Application of Driver Behavior and Comprehension to Dilemma Zone Definition and Evaluation

APPLICATION OF DRIVER BEHAVIOR AND COMPREHENSION TO DILEMMA ZONE DEFINITION AND EVALUATION

A Dissertation Presented

by

DAVID S. HURWITZ

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DEDICATION

To my wife Sara, brother Bryan, and parents Chuck and Nancy.

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I would like to thank all four members of my dissertation committee for their tireless commitment to the successful completion of this research effort. In particular, committee chair, Dr. Michael Knodler, who as a valued mentor and friend has imparted a wealth of knowledge and guidance on every aspect of my development as an academic and individual. Dr. Donald Fisher, who as a member of my committee and director of my research efforts with the Human Performance Laboratory has provided invaluable guidance with my driving simulator and human factors work. Dr. John Collura, committee member who has always donated his time generously and provided his expertise and perspective on my research and career development. Additionally, Dr. Daiheng Ni has been a committee member whose probative inquires never fail to augment the quality of my work.

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ABSTRACT

APPLICATION OF DRIVER BEHAVIOR AND COMPREHENSION TO DILEMMA ZONE DEFINITION AND EVALUATION

SEPTEMBER 2009

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Among the most critical elements at signalized intersections are the design of vehicle detection equipment and the timing of change and clearance intervals. Improperly timed clearance intervals or improperly placed detection equipment can potentially place drivers in a Type I dilemma zone, where approaching motorists can neither proceed through the intersection before opposing traffic is released nor safely stop in advance of the stop bar. Type II dilemma zones are not necessarily tied to failures in design, but are more readily tied to difficulties in driver decision making associated with comprehension and behavior. The Type II dilemma zone issues become even more prevalent at high-speed intersections where there is greater potential for serious crashes and more variability in vehicle operating speeds. This research initiative attempts to further describe the impact of driver behavior and comprehension on dilemma zones. To address this notion several experiments are proposed. First, a large empirical observation of high-speed signalized intersections is undertaken at 10 intersection approaches in Vermont. This resulted in the collection of video and speed data as well as full intersection inventories and signal timings. These observations are reduced and analyzed for the

purpose of reexamining the boundaries of a Type II dilemma zone. Second, a comparison of point and space sensors for the purpose of dilemma zone mitigation was conducted. This experiment provides evidence supporting the notion that space sensors have the potential for providing superior dilemma zone protection. Third, a computer based survey is conducted to identify if drivers comprehend the correct meaning of the solid yellow indication and how this relates to their predicted behavior. Lastly, a regression model is developed drawing on the data collected from the field observation as well as the static survey to determine how characteristics such as the speed and position of the vehicle as well as driver age and experience influence driver behavior in the Type II dilemma zone. Cumulatively, these experiments will shed additional light on the influence of driver behavior and comprehension on the Type II dilemma zone.

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LIST OF ABBREVIATIONS

VTrans	Vermont Agency of Transportation
Highway Tech	Highway Tech Signal Systems
MUTCD	Manual of Uniform Traffic Control Devices
ITE	Institute of Transportation Engineers
NCDOT	North Carolina Department of Transportation
NCSITE	North Carolina Section of the Institute of Transportation Engineers
DZ	Dilemma Zone
CR	Circular Red
CG	Circular Green
CY	Circular Yellow
RA	Red Arrow
GA	Green Arrow
YA	Yellow Arrow

CHAPTER I

INTRODUCTION

In the United States, intersection-related crashes are of significant concern to transportation engineers and the motoring public. In 2000, more than 2.8 million intersection-related crashes occurred, representing approximately 44 percent of all crashes that took place in the U.S. that year. In addition, approximately 8,500 fatalities and 23 percent of all fatal crashes occurred at intersections; while another one million intersection crashes resulted in injuries. These crashes had an estimated societal cost of approximately $40 billion (1).

The inherent difficulty with signalized intersections is the antagonistic relationship that often exists between safety and mobility. In many instances, design modifications that increase the operational efficiency of a signalized intersection may also increase the speed of approaching vehicles or the potential for vehicle interactions, both of which can negatively impact the safety of the intersection.

Among the most critical elements at signalized intersections is the physical design of the intersection, the equipment used to detect the presence of vehicles, and the timing of the traffic signals. A specific application of the relationship between traffic signal timing and safety is the timing of clearance intervals, which are used to transition between alternating phases. Improperly timed clearance intervals can potentially place drivers in a Type I dilemma zone, when approaching motorists can neither proceed through the intersection before opposing traffic is released or safely stop in time in front of the stop bar. Dilemma zone issues become even more prevalent at high-speed

intersections where there is greater potential for serious crashes and more variability in vehicle operating speeds.

The presence of dilemma zones at signalized intersections has the potential to increase crash frequency and/or severity. This has motivated the design of signalized intersections aimed at the minimization of the dilemma zone. There are however several challenges existing with this notion. For example, much of the data collected in previous literature for the use of identifying driver behavior and the boundaries of the dilemma zone was collected over 20 years ago. Additionally, because of the substantial variability that exists with driver behavior and vehicle types, defining a relationship between difficulties in driver decision making and the explicit definition of the boundaries of a Type II dilemma zone has proven to be a challenge. There is a critical need for research to more explicitly quantify and model driver comprehension and behavior related to existing clearance interval practices through the comprehensive evaluation of the identified research hypotheses purported by this research effort.

Research Problem Statement

There is a critical need to expand upon our understanding of driver behavior resulting from incursions with the solid yellow indication at high-speed signalized intersections. Until the factors influencing (go/no go) driver behavior in these situation are fully understood optimal design solutions to the timing of the clearance interval and the placement of advanced vehicle detection will be difficult to achieve.

Research Hypotheses

The overarching theory postulated by this research initiative is that driver comprehension and driver behavior influence the presence and significance of Type II dilemma zones at high-speed at-grade signalized intersection.

The research hypotheses aimed at addressing this overarching theory encompass driver behavior when exposed to the solid yellow indication at a high-speed signalized intersection, the impact of vehicle sensors on dilemma zone protection, and driver comprehension of solid yellow indications. In total, three specific research hypotheses have been developed as part of the proposed research. The following sections provide supplemental information regarding the development of the four proposed research hypotheses.

Research Hypothesis 1:

- *Type II dilemma zone boundaries can be identified from observed driver behavior (stop/go action when exposed to the solid yellow indication), vehicle speed, and vehicle position for isolated at-grade high-speed signalized.*

As has been determined in many previous research efforts, there is potentially a wide range in driver performance with relation to any single decision making task. This is due to numerous factors including aspects such as the different operational characteristics of vehicles, varying driver attributes, and intersection design components. If the range of resulting behaviors can be more adequately categorized improved traffic signal design may result.

In this scenario, concern is related to the drivers' decision to stop the vehicle in advance of the stop bar or to proceed through the intersection. This behavior is strongly correlated to the speed and position of the individual vehicle.

A critical contribution to this hypothesis will be the development of an updated and improved database of observed driver behavior when encountering the solid yellow indication while approaching a solid yellow indication.

Research Hypothesis 2:

- *Advanced vehicle detection has the potential to provide superior dilemma zone protection when utilizing space sensors as compared to point sensors for isolated at-grade high-speed signalized intersections, where dilemma zone protection is defined by a reduction in the number of vehicles caught in a Type II dilemma zone.*

Some of the current limitations of signalized intersections are tied to the vehicle detection systems which are typically installed. Theoretically, if vehicles were consistently monitored for speed and position as they approached the stop bar at a signalized intersection, better intersection control could potentially be provided.

Research Hypothesis 3:

- *Driver comprehension of the circular yellow indication is less than desirable for the safe and efficient operation of signalized intersections, where comprehension is evaluated across the dimensions of meaning, duration and sequencing of the indication.*

It is important to collect quantifiable data regarding driver comprehension and predictive behavior of all traffic control devices. Clearly, the initial component of studying driver behavior must be the identification of driver comprehension. If the driver does not understand the message being presented, then the response to that message may vary substantially.

The overarching theory of the proposed research will be examined by evaluating the three identified research hypotheses associated with driver comprehension and behavior upon exposure to the solid yellow indication. It is entirely likely, and therefore worthy of note, that additional research questions may be developed through the pursuit of completing the existing hypotheses.

Scope

The intent of the proposed research is to address the aforementioned research hypotheses. As a result, only high-speed signalized intersections on arterial roadways will be considered. High-speed intersections are the focal point of this effort due to the relative severity of crashes resulting from dilemma zone incursions on these types of facilities and the increased variability in dilemma zone issues at these intersections.

Organization of Dissertation

This dissertation is comprised of 7 chapters; the sequencing of chapters can be seen in Figure 1.

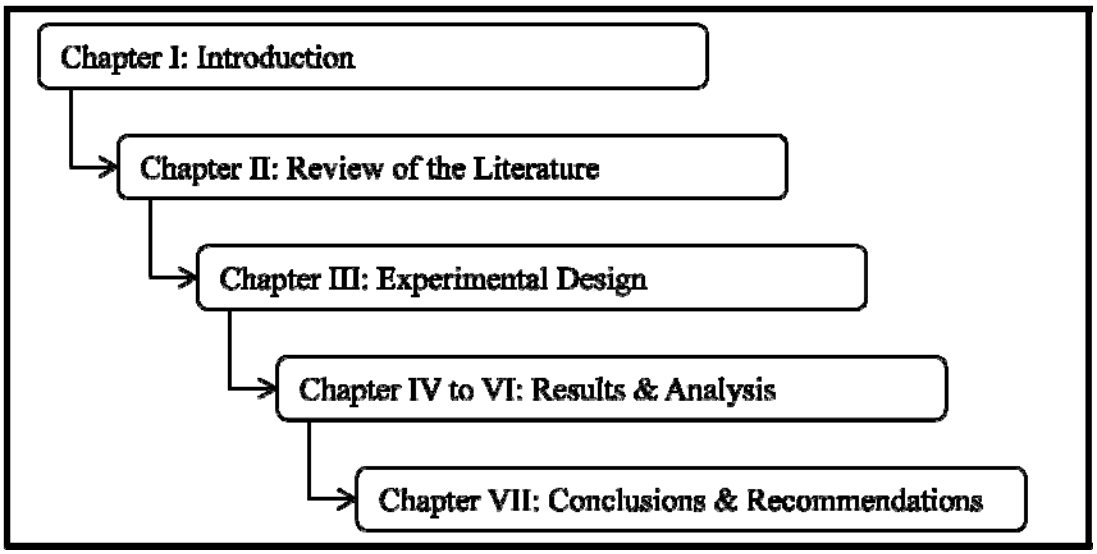

Figure 1 Organization of Dissertation

Chapter 1 outlines the problem statement, describes the specific research hypotheses, and establishes the scope of this research effort. Chapter 2 delves into accepted literature to complement the framing of the problem addressed by this research and presented in the problem statement. In addition, Chapter 2 it provides information about the different technologies and experimental procedures implemented as components of this research. Chapter 3 describes the design of each experiment and the manner in which they address the research hypotheses. Chapters 4 through 6 present the data recorded from the experiments and the subsequent analyses that were conducted. Finally, Chapter 7 provides the conclusions and recommendations derived from examination of the information and analyses presented in Chapters 4 through 6.

CHAPTER II

REVIEW OF THE LITERATURE

This state of the practice review attempts to pull from as many relevant sources as could be identified. The review began with generally accepted design manuals accessible to practicing professionals, it expanded into technical documents produced by state departments of transportation (DOT), and culminated with a survey of applicable technical journal writings and conference presentations on the subject.

The state of the practice regarding signal design as it relates to the minimization of dilemma zone issues was condensed into the following key areas: change and clearance intervals, dilemma zone definitions, dilemma zone mitigation strategies, and driver decision making including driver behavior and driver decision making. The following sections outlined in Figure 2, present each of these areas in greater detail.

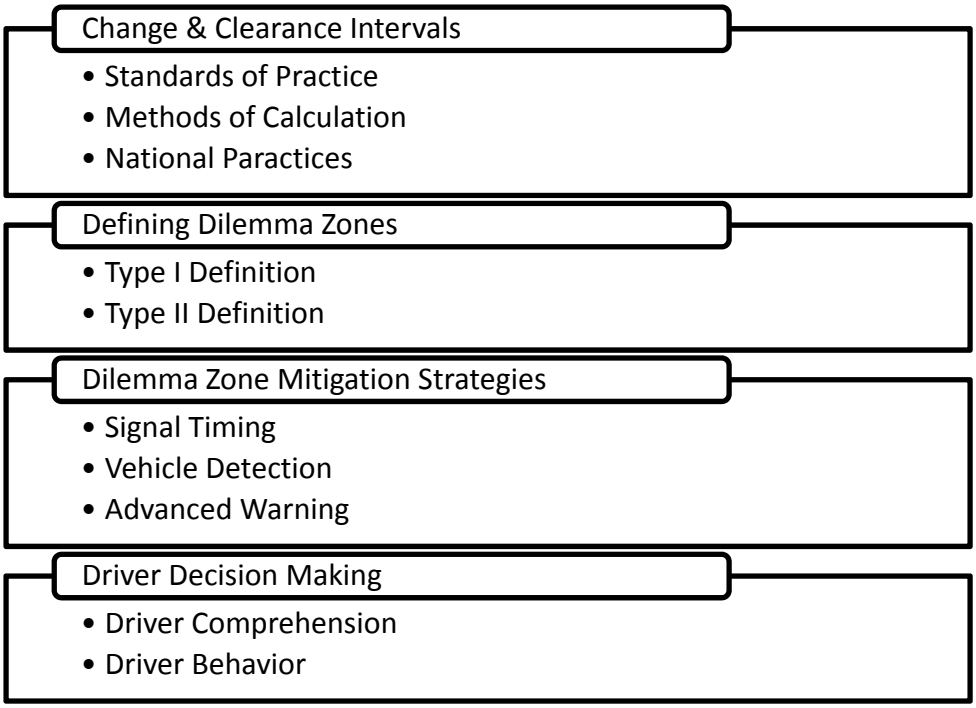

Figure 2 Review of the Literature Organizational Structure

Change and Clearance Intervals

The long history of literature regarding signal design reveals that the terms "change" and "clearance" have been used in a wide variety of ways (2). For the purpose of clarity, this document will adopt a consistent usage of both terms. The change interval describes the yellow indication which is displayed at the termination of the green indication and in advance of the red or all red indication. The clearance interval refers to the all red interval (2).

The change interval serves to alert oncoming vehicles that the right-of-way currently allocated to their approach is about to be reassigned (3). It allows for an approaching vehicle presented with the termination of the green indication, while within safe stopping distance from the stop line to maintain its speed and legally enter the intersection on the yellow (2). Crossing the stop line with the front wheels of the vehicle

is the accepted definition of entering the intersection (2). The typical duration for the change interval at a high-speed intersection is approximately 5 seconds (3).

The clearance interval displays the red indication to all approaches to allow any vehicle that entered the intersection during the change interval to safely clear the intersection before conflicting movements are released (2). The typical duration of the clearance interval at a high-speed intersection is approximately 2 sec (3). This process is intended to mitigate potentially serious right-angle crashes. However, the inclusion of a clearance interval has the potential to increase red light running (RLR) at signalized intersections.

Standards of Practice

The Manual on Uniform Traffic Control Devices (MUTCD) is the generally accepted authority on the application of traffic signs, signals, and pavement markings within the United States. The MUTCD is predominately limited in its guidance of change and clearance intervals, beyond the basics. However, this is appropriate since this is fundamentally a question of signal timing, existing outside the parameters of the MUTCD. The only change interval standards discussed in the MUTCD are the following:

> *A Yellow signal indication shall be displayed following every CIRCULAR GREEN or GREEN ARROW signal indication. The exclusive function of the yellow change interval shall be to warn traffic of an impending change in the right-of-way assignment. The duration of a yellow change interval shall be predetermined (4).*

Therefore, the place in the phasing sequence occupied by the yellow indication is required as well as the meaning of the indication. However, there is no required method for the calculation of the length of the change interval. The only guidance provided on the calculation of the change interval is the statement by the MUTCD that:

> *A yellow change interval should have approximately 3 to 6 second duration. The longer intervals should be reserved for use on approaches with higher speeds (4).*

Similar guidance is provided in the standards regarding the clearance interval. The MUTCD standard for the clearance interval states that, "*The duration of a red clearance interval shall be predetermined.*" While, the guidance states that, "*A red clearance interval should have a duration not exceeding 6 seconds (4).*"

Accepted Methods of Calculation

Since there is no design standard for the calculation of change or clearance intervals, several approaches have been adopted by different agencies across the country. In response to the lack of design standards ITE has developed a recommended calculation which accounts for grade of approach roadway, perception-reaction time of driver, deceleration rate of vehicle, velocity of approaching vehicle, length of car, and the width of the intersection. The ITE equation for the change interval (3,5) is as follows:

$$y = t + \frac{V}{2a + 64.4g}$$

Where:

y = length of change interval (sec)

t = driver reaction time (typically 1 sec)

V = 85th percentile speed, posted speed limit, or design speed as appropriate (ft/s)

a = deceleration rate of vehicles (typically 10 ft/s^2)

g = grade of approach (pos. for upgrade, neg. for downgrade, express as decimal)

64.4 = twice the acceleration of gravity (ft/s/s)

The ITE equation for the clearance interval (3,5) is calculated as:

$$r = \frac{W + L}{V}$$

Where:

r = length of clearance interval (sec)

W = width of intersection (ft)

L = length of vehicle (typically 20 ft)

V = 15th percentile speed (ft/s)

Several alternative practices to the ITE recommended calculations have been adopted to handle change and clearance intervals. For intersections with relatively level approaches, some authorities calculate the yellow clearance interval as the operating speed of the approach vehicles divided by 10, with a red clearance interval of 1 or 2

seconds. Additionally, some jurisdictions will apply the same change and clearance timings to roads of similar functional classification or closely grouped intersections (3,5).

Current National Practices

The current practices employed by State Departments of Transportation regarding the calculation of clearance and change intervals vary considerably. A survey that was conducted by ITE to identify State DOT practices for the calculation of change and clearance intervals at signalized intersections highlights national trends (5). The survey asked respondents to identify if any of the following practices were implemented within their agencies jurisdiction; one standard amount of time for all intersections, one standard amount of time for different functional classes of streets, the ITE recommended formula, or another practice. Please note that when the results of the survey are totaled they exceed 100% because multiple practices could take place within a single jurisdiction. Figure 3 displays the results of the survey regarding the calculation of change intervals.

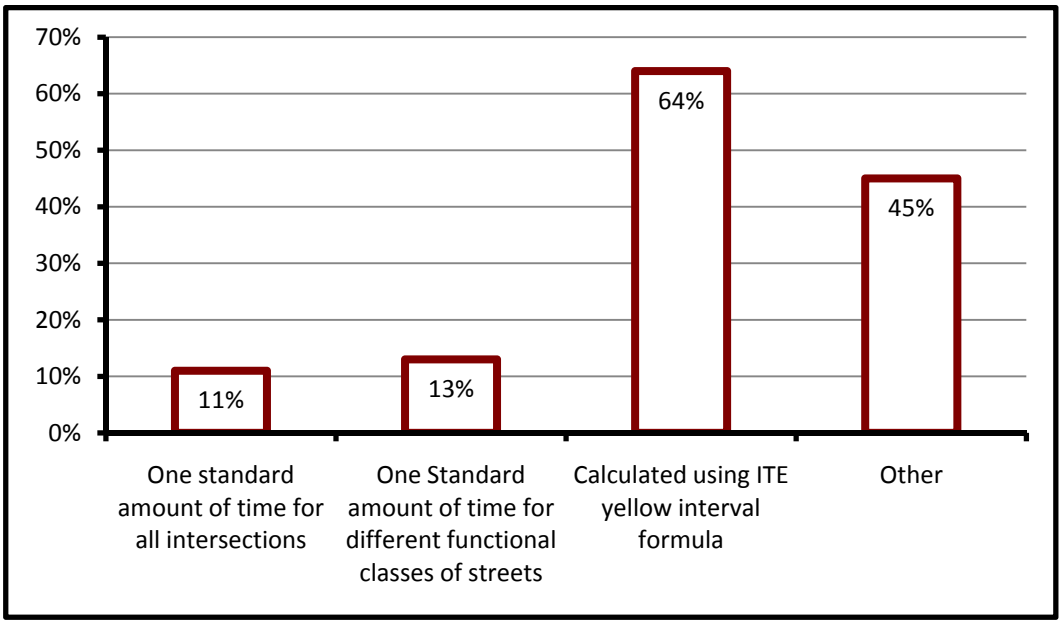

Figure 3 Yellow Change Current Practices (5)

It should be noted that the "other" category for the change interval included strategies such as yellow times proportional to the approach speed or red interval, values adjusted based on vehicle speeds, increases for high speed or wide intersections, and if the yellow is abused, add extra all red time, etc. The most popular approach for the determination of change intervals (with 64%) is the ITE recommended equation. It is important to consider the potential bias that may exist in the perspectives held by those engineers who respond to an ITE sponsored survey.

Figure 4 displays the results of the survey regarding the calculation of clearance intervals. The "other" category represents values adjusted by vehicle speed, field observation, engineering judgment, and added red time if the yellow is being abused. Again, the most popular approach for the determination of clearance intervals (with 57%) is the ITE recommended equation.

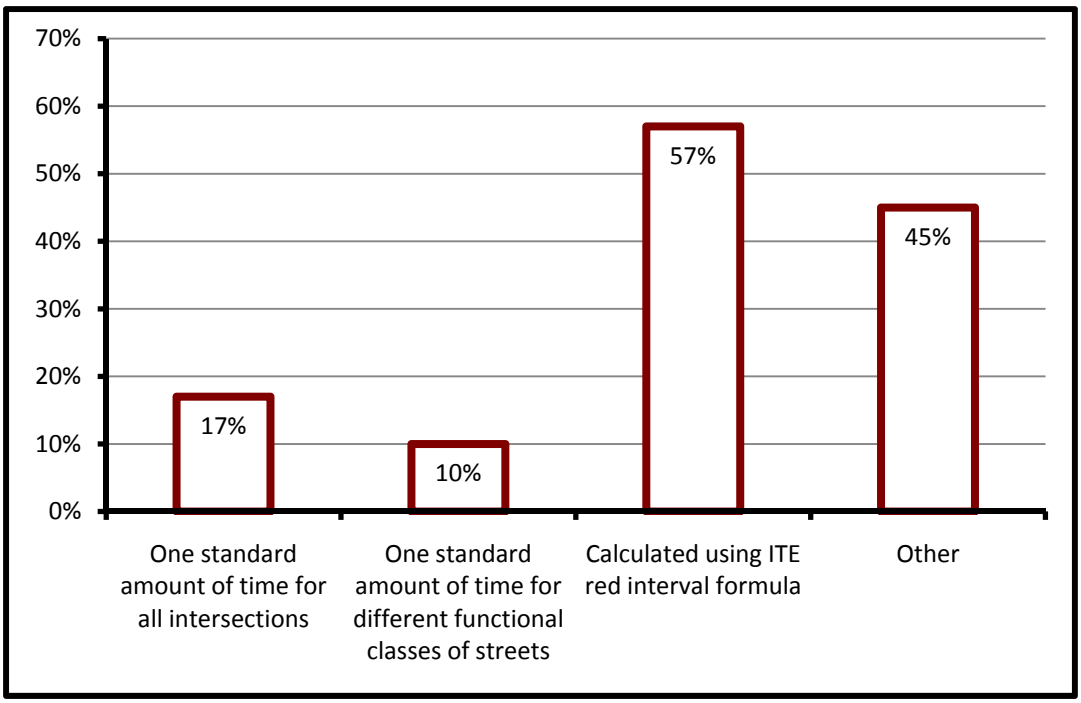

Figure 4 Red Clearance Current Practices (5)

The survey shows that the most popular approach to calculating change and clearance intervals are the recommended ITE formulas. However, the ITE formula is less dominant when calculating the clearance interval as opposed to the change interval. One of the most critical issues with the calculation of change and clearance intervals is the avoidance of dilemma zones.

Dilemma Zones

The development of successful design solutions to transportation problems, or any other complex system, can be greatly hindered by poor problem identification. Such has been the case in the diagnosing of dilemma zone issues at signalized intersections. It is critical that a common lexicon be established if this traffic safety issue is to be adequately addressed. This document, building on previously established terminology, will refer to 2 general classes of dilemma zone conflicts (Type I and Type II). The Type I dilemma

zone was first referenced in the literature by Gazis et. al. in 1960 (6). Figure 5 shows a diagram of a traditional type I dilemma zone.

