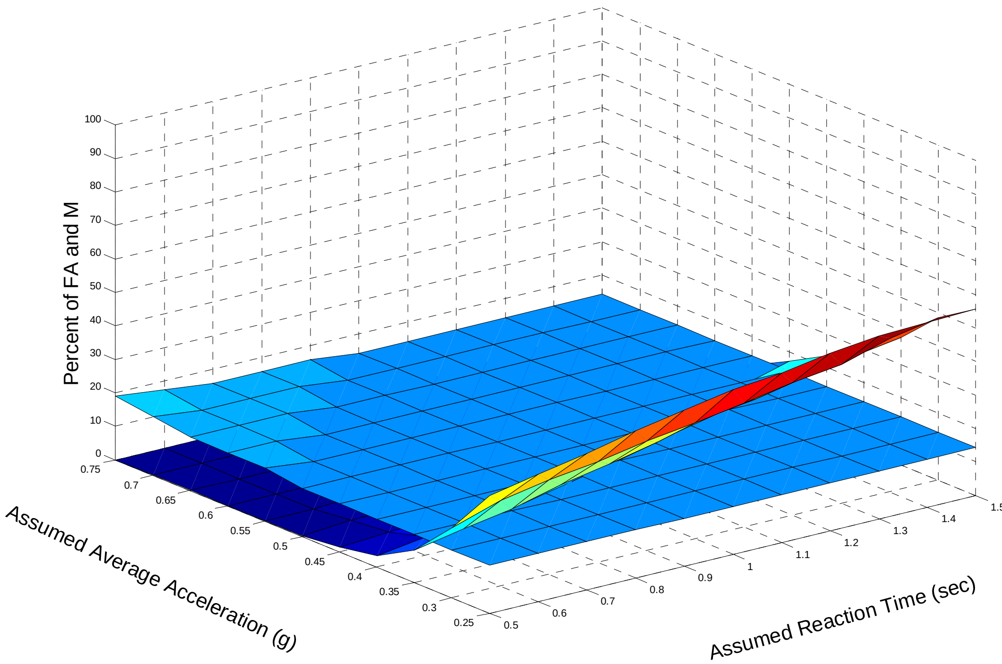
Case 2: Basic Kinematics, Deceleration

The Case 2 algorithm is structurally the same as the Case 1 algorithm, with the sole exception that a braking restriction is imposed. Thus, in addition to the tests normally performed for the Case 1 algorithm, an additional test determines whether the vehicle is braking. A level of 0.1 *g* was selected as the braking threshold after several trials were performed with other levels.

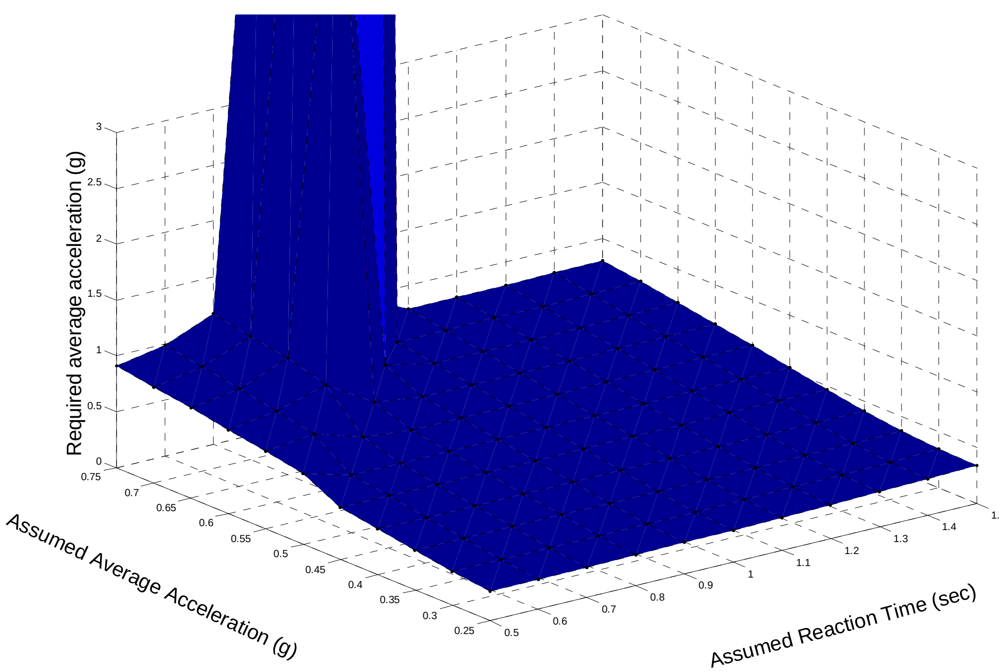
If braking is detected (vehicle deceleration > 0.1 *g*), the algorithm operation is suspended for that sampling cycle and no warning is presented.

The Level 1 false alarms range from a minimum of 0 percent to a maximum of 55.76 percent (Figure G-7). The false alarms observed were due to combinations of braking effort and reaction time that were more aggressive than those used to determine the threshold (Figure G-8). As expected, false alarms decrease as the assumed deceleration level is increased and as the reaction time is decreased (i.e., as the warning is skewed toward aggressive drivers).

Level 1 misses remain mostly constant, at approximately 15 percent. Compared to Case 1, there are more misses for the Case 2 algorithm (Figure G-9). The three misses described for Case 1, which could also be identified as correct rejections, are also present for the Case 2 algorithm, but additional misses are observed due to the braking restriction. This restriction supposes that a driver who is braking will modulate brake pressure to stop in the distance allowed. In the seven remaining miss cases, drivers did not comply with this assumption, and violated the light while in the process of stopping. In all of these seven cases, at the time of threshold crossing or after that time, the drivers either were stopping or had sufficient time to make it without a violation (hence the lack of warning at that point in time).



a)



b)

Figure G-7. Level 1 false alarms (a, curved surface), misses (a, flat surface), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 2 algorithm.

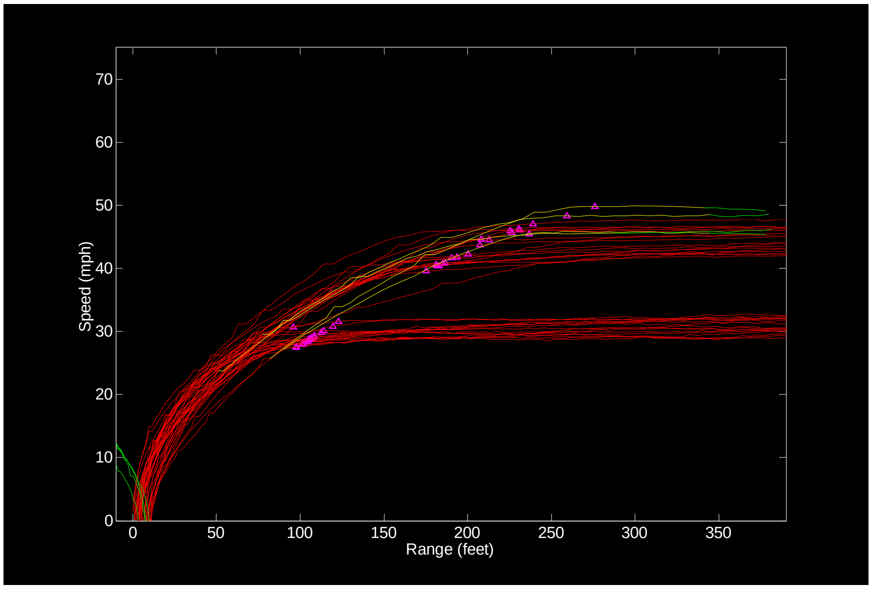


Figure G-8. Level 1 false alarms for the Case 2 algorithm. These are shown for the 0.45 *g*, 1.1-second reaction time combination. In general, the false alarms were reduced as the assumed acceleration was increased and the assumed reaction time lowered. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

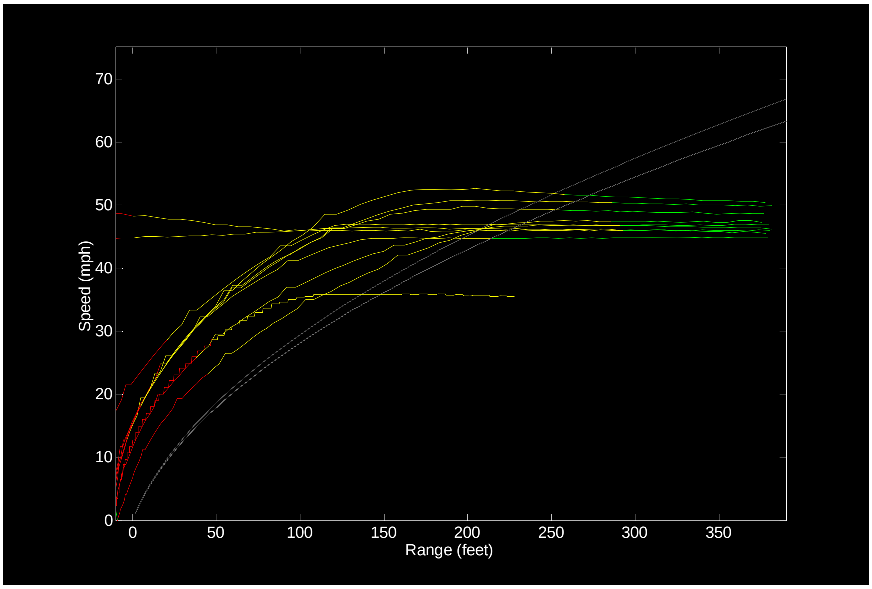


Figure G-9. Level 1 misses for the Case 2 algorithm. These are shown for the 0.25 *g*, 0.5-second reaction time combination, but are representative of the misses observed for most other parameter combinations. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Required deceleration levels were mostly below 0.9 *g* (assumed as an upper limit, see Case 1), except at high (> 0.65 *g*) assumed deceleration levels combined with reaction times near 1.0 s. In these cases, the main factor for the late warning was the driver slowing down during their approach (Figure G-10). The algorithm had calculated that the driver would have enough amber time to enter the intersection, but the driver's reduction in speed was sufficient to render this calculation incorrect. When the algorithm recalculated the warning appropriateness and issued one, the driver was close enough to the intersection to require unfeasible braking levels after the assumed reaction time.

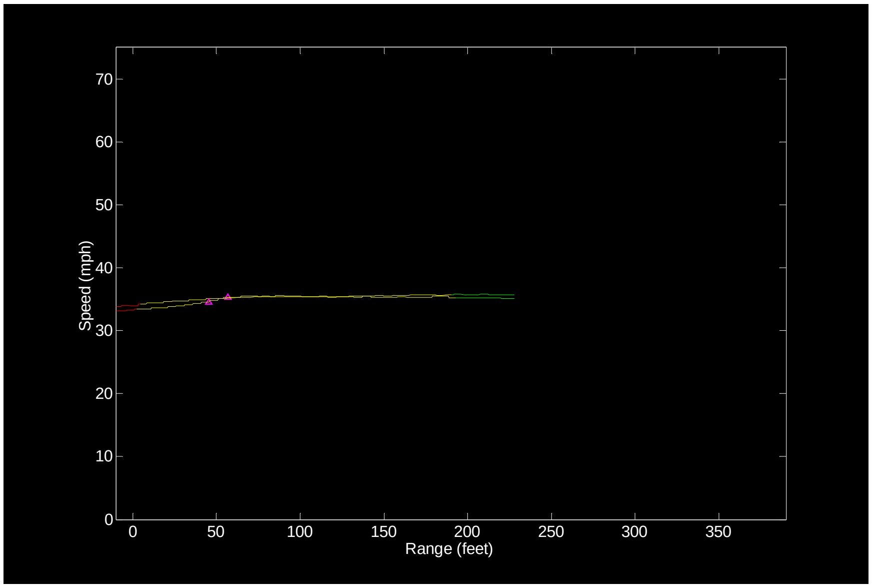
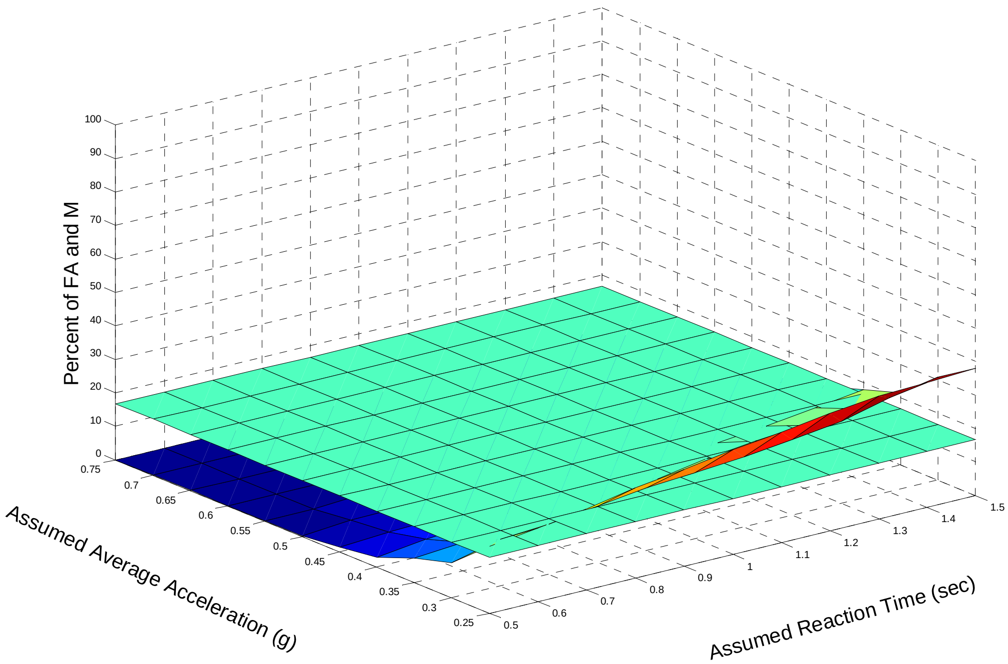
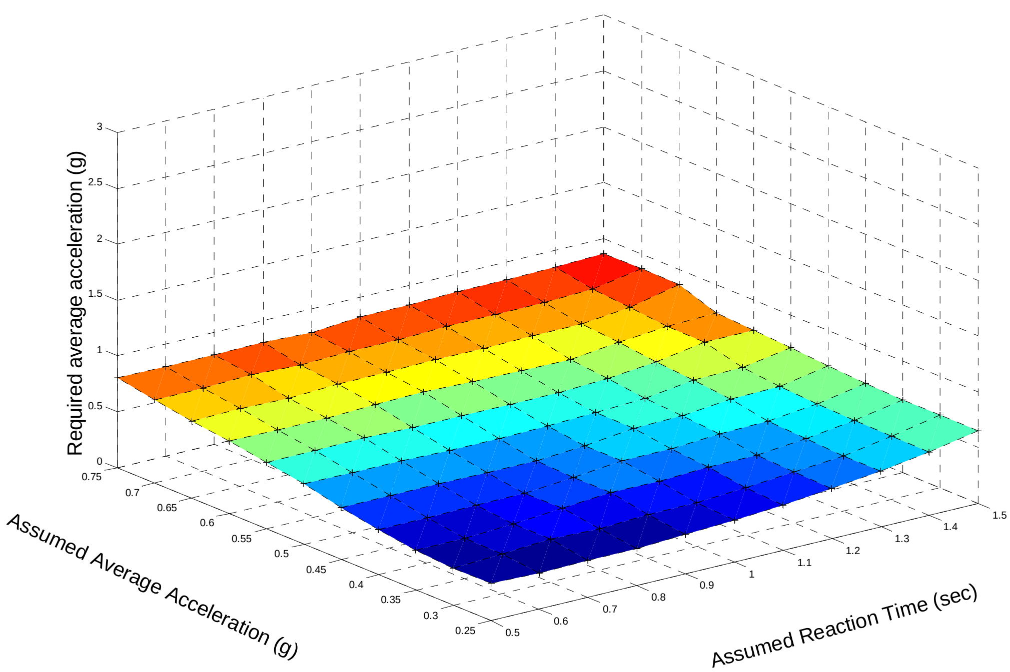


Figure G-10. Approaches with unfeasible levels of deceleration required after the Level 1 warning. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The Level 2 false alarms (Figures G-11 and G-12) ranged from a minimum of 0 percent to a maximum of 38.81 percent. For the 56.3 km/h (35 mph) IDS experiment, false alarms occurred only when the participants released the brake pedal during the deceleration after crossing the warning threshold. In the 72.4-km/h (45-mph) IDS and ICAV experiments, false alarms were the result of a lax threshold that underestimated a normal driver's braking level and/or overestimated their reaction time.

