An Evaluation of Dilemma Zone Protection Practices for Signalized Intersection Control

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An Evaluation of Dilemma Zone Protection Practices for Signalized Intersection Control

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16. Abstract

One of the most critical elements at signalized intersections is the design of detection equipment and timing of change and clearance intervals. Improperly timed change intervals can potentially place drivers in a 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. The 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 effort was conducted on behalf of the Vermont Agency of Transportation (VTrans) to identify and address potential concerns with regards to dilemma zone safety at five high-speed signalized intersections. The study included an assessment of existing VTrans change and clearance interval timing practices and detector design layouts, a review of the current state of the practice with respect to change interval design, and recommendations of potential methods of improved design practices.

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Final Report:
An Evaluation of Dilemma Zone Protection Practices for Signalized Intersection Control

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Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Vermont Agency of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Executive Summary

The research project titled, “An Evaluation of Dilemma Zone Protection Practices for Intersection Control” was undertaken by the University of Massachusetts Amherst Transportation Research Center (UMassUTC) for the Vermont Agency of Transportation (VTrans).

One of the most critical elements at signalized intersections is the design of detection equipment and timing of change and clearance intervals. Improperly timed change intervals can potentially place drivers in a 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. This research effort was conducted on behalf of the Vermont Agency of Transportation (VTrans) to identify and address potential concerns with regards to dilemma zone safety at five high-speed signalized intersections.

The study included an assessment of existing VTrans change and clearance interval timing practices and detector design layouts, a review of the current state of the practice with respect to change and clearance interval design, the empirical observations of dilemma zone incursions at 5 selected signalized intersections, the examination of a new advanced vehicle detection system for dilemma zone protection, and recommendations of potential methods of improved design practices across the state.

To complete this project the following series of tasks were undertaken:

- Task 1: Collect signal and roadway alignment plans and interview staff,
- Task 2: Collect and reduce speed data,
- Task 3: Collect and reduce vehicle position and driver behavior data,
- Task 4: Identify Vermont dilemma zone and signal timing issues,
- Task 5: Conduct literature synthesis and interviews on dilemma zone protection,
- Task 6: Conduct field test of an alternative vehicle detection system, and
- Task 7: Document findings.

These tasks were identified in collaboration with VTrans in accordance with the original project proposal, except in the case of Task 6. The opportunity to pursue Task 6 became apparent during the course of the original research project and was adopted as a critical component of the research effort with the support of VTrans representatives.

As noted, the overarching objectives of this research project were to evaluate the effectiveness of current dilemma zone practices currently utilized within the State of Vermont at high-speed signalized intersection. Similar to many agencies, the typical strategy includes a combination of signal timing and advanced detection technology. Yet, the perception was that at similar locations with a similar dilemma zone strategy, one intersection may operate safely and efficiently while another may not. To address this issue, the extent to which dilemma zone issues exist was evaluated in the field in an effort to identify factors that may be contributing to the creation of a dilemma zone. Overall, the following conclusions were drawn:

- 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.
- Based upon the field results it is recommended that consideration be given to lengthening the yellow interval times for intersection approaches where the existing yellow interval is shorter than the current ITE calculation values.
- The application of the field results can be employed in determining the extent of existing dilemma zone problems as well as to provide insight on possible mitigation, including the potential benefits associated with signal timing changes (i.e., lengthening the yellow interval) and detection strategies (i.e., detector placement).
- 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.
- Within the framework of the state of the practice review, the potential application of a dynamic detection sensor was identified. 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 RLR incidents and a redefined driver behavior plot 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 some mechanism for determining suitable locations and the associated benefits should be established.
- Given the identification of this baseline data, it is recommended that future strategies and / or changes at these intersections be evaluated in a similar manner. A specific example may include the resulting impact from lengthening of change intervals at selected locations. Additionally, the impact resulting from installation of additional Wavetronix units as well as the impact of varied settings should also be evaluated.

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1.0 Introduction

The primary goal of this project is to assist the Vermont Agency of Transportation (VTrans) in evaluating current and potential practices for dilemma zone protection, which will culminate in a recommended methodology for identifying dilemma zone issues and optimizing detector design and / or traffic signal controller settings. The study also includes an assessment of existing VTrans signal timings, detector design practices, as well as a review of the current state of the practice with respect to dilemma zone protection.

2.0 Overview of Methodology

To complete the research project goal and achieve all of the associated project objectives, a series of tasks were undertaken. The primary project tasks and corresponding interrelationships to project objectives are presented in Figure 1 to provide a model for the structure of the research project. Although many of the project tasks were completed somewhat independent of one another, much of the proposed project work was complementary in nature and happened concurrently. A brief description of the project tasks is included in the following section.