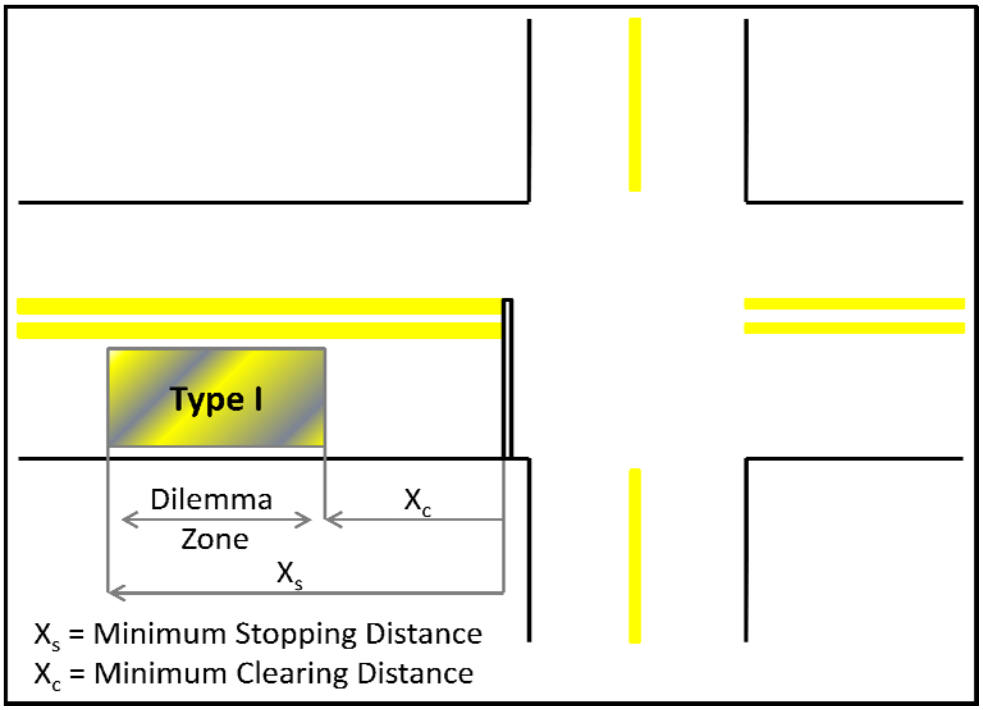

Figure 5 Type I Dilemma Zone Diagram

The Type I dilemma zone describes the possibility that a motorist when presented a yellow indication while approaching a signalized intersection will, due to the physical parameters of the situation, be unable to safely pass through the intersection or stop prior to the stop bar. It was not until 1974 that the Type II dilemma zone was formally identified in a technical committee report produced by the Southern Section of ITE (7). Figure 6 shows a diagram of a traditional Type II dilemma zone.

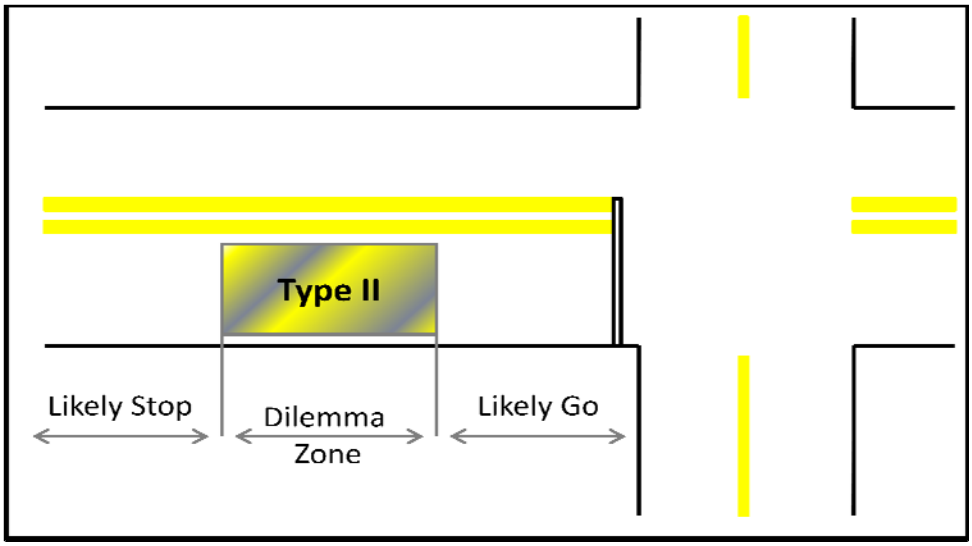

Figure 6 Type II Dilemma Zone Diagram

The boundaries of the Type II dilemma zone have proven more difficult to strictly define as they are somewhat dynamic in nature and directly influenced by diver decision making. The Type II dilemma zone describes the region of pavement which begins at the position on the approach to a signalized intersection where most people choose to stop the vehicle when presented with the yellow indication and ends at the position where most people choose to continue through the intersection.

Several attempts have been made to quantify the location of the Type II dilemma zone. In 1978, Zegeer and Deen defined the boundaries of the Type II dilemma zone in terms of driver decision making. He identified the beginning of the zone as occurring at the position where 90% of drivers stopped and the end of the zone as occurring where only 10% of the drivers stopped (8). In 1985, Chang tried to define the boundaries in terms of travel time to the stop bar. The research found that 85% of drivers stopped if they were 3 seconds or more back from the stop bar while almost all drivers continued through the intersection if they were two seconds or less from the stop bar (9). Based on

previously conducted findings it has been concluded that the Type II dilemma zone exists in the area between 5.5 seconds and 2.5 seconds from the stop bar.

The two crash situations associated with dilemma zones are abrupt stops leading to rear-end crashes, and failure to stop leading to right-angle crashes. On average right-angle crashes tend to result in more serious injuries, therefore more emphasis is typically placed on their prevention. As the approach speeds of the intersecting roadways increase so too does the severity of the collisions, which is one reason why an added emphasis is placed on dilemma zone issues at high-speed signalized intersections. The location and size dilemma zones are directly related to the speed, size, and weight of the vehicle approaching the intersection.

Mitigation

The potentially negative impact of dilemma zones on the operating capacity and safety of signalized intersections, especially at high-speed locations has initiated a great deal of effort directed towards mitigating the dilemma zone issue. This mitigation has been pursued along the three complementary paths of signal timing, vehicle detection, and advanced warning.

Signal Timings

The impact of signal timing methods and practices are of critical concern in any discussion of signalized intersection safety. Previous sections have discussed the lack of uniformly accepted standards for the effective determination of change and clearance intervals. A sampling of unique change and clearance interval timing strategies is

included in this section. Because of the difficulty associated with lengthening all-red times the North Carolina Department of Transportation (NCDOT) prepared a formal request to investigate and recommend timing practices for the determination for change and clearance intervals (10,11). The North Carolina Section of the Institute of Transportation Engineers (NCSITE) supported a task force to address the NCDOT concerns.

After much deliberation and evaluation of proposed alternatives the task force selected a preferred alternative to the timing practice of change and clearance intervals, based on the existing ITE equations.

The task force continued to support the ITE change interval calculation; however they selected the perception reaction time of 1.5 seconds and the deceleration rate of 11.2 ft/s/s as recommended by A Policy on Geometric Design of Highways and Streets (12). They also recommended rounding any calculated yellow up to a minimum time of 3.0 seconds, and holding a stakeholders meeting before accepting any yellow time greater than 6.0 seconds (10, 11). Figure 7 shows sample output for the revised application of the ITE change interval calculation.

Speed		Grade				
mph	fps	-6%	-3%	0%	3%	6%
20	29.3	3.1	3.0	2.9*	2.8*	2.7*
25	36.7	3.5	3.3	3.2	3.1	2.9*
30	44.0	3.9	3.7	3.5	3.4	3.2
35	51.3	4.3	4.1	3.8	3.7	3.5
45	66.0	5.1	4.8	4.5	4.3	4.1
55	80.7	5.9	5.5	5.2	4.9	4.6
65	95.3	6.7+	6.2+	5.8	5.5	5.2
* Less than 3.0 second minimum, increase yellow time to 3.0 + Greater than 6.0 sec threshold, requires stakeholder meeting prior to approval						

Figure 7 Sample Yellow Intervals (5, 6)

The task force was very concerned with the seemingly increasing length of all red intervals. For this purpose they recommended a modification to the calculation of the all red time. They eliminated the vehicle length term from the calculation (10, 11). If any red time is calculated to be over 3.0 seconds they would recalculate the red interval with the following equation:

$$r = \frac{1}{2}\left(\frac{W}{V} - 3\right) + 3$$

Where:

r = length of clearance interval (sec)

W = width of intersection (ft)

V = 15th percentile speed (ft/s)

Additionally, any red time that was calculated to be less than 1 second would be increased to 1 second, and any red time calculated to be greater than 4 seconds would

require a stake holder meeting. Figure 8 shows sample output for the revised application of the ITE clearance interval calculation.

Speed		Clearance Distance (feet)						
mph	fps	50	75	100	125	150	175	200
20	29.3	1.8	2.6	3.3	3.7	4.1+	4.5+	5.0+
25	36.7	1.4	2.1	2.8	3.3	3.6	3.9	4.3+
30	44.0	1.2	1.8	2.3	2.9	3.3	3.5	3.8
35	51.3	1.0	1.5	2.0	2.5	3.0	3.3	3.5
45	66.0	0.8*	1.2	1.9	1.9	2.3	2.7	3.1
55	80.7	0.7*	1.0	1.6	1.6	1.9	2.2	2.5
65	95.3	0.6*	0.8*	1.4	1.4	1.6	1.9	2.1

Shaded cells indicate mitigated red intervals
* Less than 1.0 second minimum, increase all read time to 1.0
+ Greater than 4.0 sec threshold, requires stakeholder meeting prior to approval

Figure 8 Sample Red Intervals (10, 11)

The recommendations produced by the NCSITE were adopted as design policy by the NCDOT and are now included in the state design manual. After signal timing, the next most critical component of dilemma zone mitigation is the integration of effective vehicle detection systems.

In contrast to the North Caroline approach, which was motivated by a concern of the possible disobedience and inefficiency associated with the lengthening of change and clearance intervals, substantial research has been conducted on the positive impacts of lengthening change intervals on red light running (RLR) rates. Retting et. al. found that the increasing of change interval lengths by 1.0 second on experimental signalized intersection approaches reduced RLR rates by about 36% with a 95% C.I. of (6% to 57%) when normalized against control intersection approaches which were observed nearby (13).

In 1998, Sacramento County, California strayed from the commonly adopted ITE equations for the establishment of change and clearance interval timings (14). The model used for the timing of the clearance interval is designed to address the very worst case situation of a slow moving through vehicle (traveling at the 10th percentile speed) entering the intersection at the very last moment of the yellow indication conflicting with a vehicle on the minor street that is slowing but not stopped at the stop bar when the green indication initiates. The following equation was derived to describe the motion of the minor street vehicle:

$$t_{min} = \sqrt{\frac{2D}{a_s - a_r}}$$

Where:

t_{min} = minimum amount of time

a_s = driver rate of acceleration at green onset

a_r = driver rate of deceleration prior to green onset

D = position of interest beyond the stop bar

If you assume a deceleration rate of 10 ft/sec^2 and an acceleration rate of 15 ft/sec^2 then the above equation can be reduced to the following:

$$t_{min} = 0.283\sqrt{D}$$

This equation allows for the calculation of the length of time required for the vehicle on the minor to travel any distance beyond the stop bar. However, the distance of concern in this application is the distance to the conflict point with a through vehicle.

An approach was also developed for the timing of the change interval. It was derived from the definition of the theoretical dilemma zone being the region in space starting where at the onset of the yellow indication 90% of vehicles stop and 10% go and ending where 90% of vehicles go and 10% stop. The yellow times are calculated by considering a vehicle traveling at the 90th percentile speed caught in the dilemma zone the furthest possible distance from the signalized intersection. Figure 9 displays the proposed yellow times implemented in California.

Speed (mph)	Far Dilemma Zone Boundary (ft from stop bar)	Travel Time from Far Dilemma Zone Boundary to Stop Bar = Recommended Yellow Clearance (sec)	Minimum Yellow Clearance per California MUTCD (sec)
35	200	3.9	3.6
40	250	4.3	3.9
45	300	4.6	4.3
50	350	4.8	4.7
55	400	5.0	5.0
60	450	5.1	5.4

Figure 9 Recommended Yellow Clearance Times (14)

While signal timings are the most fundamental and low cost strategy, to maximize the safety at a signalized intersection it is critical to considered integrating other strategies into the dilemma zone protection scheme such as vehicle detection which can work in tandem with signal timing strategies.

Vehicle Detection

The most typical solution to dilemma zone issues at high-speed signalized intersections is the use of advanced detection provided primarily by in-pavement inductive loops. Advanced loops allow for extensions to be added to the green such that vehicles can clear the intersection safely (8). In most situations advanced detection provides additional safety, however under moderately congested conditions the green will be extended to “max-out” exposing remaining vehicles to the safety hazard of a dilemma zone.

Many modified inductive loop systems have been examined in the literature. The Detection-Control System (D-CS) was one such system evaluated by the Texas Transportation Institute. This system is similar to other advanced detector systems however it employees an algorithm which uses vehicle size and speed to generate a prediction of a vehicles likelihood of appearing in the dilemma zone (15). The use of the algorithm has the potential to improve the performance of inductive loop advanced detection with regards to both safety and operations.

One of the very newest vehicle sensor systems designed specifically to mitigate dilemma zone conflicts is the Wavetronix SmartSensor Advance with SafeArrival technology and Digital Wave Radar. This system allows for the dynamic real-time identification of individual vehicle approach speed and position from the stop bar. The system processes that information and uses it to determine if the vehicle will be caught in a dilemma zone and extends the green time to allow for safe passage through the intersection if necessary. Figure 10 displays an image of a Wavetronix SmartSensor Advance installation in Vermont (16).

Figure 10 Installation of Wavetronix SmartSensor Advance

As with any new intelligent intersection strategy the Wavetronix SmartSensor Advance the novelty of the technology has not provided adequate time for field testing and validation by independent entities.

A number of other strategies exist for the mitigation of dilemma zones outside of signal timing and vehicle identification. One of the most promising is the use of advanced warning systems.

Advanced Warning

The concept of providing warning in advance of a signalized intersection is aimed at alerting drivers of the potential need to stop downstream such that adequate time can be allowed for breaking, thereby eliminating the critical failure of drivers entering the intersection after the right-of-way has been reallocated. The most comprehensive systems that provide this type of information are globally referred to as Advanced Warning Systems (AWS).

Figure 11 is an image, of a typical AWS configuration. This particular AWF includes a pair of amber flashing lights and a sign with a symbolic signal ahead.

Figure 11 Typical Advanced Warning Flasher (AWF)

Several surveys have been conducted nationally trying to identify all the variations of advanced warning sign and flasher combinations. Sayed et al. aggregated AWFs into the following distinctive categories:

- *"Prepare To Stop When Flashing (PTSWF): The PTSWF sign is essentially a warning sign with the text Prepare To Stop When Flashing complemented by two amber warning beacons that begin to flash a few seconds before the onset of the yellow interval (at a downstream signalized intersection) and that continue to flash until the end of the red interval.*
- *Flashing Symbolic Signal Ahead (FSSA): This device is similar to the PTSWF sign except that the words Prepare To Stop When Flashing are replaced by a schematic traffic signal composed of a rectangle with solid red, yellow, and green circles. The flashers operate in the same manner as the PTSWF sign.*

- *Continuous Flashing Symbolic Signal Ahead (CFSSA): As the name suggests, this device is identical to the FFSA sign be it has flashers that flash all the time – the flashers are not connected to the traffic signal controller"*(17).

The myriad of previous research efforts in this area has consistently revealed that the installation of AWFs leads to reduced overall crash frequency and severity, but that the results have not been found to be statistically significant. Conversely, AWFs have also been seen to increase approach speeds and RLR after the start of red (18).

One of the newest conceptions of an AWF is the Advanced Warning for End-of-Green System (AWEGS), which was developed and field tested by the Texas Transportation Institute (TTI). Several AWEGS architectures were examined during the course of the study. The preferred alternative involved a sign (text or symbolic), two amber flashers, and a pair of advanced inductive loops. The AWEGS is capable of identifying aggregate classification of the vehicle (car, truck) and its individual speed (18).

This preferred AWEGS provided less delay due to stoppages at the signal and extra dilemma zone protection by identifying high-speed vehicles and trucks. It also has the potential for reducing RLR during the first 5 seconds of the red by 38 to 42 percent based on the study results (18).

Driver Comprehension and Behavior

It is important to establish a working definition for driver comprehension as it will be referred to within this document. The manual for Human Factors and Traffic Safety

defines driver comprehension as “the ease with which the driver can understand the intended message.” With this definition in mind, it is clearly important for the driver to immediately understand the message of any traffic control device because any delay or misinterpretation can result in driver error (19).

A plethora of driver comprehension and behavior studies have been conducted within the field of transportation. Two recent studies completed at the University of Massachusetts Amherst, focused upon driver comprehension of signalization concepts and speed perception and identification, both of which are relevant to the study of dilemma zones.

Specifically, *Static and Dynamic Evaluation of the Driver Speed Perception and Selection Process*, authored by Hurwitz concentrated on determining the fidelity with which drivers could perceive their speed in real world, driving simulator, and static environments (20). This project provided preliminary evidence in the understanding of the driver speed perception and selection process as well as providing a viable data set to compare driver performance across multiple experimental mediums. The results lead the authors to the conclusion that certain types of speed-related research could be effectively examined in driving simulator and static environments.

The other study, *Driver Understanding of the Green Ball and Flashing Yellow Arrow Left-Turn Permitted Indications,* authored by Knodler focused on examining driver understanding of the green ball and flashing yellow arrow left-turn permitted indications (21). Here, both driving simulator studies and static evaluations were implemented to determine driver comprehension and behavior when exposed to the new

flashing yellow arrow signal display. These studies provide evidence that driver behavior research can be very valuable to the study of transportation.

Literature Review Summary

This literature review was not designed to be exhaustive, but rather to provide selective background information on the issues surrounding the presences of dilemma zones at signalized intersections. A consistent lexicon was provided for the term dilemma zone as well as a sampling of the previous research associated with the definition of the boundaries of the dilemma zone. It was also established that the work within this document will be focusing on the driver behavior and comprehension issues surrounding the Type II dilemma zone. The timing of yellow and all red intervals were discussed as well as the various vehicle detection strategies as both of these design features directly impact the presence of the dilemma zone. Both design characteristics were examined in terms of standards-of-practice as well as current research associated with these areas. Finally, past research was examined regarding driver behavior and comprehension studies.

CHAPTER III

EXPERIMENTAL DESIGN AND RESEARCH METHODOLOGY

A series of tasks has been developed to successfully meet and achieve each of the research hypotheses. Completing all of the evaluations associated with each of the three research hypotheses constituted a majority of the project tasks each of which consists of multiple subtasks.

Task 1: Review of the Literature

The initial task of the proposed research initiative is to conduct a substantial literature review. This review touched on current standards of practice, but primarily concentrated on the stream of academic research dealing with the dilemma zone. This task was initiated in the background section of this proposal and remained ongoing throughout the entire research process.

Task 2: Observe Driver Behavior at Onset of Solid Yellow Indication

Task 2 was developed to address research hypothesis 1, the results of which are presented in chapter 4. Task 2 addresses hypothesis 1 by more explicitly defining the impact of existing intersection characteristics on the frequency and potential severity of dilemma zone incursions experienced at a high-speed signalized intersection. The methodological approach included the following aspects:

- Experimental locations,

- Intersection inventories,
- Video data collection,
- Speed data collection, and
- Data reduction.

The inclusion of both speed and video data collection allowed for a more complete understanding of the dilemma zone influence because individual vehicle speed and position impact the potential for conflicts during clearance intervals.

As with many experiments that incorporate field observation, the identification of adequate experimental sites was of crucial importance. VTrans engineers led the selection of the test sites based upon their knowledge of the operational and safety characteristics of the Vermont state highway system. Both major approaches of the following intersections, located in the municipalities of Berlin and Rutland, were included in the experiment:

- Route 62 at Paine Turnpike (eastbound and westbound approaches),
- Route 62 at Airport Road (eastbound and westbound approaches),
- Route 62 at Berlin Road (eastbound and westbound approaches),
- Route 7 at North Shrewsbury Road (northbound and southbound approaches), and
- Route 7 at Route 103 (northbound and southbound approaches).

An intersection inventory was completed to help adequately describe some of the relevant geometric characteristics of each individual intersection approach. The results of

this inventory are shown in Table 1. Aspects such as horizontal and vertical curvature, grade, clear zones, adjacent land use, and presence of guard rails were all considered. By selecting intersection approaches with varying geometric characteristics, the impacts of those characteristics could be more readily determined.

Table 1 Geometric Characteristic of Test Site Intersection Approaches

Intersection Approach	Route 7 at				Route 62 at					
	N. Shrewsbury		Rte 103		Airport		Berlin		Paine Tpke	
	SB	NB	SB	NB	EB	WB	EB	WB	EB	WB
Horizontal Curvature	Y	N	N	N	N	Y	N	Y	N	N
Grade %	-0.5	+0.6	-0.5	+1.7	-4.0	+5.6	+0.4	-0.2	-0.9	+1.0
Presence of Guard Rails	Y	N	N	N	Y	Y	Y	N	N	N
Adjacent Land Use	Woods	Woods	Woods	Woods	Woods	Retail	Retail	Woods	Retail	Retail
Clear Zones	Y	Y	Y	Y	Y	N	N	N	N	N

An extensive data collection effort was conducted to capture video and speed data for a statistically significant sample of vehicles encountering dilemma zone conflicts on each of the 10 approaches examined. Speed data was collected on each intersection approach at the stop bar and at the advanced detector, but it was found that the most useful information was collected at the advanced detector. Due to the short term nature of the measurements (windows of approximately 48 to 72 hours) pneumatic tubes sensors were used. The data was collected on a per-vehicle basis to provide insight into individual vehicle behavior. Figure 12 shows a completed installation of an ATR in Berlin, VT.

Figure 12 Example of Typical ATR Installation

Observations of intersection operations and driver behavior were also conducted through the collection of video data. Cameras were unobtrusively mounted (15 to 20ft off the ground) on a variety of fixed structures (500 to 600ft back from the stop bar) near the roadside. The cameras were oriented to face towards the signal heads on each major intersection approach. This system allowed for the clear identification of vehicle position and signal phase from a single location for a period of up to 4hrs between tape changes. Figure 13 depicts the installation of one such camera setup.

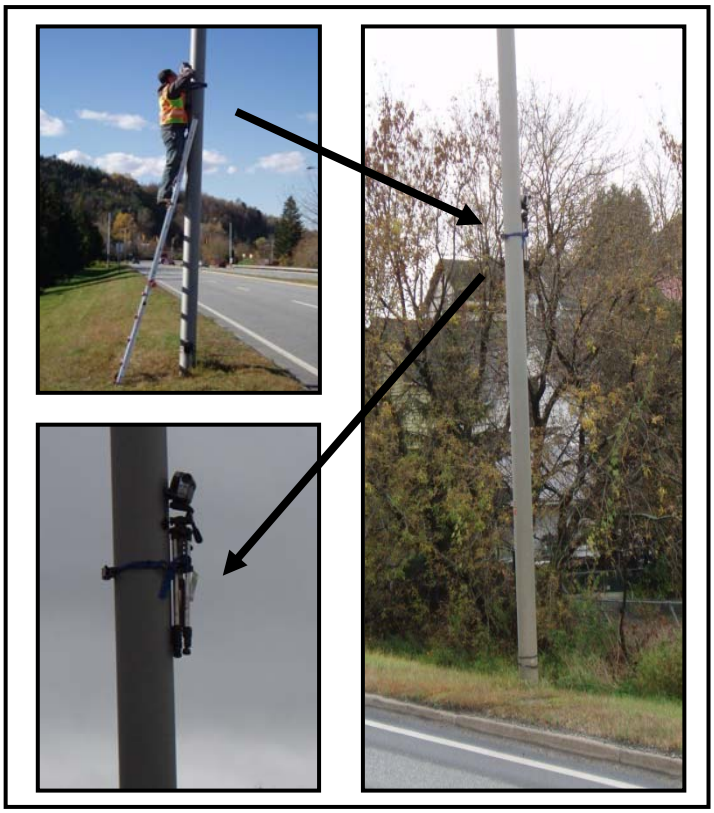

Figure 13 Example of Typical Video Camera Installation

In order to effectively use the 8mm video tapes to accurately identify the position of the vehicle at the onset of the solid yellow indication, the tapes were digitized and measurement points were transposed onto the digital files. The video camera was connected to a computer via a Pinnacle © device interface, which allowed for the captured video to be copied into a digital format onto the computer. The digital copy was then played using Windows Media Player © to help determine the individual 50 ft intervals to be marked on the intersection approaches. Screenshots from the film were taken at moments where the interval borders were indicated on the film. These screenshots were then imported into Photoshop © where the interval borders were marked by horizontal lines across the road. The colors used to indicate the interval borders were red or yellow, depending on the lighting, time of day, and the brightness of

the film. Once the interval borders were marked, the lines were exported as a PNG image file. This format allowed for the now defined intervals to be overlaid on top of a video. Sony Movie Studio was used to import and merge the digital film and the PNG file. Corrections to the location of the zone borders were needed since there was an alignment issue once the film and image were imported. Adjustments to the PNG file were made with Photoshop and once again imported with Sony Movie Studio. The Sony software exported the film as a Quicktime © video file which was then used in the dilemma zone and driver behavior analysis. Figure 14 shows a still frame of a completed digital video file overlaid with 50 ft intervals extending back from the stop bar for several hundred feet.