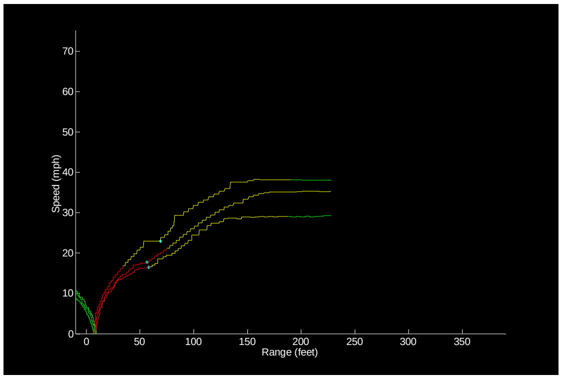


a)

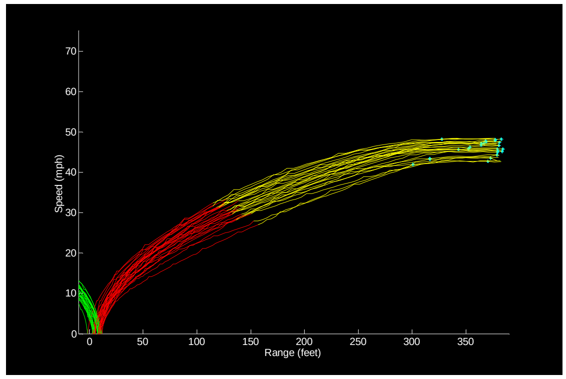


b)

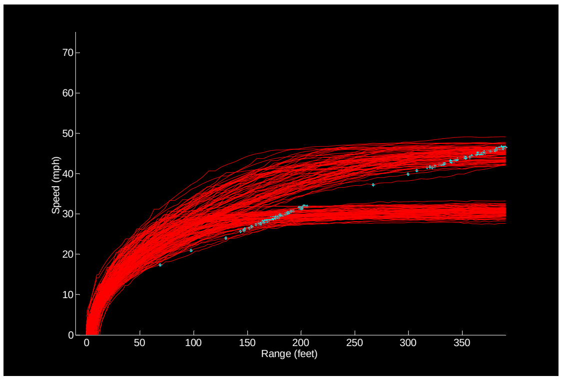
Figure G-11. Level 2 false alarms (a, curved surface), misses (a, flat surface), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 2 algorithm.



a)



b)



c)

Figure G-12. Level 2 false alarms for the Case 2 algorithm. These are shown for the 0.25 *g*, 1.5-second reaction time combination. In general, the false alarms were reduced as the assumed acceleration was increased and the reaction time lowered; thus, these values represent the upper bound. The different graphs represent values from the three different studies, a) 56.3 km/h IDS, b) 72.4 km/h IDS, and c) ICAV. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

There was a single Level 2 miss identified in these data, the same miss that appeared for the Case 1 algorithm (Figure G-6). Likewise, Level 2 warnings did not appear to be late based on the required deceleration after the warning (Figure G-7). Required deceleration levels increased mostly as the assumed deceleration increased, albeit slight increases due to increased reaction time could also be observed. This increase in required deceleration due to increased reaction time is counterintuitive, but the differences due to this factor are fairly small and likely due to the collective errors of a finite sampling rate and rounding (~0.01-0.03 *g*).

While this algorithm represents a substantial improvement over the Case 1 algorithm, two areas of concern exist. First, some Level 1 misses seem unavoidable, as some drivers may not brake hard enough to prevent a violation (albeit they seem to brake hard enough to prevent a crash, as evidenced by the relative absence of Level 2 misses). It seems that a reasonable solution to prevent these misses is to allow for a secondary, more aggressive, warning threshold that triggers a warning if insufficient braking is detected. This alternative is explored later in this document.

The second area of concern is that without constraints on the "lateness" of a warning, some warnings, especially Level 1, could be provided late, when the driver cannot physically stop before entering the intersection. An option to address this issue is the inclusion of a parameter as part of the algorithm that limits the closeness to the intersection at which a warning can be provided. Exercising this option, however, converts these situations into misses. The tradeoffs as to which is the best scenario for drivers, a late warning or a lack of warning, must be considered before this option is exercised. Drivers warned late, for example, might be startled and react unexpectedly.

There are possible false alarms – misses tradeoffs with this algorithm that were not possible for the Case 1 algorithm. Given that misses did not vary much with the input parameters (*a* and *RT*), minimization of false alarms can be accomplished by looking up the parameters that produced the minimum value, while considering parameters that are achievable by drivers trying to prevent a violation. This will also be the case for many of the other algorithms examined here and is used to generate some initial recommendations discussed in a later section.

The next section tests the alternative of modifying the kinematic equation governing the algorithm by assuming that the constant deceleration applied will be a function of the speed.

Case 3: Parameterized Kinematics, Deceleration

The Case 3 algorithm uses assumptions of reaction time and two parameters that modulate the effect of the speed term in the traditional kinematic equation (*c* and *n*). This manipulation explores the possibility that the assumed constant acceleration is a function of the speed at which the vehicle travels and thus reduces the squared velocity term to an exponent smaller than two. This algorithm option also stopped all threshold crossing tests if deceleration levels higher than 0.10 *g* were detected (Equation G-10).

$$Rw = cV^n + V * RT \qquad \text{(G-10)}$$

The result for *Rw* is then compared to the range of the vehicle, *R*. If a Level 1 or Level 2 warning is applicable (as described previously), it is presented only if:

$$R \leq Rw \qquad \text{(G-11)}$$

RT was maintained constant at 1.0 s to observe the interaction between the other two factors. The two remaining parameters, *c* and *n*, were systematically varied between 0.01 and 1.01 and 0.5 and 2.00, respectively. These limits were selected to constrain the solution space to a region centered within the traditional kinematic approach used in Cases 1 and 2. Considerable variation occurred in the thresholds produced (Figure G-13).

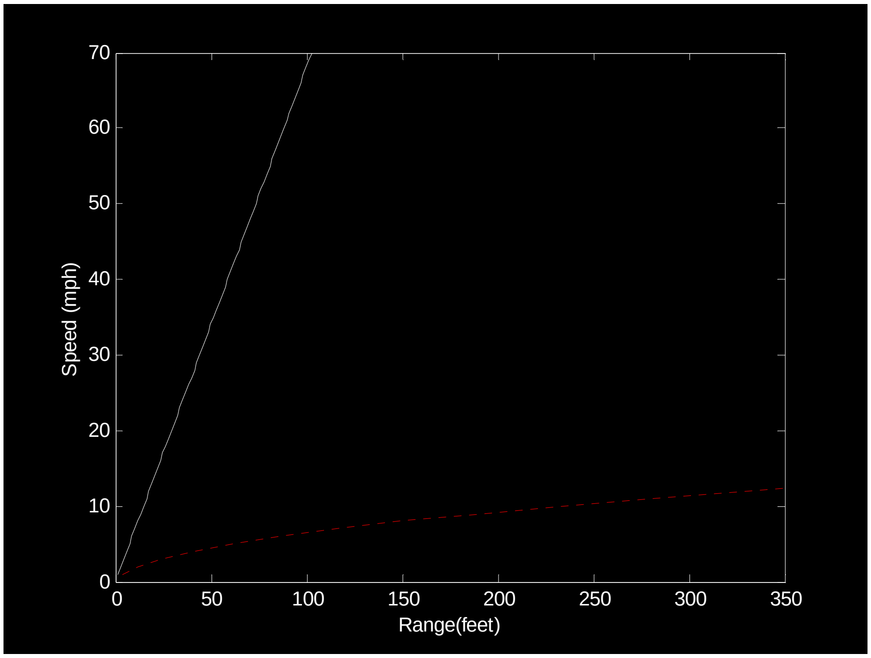
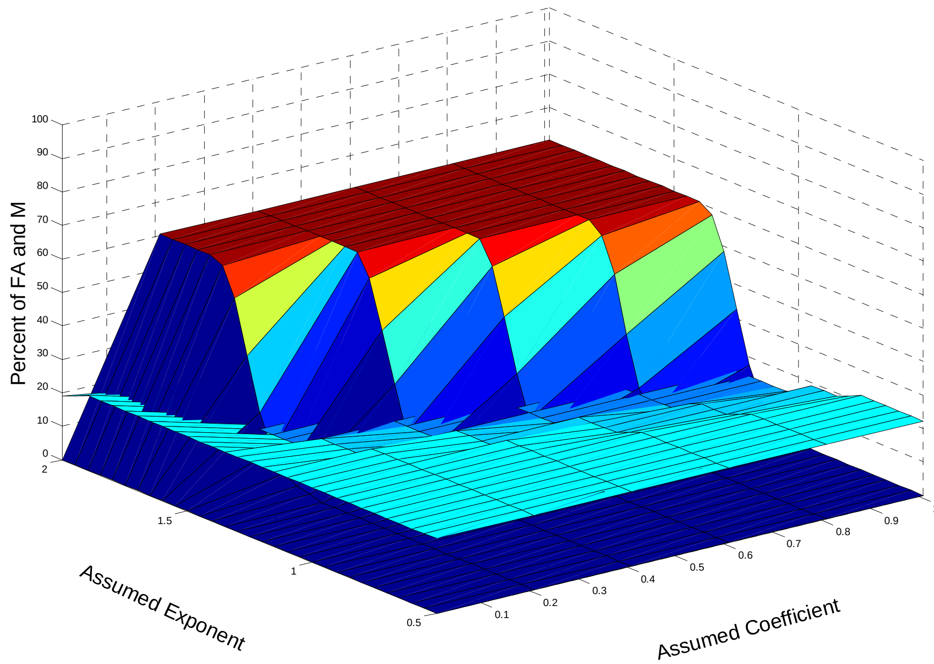


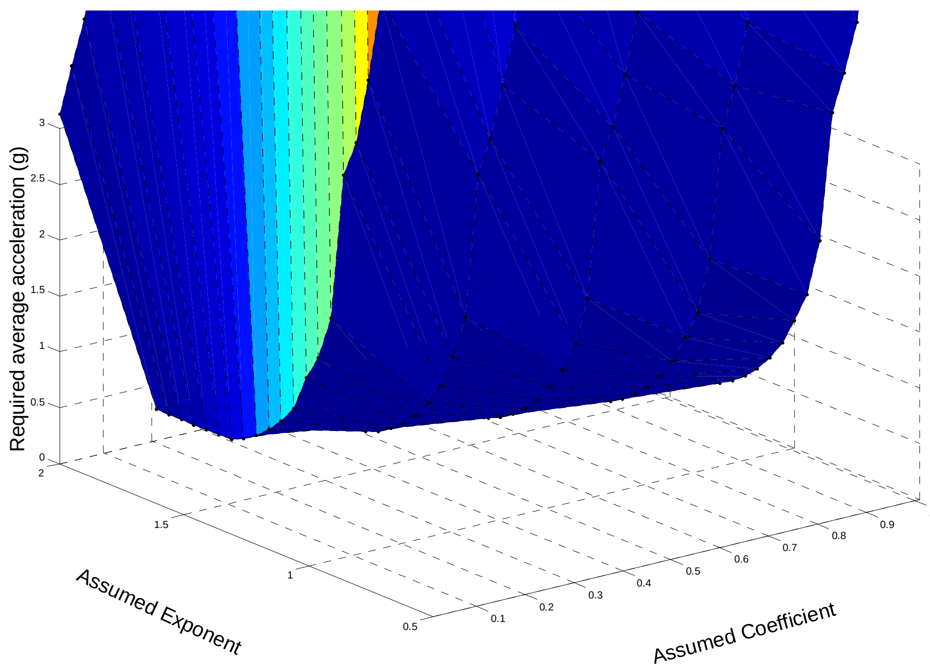
Figure G-13. Algorithm threshold limits. The dotted line represents a threshold assuming a coefficient (*c*) of 1.01 and an exponent (*n*) of 2.00, the most conservative case. The solid line represents a threshold assuming a coefficient of 0.01 and an exponent of 0.5, the most aggressive case. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The Level 1 false alarms range from a minimum of 0 percent to a maximum of 60.37 percent (Figure G-14). The false alarms observed were due to combinations of braking effort and reaction time that were more aggressive than those used to determine the threshold (Figure G-15). False alarms were zero for low levels of coefficient and exponent, but quickly rose to their peak values as these parameters increased.

Level 1 misses remain mostly constant, at approximately 15 percent, except for low values of coefficient and exponent. The percentage of misses ranged from 14.29 percent to 22.22 percent. The lower bound of this range is the same as the number of misses for the Case 2 algorithm, and the actual cases missed are also very similar (Figure G-16). This is expected given the nature of these misses and the fact that no correction was made in this algorithm to attempt to correctly classify these cases.



a)



b)

Figure G-14. Level 1 false alarms (a, mound-type surface), misses (a, flat surface), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 3 algorithm.

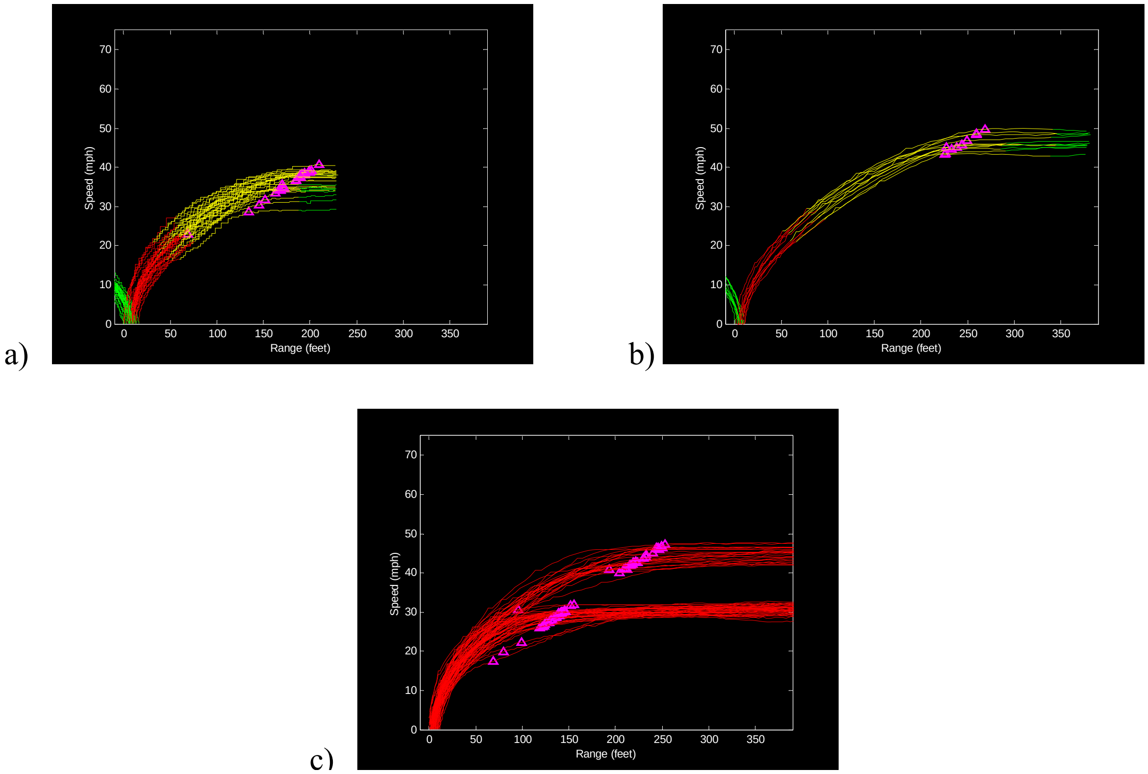


Figure G-15. Level 1 false alarms for the Case 3 algorithm. These are shown for the 0.61 and 1.25 coefficient and exponent, respectively, combination. Reaction time was maintained constant at 1.0 s. In general, the false alarms were reduced as the coefficient and exponent were reduced. The different graphs represent values from the three different studies, a) 56.3 km/h IDS, b) 72.4 km/h IDS, and c) ICAV. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