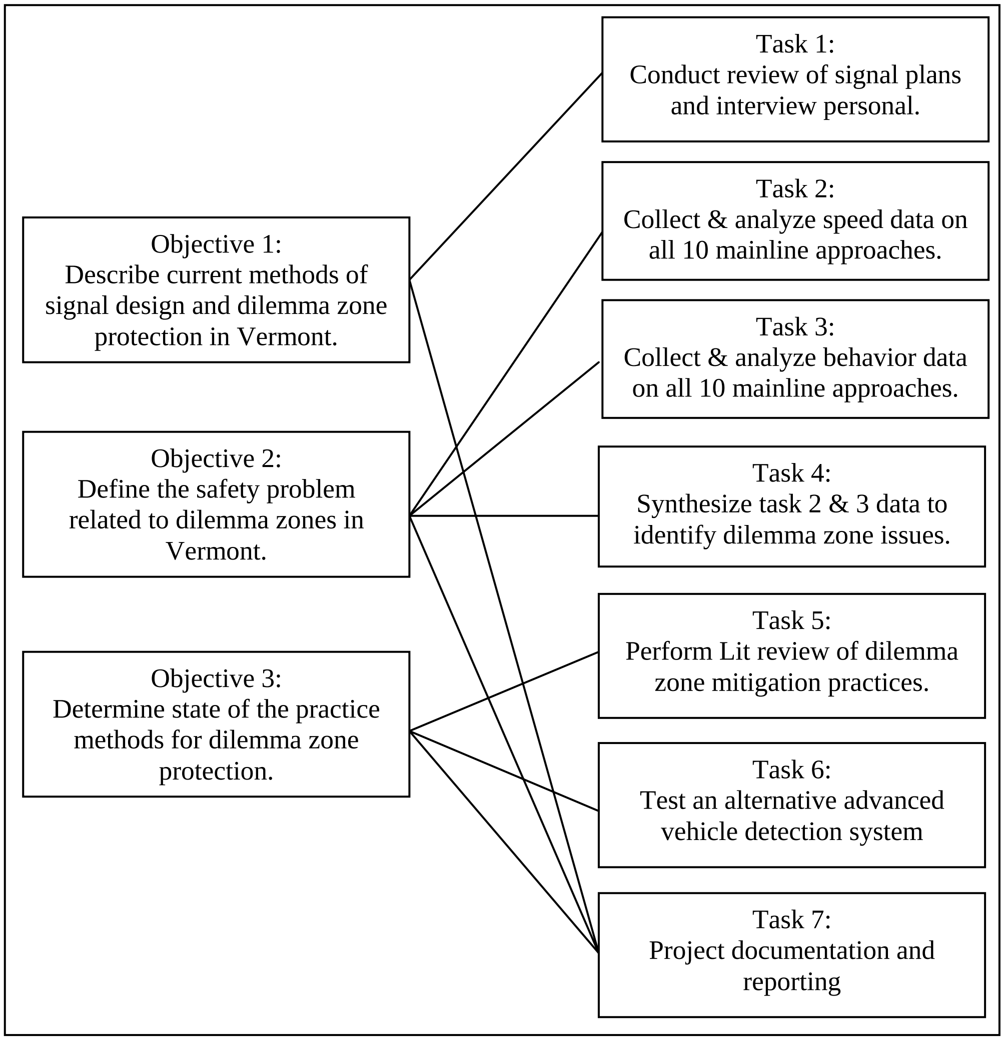

Figure 1 Relationship of project objectives and primary tasks

Task 1: Collect Signal and Roadway Alignment Plans & Interview Staff

In an effort to develop an understanding of the unique characteristics of the state owned and operated intersections, the initial project task consisted of site visits and interviews with key personnel. Primary outcomes of this task included an understanding of the design and geometric conditions of the signalized intersections, as well as a review of existing actuation and timing procedures.

Task 2: Collect and Reduce Speed Data

The speeds of vehicles approaching a signalized intersection are considered in the calculation of the change and clearance intervals at that particular intersection. The speed of a particular vehicle at the onset of the yellow also contributes to the likelihood that a particular vehicle will be caught in a dilemma zone. Therefore speeds of each passing vehicle were collected at the advanced detector on each of the 10 intersection approaches evaluated. These speeds were reduced and descriptive statistics were applied to identify the mean, 85^{th}, and 95^{th} percentile speeds.

Task 3: Collect and Reduce Vehicle Position & Driver Behavior Data

To determine the extent of the safety concerns related to dilemma zone issues at the study intersections in Vermont, it was necessary to identify the position of each approaching vehicle at the onset of the yellow indication and the related driver behavior. To accomplish this task, 60 hours of video observation was collected on each intersection approach. This information was digitized and the vehicle position was identified to the nearest 50 feet, as well as the driver reaction (stop, go on yellow, or go on red).