Figure 14 Digitized Video with Measurement Zones

Once the 8mm video tapes were digitized with the measurement zones in place, they were burned to CDs so that multiple researchers were able to reduce the data into Excel © spreadsheets simultaneously. A team of trained researchers, and collaborated on the reduction of the overall database. As a part of the training component, researchers

reviewed the same video file to ensure consistent results across researchers. In addition, random files were watched by multiple researchers in an effort to ensure consistency and validation of the research findings. A sample of this reduced data is displayed in Figure 15.

Number	Time of Yellow Onset			Car in Queue				Vehicle location at Time of Yellow Onset								Reaction		
	Hr	Min	Sec	1	2	3	4	0 to 50	50 to 100	100 to 150	150 to 200	200 to 250	250 to 300	300 to 350	350 to 400	Stop	Run Yellow	Run Red
1	7	29	51	1							1					1		
2	7	29	51		1									1		1		
3	7	30	49	1				1									1	
4	7	30	49	1					1								1	
5	7	30	49	2								1				1		
6	7	32	38	1								1				1		
7	7	32	38		1										1	1		
8	7	34	47	1				1									1	
9	7	39	53	1											1	1		
10	7	40	44	1					1								1	
11	7	45	22	1				1									1	
12	7	47	57	1					1								1	
13	7	47	57	1								1				1		
14	7	49	45	1					1								1	
15	7	50	46	1						1							1	
16	7	51	47	1				1									1	
17	7	54	55	1							1					1		
18	7	58	21	1								1				1		

Figure 15 Reduced Naturalistic Study Data

The compiled data set was then used for further analysis. This analysis is described in Chapter 4.

Task 3: Compare Dilemma Zone Protection Provided by Point and Space Sensors

Task 3 was developed to address research hypothesis 2, the results of which are presented in chapter 5. This research initiative attempted to quantify the differences between the advanced detection provided by in-pavement inductive loops and the SmartSensor Advance © in mitigating dilemma zone conflicts at high-speed state owned signalized intersections. One such high-speed signalized intersection was identified in Clarendon, Vermont, as having both the requisite safety related issues, and viable

infrastructure to allow for the successful retrofitting of the SmartSensor Advance. Dilemma zone incursions were observed during the use of advanced detection via inductive loops and with the SmartSensor Advance. Video observations measuring 8 hours in duration were collected under each condition. A comparison was made between the types and frequency of dilemma zone incursions during both conditions. This research provides additional support for the use of advanced sensor technology in order to minimize the likelihood of dilemma zone incursions at high-speed signalized intersections.

Several design and operational strategies are currently implemented by VTrans to promote the safe and efficient operation of state-owned high-speed signalized intersections. The signal timings used at these intersections include change and clearance intervals. The lengths of these intervals are applied constantly across intersections of similar functional classification in close proximity to one another. In addition to timing practices which provide drivers with a warning of an impending switch of the right of way and an all red phase to clear the intersection of potential conflicting vehicles Vermont commonly uses advanced vehicle detection.

VTrans uses in-pavement inductive magnetic loop detectors at the stop bar and approximately 200ft in advance of the stop bar. These point sensors allow for vehicles to be detected in advance of the signal and allow for extensions of 2 seconds to be added to the mainline green time, to allow for vehicles to safely continue though the intersection prior to conflicting movements being release into the intersection.

The identification of an adequate experimental site was of crucial importance. Highway Tech, a regional provider of traffic signal technology, led the selection of the

test site based on their knowledge of the operational requirements of the Wavetronix Technology. For the purposes of this evaluation a single intersection approach (the northbound approach of Route 7 at Route 103) was selected in Clarendon, Vermont. The major road (Route 7) oriented in the north/south direction intersects the minor road (Route 103) oriented in the east/west direction to form a four-way fully-actuated signalized intersection. Route 7 is a median divided state-owned roadway. Its northbound approach includes an exclusive left turn lane, two through lanes, and an exclusive right turn lane. Each lane is 12 ft wide. The left shoulder is 2 ft wide and the right shoulder is 11 ft wide. Figure 16 displays an image of the aforementioned intersection approach.

Figure 16 Rte 7 at Rte 103 Northbound Approach

The exceptionally large mast arms supporting the signal heads provided a location for the sensor to be mounted such that it was in the center of the approaching through lanes. The northbound approach has limited horizontal curvature with no obstructions,

which allowed for the sensor to work effectively and the approach to be observed via video. Figure 17 displays the installation of the sensor.

Figure 17 Installation of the SmartSensor in Vermont

Once the sensor was installed on the mast-arm and the cable was run through the cantilever into the traffic signal cabinet, its operational configuration had to be established. This was achieved by connecting the SmartSensor hardware in the traffic signal cabinet to a laptop based software program.

Figure 18 is an image of the SmartSensor Software program connected to the sensor hardware in the traffic cabinet.

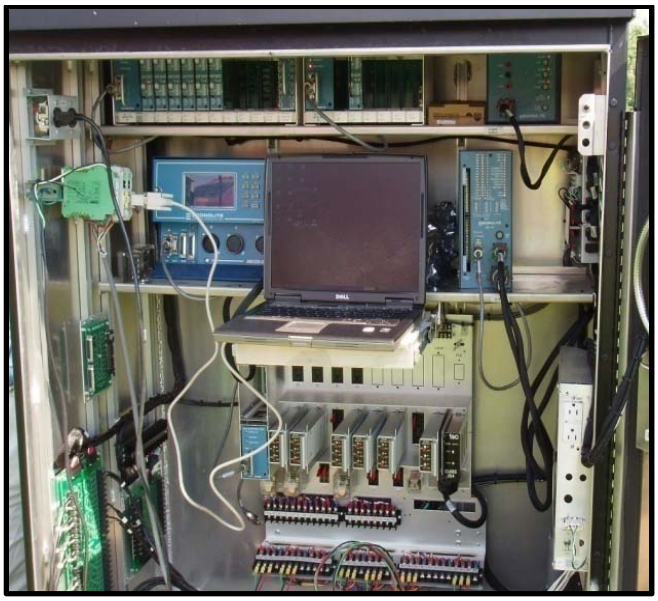

Figure 18 SmartSensor Configuration in Traffic Cabinet

SmartSensor Advance uses digital wave radar technology to provide continuous detection up to 500 ft away from the sensor head, resulting in about 400 ft continuous detection back from the stop bar. Figure 19 depicts the threshold for vehicle detection and the type of information recorded for each vehicle observation. The real time view depicts that the sensor is detecting vehicles approximately 500ft out (400ft from the stop bar). The 3-D view shows that the time and distance from the stop bar as well as the current speed of all approaching vehicles is being detected.

Figure 19 Image of SmartSensor Vehicle Detection

The sensor was configured for the purpose of monitoring stop bar arrival time detection. This allows for time, speed, and distance to be observed on a per vehicle basis every five milliseconds. The sensor system has the capability to extend the green time to any vehicle which is predicted to be caught in a Type II dilemma zone based on their position and speed at the time the yellow indication would be activated.

Based on this information an astute observer may ask, “how is the dilemma zone” defined within the construct of this system? The SmartSensor operates on a time to stop bar definition for the dilemma zone. The boundaries can be manually defined for the beginning and end of the dilemma zone as well as identifying minimum and maximum allowable speeds for an individual vehicle to be considered as encountering a dilemma zone. Figure 20 provides an example of a manually established dilemma zone boundary of 2.5 to 5.5 seconds to the stop bar, with the caveat that the vehicle must be traveling between 35 and 100 mph.

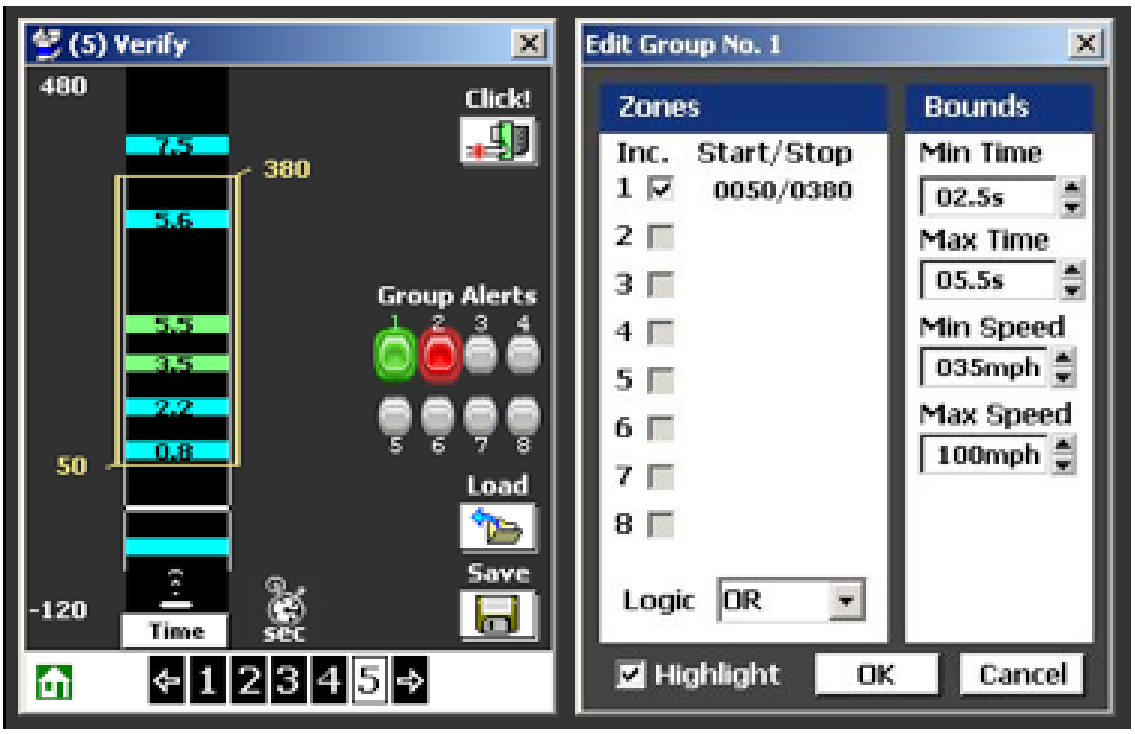

Figure 20 Manually Established Thresholds for Dilemma Zone

The methodology of the video observation conducted in the SmartSensor Advance field trial was similar to that described in Task 2 used to identify the dilemma zone conflicts that exist under the current change interval timings and inductive loop advance sensors used in Vermont.

Task 4: Determine Driver Comprehension of Solid Yellow Indication

Task 4 was developed to address research hypothesis 3, the results of which are presented in chapter 6. Task 4 was completed with the implementation of a large scale static evaluation. The study was aimed at evaluating the degree to which drivers comprehend the intended meaning of the solid yellow indication, and what if any impact

that comprehension had on drivers' predicted behavior when approaching high-speed signalized intersections.

The first section of the evaluation focused primarily on driver comprehension of the solid yellow indication. Here comprehension was examined in terms of the following 3 distinct dimensions:

- Do drivers understand the message being conveyed,
- Do drivers know what signal display comes next in the sequence, and
- Can drivers approximate the typical duration of yellow indications.

Figure 21 is an example of a comprehension question examining the drivers understanding of the message being conveyed by a circular yellow indication in a 5 section cluster.

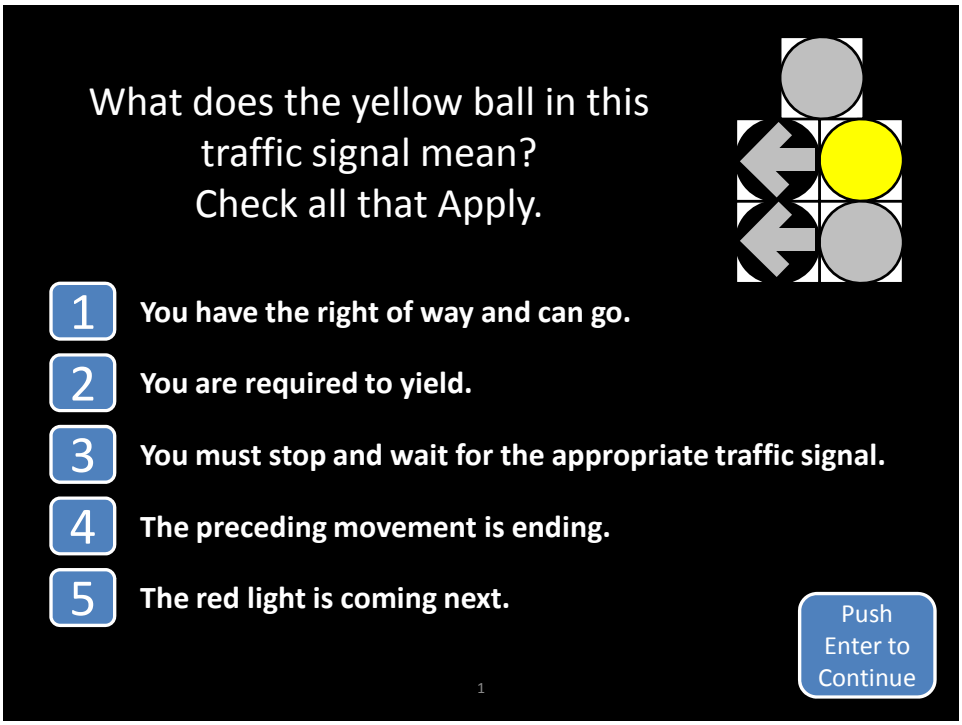

Figure 21 Example of a Computer-Based Predictive Behavior Evaluation Scenario

The second component of the static evaluation concentrated on the predictive behavior of divers when provided an image taken from a vehicle approaching a signalized intersection. The following three variables were examined as to their impact on predictive driver behavior:

- Number of approach lanes (one or two lane approaches),
- Approximate distance from the stop bar (near, mid and far), and
- Vehicle position in the approaching platoon (lead or following vehicle).

Figure 22 provides an example of a predictive behavior scenario depicting a lead vehicle on a single lane approach near the stop bar.

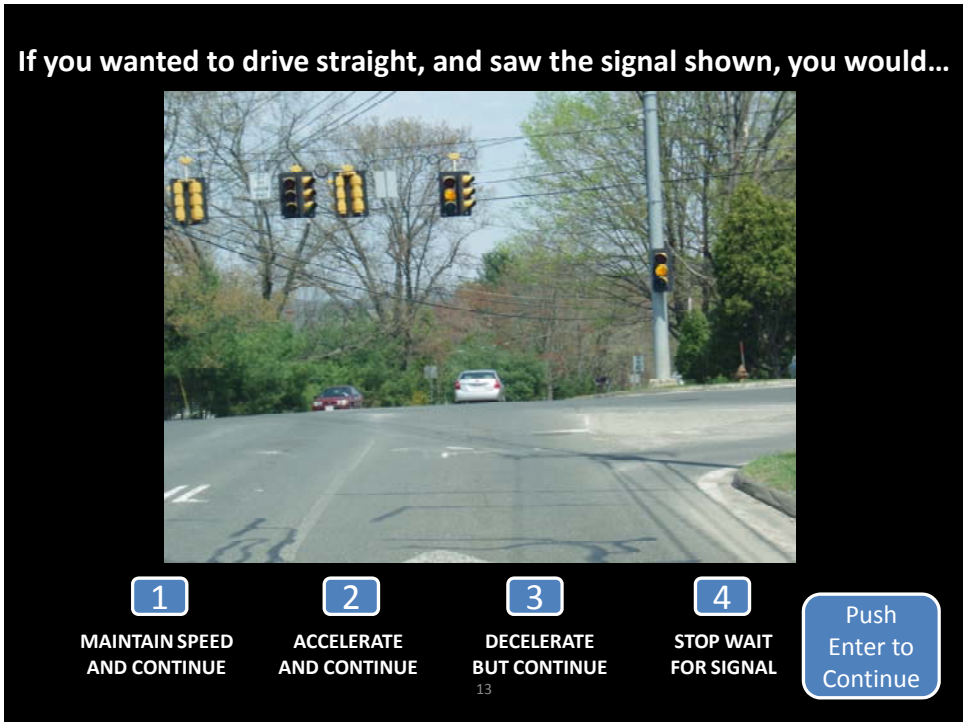

Figure 22 Example of a Computer-Based Predictive Behavior Evaluation Scenario

The static evaluations were administered via computer monitors and the scenarios were counterbalanced to minimize the potential for confounding errors. Once the data was collected it was transcribed into a spreadsheet application so that further analysis could be conducted.

Task 5: Documentation of Findings

The results of the previous tasks were documented as a doctoral dissertation in accordance with the University of Massachusetts Amherst Policy and Guidelines (22).

CHAPTER IV

DRIVER INTERACTION WITH SOLID YELLOW INDICAITONS AT HIGH-SPEED SIGNALIZED INTERSECTIONS: A NATURALISTIC STUDY

Chapter 4 presents the results which were collected in Task 2 to address the first research hypothesis, *"Type II dilemma zone boundaries can be identified from observed driver behavior (stop/go action when exposed to the solid yellow indication), vehicle speed, and vehicle position for isolated at-grade high-speed signalized."* The naturalistic field experiment included the observation of traffic signal operation, vehicle approach speeds, and resulting driver behavior. This section describes the information that was garnered from this effort.

Speed Data Results

Per vehicle speed data was collected on each of the 10 mainline intersection approaches. Data was collected for three 24 hour periods (midnight to midnight) at each location. The observations were reduced and descriptive statistics such as the mean speed, 85th, and 95th percentile speeds, as well as variance and standard deviation were calculated. Some of these calculated values are displayed in Table 2 for each intersection approach. The 85th percentile speeds on Route 7 ranged from 56 mph to 60 mph while the 85th percentile speeds on Route 62 ranged from 39 mph to 51 mph. These observations confirm that the intersections were appropriately identified as high-speed signalized intersections.

Table 2 Vehicle Approach Speeds & ADT Observed at Advanced Detector

Approach Speed	Route 7 at				Route 62 at					
	North Shrewsbury		Rte 103		Airport		Berlin		Paine Tpke	
	SB	NB	SB	NB	EB	WB	EB	WB	EB	WB
Mean	50	40	46	50	37	39	40	35	42	40
85th Percentile	59	56	57	60	46	46	48	45	51	49
95th Percentile	64	62	61	65	50	50	52	50	56	54
Speed Limit	55	55	55	55	50	50	45	45	50	50
ADTs	7458	7440	6662	3840	7396	8773	6958	5400	7120	8434

Once the speed data was reduced, different critical speed values (i.e., posted speed, mean speed, 85th and 95th percentile speeds) were inserted into the approach speed variable of the ITE change interval equation to determine the sensitivity of the predicted change interval duration to the selected approach speed. The results of this sensitivity analysis are displayed in Table 3. The ITE equation generated change interval lengths along Route 7 ranging from 3.88 seconds to 5.77 seconds, while the Route 62 change interval lengths ran from 3.42 seconds to 5.23 seconds.

Table 3 Existing and Calculated (ITE) Change Interval in seconds

Yellow time calculated with	Route 7 at				Route 62 at					
	North Shrewsbury		Rte 103		Airport		Berlin		Paine Tpke	
	SB	NB	SB	NB	EB	WB	EB	WB	EB	WB
Mean	4.73	3.88	4.43	4.48	4.11	3.42	3.90	3.58	4.17	3.84
85th Percentile	5.40	5.03	5.25	5.17	4.87	3.86	4.48	4.32	4.85	4.48
95th Percentile	5.77	5.46	5.55	5.52	5.21	4.11	4.76	4.69	5.23	4.84
Speed Limit	5.10	4.96	5.10	4.82	5.21	4.11	4.26	4.32	4.78	4.55
Existing	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.5	4.0	4.0

With the ITE recommended change interval lengths calculated in seconds, it was possible to calculate the distance that a particular vehicle could travel at a particular speed during the time allocated to the change interval. Table 4 demonstrates that as the length of yellow indication or the speed of the vehicle increases the potential distance traveled by the vehicle also increases. The longest potential distance traversed was 526 feet and was observed on the northbound approach to the intersection of Route 7 and Route 103.

Table 4 ITE Distance (Feet) Traveled During ITE Calculated Change Interval

Yellow time calculated with	Route 7 at				Route 62 at					
	North Shrewsbury		Rte 103		Airport		Berlin		Paine Tpke	
	SB	NB	SB	NB	EB	WB	EB	WB	EB	WB
Mean	347	227	299	328	223	196	229	184	257	225
85th Percentile	467	413	439	455	329	260	315	285	363	322
95th Percentile	542	497	496	526	382	301	363	344	429	383
Speed Limit	411	400	411	389	382	301	281	285	350	334

The impact of approach speed on the position of the Type II dilemma zone was also considered as an important component to the evaluation of the dilemma zone conflicts at each intersection approach. Table 5 presents a sensitivity analysis whereby several different critical speeds were used to calculate the position of the Type II dilemma zone for each intersection approach, based on the time to stop bar definition of 2.5 to 5.5 seconds.

Table 5 Impact of Approach Speed on DZ Boundaries (Feet from Stop Bar)

Type II DZ Calculated with	Route 7 at				Route 62 at					
	North Shrewsbury		Rte 103		Airport		Berlin		Paine Tpke	
	SB	NB	SB	NB	EB	WB	EB	WB	EB	WB
Mean	183 to 403	147 to 323	169 to 371	183 to 403	136 to 298	143 to 315	147 to 323	128 to 282	154 to 339	147 to 323
85th Percentile	216 to 476	205 to 452	209 to 460	220 to 484	169 to 371	169 to 371	176 to 387	165 to 363	187 to 411	216 to 476
95th Percentile	235 to 516	227 to 500	224 to 492	238 to 524	183 to 403	183 to 403	191 to 403	183 to 403	205 to 452	198 to 436
Speed Limit	202 to 444	202 to 444	202 to 444	202 to 444	183 to 403	183 to 403	165 to 363	165 to 363	183 to 403	183 to 403

In order to select an appropriate input speed for the definition of the Type II dilemma zone boundary, the sensitivity analysis displayed in Table 5 was examined in comparison with the evidence provided in Figure 23. As shown the application of 4 different critical speeds were used to calculate the traditionally accepted Type II dilemma zone. Based upon the consistency of driver decision making difficulty with the region generated with the 85th percentile speed, the 85th percentile speed was selected as the relevant approach speed for the calculation of the dilemma zone position.