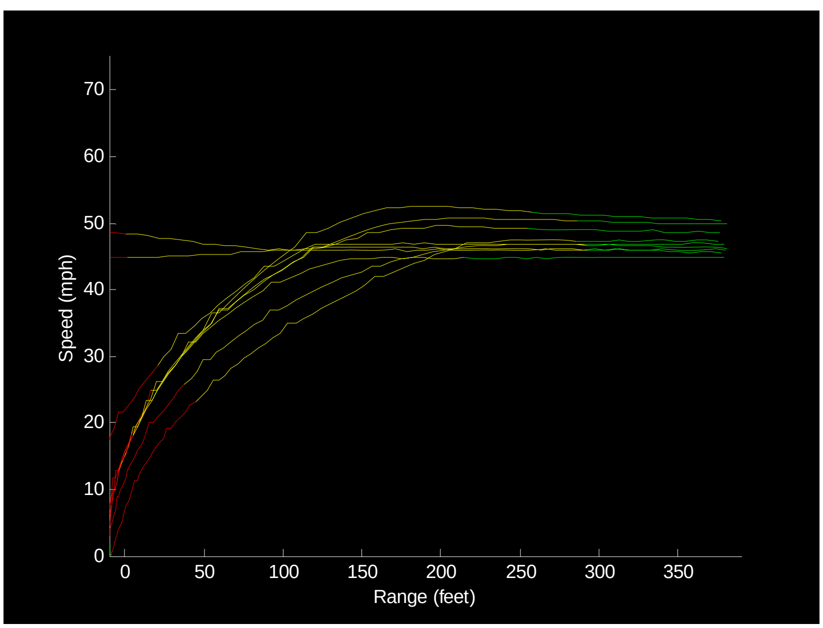
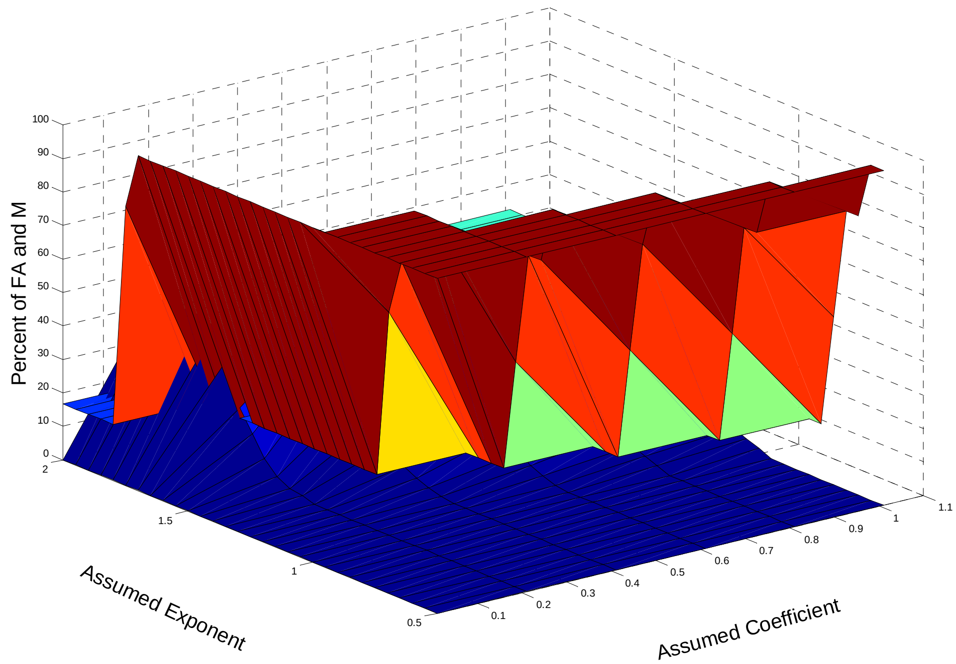


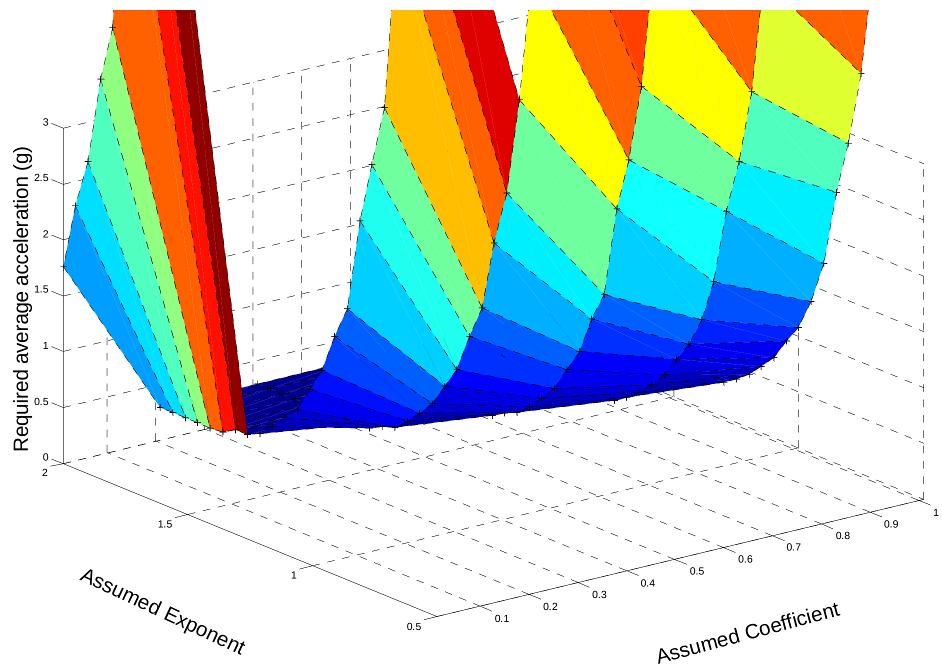
Figure G-16. Level 1 misses for the Case 3 algorithm. These are shown for the 0.61 and 1.25 coefficient and exponent combination. Reaction time was maintained constant at 1.0 s. These misses are representative of the misses observed for most other parameter combinations. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Maximum required constant deceleration levels became very high and unrealistic (i.e., > 0.9 *g*) as coefficient and exponent were reduced. Steep slopes were observed in the transition area from zero to maximum number of false alarms.

Similar patterns were observed for the Level 2 warnings (Figure G-17). Level 2 false alarms ranged from 0 percent to 42.47 percent. These false alarms were due to combinations of braking effort and reaction time that were more aggressive than those used in the threshold (Figure G-18). As with Level 1 false alarms, Level 2 false alarms were zero for low levels of coefficient and exponent, but quickly rose to their peak values as these parameters increased. The Level 2 miss present in both of the previous cases was also present here, but it was joined by others as the coefficient and exponent were reduced. As with Level 1 warnings, the maximum required constant deceleration levels also became very high as the coefficient and exponent were reduced.



a)



b)

Figure G-17. Level 2 false alarms (a, mound-type surface), misses (a, bottom surface, not visible), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 3 algorithm.

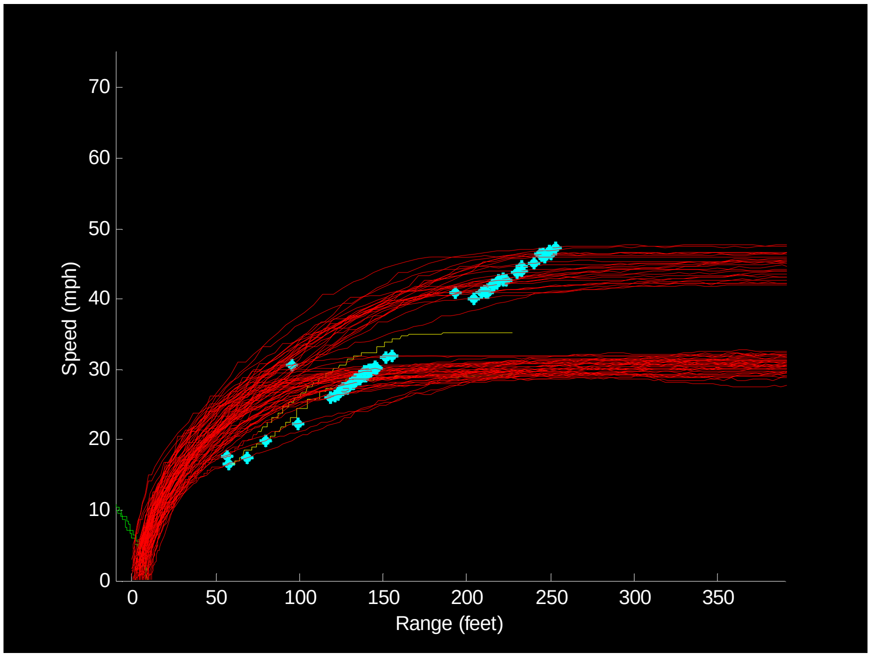


Figure G-18. Level 2 false alarms for the Case 3 algorithm. These are shown for the 0.61 and 1.25 coefficient and exponent combination. Reaction time was maintained constant at 1.0 s. In general, the false alarms were reduced as the coefficient and exponent were reduced. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Overall, while some combinations of coefficient and exponent produced similar results to other cases, there was no marked performance advantage obtained from using this algorithm approach. This approach also has the disadvantage of using parameters that are not easily translated into the kinematics realm. While it is fairly simple to understand and apply the concept of constant deceleration, it would be more difficult to do the same for the coefficient and exponent used by this approach.

Another alternative approach that is more intuitive than using these parameters directly employs TTI. This method is discussed in the next section.

Case 4: Time to Intersection

The Case 4 algorithm employs TTI to determine whether a warning is needed. A TTI value that is compared against time-based samples is assumed. The TTI value used is speed dependent, based on results of the 56.3-km/h IDS and 72.4-km/h IDS studies. The average TTI decision points in those studies were speed dependent and modeled as a line with a value of 3.2 s at 56.3 km/h and a positive slope of 0.184. This TTI was adjusted by a variable factor that allowed for the testing of solutions within a large space in order to find an optimum. The TTI threshold resulting from these manipulations was compared against the vehicle's TTI, determined as the maximum of the instantaneous amber time remaining or the instantaneous vehicle's range divided over its range rate (Equation G-12 and G-13).

$$TTI_{threshold} = 3.2 + 0.184 * (V - 51.3) - Adjustment \quad \text{(G-12)}$$

$$TTI = max(AmberTime\,Remaining,, \frac{R}{V})$$

(G-13)

If a Level 1 or Level 2 warning is applicable (as described previously), it is presented only if (Equation G-14):

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(G-14)

The minimum speed under which the algorithm operates is 24.1 km/h (15 mph). If braking is detected (vehicle deceleration > 0.1 *g*), the algorithm operation is suspended and no warning is presented for the current cycle.

The adjustment factor was systematically varied between -2 and 2 s. These limits were selected based on engineering judgment on what the solution space would be and produced considerable variation in the thresholds considered (Figure G-19).

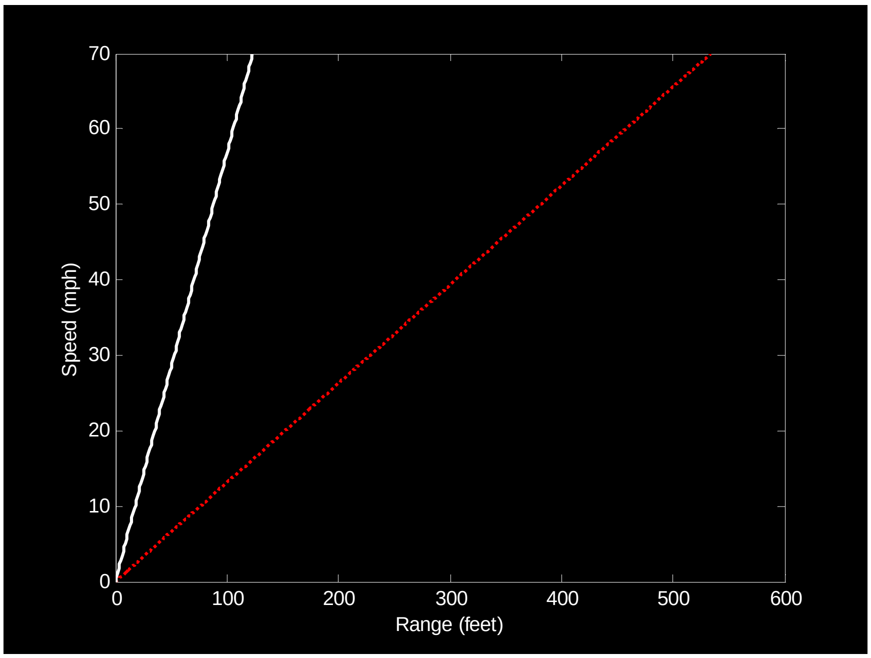
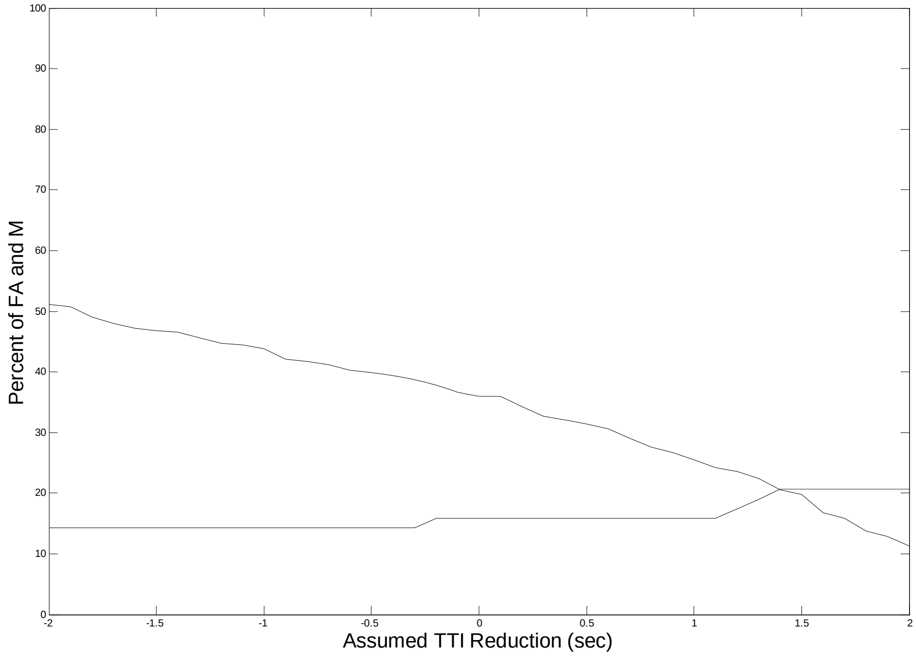
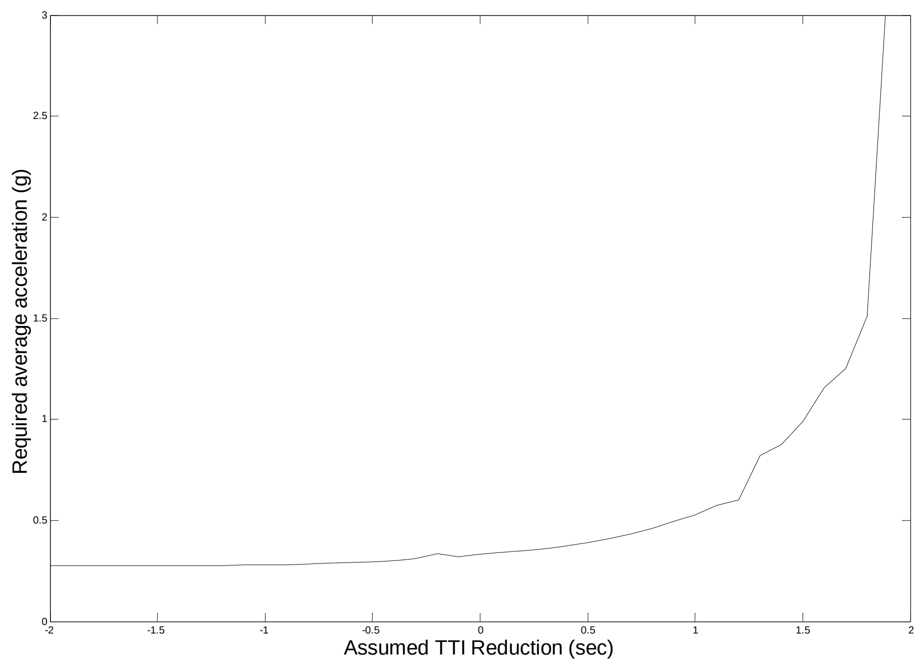


Figure G-19. Algorithm threshold limits. The dotted line represents a threshold assuming a 5.2-second TTI decision point. The solid line represents a threshold assuming a 1.2-second TTI decision point, the most aggressive threshold. These values apply to 56.3 km/h only, and would differ slightly for different speeds. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The Level 1 false alarms range from a minimum of 11.29 percent to a maximum of 51.15 percent (Figure G-20). False alarms resulted from instances in which the driver made the decision to stop after the TTI threshold used by the algorithm (Figure G-21). Level 1 misses remained mostly constant, ranging from 14.29 percent to 20.63 percent. The misses recorded were similar to those documented for previous cases (Figure G-22).



a)



b)

Figure G-20. Level 1 false alarms (a, top line), misses (a, bottom line), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 4 algorithm.