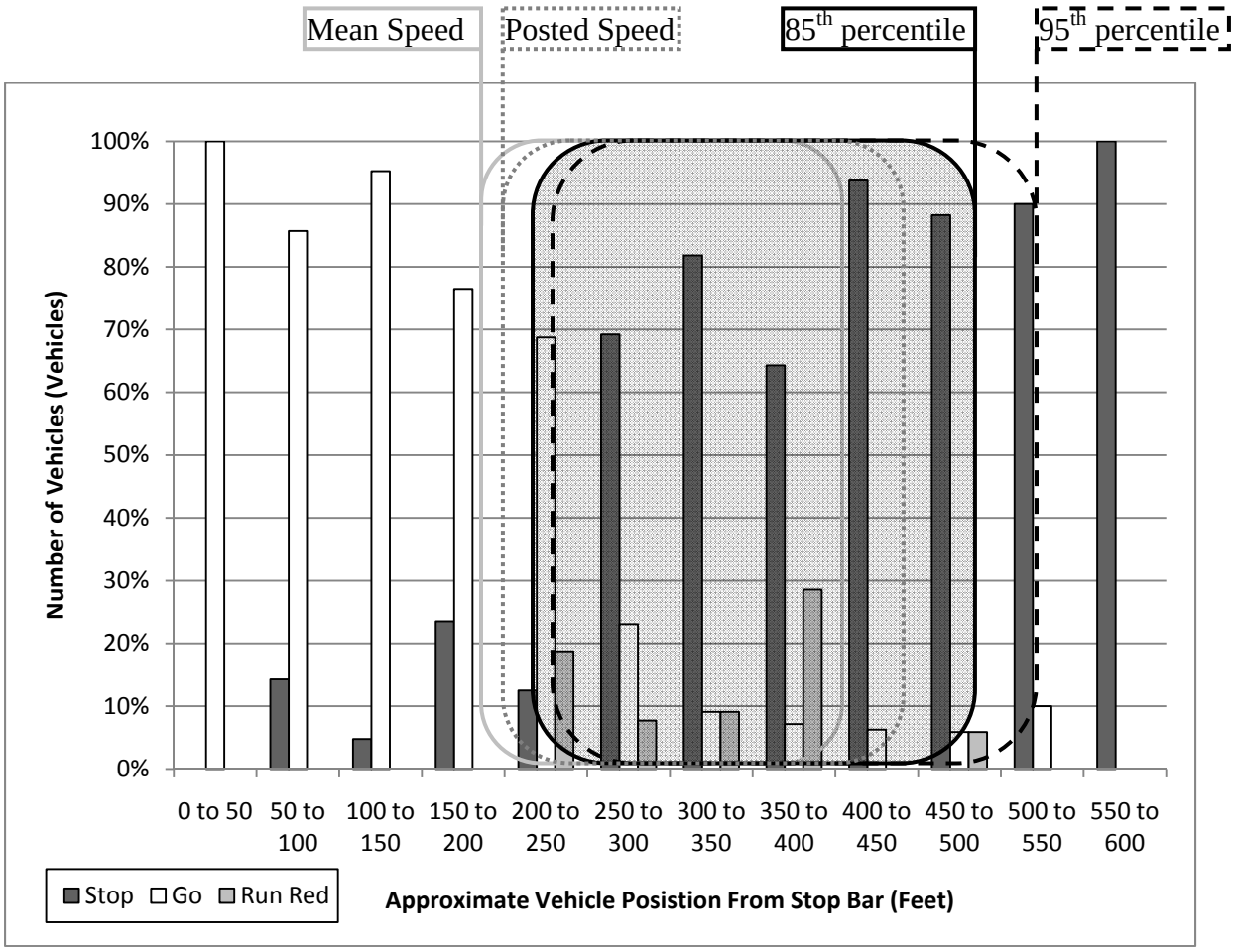

Figure 23 Influence of Selected Approach Speed on Type II DZ Boundaries

Once a determination was made on the appropriate approach speed for the calculation of the Type II dilemma zone position, the driver behaviors were considered in more detail.

Individual Intersection Approach Observations

Approximately 510 hours of video-taped observation were collected across all 10 high-speed intersection approaches. Of this 510 hour sample approximately 75 hours of video was reduced representing approximately 15 percent of the overall sample.

Table 6 shows the breakdown of tape hours collected to tape hours transcribed for each approach.

Table 6 Summary of Video Collected & Reduced Video Observations

Intersection Approach	Route 7 at				Route 62 at						Total
	N. Shrewsbury		Rte 103		Airport		Berlin		Paine Tpke		
	SB	NB[a]	SB	NB	EB	WB	EB	WB	EB	WB	
Hours Observed	52	52	52	48	56	52	64	64	32	36	508
Hours Transcribed	13	1	11	8.5	5	3.5	8	9.5	4.2	10.5	74.2
Percent Transcribed	25.0	1.9	21.2	17.7	8.9	6.7	12.5	14.8	13.1	29.2	14.6

[a] The (NB) approach of N. Shrewsbury at route 7 was eliminated from further analysis due to the quality of the video captured resulting from limitations of the approach geometry and the existing infrastructure.

The 75 hours of reduced observation yielded a sample size of approximately 1,900 vehicles which experienced an incursion with the change interval while approaching one of the signalized intersections from either direction on the main line.

The graphs displayed in Figure 24 through Figure 32 attempt to provide a visual model for presenting the relative position and driver action of vehicles at the onset of the solid yellow indication for each individual intersection approaches. These figures were also used to describe the nature of any existing dilemma zones issues for the observed approaches. The vertical axis measures the percent of vehicles performing one of three possible actions (stop on yellow, go on yellow, go on red), while the horizontal axis describes the distance from the stop bar of each individual vehicle at the onset of the solid yellow indication in 50 foot intervals. In addition to the driver behavior and vehicle position information, the Type II dilemma zone region (2.5 sec to 5.5 sec time to stop bar definition) is identified in grey for each individual graph. The Type II boundaries were established by applying the 85th percentile speed.

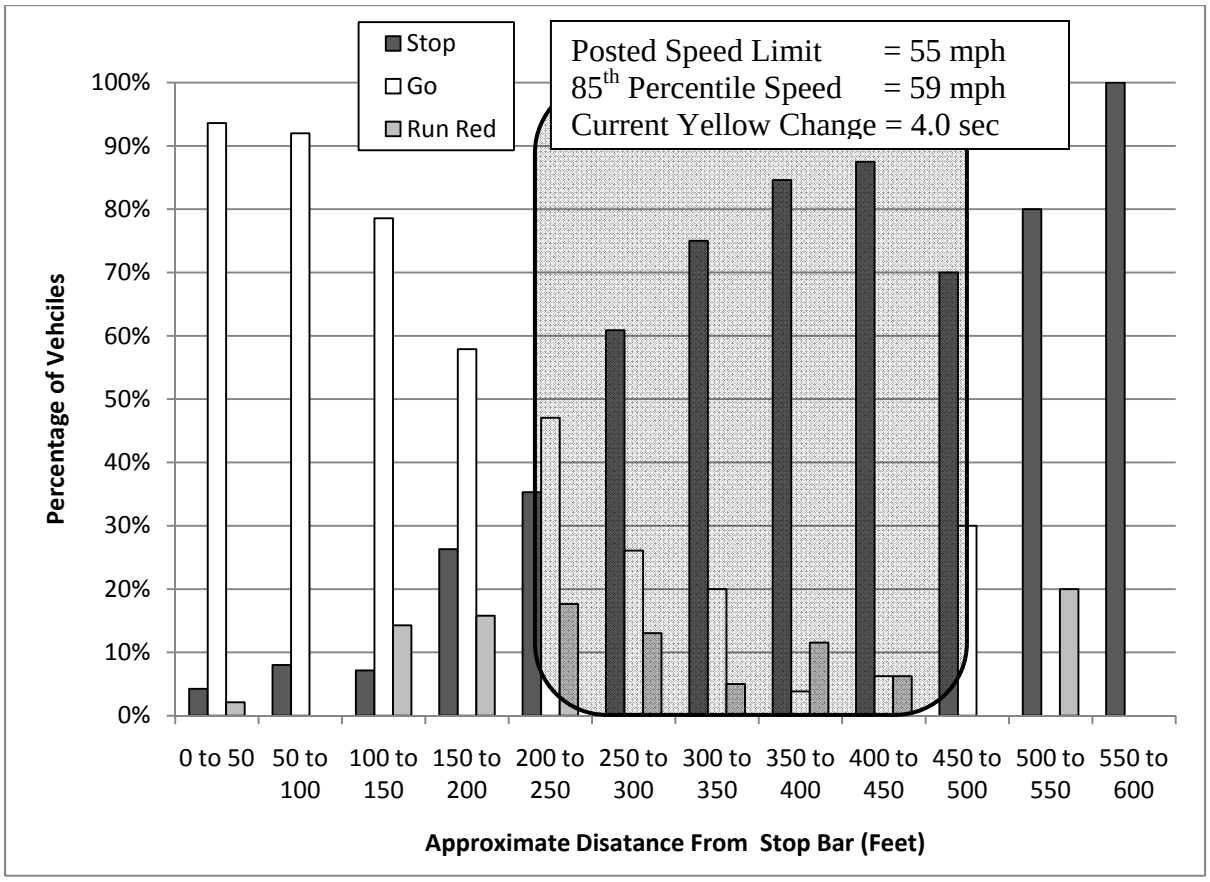

Figure 24 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication North Shrewsbury @ Route 7 (Southbound Approach)

In Figure 24, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the more likely it will be to enter the intersection. It does appear that there may be a larger than expected tendency for drivers to run the red light from the 500 to 550 ft back from the stop bar. Based on the 85th percentile speed of 59 mph, the predicted dilemma zone region exists between 216 feet to 476 feet. This region seems to correlate relatively nicely with the presence of increased percentages of red light running. Although it seems that there is some RLR in the 100 to 200 ft region, this trend is not captured. The current

change interval is programmed to last 4.0 seconds in duration, however the ITE equation predicts yellow time duration of approximately 5.4 seconds in duration.

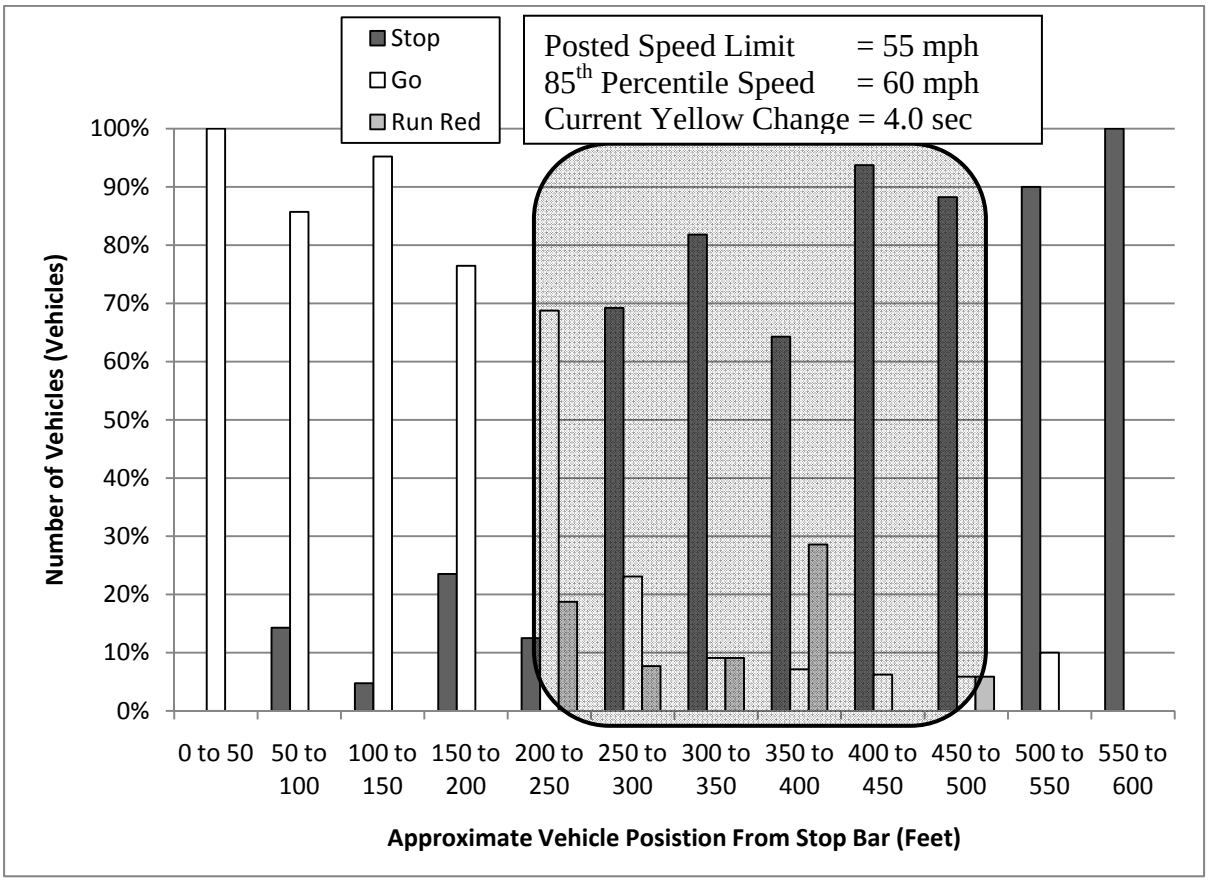

Figure 25 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Route 103 @ Route 7 (Northbound Approach)

In Figure 25, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the more likely it will be to enter the intersection. Based on the 85th percentile speed of 60 mph, the predicted dilemma zone region exists between 205 feet to 452 feet. This region seems to correlate relatively nicely with the presence of increased percentages of red light running. The current change interval is programmed to last 4.0 seconds in duration.

However, the ITE equation predicts yellow time duration of approximately 5.0 seconds in duration.

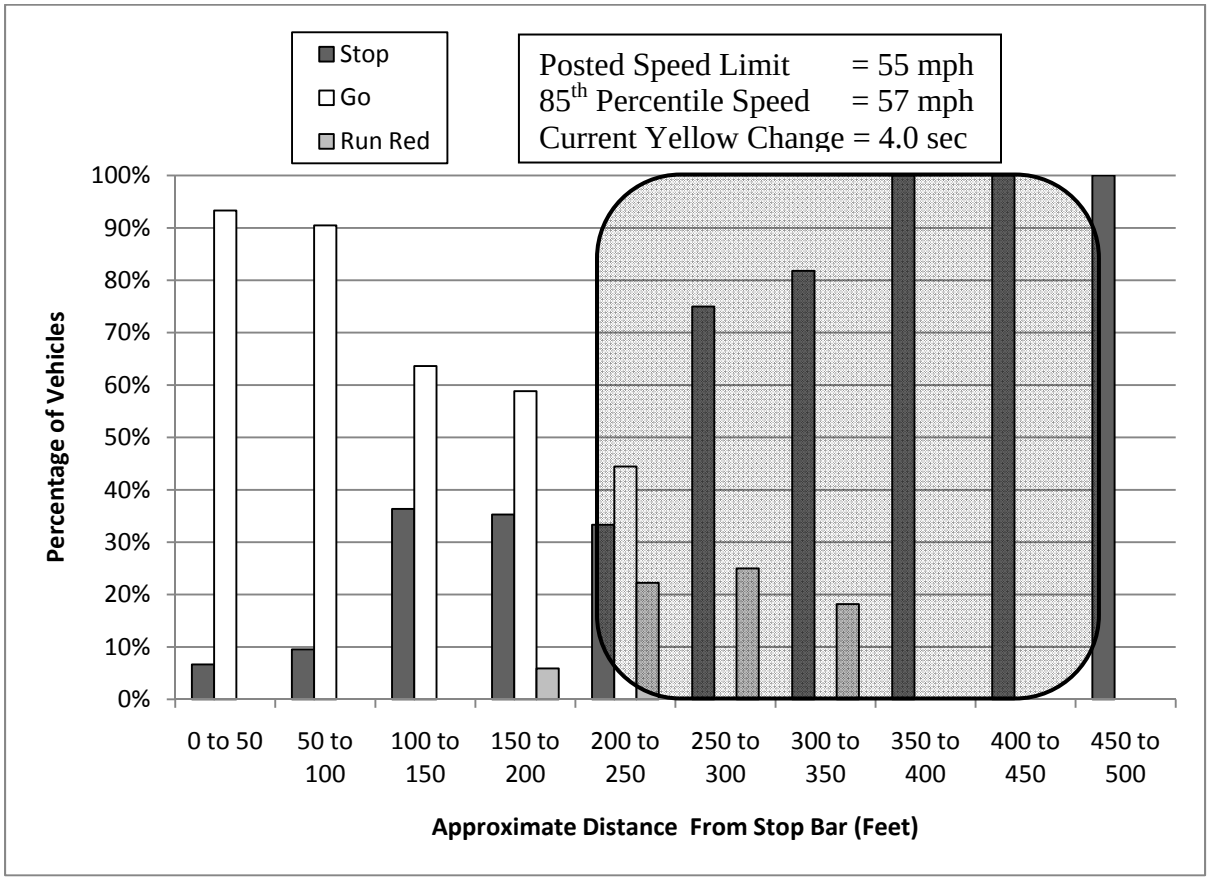

Figure 26 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Route 103 @ Route 7 (Southbound Approach)

In Figure 26, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the more likely it will be to enter the intersection. Based on the 85th percentile speed of 57 mph, the predicted dilemma zone region exists between 209 feet to 460 feet. This region seems to correlate with the presence of increased percentages of red light running, although it seems that there is some RLR in the 150 to 200 ft region that is not captured.

It also seems that the last hundred feet or so may be incorrectly identified as being within the dilemma zone due to the very high tendency of drivers to stop. The current change interval is programmed to last 4.0 seconds in duration, however the ITE equation predicts yellow time duration of approximately 5.25 seconds in duration.

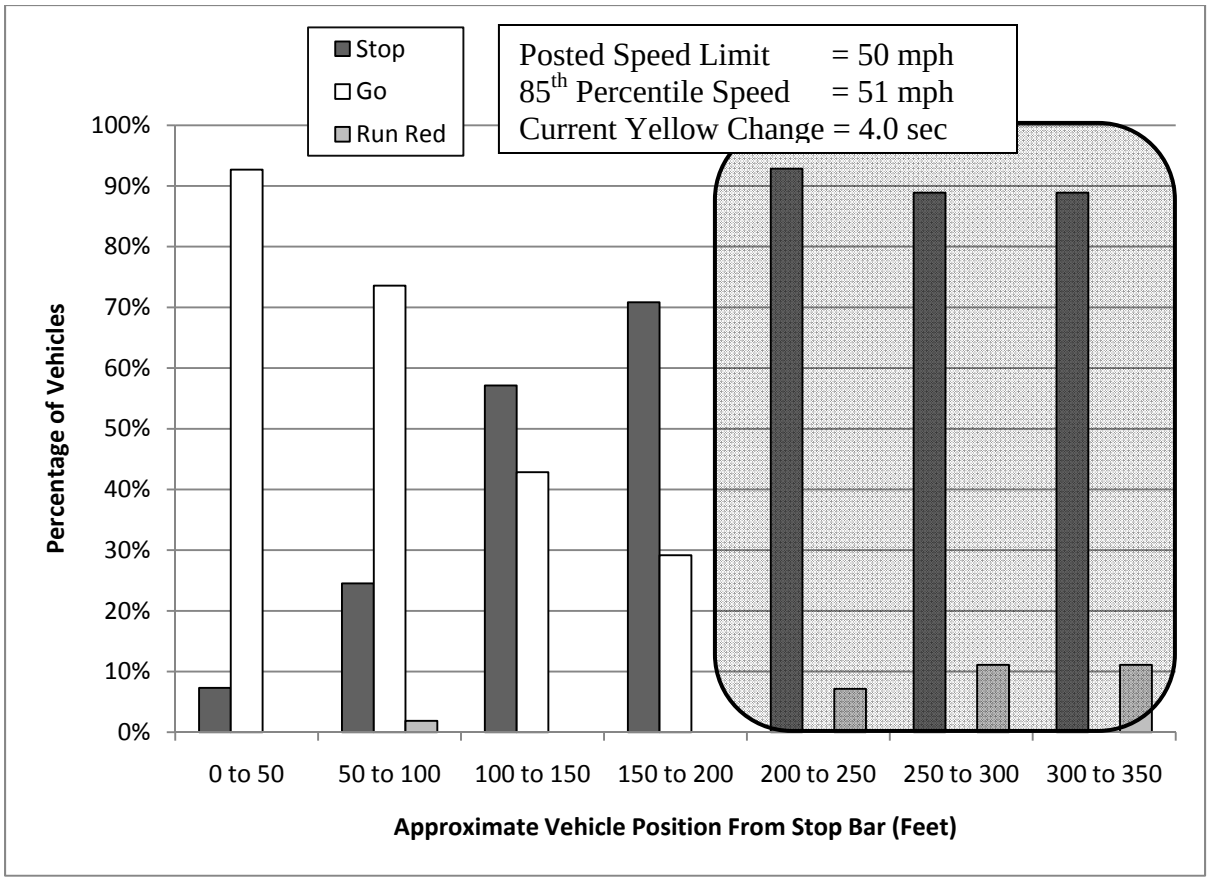

Figure 27 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Paine Turnpike @ Route 62 (Eastbound Approach)

In Figure 27, again, the overall trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the more likely it will be to enter the intersection. Based upon the 85th percentile speed of 51 mph, the predicted dilemma zone region exists between 187 feet to

411 feet. Due to the constraints of the fixed locations of infrastructure at the roadside, the observation of this approach was limited to 350 feet causing the loss of about 100 feet of desired observations. In addition, this region seems to contain an increased percentage of red light running. The current change interval is programmed to last 4.0 seconds in duration. However, the ITE equation predicts yellow time duration of approximately 4.85 seconds in duration.

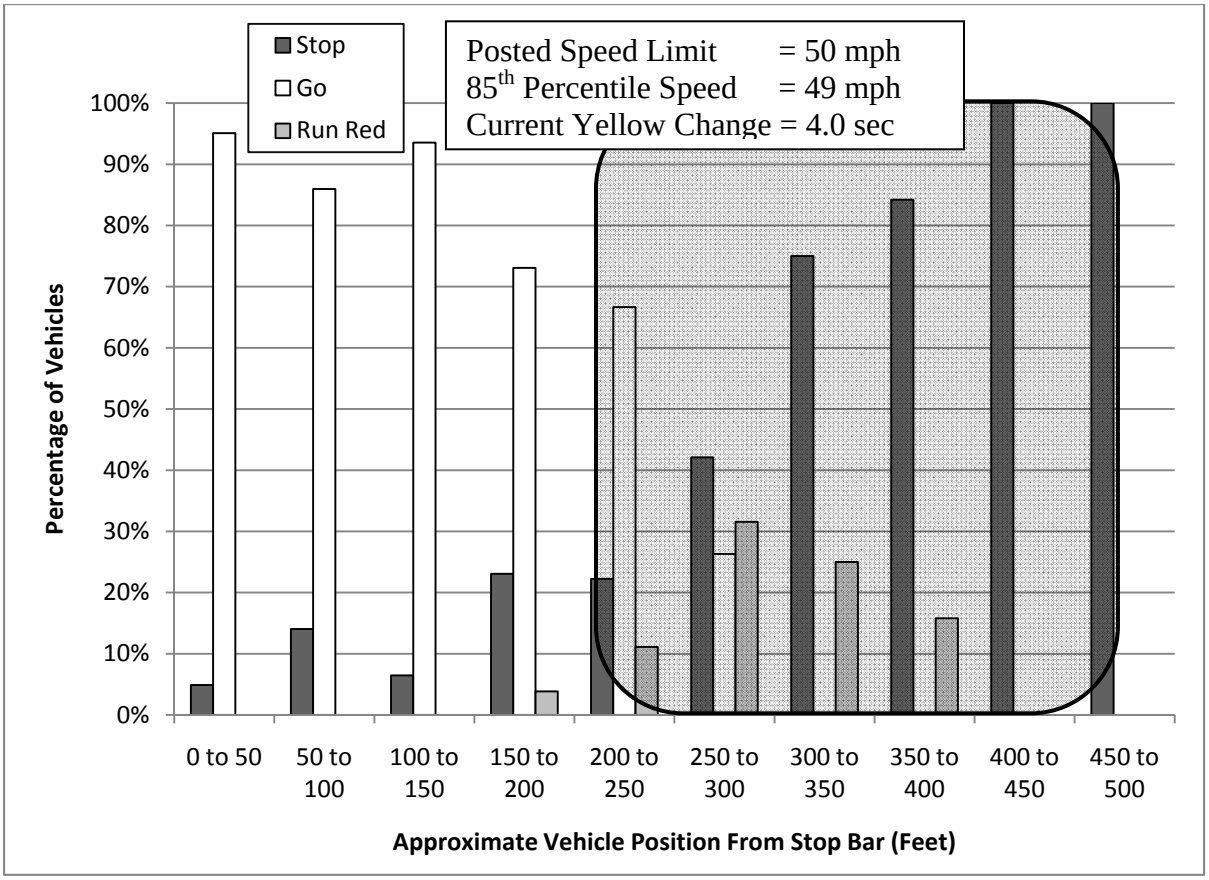

Figure 28 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Paine Turnpike @ Route 62 (Westbound Approach)

In Figure 28, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the

more likely it will be to enter the intersection. Based on the 85th percentile speed of 51 mph, the predicted dilemma zone region exists between 216 feet to 476 feet. Furthermore, according to the data, this region exhibits an increased percentage of RLR. The current change interval is programmed to last 4.0 seconds in duration. However, the ITE equation predicts yellow time duration of approximately 4.48 seconds in duration.

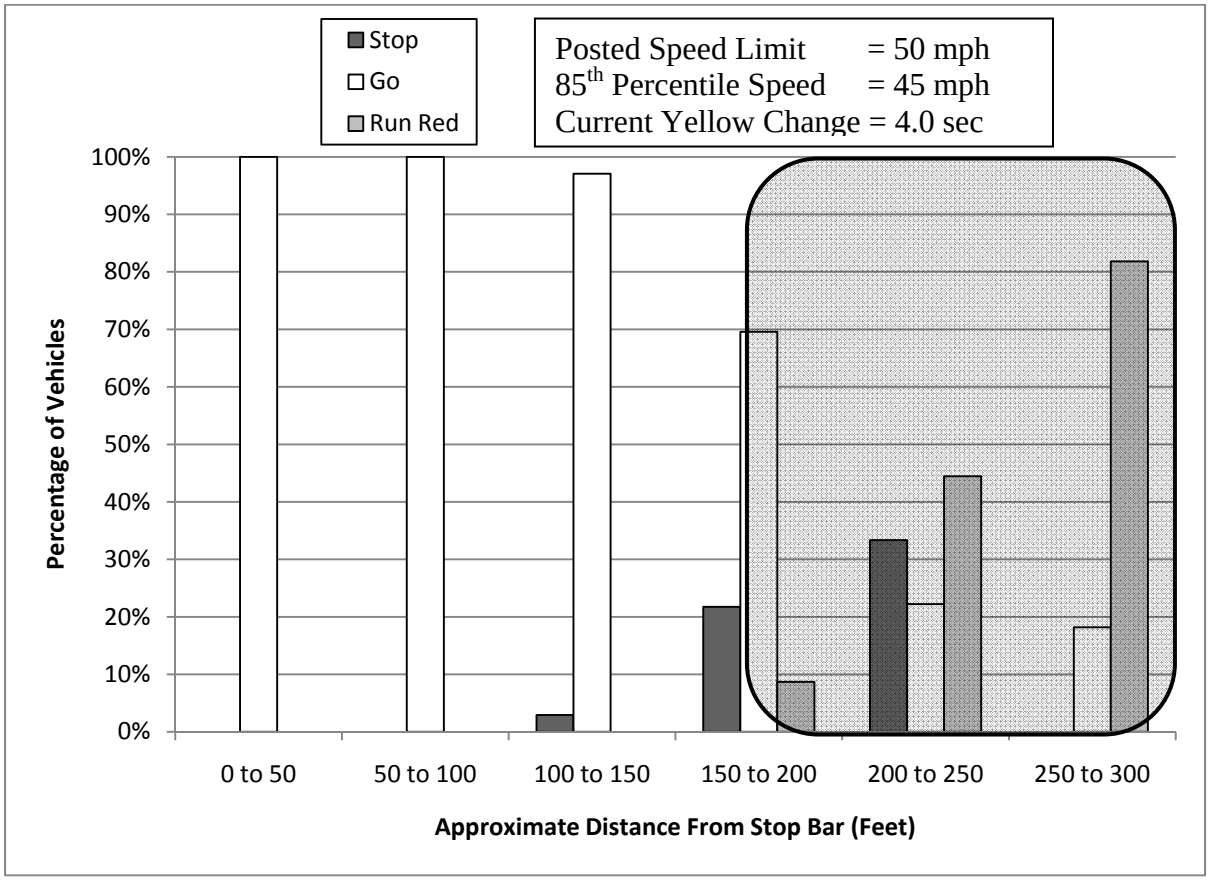

Figure 29 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Airport Road @ Route 62 (Eastbound Approach)

In Figure 29, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the more likely it will be to enter the intersection. Based on the 85th percentile speed of 45

mph, the predicted dilemma zone region exists between 169 feet to 371 feet. Due to the constraints of the fixed locations of infrastructure at the roadside the observation of this approach was limited to 300 feet causing the loss of about 100 feet of desired observations. Additionally, this region captures all of the recorded RLR. The current change interval is programmed to last 4.0 seconds in duration. However, the ITE equation predicts yellow time duration of approximately 4.87 seconds in duration.

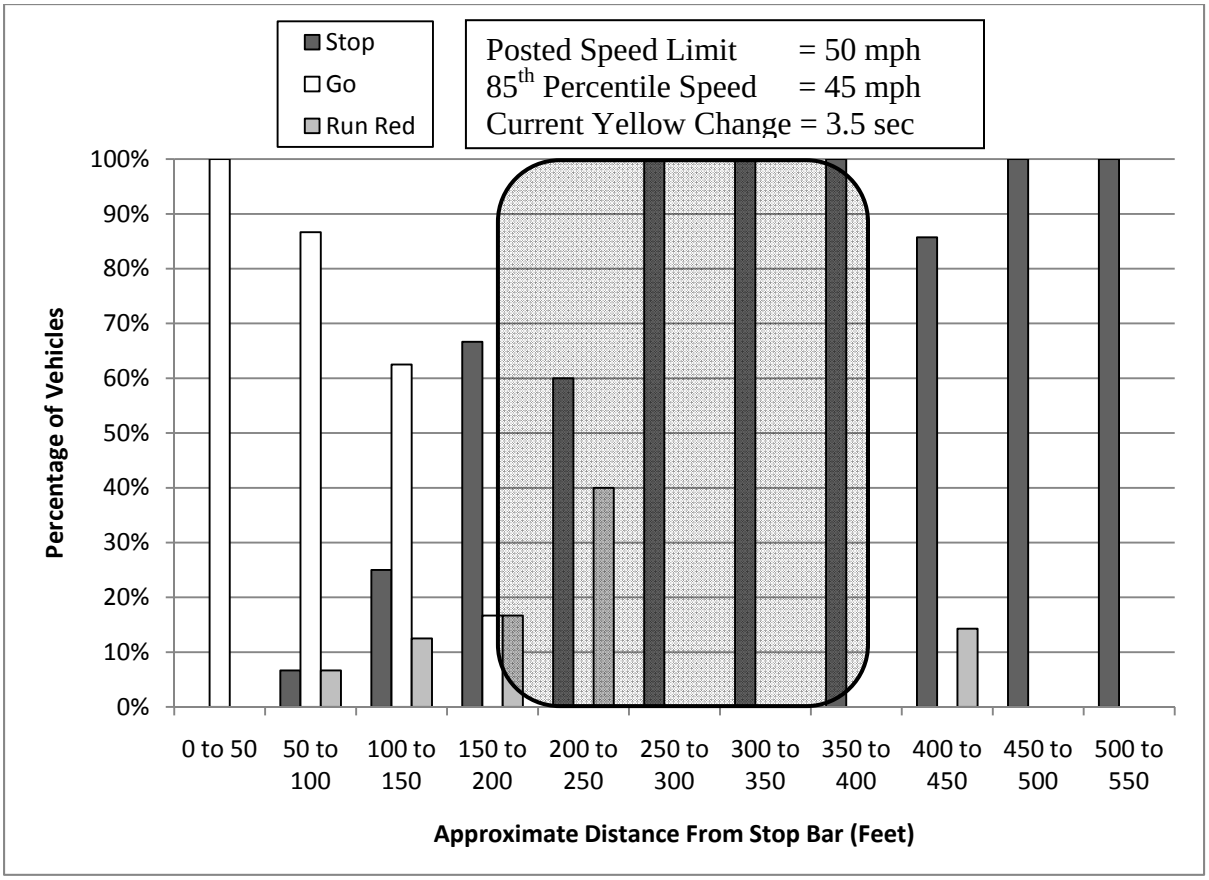

Figure 30 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Airport Road @ Route 62 (Westbound Approach)

In Figure 30, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the

more likely it will be to enter the intersection. Based on the 85th percentile speed of 45 mph, the predicted dilemma zone region exists between 169 feet to 371 feet. Similar to some of the previous figures, this region contains an increased percentage of RLR. The current change interval is programmed to last 4.0 seconds in duration. However, the ITE equation predicts yellow time duration of approximately 3.86 seconds in duration.

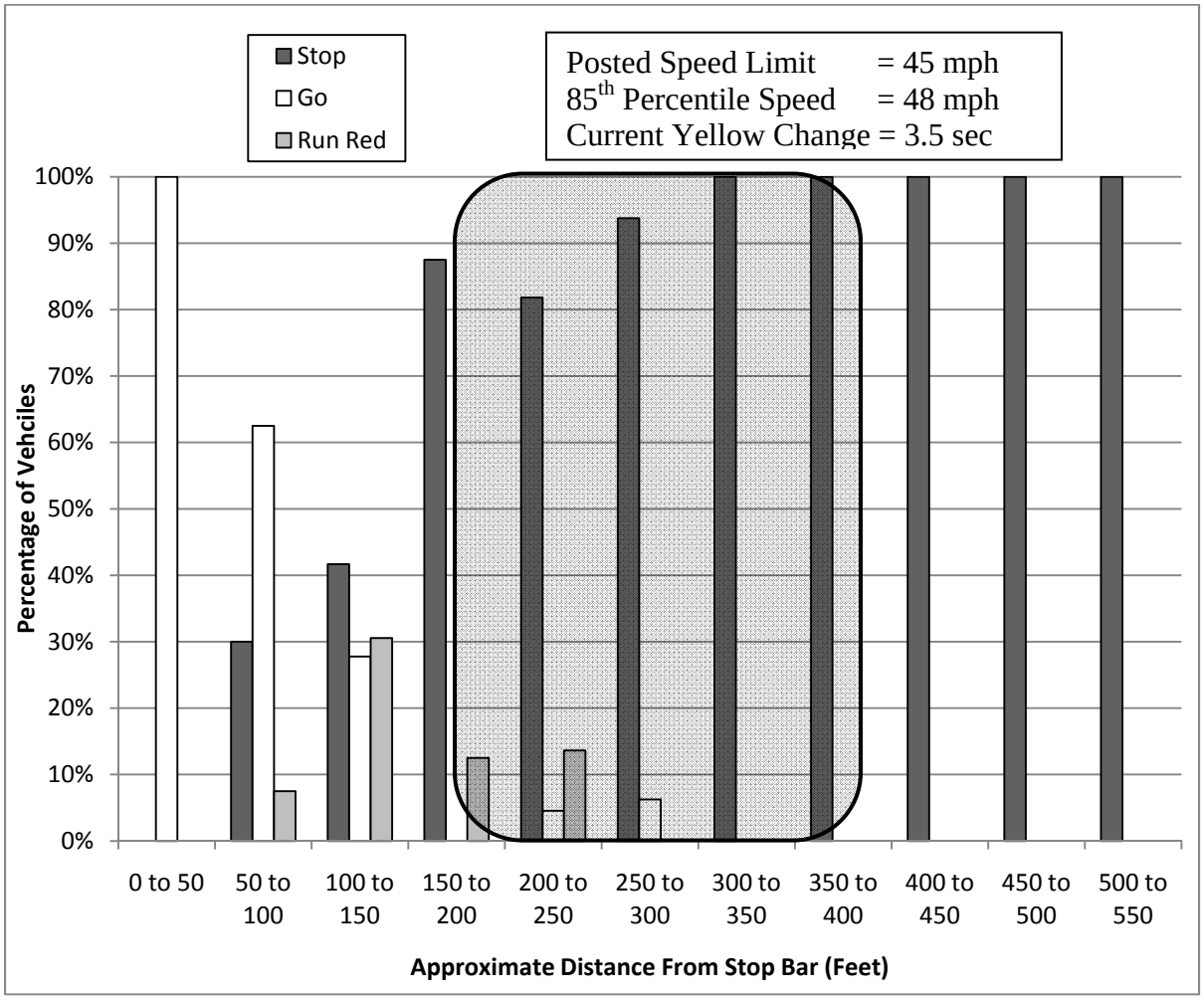

Figure 31 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Berlin Street @ Route 62 (Eastbound Approach)

In Figure 31, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the

more likely it will be to enter the intersection. It does seem that driver decision making symptomatic of dilemma zone issues is occurring in the 100 to 150 foot region in advance of the dilemma zone. Based on the 85th percentile speed of 48 mph, the predicted dilemma zone region exists between 176 feet to 387 feet. As compared to previous intersection approaches, this overlapping region does not fully capture the red light running vehicles. The current change interval is programmed to last 3.5 seconds in duration, however the ITE equation predicts yellow time duration of approximately 4.48 seconds in duration.

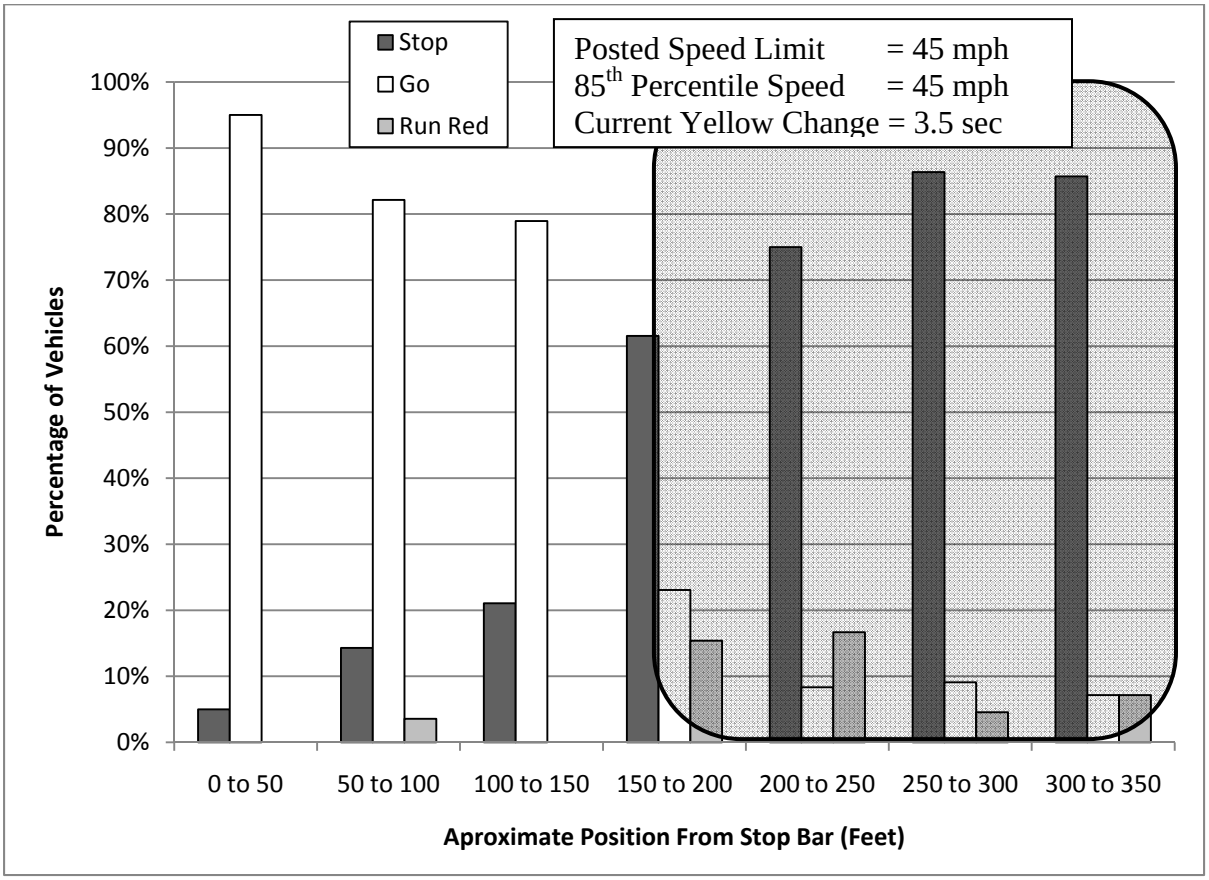

Figure 32 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Berlin Street @ Route 62 (Westbound Approach)

In Figure 32, the trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the more likely it will be to enter the intersection. Based on the 85th percentile speed of 45 mph, the predicted dilemma zone region exists between 165 feet to 363 feet. Due to infrastructure constraints the observed region is about 100 feet shorter than would have been originally desirable. This region seems to a positive correlation with the presence of red light running. The current change interval is programmed to last 3.5 seconds in duration, however the ITE equation predicts yellow time duration of approximately 4.32 seconds in duration.

Aggregated Intersection Approach Observations

After the examination of driver behavior at the individual intersection approaches was considered using the 2.5 to 5.5 second definition based on an 85th percentile speed, a question of interest persisted. Might there be any new insight garnered by the reconsideration of the boundary definition (time to stop bar vs. driver decision to stop) for the Type II dilemma zone for the updated database. Numerous Chi-square tests were conducted to better understand the distribution of vehicles and driver behaviors described by the data for each definition. Table 7 displays the data for the first group of Chi-square tests which were conducted.

Table 7 Comparison of Vehicle Distributions Across Boundary Definitions

Intersection Approach	2.5 sec to 5.5 sec			10% to 90%			Chi-square P-value
	Down-stream	In DZ	Up-stream	Down-stream	In DZ	Up-stream	
Rte 7 @ Rte 103 (SB)	64	31	14	15	73	21	< 0.001
Rte 62 @ Airport (WB)	48	19	19	25	37	24	0.001
Rte 62 @ Berlin (WB)	87	73	0	40	120	0	NA
Rte 62 @ Airport (EB)	88	43	0	54	77	0	NA
Rte 7 @ N. Shrew (SB)	137	154	32	83	208	32	< 0.001
Rte 62 @ Paine Tpke (WB)	216	127	0	102	194	47	< 0.001
Rte 62 @ Paine Tpke (EB)	163	56	0	0	210	9	< 0.001
Rte 7 @ Rte 103 (NB)	76	98	19	38	146	9	< 0.001
Rte 62 @ Berlin (EB)	151	109	50	75	138	97	< 0.001
Total	1030	710	134	432	1203	239	< 0.001

The first group of Chi-square tests specifically asked the question, when a single definition (either time to stop bar or decision to stop) is applied to the distribution of vehicles that are downstream of the DZ, in the DZ, or upstream of the DZ across all nine intersection approaches, is there any difference between individual approaches. The P-values for the time stop bar and the decision to stop boundaries were ($P < 0.001$ and $P < 0.001$) respectively. Therefore, under each definition individual intersection approaches show statistically significant differences at the 99% confidence interval in the distribution of vehicles in each of the three aggregated positions.

The second comparison in group one examined the total number of vehicles observed at every intersection approach downstream, in, and upstream of the DZ across both definitions resulting in a statistically significant difference in the distribution of vehicles for each boundary definition ($P < 0.001$). The time to stop bar definition results

in far more vehicles predicted to exposure of the solid yellow indication downstream of the DZ, while the decision to stop definition resulted in far more vehicles predicted to capture within the DZ and upstream from the DZ.

The third comparison looked at each individual intersection approach and compared the distribution of vehicles downstream, in, and upstream of the DZ across both definitions resulting in the P-values displayed in the right most column of Table 7. These tests show statistically significant results which mirrored exactly the trends of the total vehicle distribution at eight of the ten approaches which could be analyzed in this way.

The second group of Chi-square tests looked more closely at the driver behavior (stop, go, run red) which was evident within the dilemma zone across each intersection approach. Table 8 displays the data collected for the second group of Chi-square tests.

Table 8 Comparison of DZ Driver Behavior Across Boundary Definitions

Intersection Approach	2.5 sec to 5.5 sec			10% to 90%		
	Stop	Go	Run Red	Stop	Go	Run Red
Rte 7 @ Rte 103 (SB)	22	4	5	27	40	6
Rte 62 @ Airport (WB)	15	1	3	13	19	5
Rte 62 @ Berlin (WB)	57	8	8	65	46	9
Rte 62 @ Airport (EB)	8	20	15	9	53	15
Rte 7 @ N. Shrew (SB)	99	34	21	103	81	24
Rte 62 @ Paine Tpke (WB)	93	17	17	62	114	18
Rte 62 @ Paine Tpke (EB)	46	7	3	73	134	3
Rte 7 @ Rte 103 (NB)	67	20	11	81	54	11
Rte 62 @ Berlin (EB)	101	2	6	81	37	20
Total	508	113	89	514	578	111

When a single definition (either time to stop bar or decision to stop) is applied to the driver behavior (stop, go, run red) within the dilemma zone at each intersection

approach is there any difference between individual approaches. Both the time stop bar and the decision to stop boundaries resulted in statistically significant differences ($P > 0.001$).

The second comparison in group two examined the total number of vehicles observed performing each driver behavior across both definitions resulting in statistical significance ($P < 0.001$). The time to stop bar definition results in far more vehicles predicted to exposure of the solid yellow indication downstream of the DZ, while the decision to stop definition resulted in far more vehicles predicted to capture within the DZ and upstream from the DZ.

Lastly, a Chi-square test was conducted on the percent of red light running captured within the dilemma zone for all approaches under each definition yielding no statistical significance ($P = 0.98$).

Numerous individual factors were isolated for the purpose of determining their impact on driver behavior. Figure 33 displays the impact of two such variables on the likelihood of a driver choosing to stop, depending on the distance from the stop bar. Specifically, the influence of a lead vehicle choosing to enter the intersection no more than 100 feet in advance of the following car, and the influence of the presence of a vehicle in an adjacent through lane no more than 50 feet in advance of the adjacent car. The vertical axis represents the percent of drivers choosing to stop, while the horizontal axis represents the distance from the stop bar. Figure 33 contains the combined data of two approaches observed in Vermont representing over 500 vehicle incursions with the solid yellow indication.

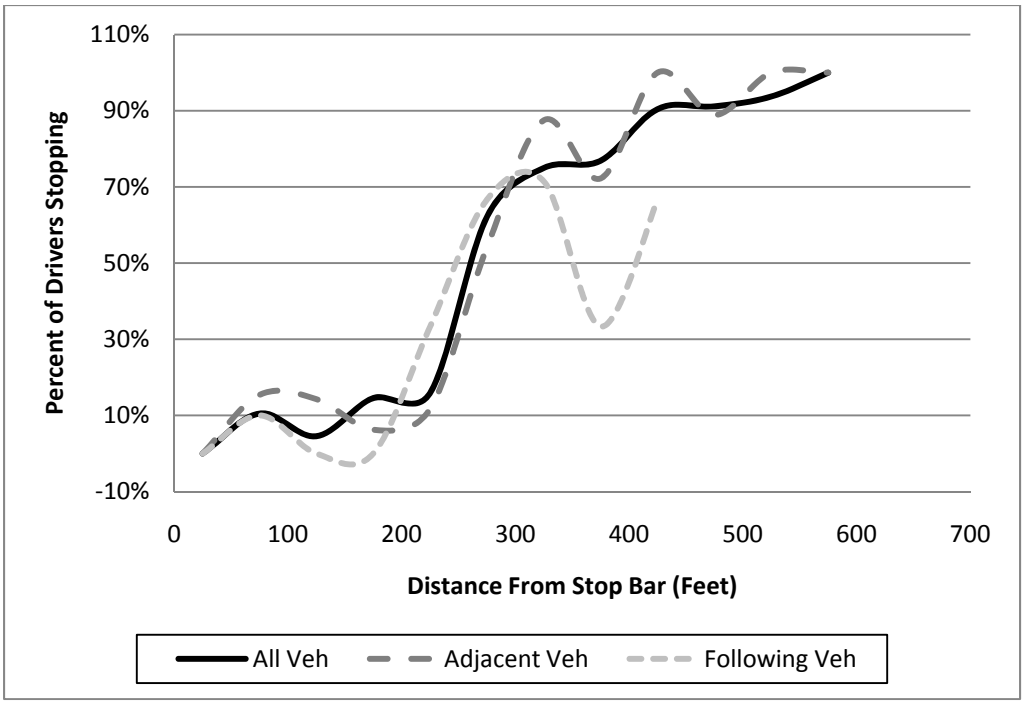

Figure 33 Impact of Adjacent & Following Vehicles on Driver Behavior

Upon visual inspection it can be observed that there is relatively little variation in the percentage of drivers choosing to stop in the entire sample and those who were exposed to an adjacent vehicle. However, when compared to the following vehicle, a difference seems to exist in the region of 300 to 400 feet. It appears that a moderate decrease in the percentage of drivers stopping for those following vehicles.