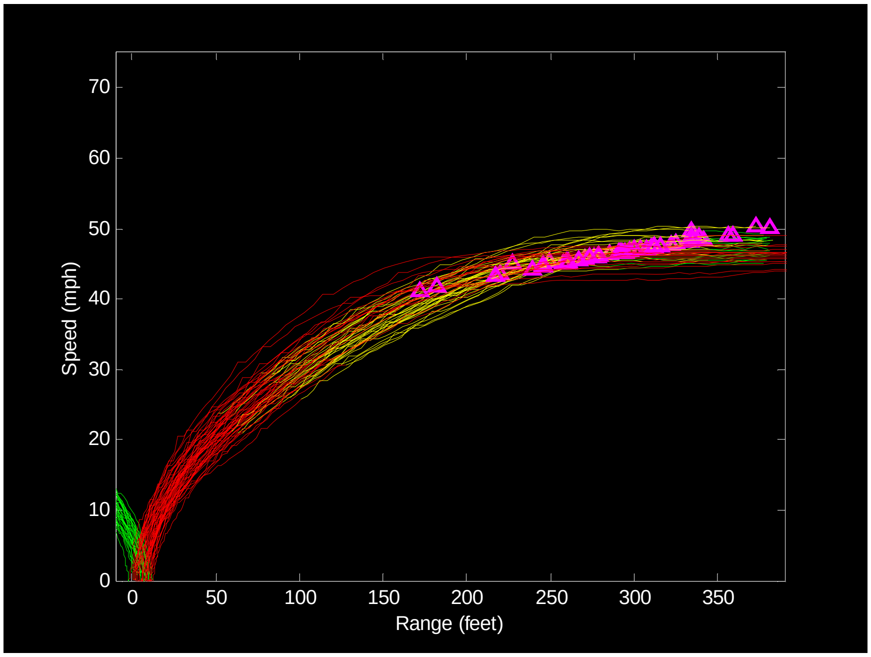


Figure G-21. Level 1 false alarms for the Case 4 algorithm. These are shown for the 2-second TTI reduction, the case with the lowest number of false alarms. In general, the false alarms increased as the TTI reduction decreased (i.e., as the effective TTI increased). (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

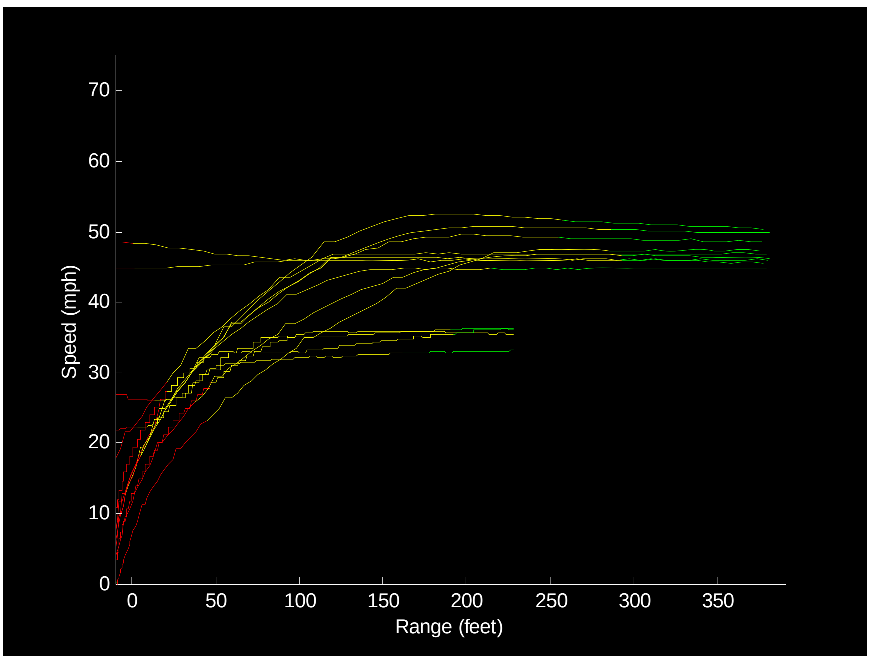
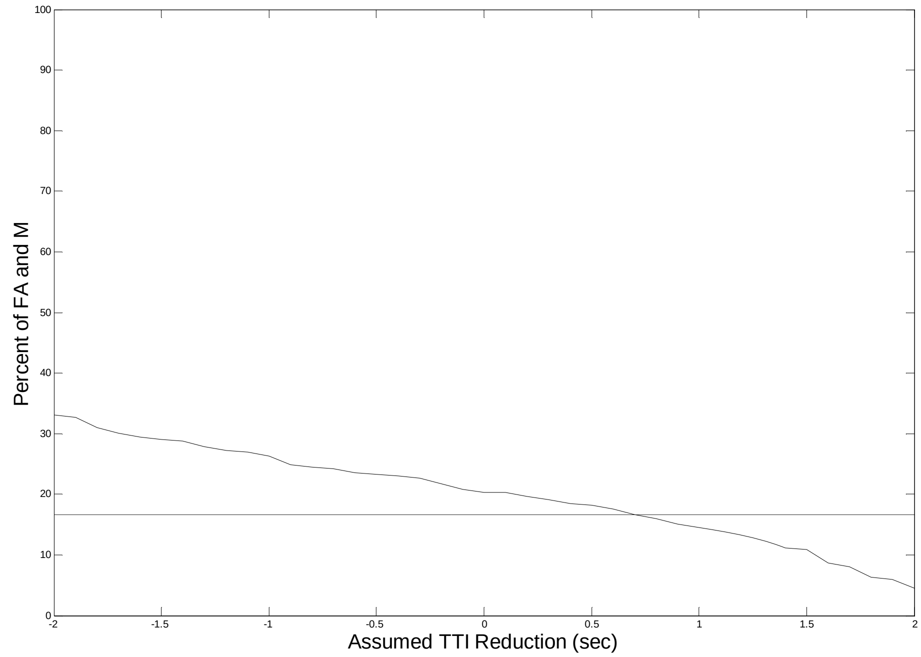


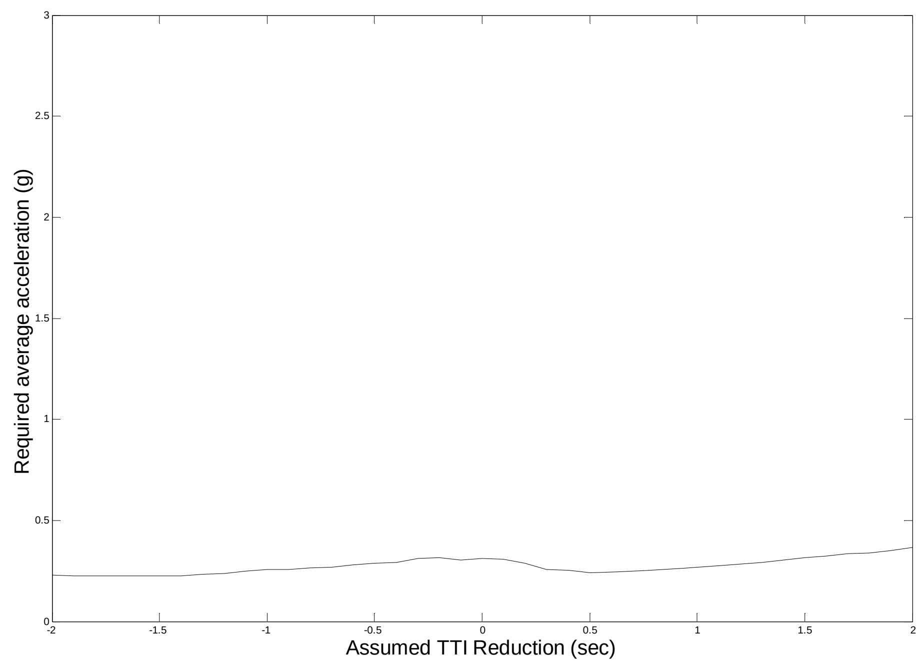
Figure G-22. Level 1 misses for the Case 4 algorithm. These are shown for the 2-second TTI reduction, the case with the highest number of false alarms. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Maximum required deceleration levels were unrealistically high for TTI reductions of more than 1.5 s, indicating that any threshold level should be maintained below this limit. Before this area, the curve remained fairly flat requiring less than a 0.5 *g* constant braking level for the most part.

Similar patterns were observed for the Level 2 warnings (Figure G-23). Level 2 false alarms ranged from 4.57 percent to 33.11 percent. These false alarms were due to combinations of braking effort and reaction time that were more aggressive than those used in the threshold (Figure G-24). One Level 2 miss was observed, the same as in Case 1. The maximum required constant deceleration levels remained in a realistic range all through the sampling area, as was the case for the majority of the Level 1 warnings.



a)



b)

Figure G-23. Level 2 false alarms (a, top curve), misses (a, bottom curve), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 4 algorithm.

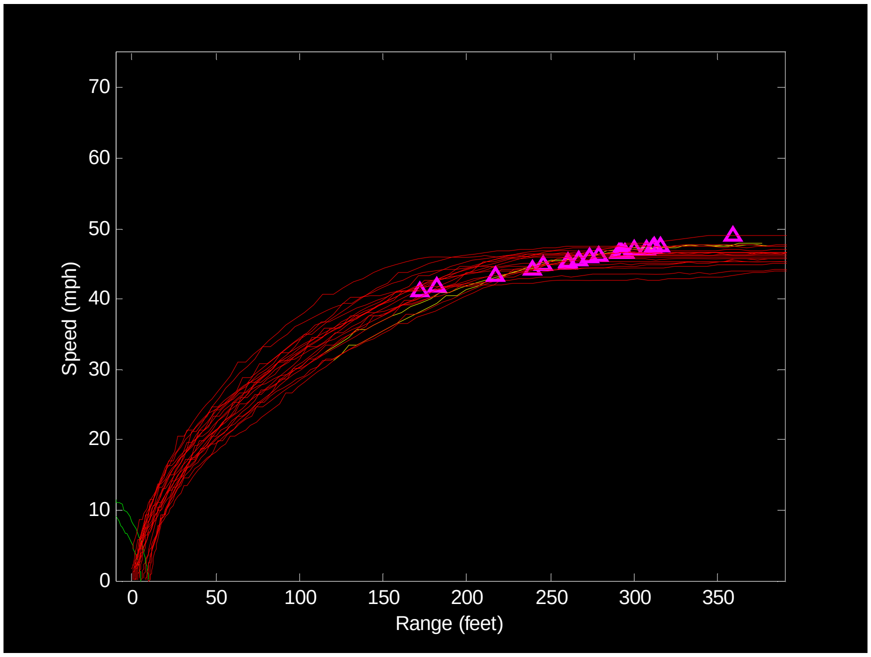


Figure G-24. Level 2 false alarms for the Case 4 algorithm. These are shown for the 2-second TTI reduction, the case with the lowest number of false alarms. In general, the false alarms increased as the TTI reduction decreased (i.e., as the effective TTI increased). (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The Case 4 algorithm performed slightly worse than more complex algorithms, although it required deceleration levels that were comparatively lower. Values of TTI reduction higher than 1.5 s should not be used (resulting in a minimum TTI of 1.7 s at 56.3 km/h), and this constrains the solution space to an area where the false alarms are relatively high when compared to other approaches, even though the number of misses remains very similar. Thus, while computationally attractive, a TTI solution lacks the level of complexity required to make correct classifications at a sufficiently high rate.

All of the algorithm alternatives considered so far have assumed the presence of a detector (or detectors) that provides information about vehicle range, range rate, and (in some cases) acceleration at constant time intervals. The next case examines the classification performance of a single detector that provides the vehicle's range and range rate at a point located a certain distance from the intersection.

Case 5: Dual Threshold

The Case 5 algorithm is equivalent to the Case 2 algorithm, but an additional threshold is added. Thus, the algorithm is based on assumptions of constant deceleration, reaction time, and deceleration level that represent braking. The vehicle's range, range rate, and longitudinal acceleration are the only inputs. The minimum speed at which the algorithm operated was 24.1 km/h (15 mph). The algorithm also shut down if the deceleration level that represented braking (set at 0.1 *g*) was exceeded. However, a secondary threshold was added. If the vehicle's range vs. range rate profile exceeded this secondary threshold at any point, a warning was issued if enough cruising time was not available to avoid a violation, even if the driver was already braking. The secondary threshold was the same as the first threshold, but without inclusion of the reaction time parameter (Equation G-15):

Error! Objects cannot be created from editing field codes.

(G-15)

The result for Rw_2 is then compared to the range of the vehicle, *R*. If a Level 1 or Level 2 warning is applicable (based on the available cruising time), it is presented only if (Equation G-16):

Error! Objects cannot be created from editing field codes.

(G-16)

The two algorithm parameters, *a* and *RT*, were systematically varied between 0.25 and 0.75 *g* and 0.5 and 1.5 s, respectively, as they were for the Case 2 algorithm. The thresholds are similar to those for Case 2, but the secondary thresholds are added (Figure G-25).

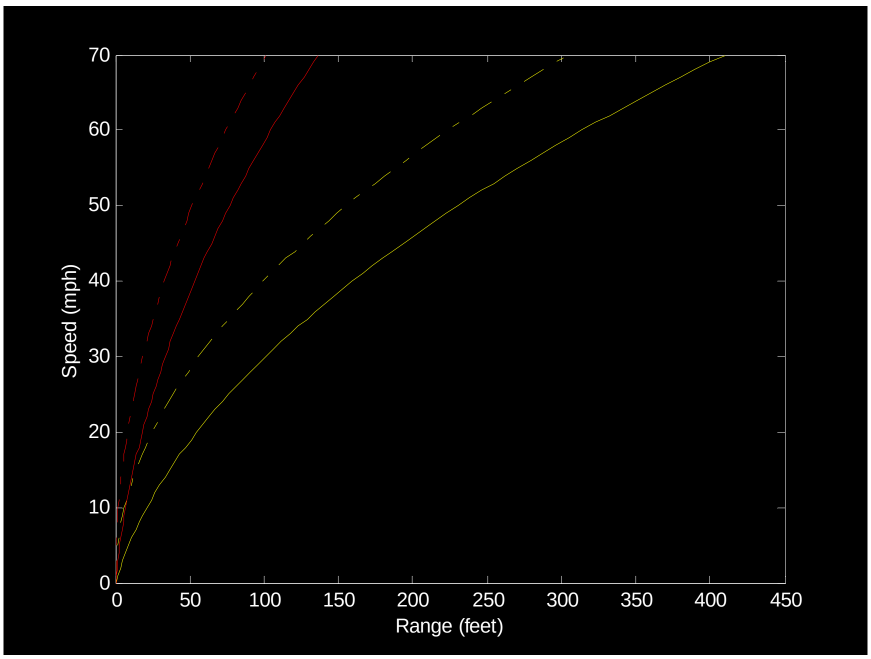
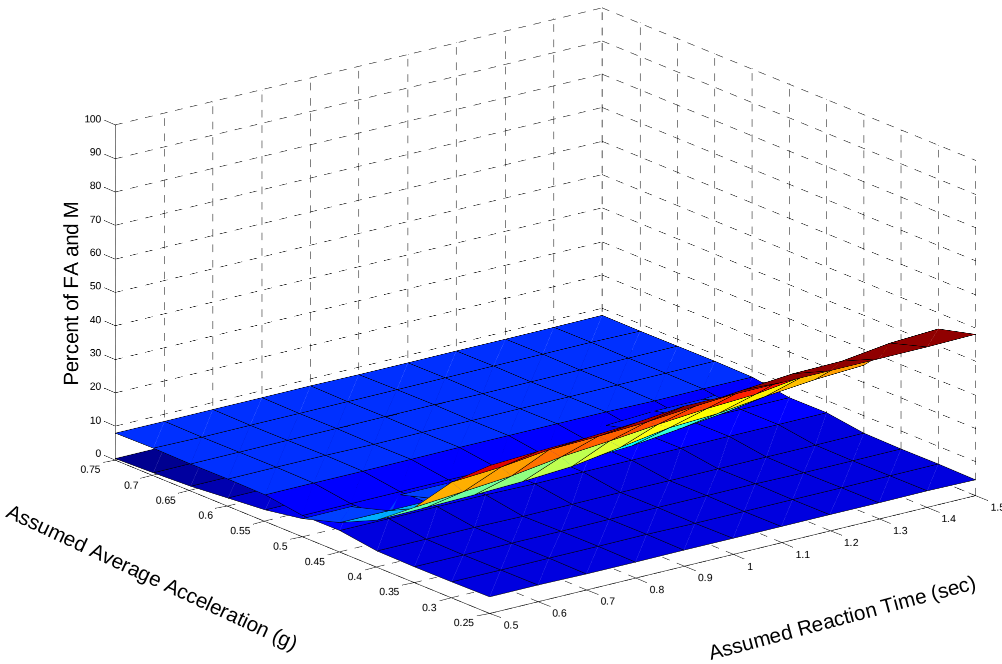


Figure G-25. Case 5 algorithm threshold limits. The dashed lines represent the secondary thresholds for the most aggressive (the two steepest lines) and least aggressive (the two flattest lines) cases. The most aggressive threshold assumes a 0.5-second reaction time and a 0.75 *g* constant deceleration level, while the least aggressive threshold assumes a 1.5-second reaction time and a 0.25 *g* constant deceleration level. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

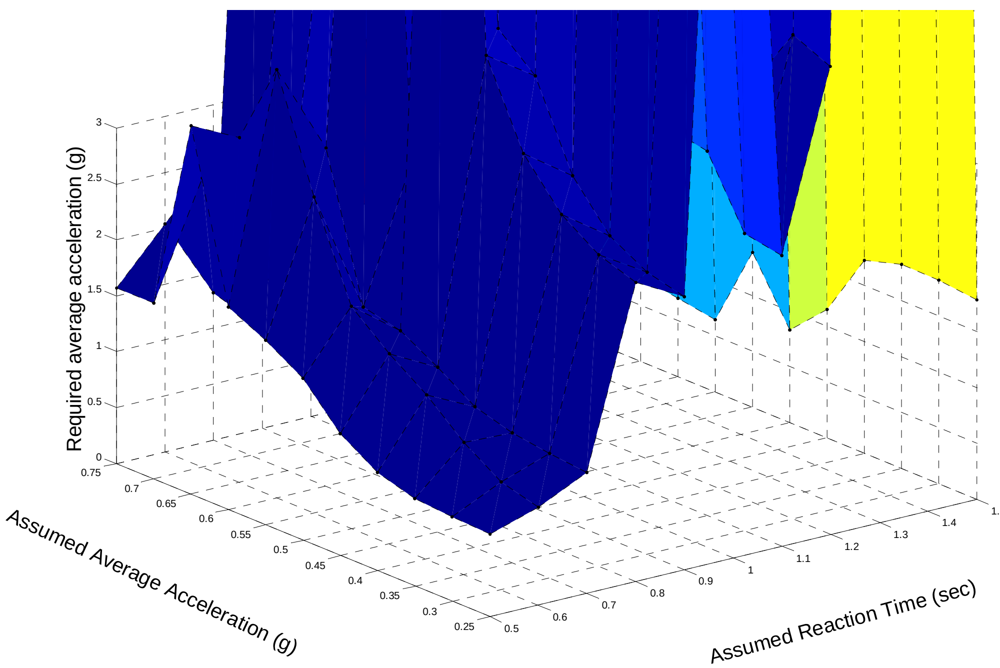
The Level 1 false alarms range from a minimum of 0.46 percent to a maximum of 48.16 percent (Figure G-26). The false alarms observed were due to combinations of braking effort and reaction time that were more aggressive than those used to determine the thresholds, especially the secondary threshold (Figure G-27). As expected, false alarms decrease as the assumed deceleration level is increased and as the reaction time is decreased (i.e., as the warning is skewed toward aggressive drivers). Note that a considerable number of the warnings are issued when the driver is already braking, which indicates that the warning was triggered by a secondary threshold crossing. This in turn is partly responsible for the high levels of required constant deceleration level. These numbers, however, are somewhat misleading in this instance, since any warning issued under the secondary threshold will likely require reduced reaction times, and these deceleration levels were derived using the reaction time parameter value for the condition under analysis.