CHAPTER V

POINT AND SPACE SENSORS FOR DILEMMA ZONE PROTECTION: A FIELD STUDY

Chapter 5 presents the results which were collected in Task 3 to address the second research hypothesis, *"Advanced vehicle detection has the potential to provide superior dilemma zone protection when utilizing space sensors as compared to point sensors for isolated at-grade high-speed signalized intersections, where dilemma zone protection is defined by a reduction in the number of vehicles caught in a Type II dilemma zone."*

The comparison study focused on quantifying the observed differences in dilemma zone protection afforded under advanced vehicle detection provided by inductive loops and the SmartSensor Advance. This section describes the information gleaned from the effort. The results were reduced and organized in a very similar manner to those results presented from the naturalistic study of driver behavior.

Every vehicle approaching the signalized intersection of Route 7 and 103 that encountered a yellow indication within 550 ft of the stop line was observed during an 8 hour period where advanced detection was provided with in pavement inductive loops and with the SmartSensor Advanced.

Figure 34 displays the driver behavior observed with advance vehicle protection provided from inductive loops. The position of the Type II dilemma zone (time to stop bar 2.5 to 5.5 sec) is highlighted in grey. The frequency of vehicles caught within the dilemma zone is also identified as being 12.3 vehicles per hour.

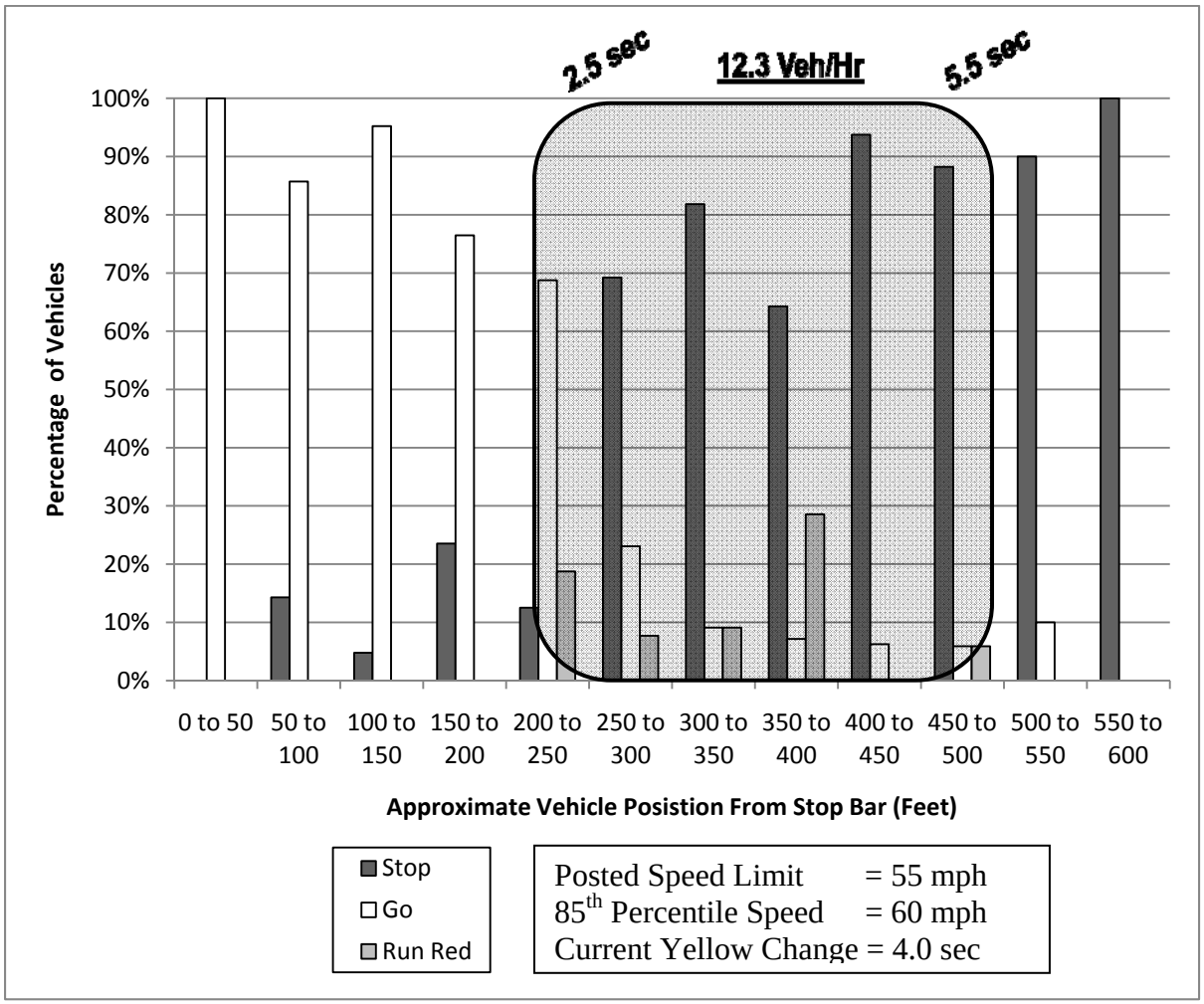

Figure 34 In-Pavement Inductive Loop DZ Protection

The trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the more likely it will be to enter the intersection. Based on the 85th percentile speed of 60 mph, the predicted dilemma zone region exists between 220 feet to 484 feet. This region includes all stances of red light running. The current change interval is programmed to last 4.0 seconds in duration, however the ITE equation predicts yellow time duration of approximately 5.0 seconds in duration.

Figure 35 displays the driver behavior observed with advance vehicle protection provided from the SmartSensor Advanced. The position of the Type II dilemma zone (time to stop bar 2.5 to 5.5 sec) is highlighted in grey. Also, the frequency of vehicles caught within the dilemma zone is identified as being 9.8 vehicles per hour.

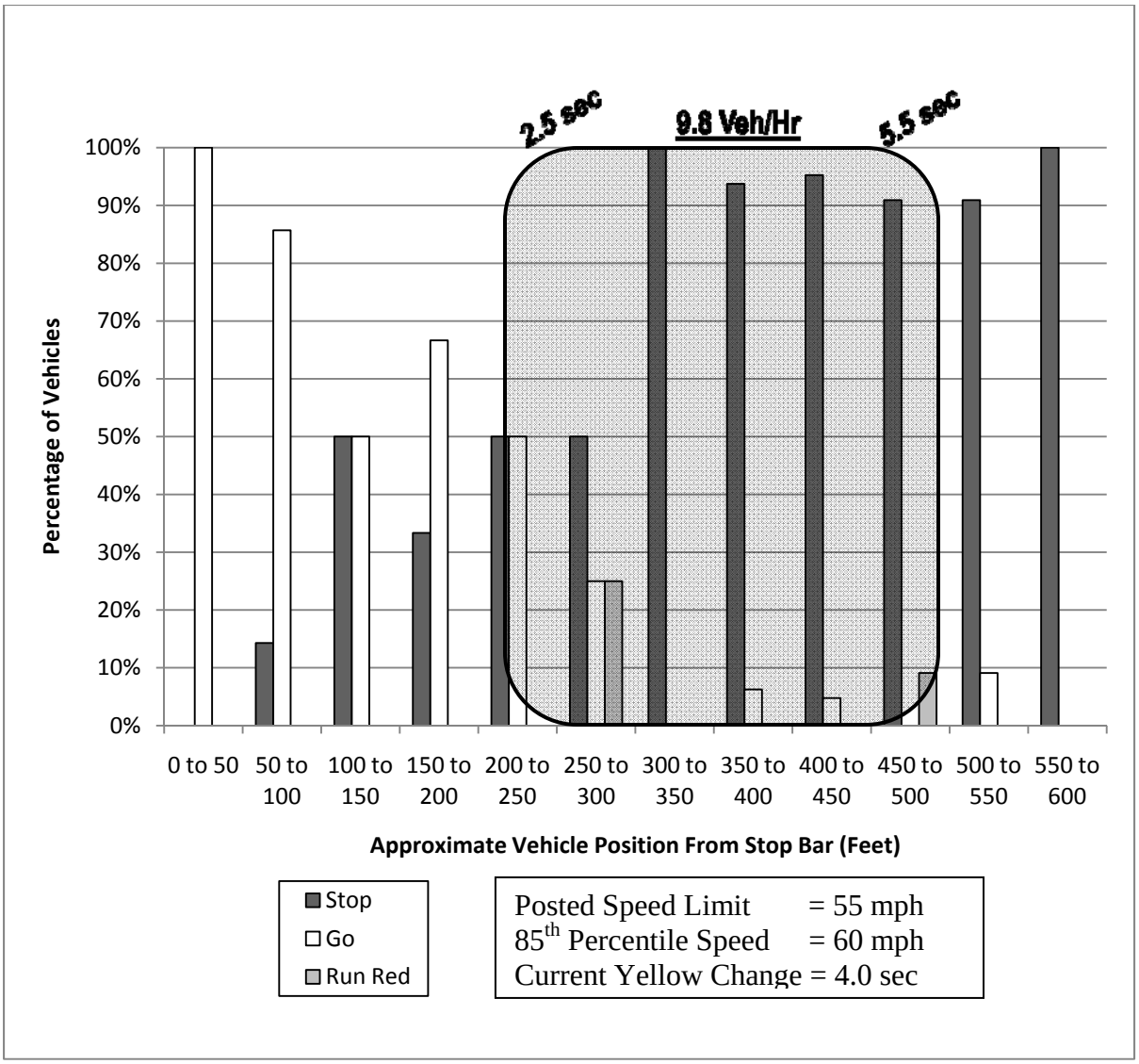

Figure 35 SmartSensor Advance DZ Protection

The trends in frequency of stop/go driver behavior seem logical in that the closer the vehicle is to the stop bar at the onset of the solid yellow indication the more likely it

will be to enter the intersection. The 85th percentile speed and location of the dilemma zone are the same as in the inductive loop condition. Upon a visual inspection, although the RLR still appears to occur within the dilemma zone region, it has reduced in frequency.

By comparison, a visual inspection of the distribution of driver behaviors shows that the SmartSensor seems to have shifted some of the vehicles to a position downstream of the dilemma zone. The distribution of vehicles in each condition was compared with a Chi-square test, resulting in a statistically significant difference with a confidence of greater than 95%. An observed reduction of the frequency of vehicles exposed to the solid yellow indication while within the dilemma zone from 12.3 vehicles to 9.8 vehicles per hour was also observed.

The most critical driver behavior failure when interacting with a dilemma zone is the running of a red light. RLR was examined as another metric for comparing the systems. **Error! Reference source not found.** 9 includes some summary information of the database, such as the length of the observations and the number of vehicles that encountered a yellow indication during each condition. The average rate of RLR incidences per unit time is decreased by more than 3 times with the use of the SmartSensor.

Table 9 Summary of Reduced Observations

Type of Advanced Detection	Length of Observation (min)	(Y) Indication Incursion (veh)	Rate of (Y) Incursion (veh/min)	Red Light Running (veh)	Rate of RLR (veh/min)
Inductive Loops	467	208	2.25	11	1/42.45
SmartSensor	305	140	2.18	2	1/152.50

A Chi-square statistical test was conducted in SPSS to determine if the rate of RLR was statistically different between the two conditions (advanced detection with inductive loops or SmartSensor). No statistically significant difference was found ($P = 0.063$). This means that the difference in the rates of RLR observed when the SmartSensor Advanced was used in place of inductive loops was approaching a statistically significant reduction.

CHAPTER VI

DRIVER COMPREHENSION AND PREDICTED BEHAVIOR OF THE CIRCULAR YELLOW INDICAITON: A STATIC EVALUATION

Chapter 6 presents the results which were collected in Task 4 to address the third research hypothesis, "*Driver comprehension of the circular yellow indication is less than desirable for the safe and efficient operation of signalized intersections, where comprehension is evaluated across the dimensions of meaning, duration and sequencing of the indication.*"

The static evaluation was designed to examine driver comprehension and predictive behavior when exposed to the circular yellow indication. Driver comprehension of the circular yellow was evaluated with regard to the meaning conveyed, the sequencing, and the duration of the indication, while predictive behavior was evaluated with regard to several factors including number of approach lanes, distance from the stop bar, and position in the platoon of approaching vehicles.

An effort was made to balance driver demographics across the major dimensions of gender, age, and driving experienced Table 10 displays the demographics of 65 drivers who participated in the static evaluation.

Table 10 Static Evaluation Demographics

Gender		Age (in years)			Miles Driven Last year (in thousands)		
Male	Female	< 25	25 to 45	> 45	> 10K	10K-20K	> 20K
45%	55%	28%	45%	28%	41%	40%	19%

It can be seen that a relatively even distribution of drivers was captured across each of the three dimensions of driver demographics as a part of this study.

Meaning of the CY Indication

It is critical that the simple messages intended to be conveyed by traffic control devices are in fact comprehended by the motoring public. To evaluate if the correct messages were being conveyed by the circular yellow and yellow arrow the following five scenarios were presented:

- 5 section cluster displaying a
    - CY
    - YA + CG
    - YA + CY
- 3 section vertical displaying a
    - CY
    - YA

In each of the five scenarios the following five possible responses were provided:

- *Red light is coming next,*
- *Preceding movement is ending,*
- *Stop and wait for the appropriate signal,*
- *You are required to yield, and*
- *You have the right of way*

The data collected from the five possible scenarios described above is displayed in Figure 36 through Figure 40. In each figure the vertical axis represents the five possible

responses which the driver could have selected. The horizontal axis represents the percent of driver responses for each alternative presented in each scenario. In this series of scenarios it is important to note that the driver could select more than one response for each scenario.

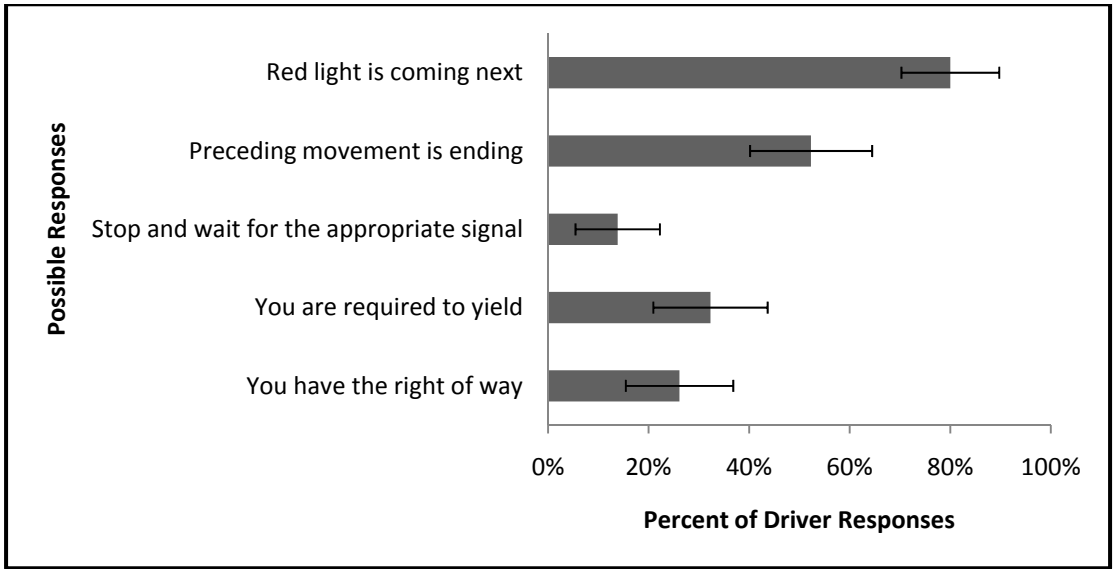

Figure 36 Meaning of a CY in a 5 Section Cluster with 95% CI

In Figure 36, the five section cluster displaying a CY, the most common response was that the *red light is coming next* registering at 80 percent of all drivers with a confidence with a 95% confidence. The least common response was to *stop and wait for the appropriate signal* with a 14 percent response rate, but this was found to not be statistically different at a 95% confidence rate when compared to *you are required to yield* and *you have the right of way*. The correct responses *red light is coming next* and *preceding movement is ending* came in at 80 percent and 52 percent respectively. There was however no statistical difference seen between the *preceding movement ending* and being *required to yield*.

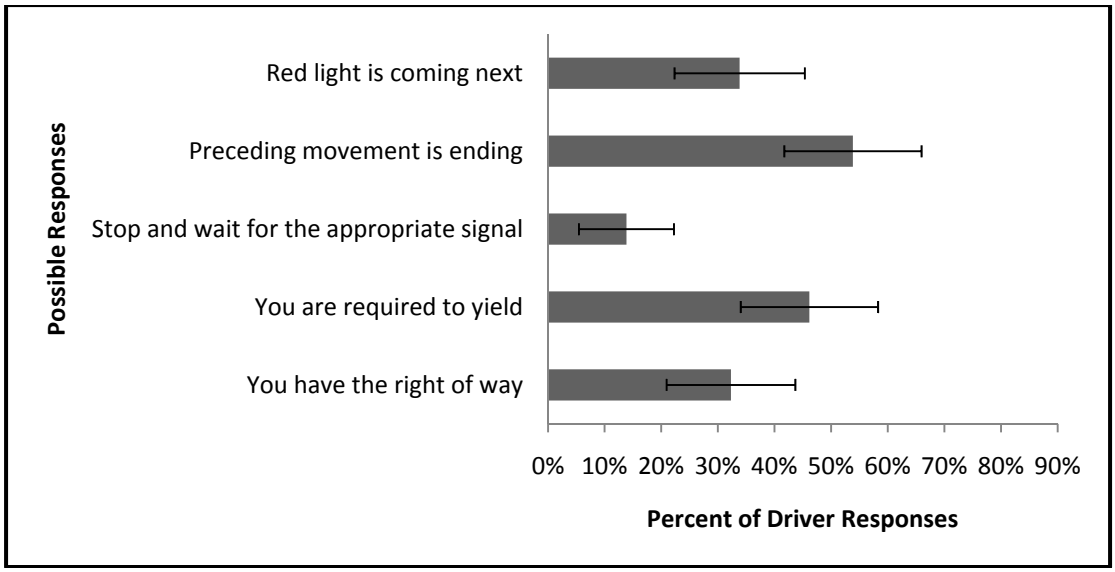

Figure 37 Meaning of a YA+CG in a 5 Section Cluster with 95% CI

The driver responses captured in Figure 37 are more evenly distributed. The most common response is that the *preceding movement is ending* registering at just over half of all drivers. This response is only statistically different from the least common response, *stop and wait for the appropriate signal* which had a14 percent response rate. The correct responses *red light is coming next* and *preceding movement is ending* came in at 34 percent and 54 percent respectively.

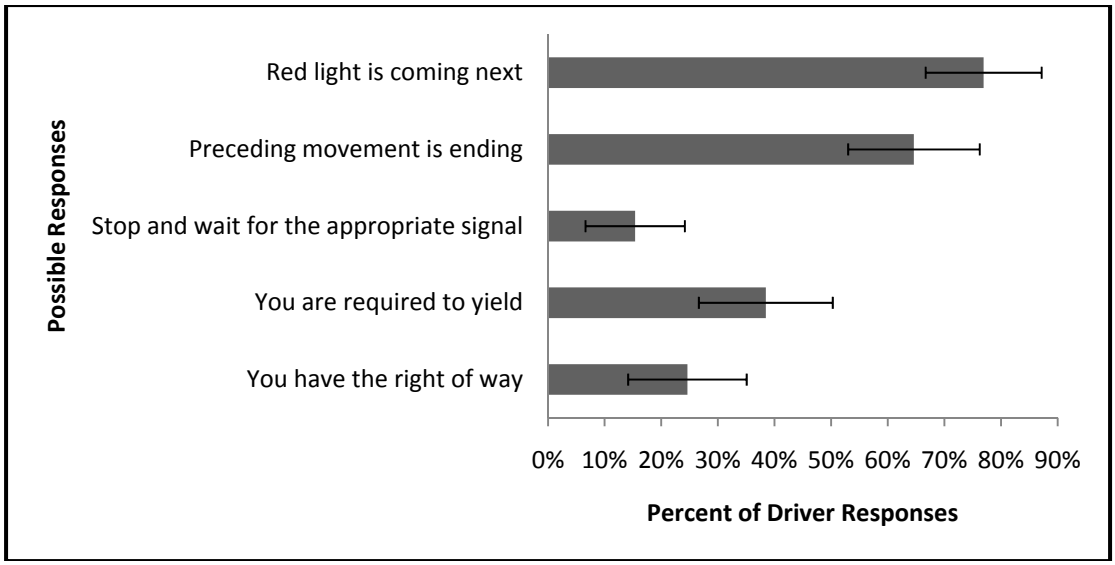

Figure 38 Meaning of a YA+CY in a 5 Section Cluster with 95% CI

In Figure 38, the scenario containing a five section cluster displaying a YA+CY, the most common response is that the *red light is coming next* registering at 77 percent of all drivers. The least common response was to *stop and wait for the appropriate signal* with a 15 percent response rate, but there was no statistical difference between that response and *you have the right of way*. The correct responses *red light is coming next* and *preceding movement is ending* came in at 77 percent and 65 percent respectively. No statistical difference was identified between the two responses; however, they were statistically different from all three incorrect responses.

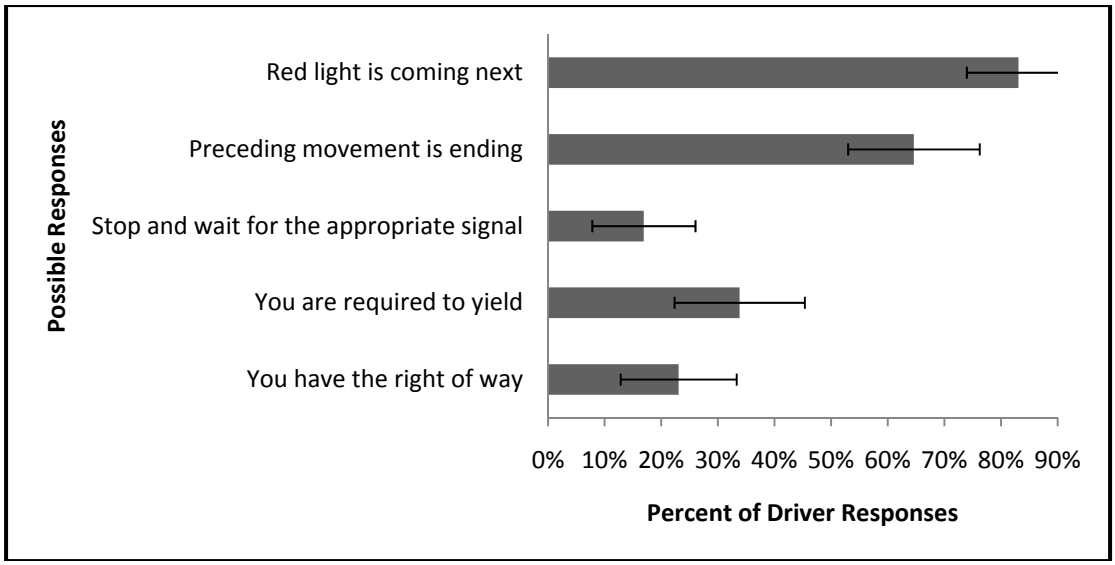

Figure 39 Meaning of a CY in a 3 Section Vertical with 95% CI

In Figure 39, the scenario containing a three section vertical displaying a CY, the most common response was that the *red light is coming next* registering at 83 percent of all drivers. The least common response was to *stop and wait for the appropriate signal* with a 17 percent response rate, but no statistical difference was seen between this response and *you are required to yield* or *you have that right of way*. The correct responses *red light is coming next* and *preceding movement is ending* came in at 83 percent and 65 percent respectively. While no statistical difference was identified between the two, they were found to be statistically different from all of the incorrect answers.

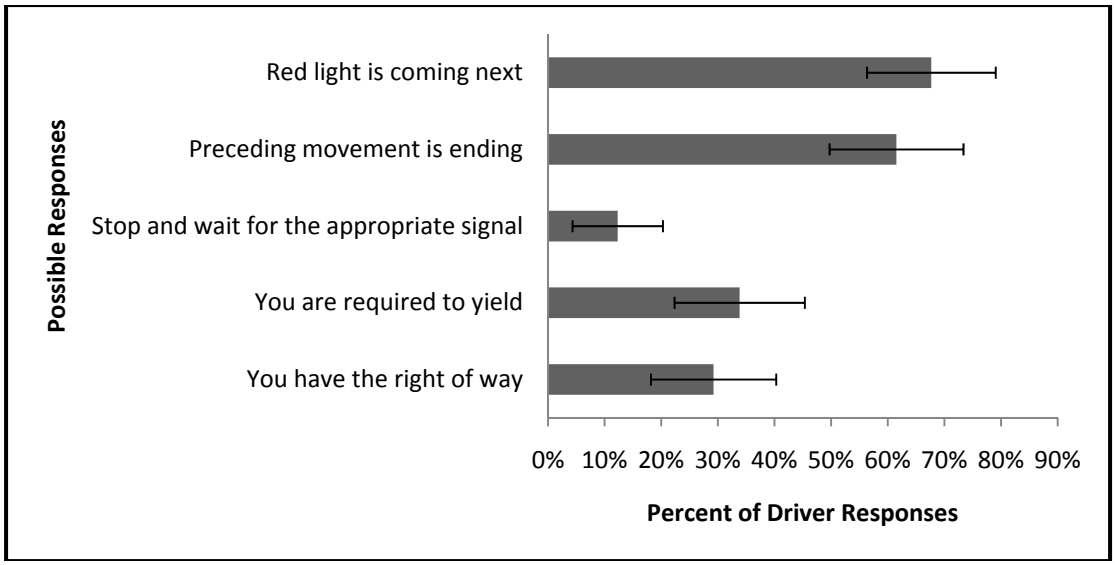

Figure 40 Meaning of a YA in a 3 Vertical Cluster with 95% CI

In Figure 40, the scenario containing a three section vertical displaying a CY, the most common response is that the *red light is coming next* registering at 68 percent of all drivers. The least common response was to *stop and wait for the appropriate signal* with a 12 percent response rate, but no statistical difference was seen between that response and you have the right of way. The correct responses *red light is coming next* and *preceding movement is ending* came in at 68 percent and 62 percent respectively, but no statistical difference was identified between the two responses.

To better understand how driver compression of the intended meaning of the 5 signal displays compared to one another, several Chi-square tests were conducted. The data in Table 11 represents the raw driver responses for each of the 5 scenarios, and was used to conduct the Chi-square tests

Table 11 Driver Comprehension of CY Meaning for Different Signal Displays

Possible Driver Responses	5 Section Cluster			3 Section Vertical	
	CY	YA+CG	YA+CY	CY	YA
You have the right of way	17	21	16	15	19
You are required to yield	21	30	25	22	22
Stop and wait for the appropriate signal	9	9	10	11	8
Preceding movement is ending	34	35	42	42	40
Red light is coming next	52	22	50	54	44

First the 5 section cluster displays (CY, YA+CG, and YA+CY) were compared to identify if any differences in the distributions existed. A statistical difference was identified (P = 0.05). Delving deeper into the 5 section cluster displays a comparison for the shared signal displays (YA+CG and YA+CY) was conducted to determine if the meaning way better understood for a particular display. A statistically significant difference was identified (P = 0.04), confirming that the YA+CY display was more consistently understood than the SYA+CG display. The 3 section vertical displays (CY+YA) were examined next, yielding no statistical differences (P = 0.81). Lastly, the CY indication presented alone in both the 5 section cluster and the 3 section vertical was compared yielding no statistical difference in the distribution (p = 0.63). Figure 41 provides additional data to examine the correct responses across all 5 signal displays.

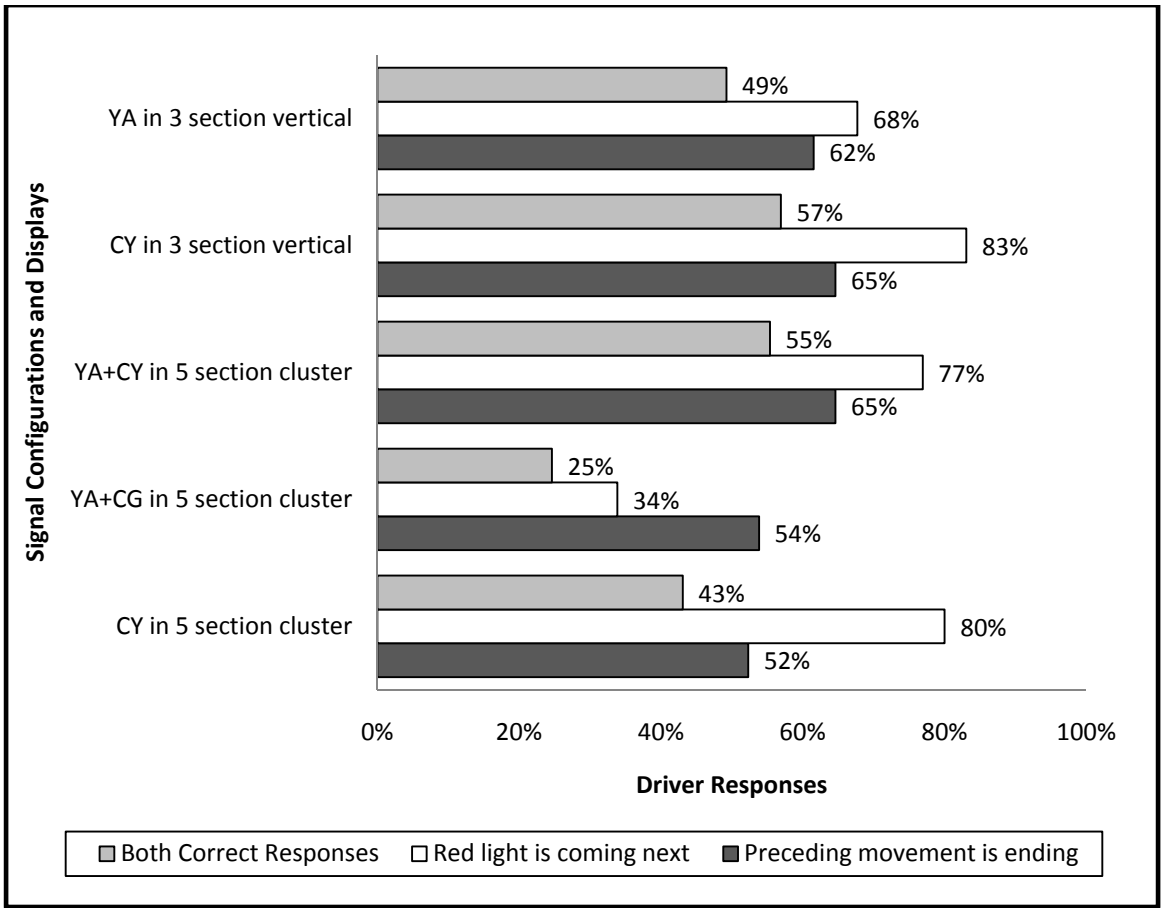

Figure 41 Correct Responses for SY Meaning

In four of the five scenarios, all but the YA+CG displayed in a five section cluster, the comprehension of the *red light coming next* was much more common than the comprehension that the *preceding movement was ending*. In general, the signal displays where the YA were present resulted in lower rates of correct driver responses than those signal displays that did not contain a YA. In all five scenarios the percentage of drivers who captured both correct responses was approximately 50 percent, except for the YA+CG displayed in a five section cluster which only capture about 25 percent.

To further examine the correct and incorrect interpretations of signal display meaning a series of one-way ANOVA tests were conducted. First all 5 signal displays were tested in conjunction with one another. The results of this test can be seen in Figure

42. A statistically significant difference between the correct responses recorded for at least one of the signal displays was identified (P = 0.001).

ANOVA

Response

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4.443	4	1.111	4.662	.001
Within Groups	76.246	320	.238		
Total	80.689	324			

Figure 42 ANOVA Output Comparing Meaning of 5 Signal Displays

Next a post hoc Tukey test was conducted for the purpose of identifying specifically where the differences in correct responses existed. Figure 43 displays the output of the Tukey test.

Multiple Comparisons

Dependent Variable: Response

Tukey HSD

(I) Sig_Dis	(J) Sig_Dis	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	.18462	.08562	.199	-.0503	.4195
	3.00	-.12308	.08562	.604	-.3580	.1118
	4.00	-.13846	.08562	.488	-.3734	.0964
	5.00	-.06154	.08562	.952	-.2964	.1734
2.00	1.00	-.18462	.08562	.199	-.4195	.0503
	3.00	-.30769*	.08562	.003	-.5426	-.0728
	4.00	-.32308*	.08562	.002	-.5580	-.0882
	5.00	-.24615*	.08562	.035	-.4811	-.0113
3.00	1.00	.12308	.08562	.604	-.1118	.3580
	2.00	.30769*	.08562	.003	.0728	.5426
	4.00	-.01538	.08562	1.000	-.2503	.2195
	5.00	.06154	.08562	.952	-.1734	.2964
4.00	1.00	.13846	.08562	.488	-.0964	.3734
	2.00	.32308*	.08562	.002	.0882	.5580
	3.00	.01538	.08562	1.000	-.2195	.2503
	5.00	.07692	.08562	.897	-.1580	.3118
5.00	1.00	.06154	.08562	.952	-.1734	.2964
	2.00	.24615*	.08562	.035	.0113	.4811
	3.00	-.06154	.08562	.952	-.2964	.1734
	4.00	-.07692	.08562	.897	-.3118	.1580

*. The mean difference is significant at the .05 level.

Figure 43 Tukey Output Comparing Meaning of 5 Signal Displays

By examining the output of Figure 43 it can be determined that the only statistically significant differences exist between the YA+CG in a 5 section cluster and the following three signal displays (YA+CY in a 5 section cluster, CY in a 3 section vertical, and YA in a 3 section vertical) In all three comparisons it was determined that fewer correct pairs of responses were reported in the YA+CG configuration at a 95% confidence level.

Signal Display Sequence after the CY Indication

The second component of comprehension examined was driver understanding of the allowable sequencing of traffic signal indications. Specifically, what signal display comes next in the sequence after that of the circular yellow or yellow arrow? This sequencing question was tested in five scenarios with the same signal head configurations provided in the previous section on indication meaning. The vertical axis shows the possible responses which included five of the alternative signal displays that could theoretically be activated next in the sequence. The horizontal axis shows the percent of driver responses for each alternative signal display. Drivers were only allowed to select one display per scenario. The results of these five scenarios are displayed in Figure 44 through Figure 48.

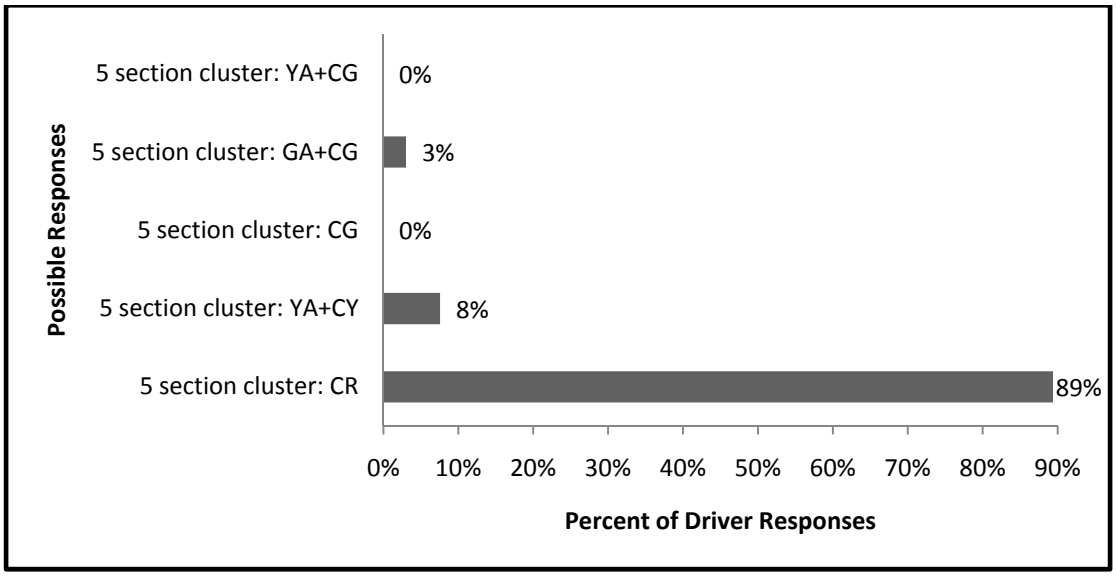

Figure 44 Display to Appear after CY in a 5 Section Cluster

Figure 44 shows the data captured when drivers were asked to identify the signal display which would occur next in the sequence after the CY in a five section cluster. It

can be seen that 89 percent of drivers selected the correct response which said that the CR was the next display in the sequence. Of the 11 percent who selected incorrect displays, answers were divided between GA+CG and YA+CY.

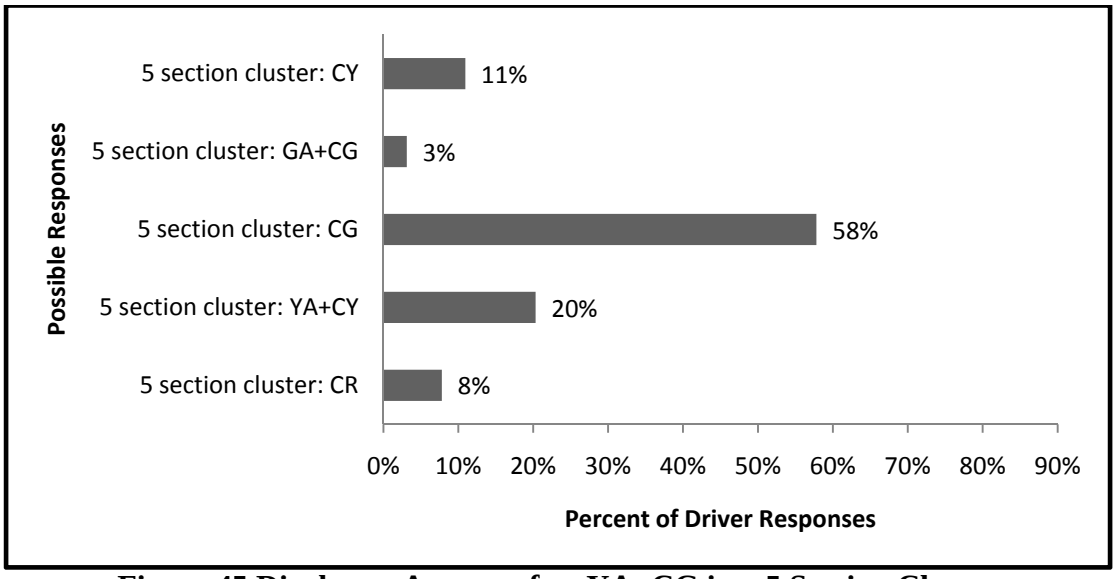

Figure 45 Display to Appear after YA+CG in a 5 Section Cluster

Figure 45 shows the data captured when drivers were asked to identify the signal display which would occur next in the sequence after the YA+CG in a five section cluster. It can be seen that only 58 percent of drivers selected the correct response which said that the CG was the next display in the sequence. Of the 42 percent who selected incorrect displays, answers were divided amongst the remaining possibilities.

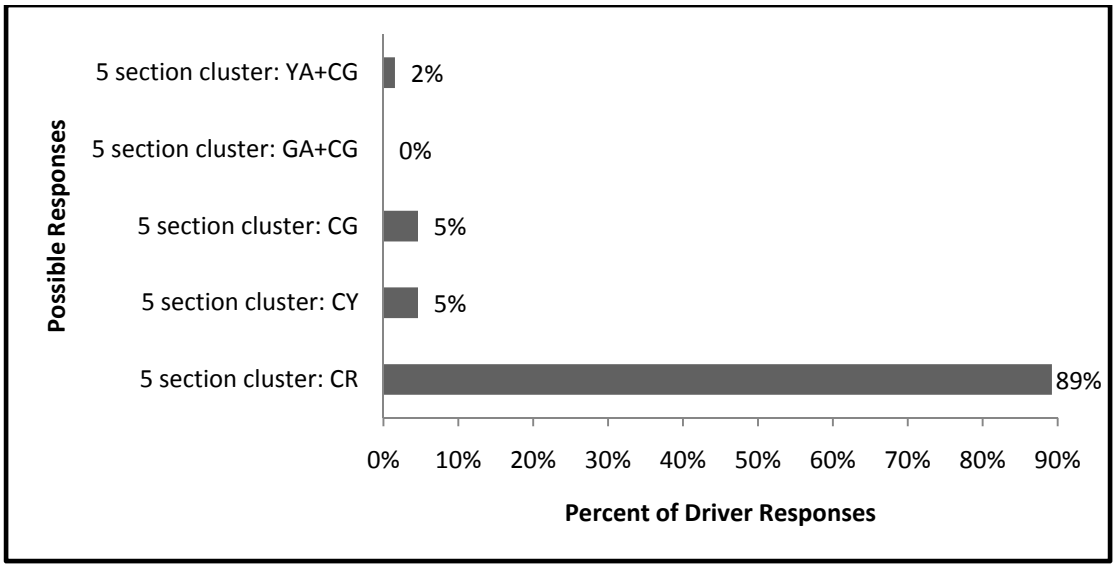

Figure 46 Display to Appear after YA+CY in a 5 Section Cluster

Figure 46 shows the data captured when drivers were asked to identify the signal display which would occur next in the sequence after the YA+CY in a five section cluster. It can be seen that 89 percent of drivers selected the correct response which said that the CR was the next display in the sequence. Of the 11 percent who selected incorrect displays, answers were divided among the remaining alternatives.

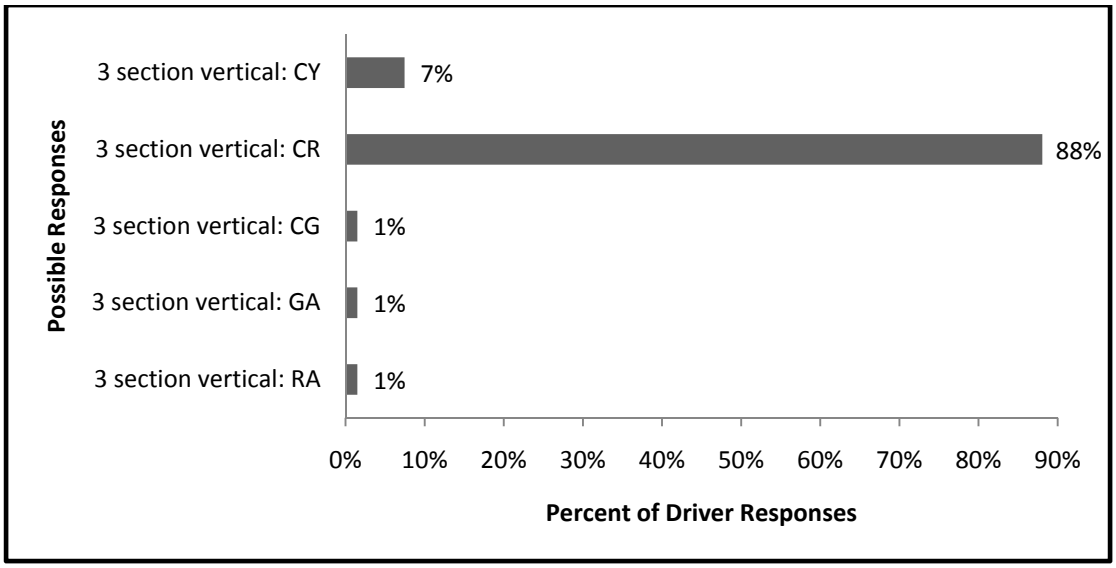

Figure 47 Display to Appear after CY in a 3 Section Vertical

Figure 47 shows the data captured when drivers were asked to identify the signal display which would occur next in the sequence after the CY in a three section vertical. It can be seen that only 88 percent of drivers selected the correct response which said that the CR was the next display in the sequence. Of the 12 percent who selected incorrect displays, answers were divided among the alternative displays.

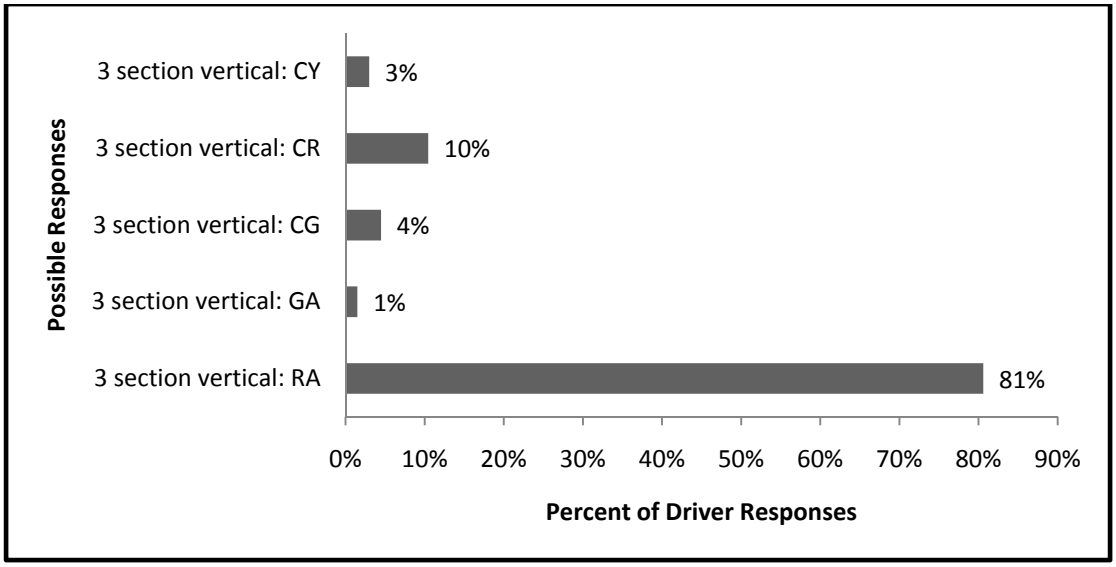

Figure 48 Display to Appear after YA in a 3 Section Vertical

Figure 48 shows the data captured when drivers were asked to identify the signal display which would occur next in the sequence after the YA in a three section vertical. It can be seen that only 81 percent of drivers selected the correct response which said that the RA was the next display in the sequence. Of the 19 percent who selected incorrect displays, answers were divided among the other choices. However 10 percent responded that the CR would be the next display.

To expand upon the analysis of correctly predicting the next display in sequence each of the 5 signal display scenarios were compared with one another using ANOVAs and Tukey post hoc comparisons in a similar manner to that of the meaning scenarios. First it was determined through an ANOVA that a difference did in fact exist in the means of correct answers ($P < 0.001$). Upon closer examination it was determined that the YA+GC in the 5 section cluster display did yield less correct responses than each of the 4 alternative signal displays with statistical significance. No other differences were uncovered.

Duration of the CY Indication

The third component of the comprehension section dealt with the understanding of the acceptable duration of the CY. For this question two scenarios were developed; one representing a high-speed roadway posted at 50 mph and another representing a low speed roadway posted at 30 mph. Figure 49 and Figure 50 show the data collected from these scenarios. The vertical axis shows the alternative durations in seconds that drivers were allowed to select from. They range from 0 to 10 seconds increasing in one second intervals. The horizontal axis shows the percent of driver responses.

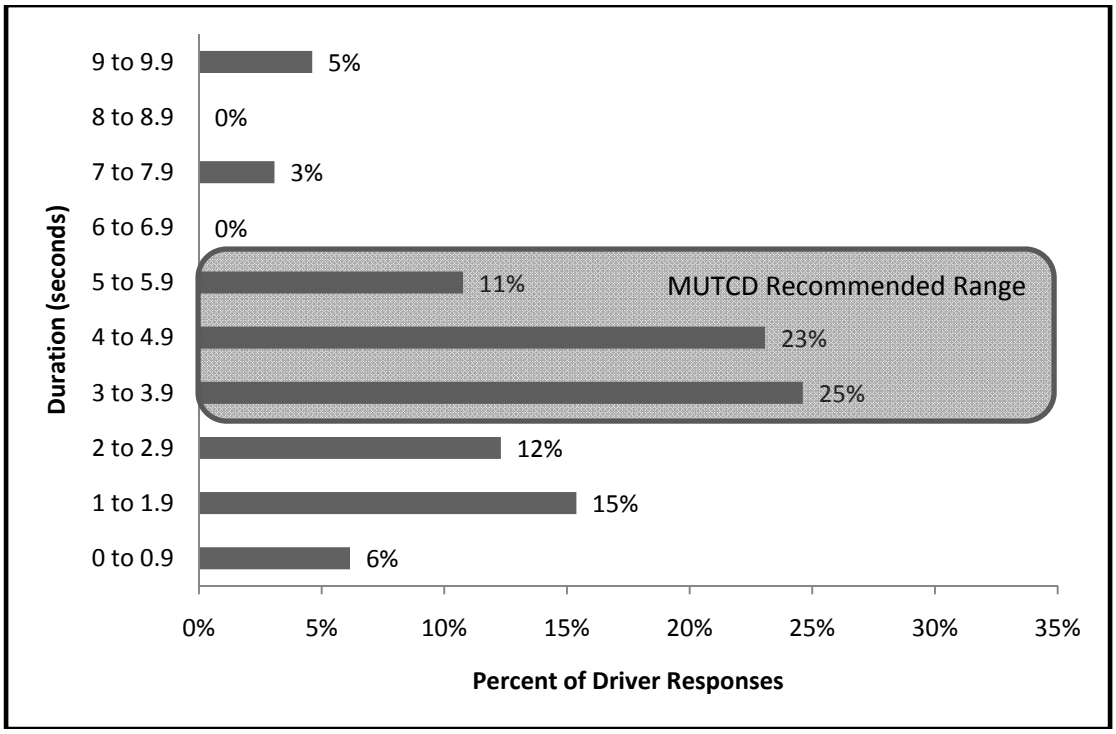

Figure 49 Predicted Duration of a CY on a High-Speed Roadway

Figure 49 displays the results for the driver predicted duration of a CY light on a High-Speed Roadway posted at 50 mph. The recommended range of CY duration is identified by the grayed out region. A total of 59 percent of driver responses appeared within the MUTCD region of three to six seconds, eight percent appeared in the region above six seconds and 33 percent appeared in the region below three seconds.