Level 1 misses were low, ranging from 4.76 percent to 7.94 percent (Figure G-28). The three misses described for Case 1 and Case 2, which could also be identified as correct rejections, are also present here. The remaining additional miss represents a driver who was braking below the threshold during the whole approach, but who failed to stop on time. The reason for this behavior was not clear from any of the analyses performed.

The Level 2 false alarms (Figure G-29) ranged from a minimum of 0 percent to a maximum of 28.77 percent. The alarms occurred due to a lax secondary threshold that underestimated a normal driver's braking level and/or overestimated their reaction time. Only one Level 2 miss occurred, the same one that has already been discussed for previous cases (Figure G-30). Required decelerations were moderate until high reaction times were used. Again, this is mostly an effect of the inclusion of a reaction time in their calculation of derived acceleration. Although a small reaction time is expected, it is likely to be lower than the normal assumptions, as no foot movement from the throttle to the brake pedal is required.



a)



b)

Figure G-26. Level 1 false alarms (a, curved surface), misses (a, flat surface), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 5 algorithm.

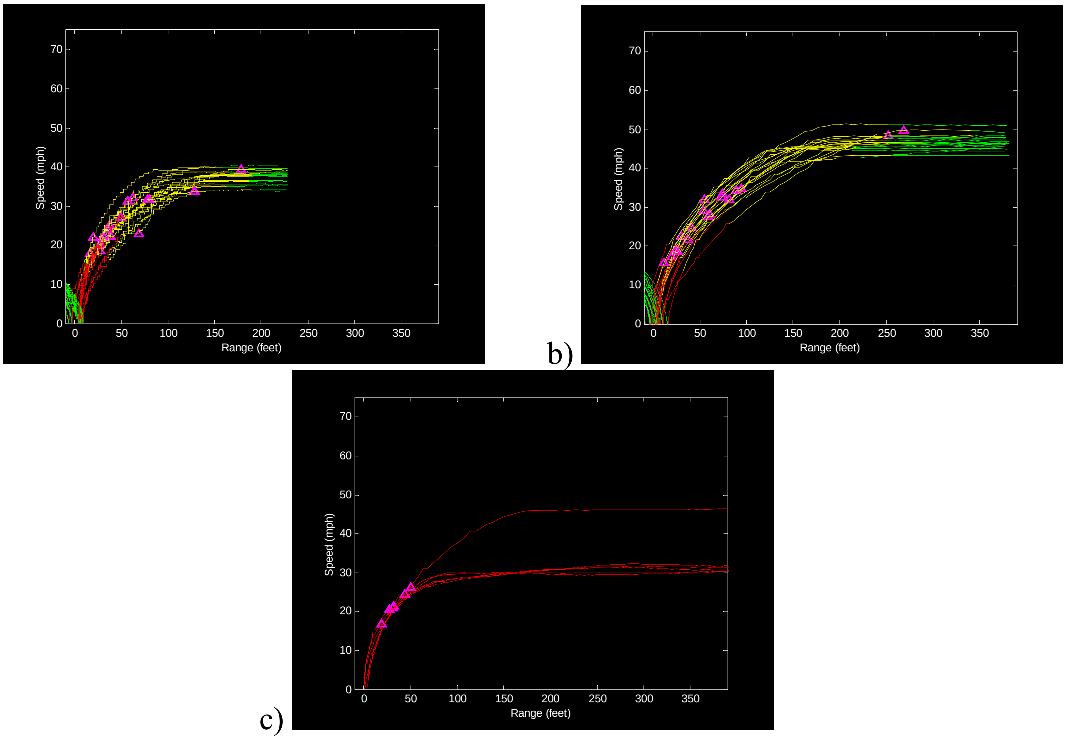


Figure G-27. Level 1 false alarms for the Case 5 algorithm. These are shown for the 0.45 *g*, 1.1-second reaction time combination for the IDS 56.3 km/h (a), IDS 72.4 km/h (b), and ICAV (c) experiments. In general, the false alarms were reduced as the assumed acceleration was increased and the assumed reaction time lowered. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

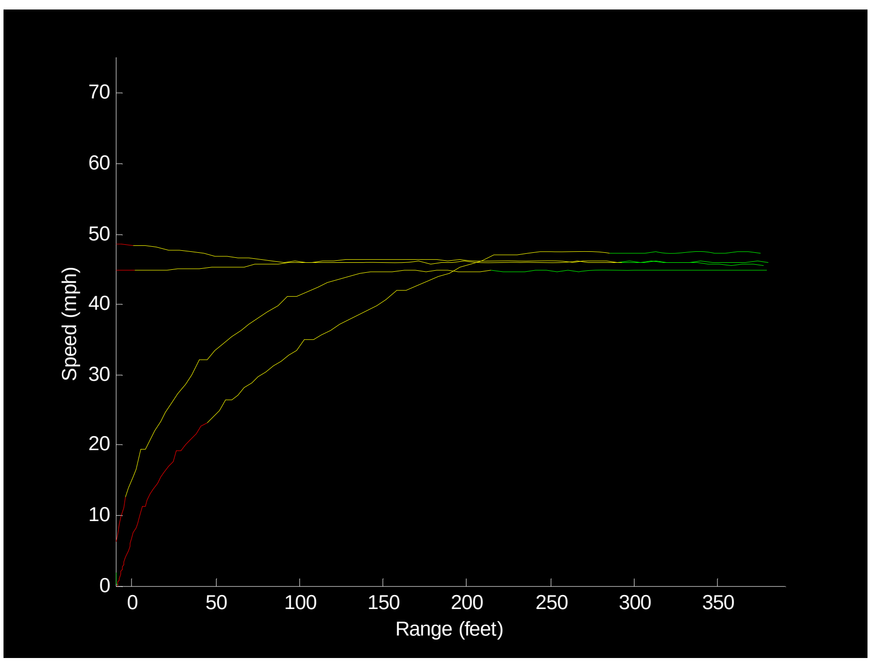
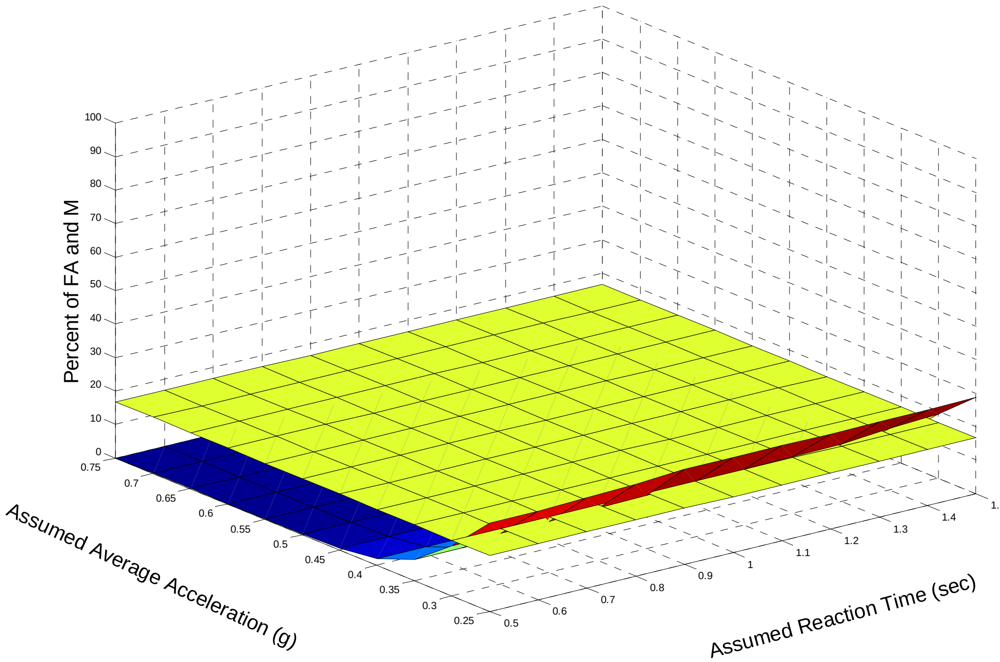
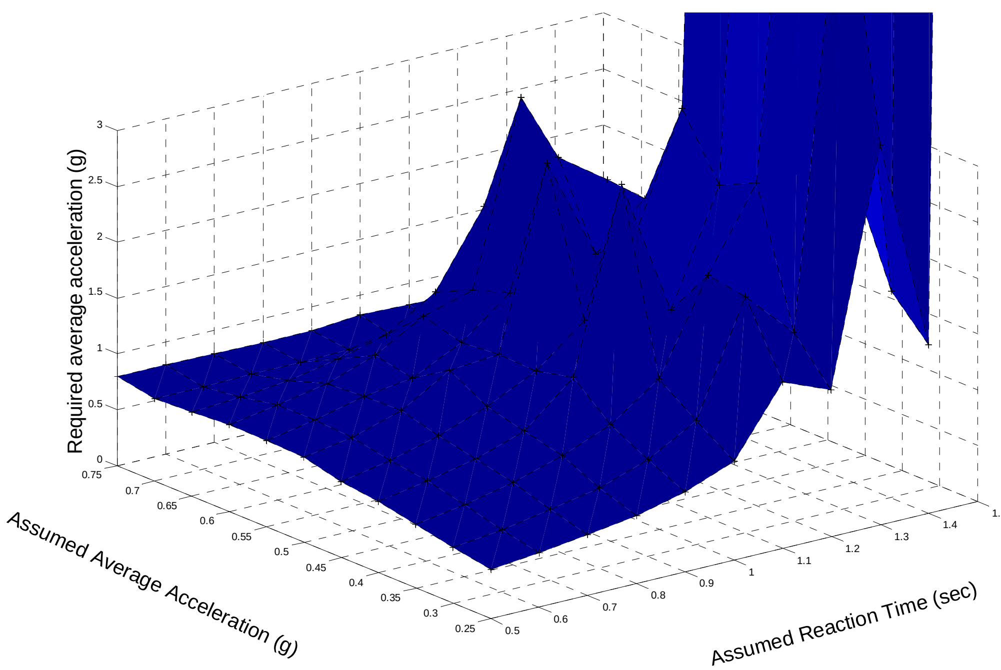


Figure G-28. Level 1 misses for the Case 5 algorithm. These are shown for the 0.45 *g*, 1.1-second reaction time combination, but are representative of the misses observed for most other parameter combinations. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)



a)



b)

Figure G-29. Level 2 false alarms (a, curved surface), misses (a, flat surface), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 5 algorithm.

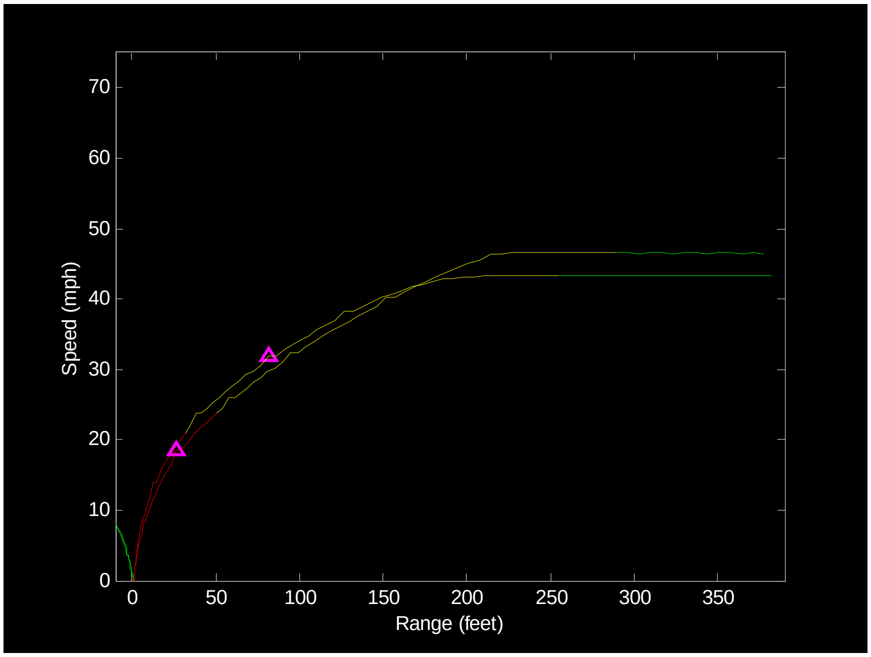


Figure G-30. Level 2 false alarms for the Case 5 algorithm. These are shown for the 0.45 *g*, 1.1-second reaction time combination. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

This algorithm represents, for almost all parameters, an improvement over the Case 2 algorithm, as it substantially reduces the number of misses while hardly compromising the low rate of false alarms. The high levels of deceleration are of some concern, but this is minor as most of the elevated levels are due to the consideration of high reaction times in the derived decelerations for secondary threshold calculations.

The next section tests the alternative of employing the logistic regression approach suggested by CAMP (Kiefer et al., 2005). This algorithm uses the assumption of continuous detection, but the prediction of a violation is made based on an inverse-TTI methodology.

Case 6: CAMP Inverse Time To Intersection

The Case 6 algorithm adapts the CAMP (Kiefer et al., 2005) inverse TTC equation to the intersection case, and uses it to determine the violation thresholds. The inputs to the algorithm are the vehicle's range, range rate, and acceleration (note that some input velocities must have units of mph due to the units used in the coefficient derivation process; these are indicated by V_{mph} below). The algorithm deactivates if the driver is decelerating at more than a preset threshold (selected to be 0.1 *g*) or if the vehicle's range rate is less than 24.1 km/h (15 mph). The algorithm then determines the required warning range based on the following equation (Equation G-17):

Error! Objects cannot be created from editing field codes. (G-17)

The result for *Rw* is then compared to the range of the vehicle, *R*. If a Level 1 or Level 2 warning is applicable (as described previously), it is presented only if (Equation G-18):

$$R \leq Rw \quad \text{(G-18)}$$

The logistic regression parameter, *x*, was systematically varied between 0.40 and 0.95. These limits were selected based on a review of the CAMP work with the equation. The reaction times were varied between 0.5 and 1.5 s. Considerable variation in the thresholds used could be observed (Figure G-31).

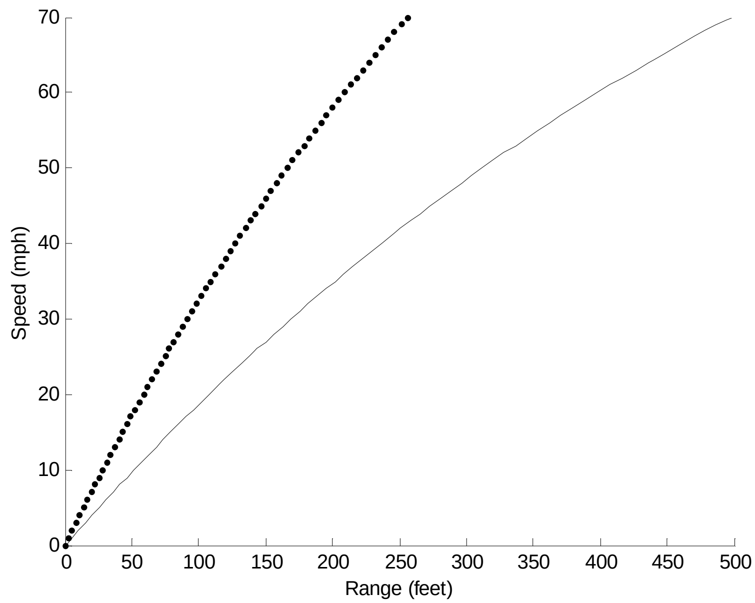
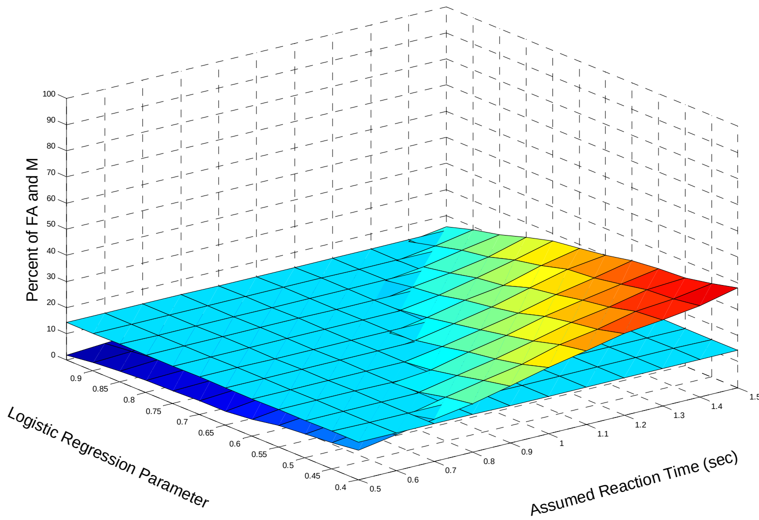


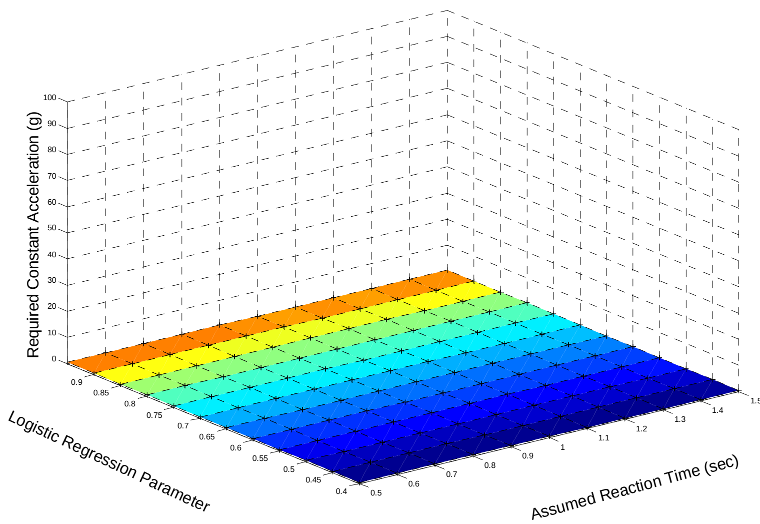
Figure G-31. Warning thresholds for the Case 6 algorithm. The lower (solid) line represents a logistic regression parameter of 0.40 and a reaction time of 1.5 s, the least aggressive option used. The upper (dotted) line represents a parameter of 0.95 and a reaction time of 0.5 s, the most aggressive option used. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The Level 1 false alarms range from a minimum of 1.84 percent to a maximum of 38.25 percent (Figure G-32). The false alarms observed were due to combinations of braking effort and reaction time that were more aggressive than those used to determine the threshold (Figure G-33). False alarms decrease as the logistic regression parameter is increased and the reaction time is decreased. Required deceleration levels remained in a reasonable range.

Level 1 misses remained constant throughout all parameter combinations, at approximately 15 percent. These misses are comparable to those observed in previous cases and are due to instances of insufficient braking and two cases of sampling error that could be classified as correct rejections (Figure G-34).



a)



b)

Figure G-32. Level 1 false alarms (a, curved surface), misses (a, flat surface), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 6 algorithm.

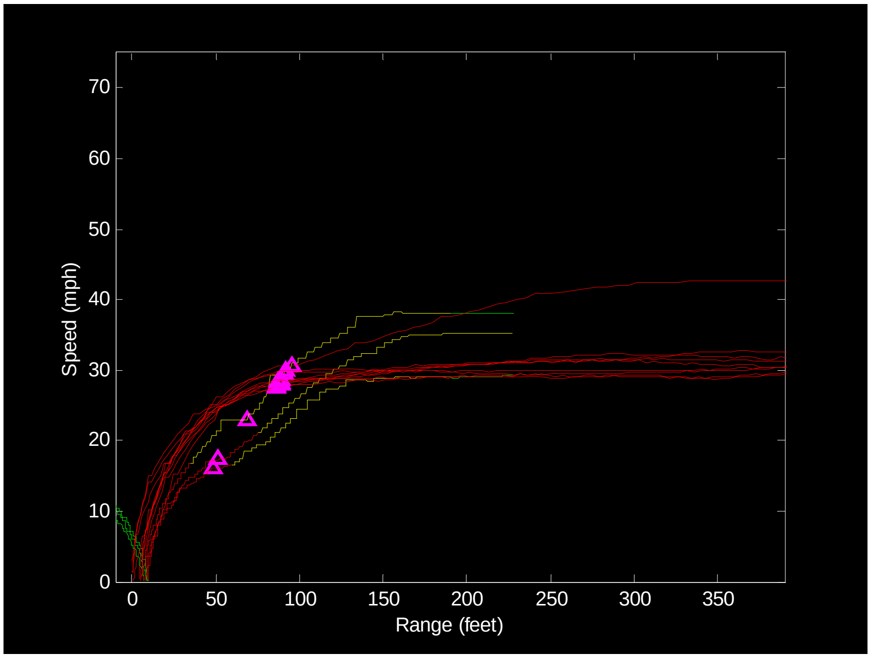


Figure G-33. Level 1 false alarms for the Case 6 algorithm. These are shown when the logistic regression parameter is set at 0.95 and the reaction time at 0.5 s, representing the minimum number of false alarms obtained. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

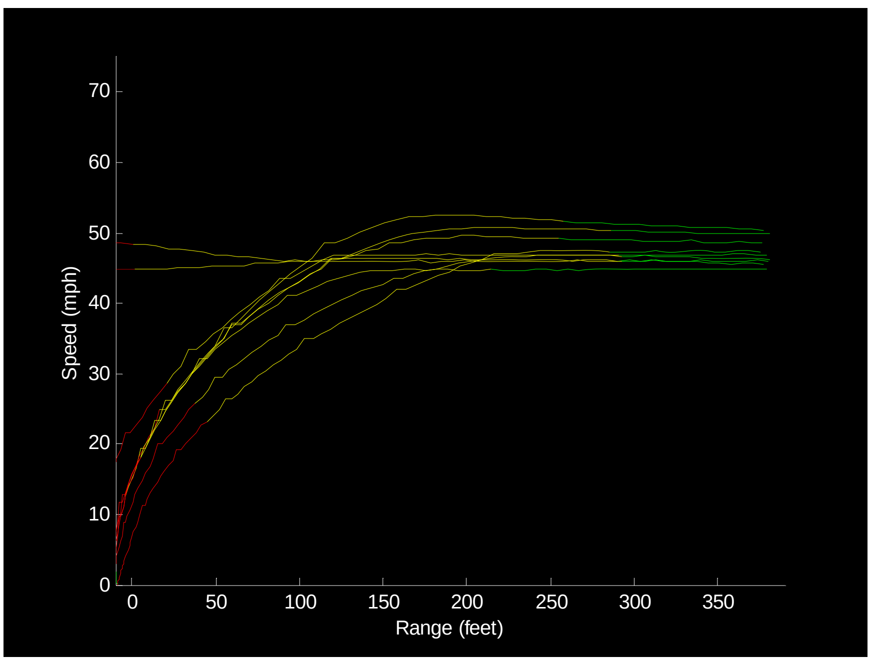
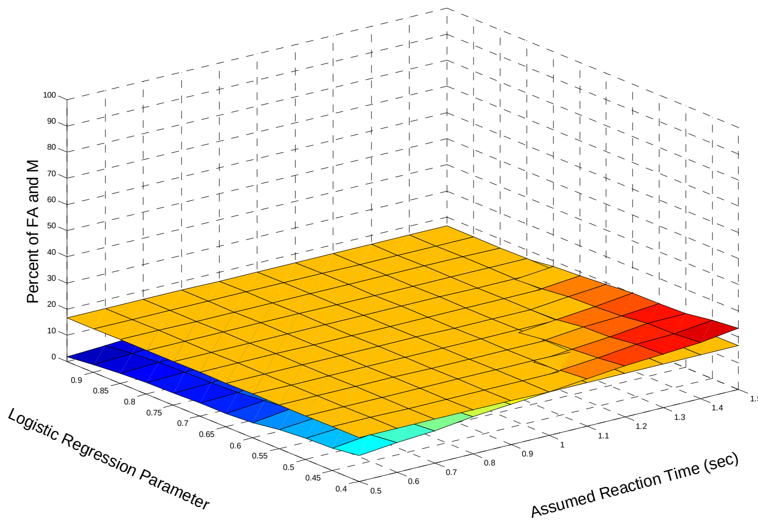
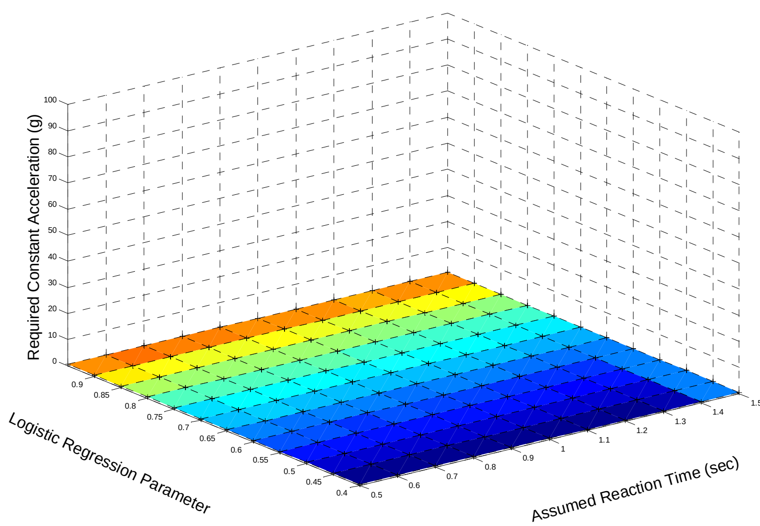


Figure G-34. Level 1 misses for the Case 6 algorithm. These are shown when the logistic regression parameter is set at 0.95 and the reaction time at 0.5 s, but are representative of other parameter combinations. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The Level 2 false alarms (Figure G-35) ranged from a minimum of 1.83 percent to a maximum of 23.29 percent. Reasons for the false alarms were similar to those in Case 1. Level 2 misses remained constant at 16.67 percent, essentially representing the single miss that has been discusses in previous cases. Maximum required deceleration levels remained in a reasonable range (i.e., < 0.9 *g*).



a)



b)

Figure G-35. Level 2 false alarms (a, curved surface), misses (a, flat surface), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 6 algorithm. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

The performance of this algorithm compares favorably to that of others. The number of misses is comparable to other approaches, with a relatively small number of false alarms. Also, required constant deceleration rates are well within the performance limits for a vehicle.

The next section considers another point-detection alternative: the measurement of vehicle acceleration at a certain distance away from the intersection.

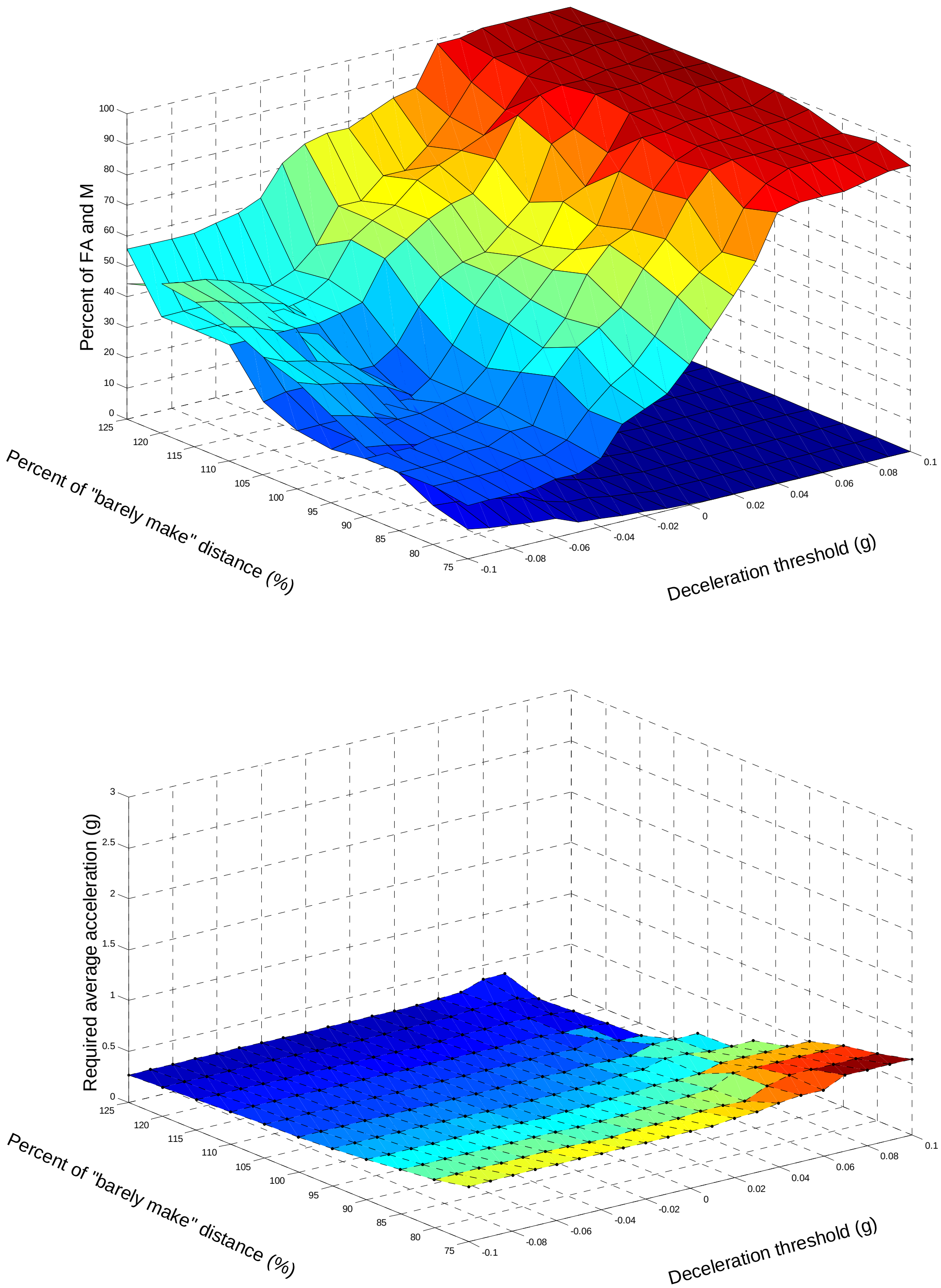
Case 7: Point Detection of Acceleration

The Case 7 algorithm consisted of a simulated point-detection system, in which the vehicle's acceleration would be known at a single point located a certain distance from the intersection. If the vehicle's acceleration at that location is higher than a preset threshold level (implying that no stopping action is apparent), a warning is issued. Thus, the parameters that were varied in this case were the detection distance and the acceleration threshold used. The detection distance was varied between 75 percent and 125 percent of the cruising distance provided by the amber light at the experimental design speed (i.e., speed at which participants were told to drive). The acceleration threshold was varied between -0.10 *g* and 0.10 *g*. No graphs are used to illustrate this approach since the detection threshold would be a single point on the graph. Any vehicle crossing that point above a certain acceleration would receive a warning, any vehicle traveling below that acceleration would not receive a warning.

The Level 1 false alarms range from a minimum of 0 percent to a maximum of 48.85 percent (Figure G-36). False alarms resulted from instances in which the driver stopped even though his or her acceleration was higher than the threshold acceleration at the detection point (Figure G-37). False alarms decreased as the acceleration used as a threshold increased and decreased as the distance from the intersection of the detection device decreased. Level 1 misses (Figure G-38) increased from 17.46 percent to 100 percent as the acceleration used as a threshold increased, but remained relatively constant for the range of distances that were studied. While some of the misses were due to inappropriate driver actions (e.g., braking insufficiently), the majority were due to the thresholds inability to consider more than one point in the approach. Some combinations of parameters appear promising as far as providing minimal levels of false alarms and warnings.

Maximum required deceleration levels were always less than 0.9 *g* and were highest for the high acceleration values and low distances that resulted in large numbers of misses (with zero false alarms).

Patterns for the Level 2 warnings were similar to those in Level 1, but skewed toward lower levels (Figure G-39). False alarms range from 0 percent to 36.07 percent. The miss pattern ranges from 16.67 percent (representing one miss, the same that occurred in Case 1) to 100 percent (representing six misses, see Figure G-40). This is troubling, as a miss here represents a very high probability of a crash. Note that the occurrence of misses here is due to overly stringent thresholds. The deceleration rates required by the alarms remained within reasonable limits.



a)

b)

Figure G-36. Level 1 false alarms (a, surface that starts out at ~55 percent and decreases), misses (a, curve that reaches 100 percent), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 7 algorithm.