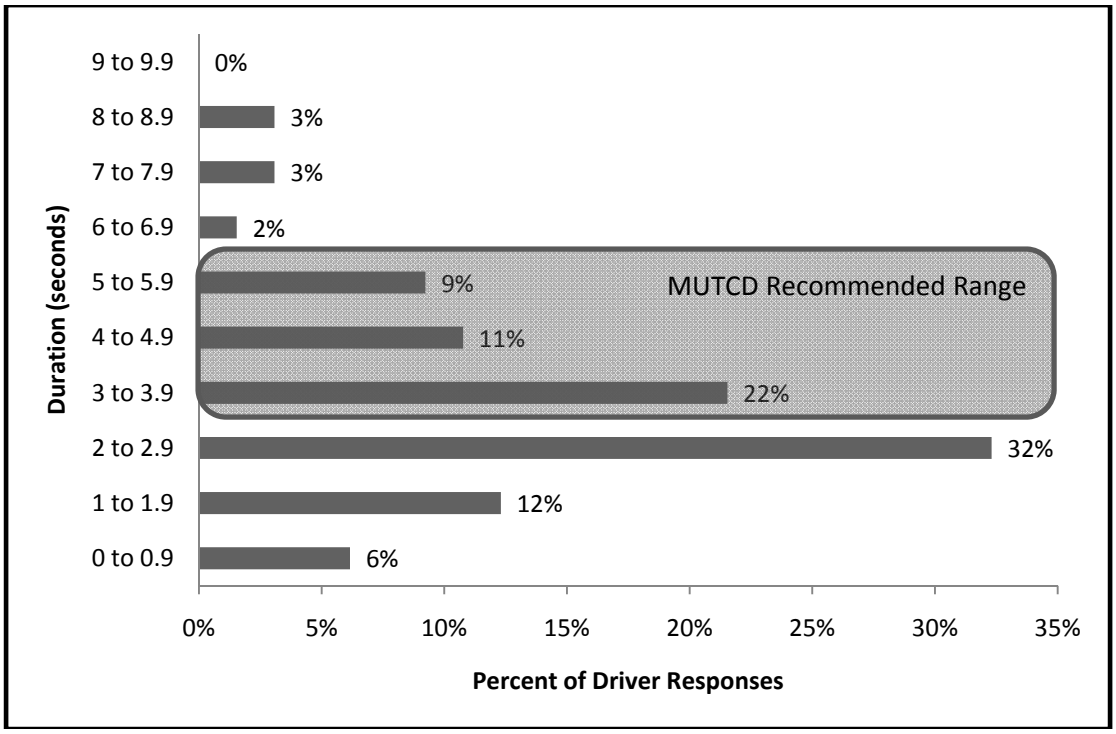

Figure 50 Predicted Duration of a CY on a Low-Speed Roadway

Figure 50 displays the results for the driver predicted duration of a CY light on a Low-Speed Roadway posted at 30 mph. The recommended range of CY duration is identified by the grayed out region. A total of 42 percent of driver responses appeared within the MUTCD region of three to six seconds, eight percent appeared in the region above six seconds, and 50 percent appeared in the region below three seconds.

A series of Chi-square tests were conducted to determine if there was any difference in the distributions of predicted duration in the high-speed and low-speed scenarios presented in above. It was determined that no such differences could be assessed at a confidence level of 95%.

Predictive Behavior

In the pursuit of understanding driver comprehension issues it has been established that predictive behavior may act as a surrogate measure for comprehension.

For this reason predictive behavior was examined regarding the CY indication. Figure 51 through Figure 54 display the data from the predictive driver behavior evaluation. The vertical axis displays the alternative actions that the driver could select from, while the horizontal axis shows the actual driver responses for each alternative action. Drivers were only allowed to select one action per scenario. Each figure represents a given scenario at three different distances.

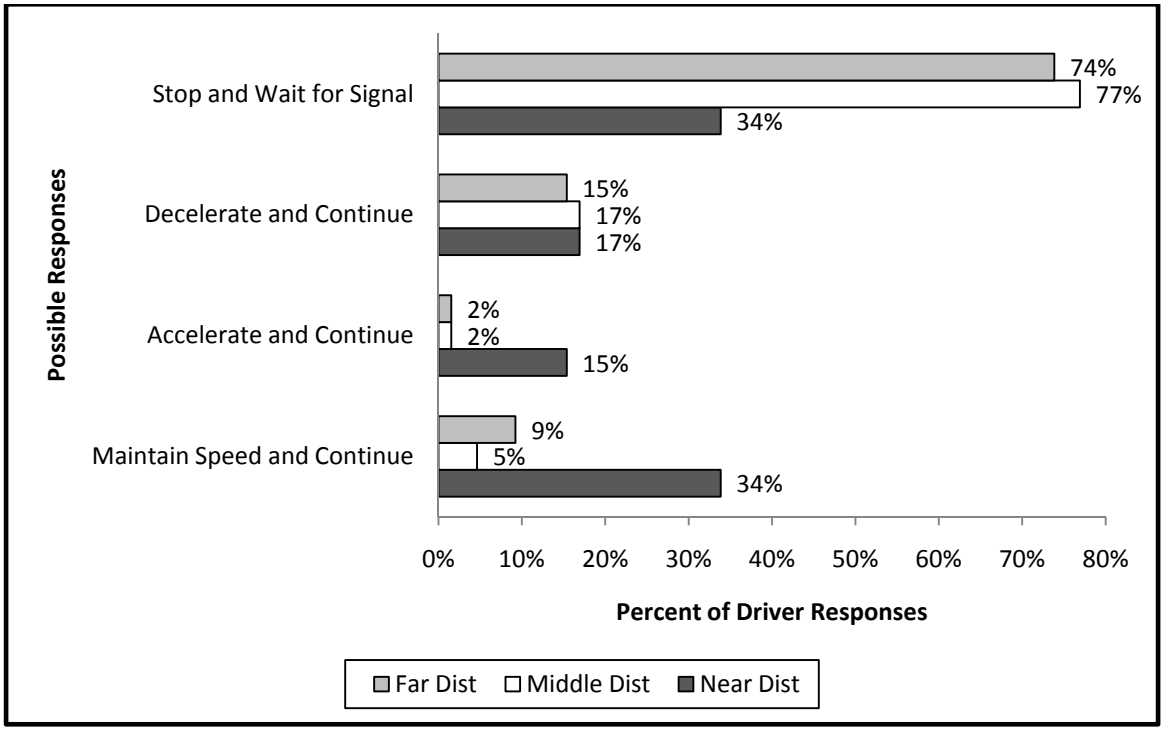

Figure 51 Predictive Behavior on 1 Lane Approach as Lead Vehicle

The data shown in Figure 51 represents three scenarios each of which involve an image taken from the driver seat of a lead vehicle heading towards a CY indication on a single lane approach. Each scenario is taken from a different distance, far (200 ft), middle (100 ft), near (50 ft). The responses collected from the far and middle distances are fairly similar across all four possibilities. For these two scenarios 75 percent of drivers

determined that they would *stop and wait for the signal*. For the near distance far fewer said that they would *stop and wait*, only 34 percent. The near distance also generated a much higher response for *maintain speed and continue* at 34 percent.

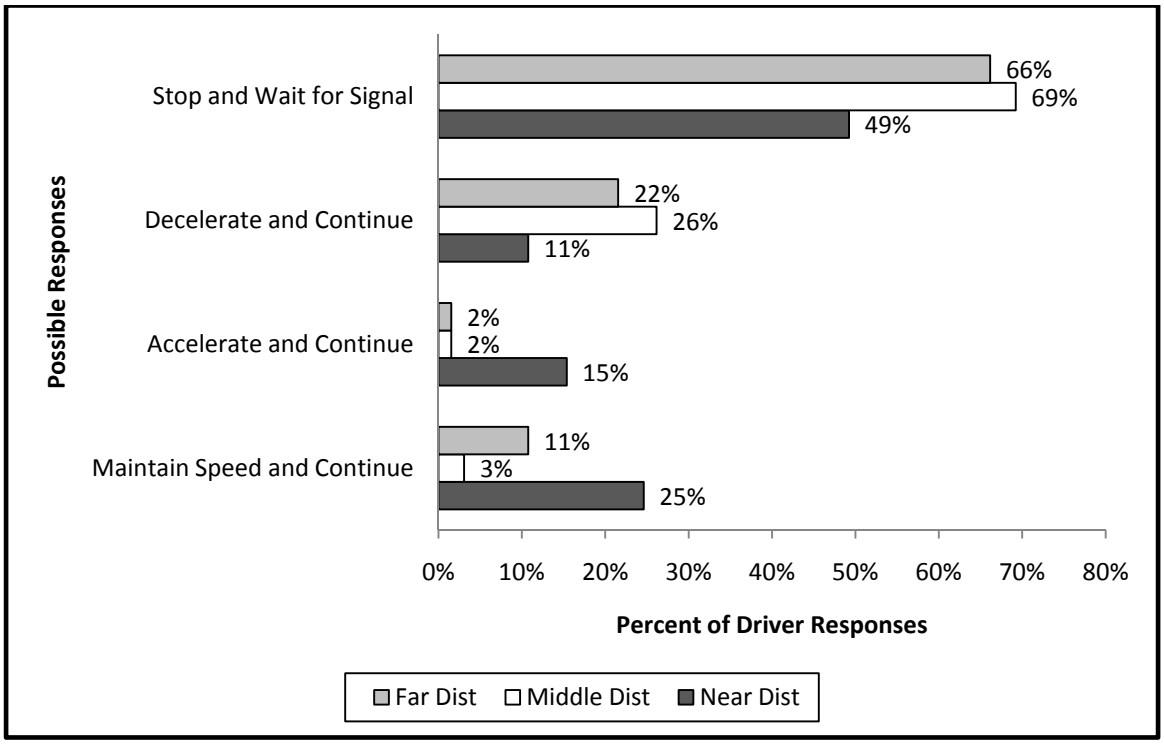

Figure 52 Predictive Behavior on 1 Lane Approach as Follow Vehicle

The data in Figure 52 represents three scenarios each of which involve an image taken from the driver seat of a following vehicle heading towards a CY indication on a single lane approach. Each scenario is taken from a different distance, far (200 ft), middle (100 ft), near (50 ft). The responses collected from the far and middle distances are fairly similar across all four possibilities. For these two scenarios 66 and 69 percent of drivers determined that they would *stop and wait for the signal*. For the near distance far fewer said that they would *stop and wait*, only 49 percent. The near distance also generated a much higher response for *maintain speed and continue* at 25 percent.

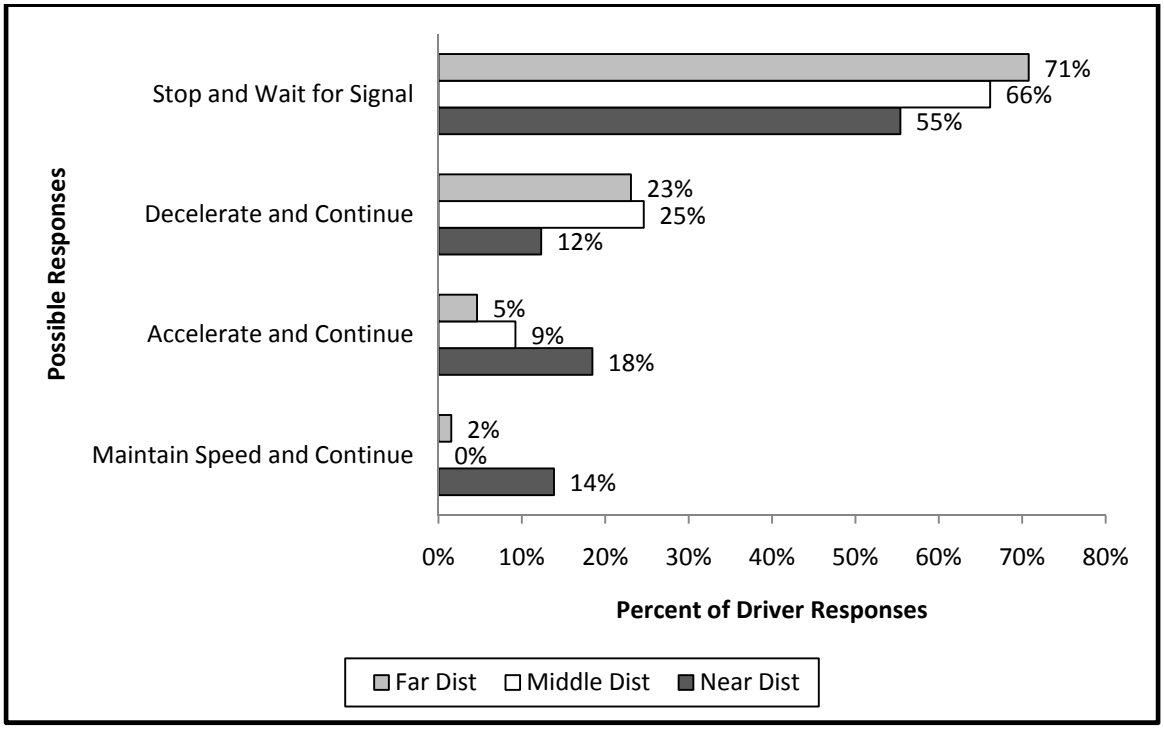

Figure 53 Predictive Behavior on 2 Lane Approach as Lead Vehicle

The information in Figure 53 represents three scenarios each of which involve an image taken from the driver seat of a lead vehicle heading towards a CY indication on a two lane approach. Each scenario is taken from a different distance, far (200 ft), middle (100 ft), near (50 ft). The responses collected from the far and middle distances are fairly similar across all four possibilities. For these two scenarios 71 and 66 percent of drivers determined that they would *stop and wait for the signal*. For the near distance far fewer said that they would *stop and wait*, only 55 percent. The near distance also generated a much higher response for *maintain speed and continue* at 14 percent.

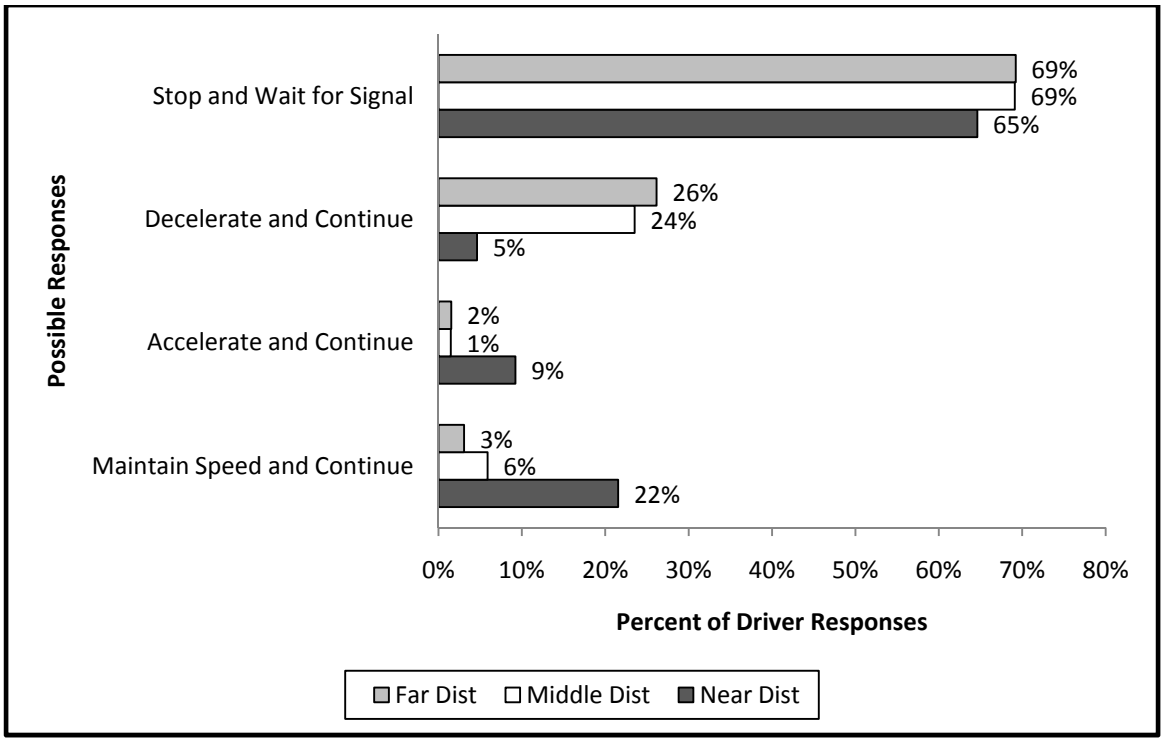

Figure 54 Predictive Behavior on 2 Lane Approach as Follow Vehicle

Figure 54 represents three scenarios each of which involve an image taken from the driver seat of a following vehicle heading towards a CY indication on a two lane approach. Each scenario is taken from a different distance, far (200 ft), middle (100 ft), near (50 ft). The responses collected from the far and middle distances are fairly similar across all four possibilities. For these two scenarios 69 percent of drivers determined that they would *stop and wait for the signal*. For the near distance far fewer said that they would *stop and wait*, 65 percent. The near distance also generated a much higher response for *maintain speed and continue* at 22 percent.

To expand upon the results from the predictive behavior evaluation numerous Chi-square tests were conducted. First, Chi-square tests were conducted on the data for each of the four figures (1 lane following vehicle, 1 lane lead vehicle, 2lane following vehicle, 2 lane lead vehicle) all four were determined to have statistically significant

differences in the distributions ($P < 0.001$). Next, the responses were examined across each of the four scenarios by distance (near, middle, far). Statistical differences in distribution were identified for both the near ($P = 0.029$) and middle ($P = 0.006$) distances but not the far distances ($P = 0.301$). Therefore, responses at the far distance were not impacted by scenario.

Lastly, the individual responses were considered in greater detail across each scenario. No statistical differences were identified for *stop and wait for signal* or for *accelerate and continue*. A closer examination of *maintain speed and continue* revealed that there was no difference being a lead or following vehicle on a one lane road ($P = 0.13$) however, on a two lane road drivers were much more likely to *maintain speed and continue* if they were the following vehicle ($P = 0.004$). It was also determined that while there was no difference between being a following vehicle on a one or two lane road ($P = 0.179$), it was more likely to maintain speed and continue if you were a lead vehicle on a one lane road rather than a two lane road ($P = 0.007$).

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

This chapter details the conclusions and recommendations that were developed from an examination of the results presented in Chapter 7. The conclusions and recommendations have been segmented to provide a better understanding of driver behavior and comprehension regarding the incursion of the solid yellow indication when approaching high-speed signalized intersections. The research scientifically evaluated the proposed research hypotheses.

The compilation of the results from each study hypothesis provided an increased understanding of driver behavior and comprehension when exposed to the solid yellow indication. This understanding has contributed to the improved design of vehicle detection systems and signal timing practices to provide increased dilemma zone protection thus augmenting intersection safety.

Conclusions of Research Hypotheses

The research presented herein was directed at addressing the research hypotheses. The following provides a review of the research hypotheses and research findings that pertain to each. A discussion of the research results is also included.

Hypothesis 1: Type II dilemma zone boundaries can be identified from observed driver behavior (stop/go action when exposed to the solid yellow indication), vehicle speed, and vehicle position for isolated at-grade high-speed signalized.

- Research results tend to support this hypothesis. The approach undertaken in the field allowed for an evaluation of the relationship between driver behavior and the various aspects of the intersection design, including geometry, signal timing, and detection strategies. Consistent with initial perceptions a similarly employed strategy at seemingly similar intersections resulted in varying degrees of driver behavior, including but not limited to stop / go behavior and red light running.
- The most significant contributions to the identified dilemma zones were the identified speed distributions and change interval timing. Using the plotted driver behaviors in Figures 16 to 24, there is some evidence to suggest that lengthening the yellow change interval duration may provide an added timeframe for safe driver decision making behavior. The plots can prove useful in determining both the presence and location of possible dilemma zones along the intersection approaches, information which will provide valuable in the development of strategies that will be used to eliminate and/or shorten the range.

Hypothesis 2: Advanced vehicle detection has the potential to provide superior dilemma zone protection when utilizing space sensors as compared to point sensors for isolated at-grade high-speed signalized intersections, where dilemma zone protection is defined by a reduction in the number of vehicles caught in a Type II dilemma zone.

- Research results tend to support this hypothesis. Within the framework of the state of the practice review, the potential application of a dynamic detection sensor was identified. In cooperation with Wavetronix, HighwayTech, and VTrans, a unit was installed at one of the intersection approaches and evaluated within the framework of this research study. The results were very positive with a reduction in red light running incidents and a redefined driver behavior plot (see Figure 31) which provided evidence of a smaller range of dilemma zone and fewer vehicles within the 2.5 to 5.5 second range. A resulting recommendation is that additional units be installed at potentially problematic intersections. However, an efficient mechanism that determines suitable locations by measuring the associated benefits should be established.

Hypothesis 3: Driver comprehension of the circular yellow indication is less than desirable for the safe and efficient operation of signalized intersections, where comprehension is evaluated across the dimensions of meaning, duration and sequencing of the indication.

- Research results tend to support this hypothesis. Several conclusions regarding driver comprehension can be reached based on an examination of the results from the static evaluation. With regards to the meaning of the solid yellow indication correct responses across all displays ranged from a low of 34 to 83 percent. This was an unexpected result potentially contradicting the belief that drivers have a high comprehension rate for the solid yellow indication.

- Only between 42 to 59 percent of drivers were able to recognize the MUTCD recommended duration of a yellow indication. If drivers cannot predict the length of the yellow indication they will have significant difficulty in performing the correct behavior, and
- On average drivers showed a high level of understanding (greater than 80%) when identifying what display would follow after the YA or CY. However, drivers showed significant difficulty in comprehending both the meaning of and the appropriate sequencing of the five section cluster when presenting a YA+CG display. This adds to the existing concern about dual indications and drivers ability to comprehend them.

Recommendations

The data and conclusions of this research effort has led to a series of research recommendations as follows:

- The field evaluation and data collection strategy undertaken could be formalized and developed as a routine evaluation technique that could be used at other locations to evaluate the nature and extent of dilemma zone issues. Consideration should be given to the creation of a formal dilemma zone identification field study.
- The implementation of space sensors at high-speed signalized intersections for the provision of dilemma zone protection can be a beneficial strategy under the appropriate conditions.

- An additional recommendation is that consideration be given to expanding upon the results herein through future research as described in the following section.

Future Research

Several additional areas of future research related to the topics detailed herein have been identified. Future research recommendations include but are not limited to the following:

- This body of work generated a wealth of field data, although the results of this study were determined to be significant, future study ought to expand upon the sample size of dilemma zone incursions in the field. These additional observations should be collected at a variety of signalized intersections where aspects such as regional variation, geometric characteristics, functional classification, approach speeds and other traffic stream parameters vary.
- This study provided preliminary evidence to suggest that valuable information can be acquired through static evaluation. Larger samples of drivers must be recruited to participate in the static evaluation. An effort should be made to identify the impact of at risk user groups, such as younger and older drivers, as well as the impact of geographic variability on driver behavior,
- The comprehension data collected from the static evaluation should be regressed against the predictive behavior with larger sample sizes and geographic variability, and

- The data collected in the naturalistic study and the static evaluation should be incorporated into a mathematical model of both driver behavior and the boundaries of the dilemma zone.

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