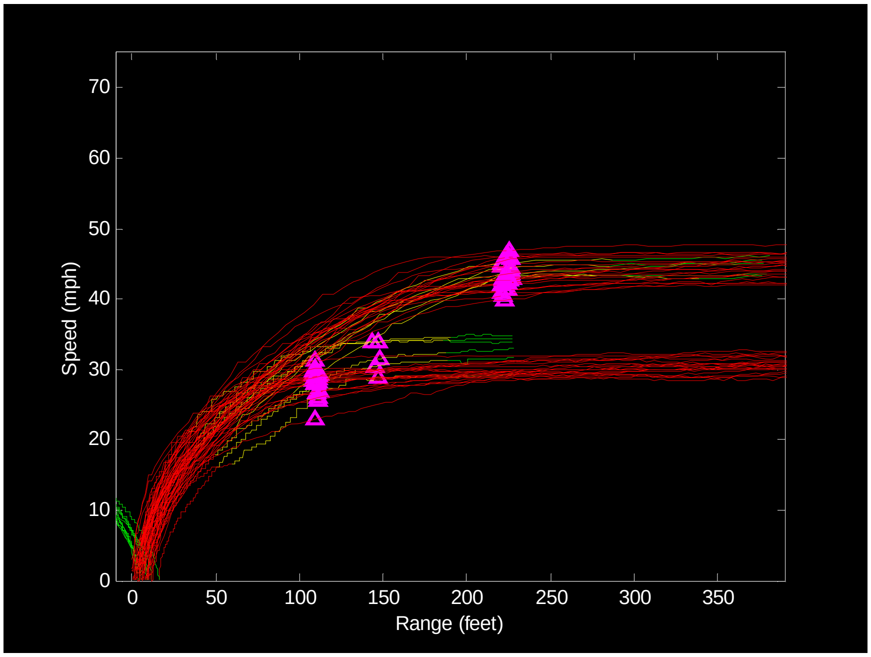


Figure G-37. Level 1 false alarms for the Case 7 algorithm. These are shown for the 75 percent amber-time cruising distance and the -0.1 *g* acceleration threshold. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

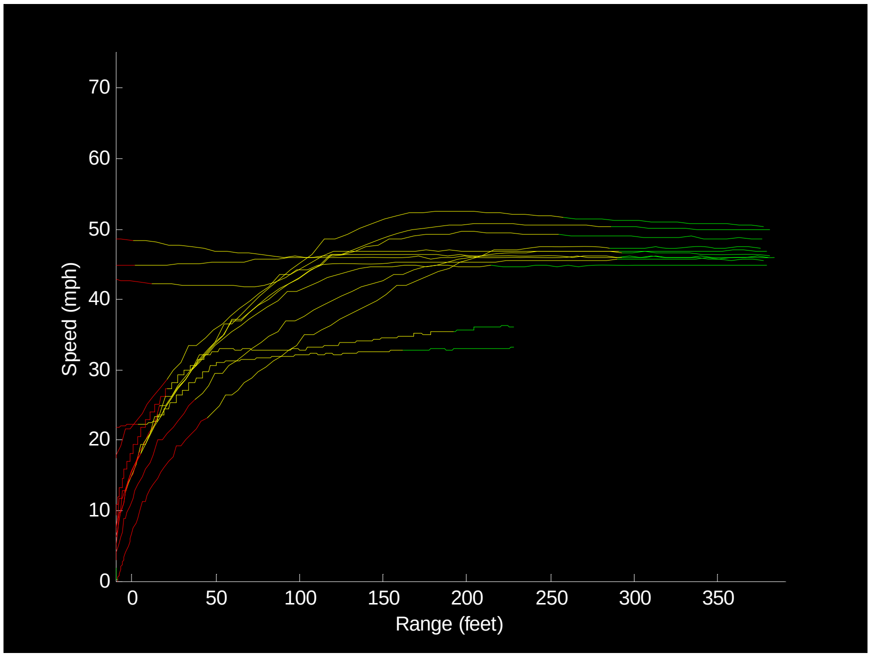
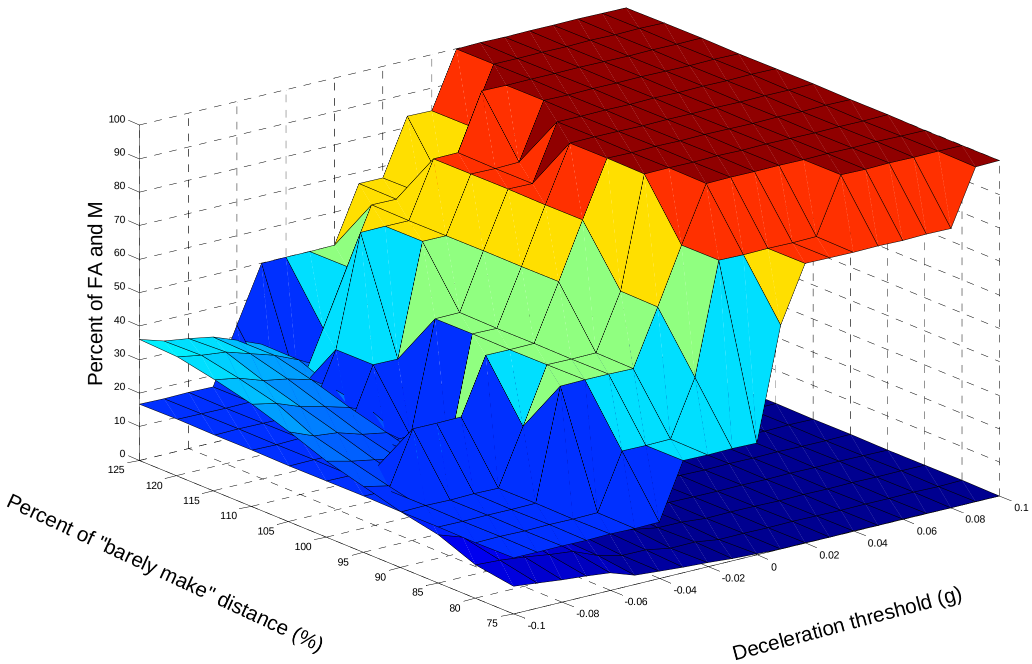
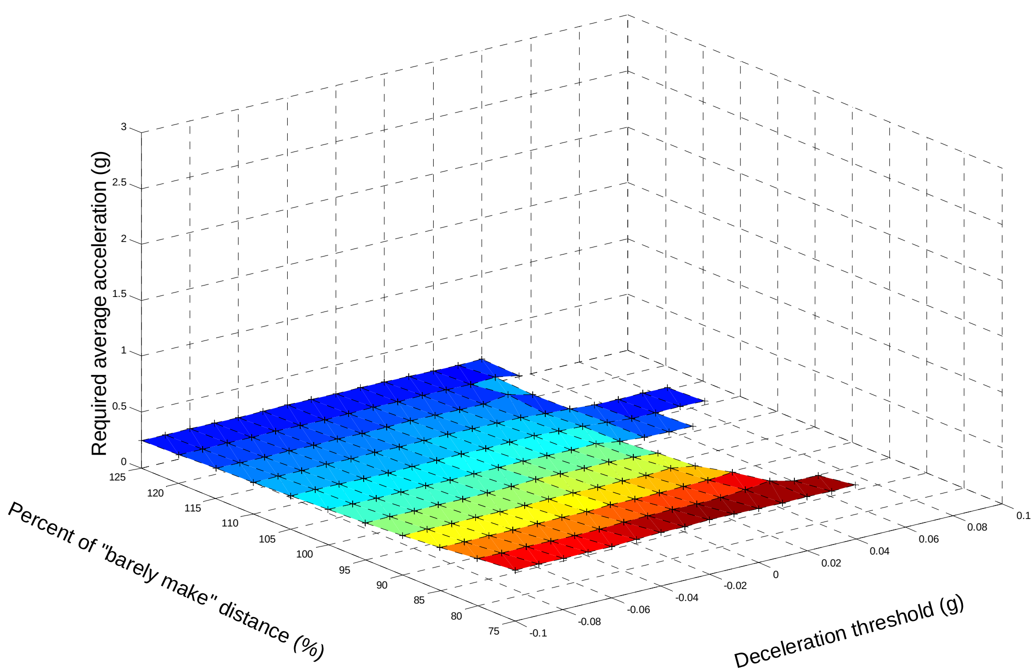


Figure G-38. Level 1 misses for the Case 7 algorithm. These are shown for the 75 percent amber time cruising distance and the -0.1 *g* acceleration threshold. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)



a)



b)

Figure G-39. Level 2 false alarms (a, curve that does not reach 100 percent), misses (a, curve that goes up to 100 percent), and maximum required constant deceleration (b, decelerations were averaged across participants and trials for each experiment) for the Case 7 algorithm.

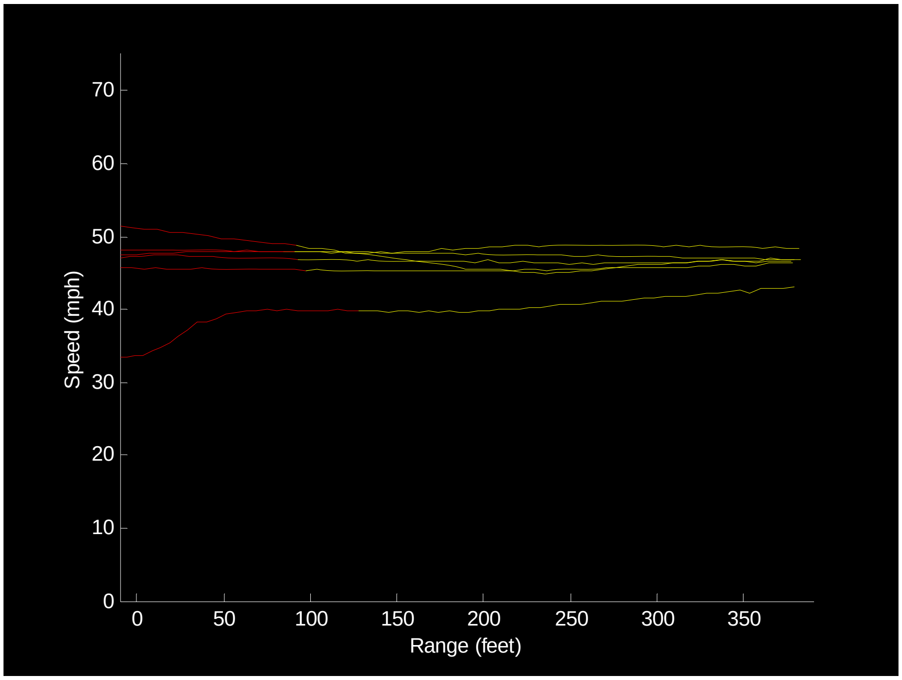


Figure G-40. Level 2 misses for the Case 7 algorithm. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Conclusions

Some of the continuous detection algorithm alternatives appear feasible for use in an IDS system. These feasible alternatives provide reasonable trade-offs between the number of missed and nuisance alarms. However, further testing on a larger number and type of intersection approaches should be undertaken before these algorithms are used in the real-world.

Appendix H: Algorithm Multi-Point Detection

Multi-point detection algorithms are similar in form to continuous-point detection algorithms, but they only have vehicle kinematics information for discrete points in the intersection approach. They are different from single-point detection algorithms in that samples from more than one point in the vehicle approach to the intersection can be used. However, the data that they have available falls short of the much more continuous stream of data available under continuous detection.

In a previous appendix, the inefficacy of single point detection was shown. In a different previous appendix, the promise of some continuous detection algorithms was also shown. This appendix quantifies the effects in algorithm performance when gradually shifting from a continuous detection scheme (which can be conceived as a very large number of discrete detectors placed along the intersection approach) to a single-point detection scheme (in which a single discrete detector is available).

A subset of the algorithms tested under the continuous detection scheme, those showing the best results, was selected for testing in this exercise. The procedure involved testing the algorithms under carefully selected multi-point detection conditions representing different inter-sensor spacing.

Results

The first algorithm tested under the multi-point detection scheme was the Case 2 “basic kinematics with acceleration” algorithm. From the analysis described in the last section, the optimal point for this algorithm was located at the 0.6-second RT and 0.55 *g* parameter combination. Each of the studies at different speeds required a different analysis, since the alarm clusters differed considerably.

The initial analysis was performed for the 56.3-km/h (35-mph) case (Figure H-1). For this case, the alarms were concentrated in the 30.5- to 45.7-meter (100- to 150- foot) range, with three alarms scattered around 15.2 m (50 ft) and one alarm approximately 3.0 m (10 ft) from the intersection. These last four alarms were considered late, and these distances were not included in the analysis to determine the number and location of points.

Given the distribution of points at 56.3 km/h, it was determined to place detectors evenly spread (every 1.5 m [5 ft]) from 29.0 m (95 ft) away from the intersection to 47.2 m (155 ft) away from the intersection. The results show a small decrease in the number of alarms presented to the driver as the detection points were decreased (Table H-1). No Level 2 alarms were required at this speed. While the number of false alarms remained low across the detector positions, the number of misses increases as the number of detectors is decreased.

A secondary analysis was performed for the 72.4-km/h (45-mph) speed. Results are similar to those obtained for the 56.3 km/h (35 mph) speed. However, the distances at which the detectors were placed increased due to the increase in speed (Figure H-2 and Table H-2).

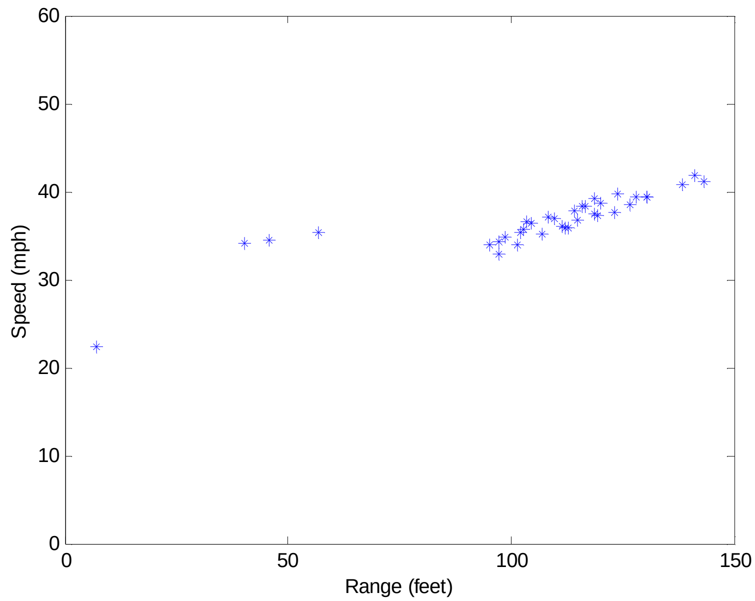


Figure H-1. Range and range rate distribution of the alarms provided in the optimal Case 2 parameter combination at 56.3 km/h (35 mph). (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table H-1. Alarms as a function of detector frequency for the optimal Case 2 parameter combination at 56.3 km/h (35 mph). (Note: 1 ft = 0.305 m)

Spacing	# of Level 1 Alarms	# of Level 2 Alarms	% Level 1 FA/M	% Level 2 FA/M
Full Detection	36	0	0.0 / 0.0	0.0 / 0.0
5 ft. freq. (95 to 155 ft.)	32	0	0.0 / 13.3	0.0 / 0.0
10 ft. freq. (95 to 155 ft.)	30	0	0.0 / 16.7	0.0 / 0.0
20 ft. freq. (95 to 155 ft.)	27	0	0.0 / 20.0	0.0 / 0.0
40 ft. freq. (95 to 155 ft.)	25	0	0.0 / 20.0	0.0 / 0.0
60 ft. freq. (one @ 95 ft.)	25	0	0.0 / 20.0	0.0 / 0.0

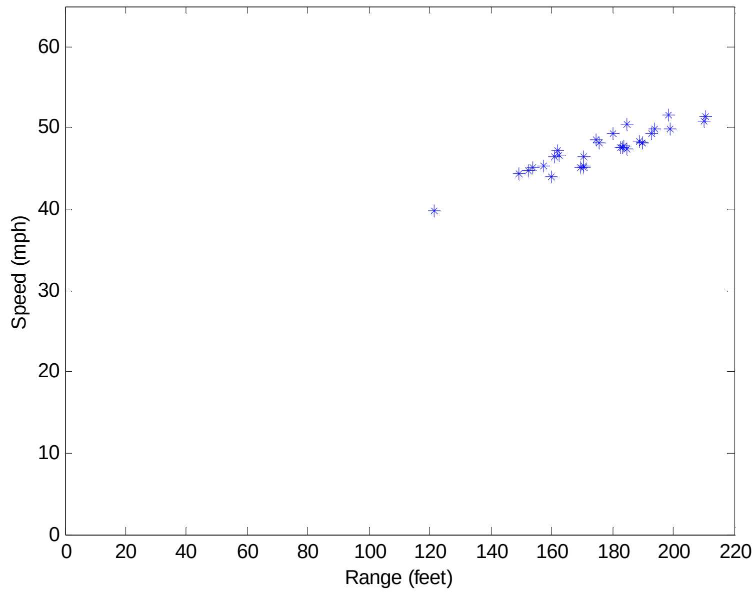


Figure H-2. Range and range rate distribution of the alarms provided in the optimal Case 2 parameter combination at 72.4 km/h (45 mph). (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table H-2. Alarms as a function of detector frequency for the optimal Case 2 parameter combination at 72.4 km/h (45 mph). (Note: 1 ft = 0.305 m)

Spacing	# of Level 1 Alarms	# of Level 2 Alarms	% Level 1 FA/M	% Level 2 FA/M
Full Detection	30	5	0.0 / 28.1	0.0 / 16.7
10 ft. freq. (120 to 220 ft.)	30	5	0.0 / 28.13	0.0 / 20.0
20 ft. freq. (120 to 220 ft.)	25	5	0.0 / 31.3	0.0 / 20.0
40 ft. freq. (120 to 200 ft.)	24	5	0.0 / 34.4	0.0 / 20.0
60 ft. freq. (120 to 180 ft.)	24	4	0.0 / 34.4	0.0 / 50.0
100 ft. freq. (one @ 120 ft.)	19	4	0.0 / 40.6	0.0 / 50.0

While it appears that a reasonable number of alarms can still be provided using frequent point detectors, the tradeoff is an increase in misses, especially in the 72.4-km/h case. Sensor frequency and the corresponding increase in misses must be carefully weighted against the factors that make point detection a desirable alternative.

Similar analyses were completed for the remaining three algorithm alternatives (multi-point detection was not considered for Case 7, as the sensing for this alternative is already in the form of point detection). Trends are similar across all the algorithms tested. Thus, the results are not individually discussed. For reference, the tables and figures below summarize the results of each detection/algorithm combination. Due to the speed sensitive nature of point detection, separate analyses were performed for the 56.3-km/h and 72.4-km/h travel speeds (Figures H-3 through H-8 and Tables H-3 through H-8).

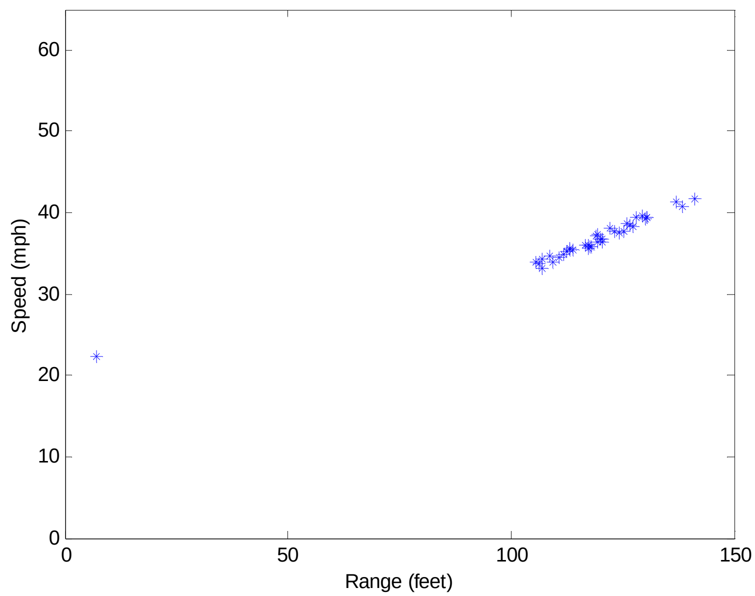


Figure H-3. Range and range rate distribution of the alarms provided in the optimal Case 3 parameter combination at 56.3 km/h. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table H-3. Alarms as a function of detector frequency for the optimal Case 3 parameter combination at 56.3 km/h. (Note: 1 ft = 0.305 m)

Spacing	# of Level 1 Alarms	# of Level 2 Alarms	% Level 1 FA/M	% Level 2 FA/M
Full Detection	39	0	0.0 / 0.0	0.0 / 0.0
5 ft. freq. (100 to 150 ft.)	19	0	0.0 / 46.7	0.0 / 0.0
10 ft. freq. (100 to 150 ft.)	18	0	0.0 / 46.7	0.0 / 0.0
20 ft. freq. (100 to 140 ft.)	17	0	0.0 / 46.7	0.0 / 0.0
40 ft. freq. (100 to 140 ft.)	17	0	0.0 / 46.7	0.0 / 0.0
60 ft. freq. (one @ 100 ft.)	17	0	0.0 / 46.7	0.0 / 0.0

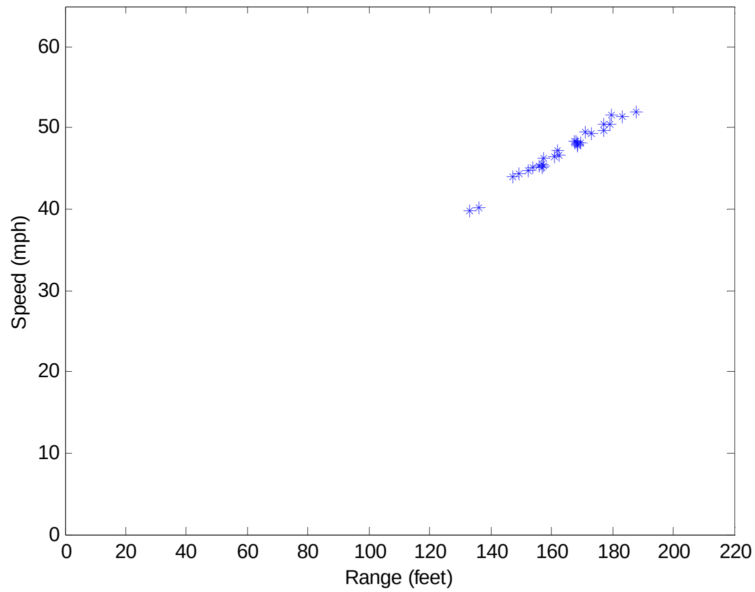


Figure H-4. Range and range rate distribution of the alarms provided in the optimal Case 3 parameter combination at 72.4 km/h. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table H-4. Alarms as a function of detector frequency for the optimal Case 3 parameter combination at 72.4 km/h. (Note: 1 ft = 0.305 m)

Spacing	# of Level 1 Alarms	# of Level 2 Alarms	% Level 1 FA/M	% Level 2 FA/M
Full Detection	28	5	0.0 / 28.1	0.0 / 9.1
10 ft. freq. (120 to 220 ft.)	21	4	0.0 / 34.4	0.0 / 50.0
20 ft. freq. (120 to 220 ft.)	19	4	0.0 / 40.6	0.0 / 50.0
40 ft. freq. (120 to 200 ft.)	18	3	0.0 / 43.8	0.0 / 100.0
60 ft. freq. (120 to 180 ft.)	18	3	0.0 / 43.8	0.0 / 100.0
100 ft. freq. (one @ 120 ft.)	18	3	0.0 / 43.8	0.0 / 100.0

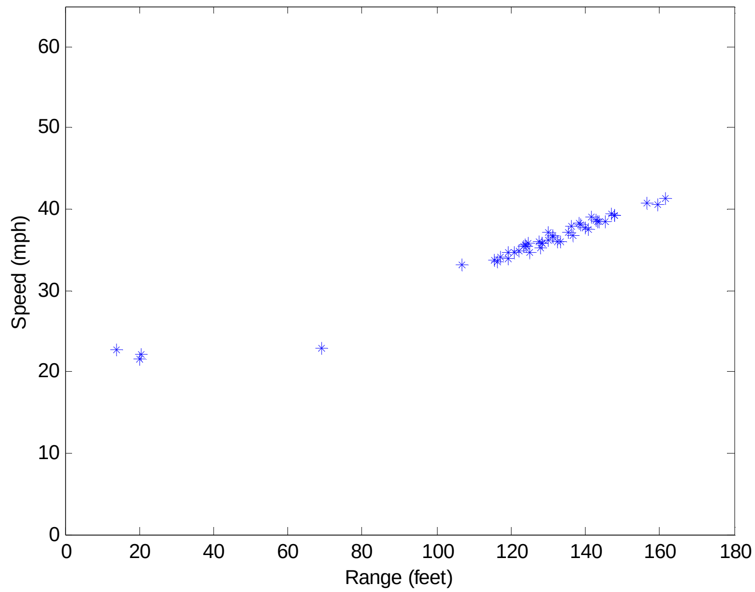


Figure H-5. Range and range rate distribution of the alarms provided in the optimal Case 5 parameter combination at 56.3 km/h. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table H-5. Alarms as a function of detector frequency for the optimal Case 5 parameter combination at 56.3 km/h. (Note: 1 ft = 0.305 m)

Spacing	# of Level 1 Alarms	# of Level 2 Alarms	% Level 1 FA/M	% Level 2 FA/M
Full Detection	45	0	1.4 / 0.0	0.0 / 0.0
5 ft. freq. (100 to 180 ft.)	29	0	0.0 / 23.3	0.0 / 0.0
10 ft. freq. (100 to 180 ft.)	28	0	0.0 /26.7	0.0 / 0.0
20 ft. freq. (100 to 180 ft.)	24	0	0.0 / 26.7	0.0 / 0.0
40 ft. freq. (100 to 180 ft.)	23	0	0.0 / 26.7	0.0 / 0.0
80 ft. freq. (one @ 100 ft.)	23	0	0.0 / 26.7	0.0 / 0.0

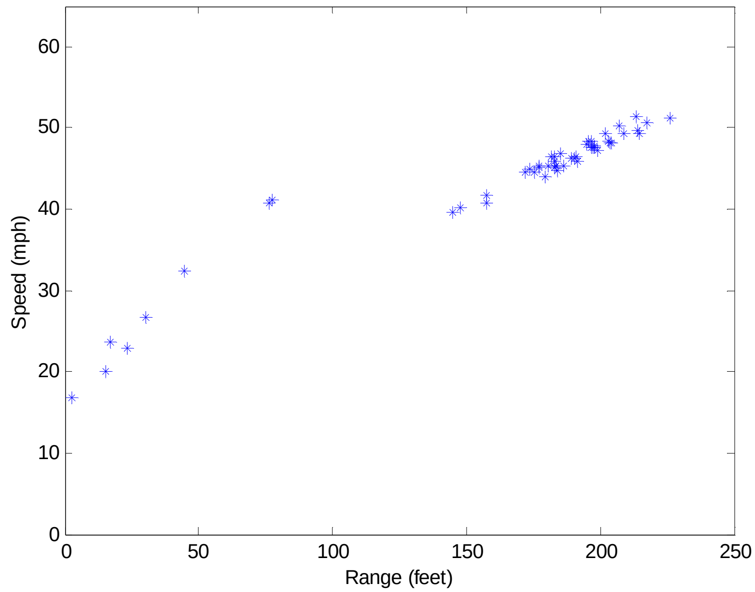


Figure H-6. Range and range rate distribution of the alarms provided in the optimal Case 5 parameter combination at 72.4 km/h. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table H-6. Alarms as a function of detector frequency for the optimal Case 5 parameter combination at 72.4 km/h. (Note: 1 ft = 0.305 m)

Spacing	# of Level 1 Alarms	# of Level 2 Alarms	% Level 1 FA/M	% Level 2 FA/M
Full Detection	51	7	0.0 / 12.5	0.0 / 16.7
10 ft. freq. (120 to 250 ft., additional detector @ 50 ft)	30	5	0.0 / 28.1	0.0 / 20.0
20 ft. freq. (120 to 240 ft., additional detector @ 50 ft.)	25	5	0.0 / 31.3	0.0 / 20.0
40 ft. freq. (120 to 240 ft., additional detector @ 50 ft)	22	5	0.0 / 34.4	0.0 / 20.0
60 ft. freq. (120 to 240 ft., additional detector @ 50 ft)	24	4	0.0 / 34.4	0.0 / 50.0
130 ft. freq. (one @ 120 ft., additional detector @ 50 ft)	22	4	0.0 / 34.4	0.0 / 50.0

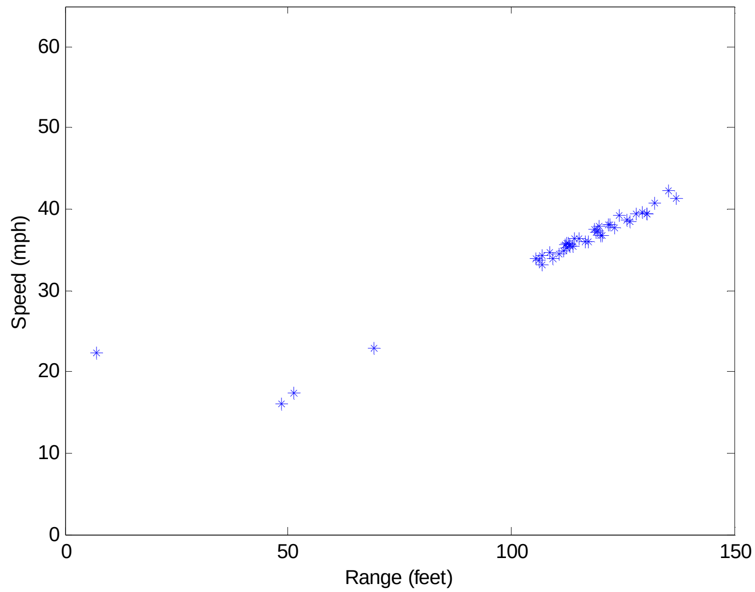


Figure H-7. Range and range rate distribution of the alarms provided in the optimal Case 6 parameter combination at 56.3 km/h. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table H-7. Alarms as a function of detector frequency for the optimal Case 6 parameter combination at 56.3 km/h. (Note: 1 ft = 0.305 m)

Spacing	# of Level 1 Alarms	# of Level 2 Alarms	% Level 1 FA/M	% Level 2 FA/M
Full Detection	42	2	2.2 / 0.0	1.4 / 0.0
5 ft. freq. (100 to 155 ft.)	30	0	0.0 / 20.0	0.0 / 0.0
10 ft. freq. (100 to 150 ft.)	29	0	0.0 / 20.0	0.0 / 0.0
20 ft. freq. (100 to 140 ft.)	25	0	0.0 / 23.3	0.0 / 0.0
40 ft. freq. (100 to 140 ft.)	24	0	0.0 / 23.3	0.0 / 0.0
60 ft. freq. (one @ 100 ft.)	24	0	0.0 / 23.3	0.0 / 0.0

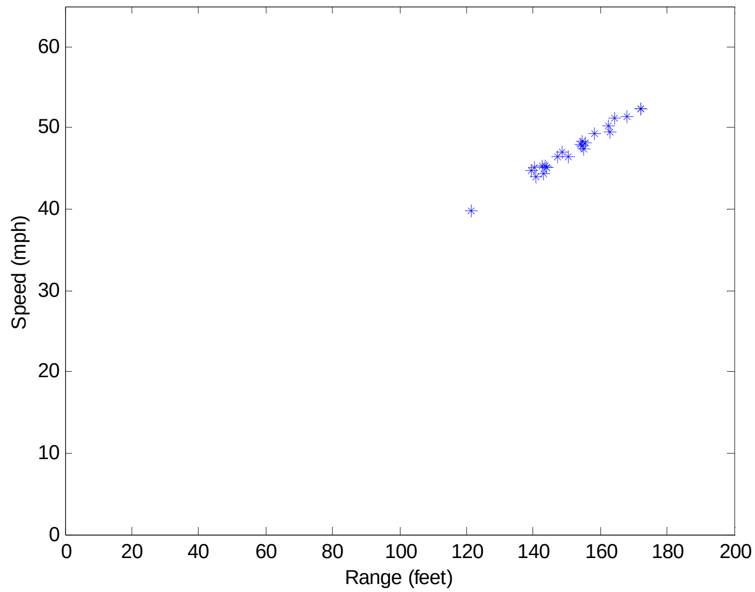


Figure H-8. Range and range rate distribution of the alarms provided in the optimal Case 7 parameter combination at 72.4 km/h. (Note: 1 ft = 0.305 m; 1 mph = 1.61 km/h)

Table H-8. Alarms as a function of detector frequency for the optimal Case 7 parameter combination at 72.4 km/h. (Note: 1 ft = 0.305 m)

Spacing	# of Level 1 Alarms	# of Level 2 Alarms	% Level 1 FA/M	% Level 2 FA/M
Full Detection	26	5	0.0 / 28.1	0.0 / 16.7
10 ft. freq. (120 to 220 ft.)	25	5	0.0 / 28.1	0.0 / 20.0
20 ft. freq. (120 to 220 ft.)	23	5	0.0 / 31.3	0.0 / 20.0
40 ft. freq. (120 to 200 ft.)	21	4	0.0 / 37.5	0.0 / 50.0
60 ft. freq. (120 to 180 ft.)	19	4	0.0 / 40.6	0.0 / 50.0
100 ft. freq. (one @ 120 ft.)	19	4	0.0 / 40.6	0.0 / 50.0

Conclusion

Multi-point detection might be a feasible alternative for an IDS system. When the range of distances at which detectors were placed and their spacing were appropriate, multi-point detection performance was indistinguishable from continuous detection. However, further research is needed using a more diverse set of intersection approaches that includes special cases that could not be explicitly addressed here (e.g., speeding driver)