Task 4: Identify Vermont Dilemma Zone & Signal Timing Issues

A variety of different speeds were used to calculate proposed change and clearance interval timings, which were compared to the current timings employed by the state. Theoretical dilemma zones were calculated for each of the intersection approaches using the observed speeds and driver behaviors. Dilemma zone incursions were identified using vehicle speed and position. Then, the reactions of vehicles identified to have been caught in a dilemma zone were examined.

Task 5: Conduct Literature Synthesis and Interviews on Dilemma Zone Protection

A review of published technical reports and academic journal articles was conducted for the purpose of identifying state of the art practices regarding signal timing, vehicle detection, and advanced warning to providing dilemma zone protection.

Task 6: Test an Alternative Advanced Vehicle Detection System

A field comparison of a new advanced vehicle detection technology was conducted. The experiment was specifically designed for the purpose of identifying the degree to which the new system could provide improved dilemma zone protection as compared to the existing protection provided by the currently implemented VTrans strategies.

Task 7: Documentation of Findings

The final project task was the completion of documentation, represented by the submission of this report. This project was intended to identify current VTrans procedures for the timing of change and clearance intervals as well as for providing dilemma zone protection, to define the severity of dilemma zone issues at 5 intersections in Vermont, and to propose dilemma zone protection techniques currently used by other state agencies. This report is written to document the research conducted and as a resource for personnel responsible for decisions on the development of dilemma zone protection at high-speed signalized intersections within VTrans.

3.0 State of the Practice

3.1 Introduction

This state of the practice review attempts to include relevant information from as many sources as could be readily 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 review of applicable technical journals and conference presentations on the subject. Figure 2 is a schematic of the organizational structure and approach implemented in the state of the practice review.

The state of the practice regarding signal design as it relates to the minimization of dilemma zone issues was condensed into the three key areas: change and clearance intervals, dilemma zone definitions, and dilemma zone mitigation strategies. The following subsections will delve into each of these areas with greater concentration.

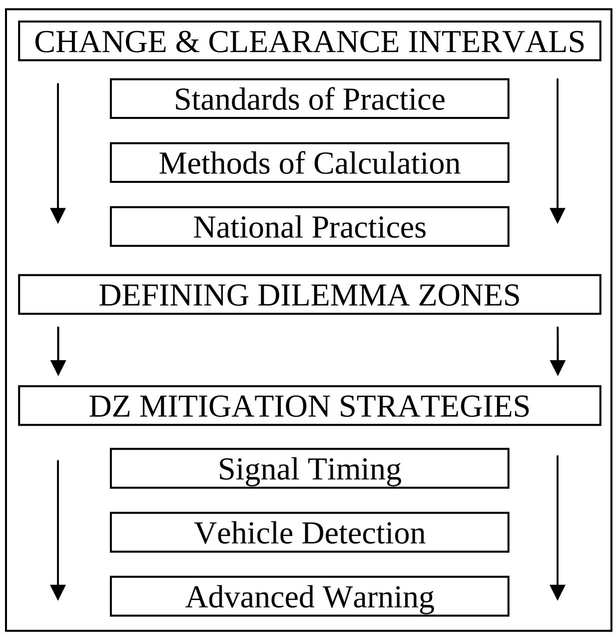

Figure 2 State of the Practice Organizational Structure

3.2 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 (1). For the purpose of clarity, this document will adopt a consistent usage of both terms. The change interval describe the yellow indication which is displayed at the termination of the green indication in advance of the red or all red interval, and the clearance interval will refer to the all red interval (1). The change interval serves to alert oncoming vehicles that the right-of-way allocated to the current approach is about to be reassigned (2). It allows for an approaching vehicle which is presented with the termination of the green indication, and which has insufficient stopping distance to decelerate and safely come to rest at the stop line, to maintain its speed and legally enter the intersection on the yellow (1). Crossing the stop line with the front wheels of the vehicle is the accepted definition of entering the intersection (1). The typical duration for the change interval at a high-speed intersection is approximately 5 seconds (2).

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 (1). The typical duration of the clearance interval at a high-speed intersection is approximately two seconds (2). This process is intended to mitigate potentially serious right-angle crashes.

3.2.1 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 somewhat 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 (3).*

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 chance interval is the statement by the MUTCD that:

> *A yellow change interval should have a duration of approximately three to six seconds. The longer intervals should be reserved for use on approaches with higher speeds (3).*

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 (3).*"

3.2.2 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 (2,4) is as follows:

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

Where:

y = length of change interval (seconds)
t = driver reaction time (typically 1 second)
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 (positive for upgrade, negative for downgrade, express as decimal)
64.4 = twice the acceleration of gravity (ft/s/s)

While the ITE equation for the clearance interval (2,4) is calculated as:

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

Where:

r = length of clearance interval (second)
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 (2,4).

3.2.3 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 (4). 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 the results do not add up to 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.

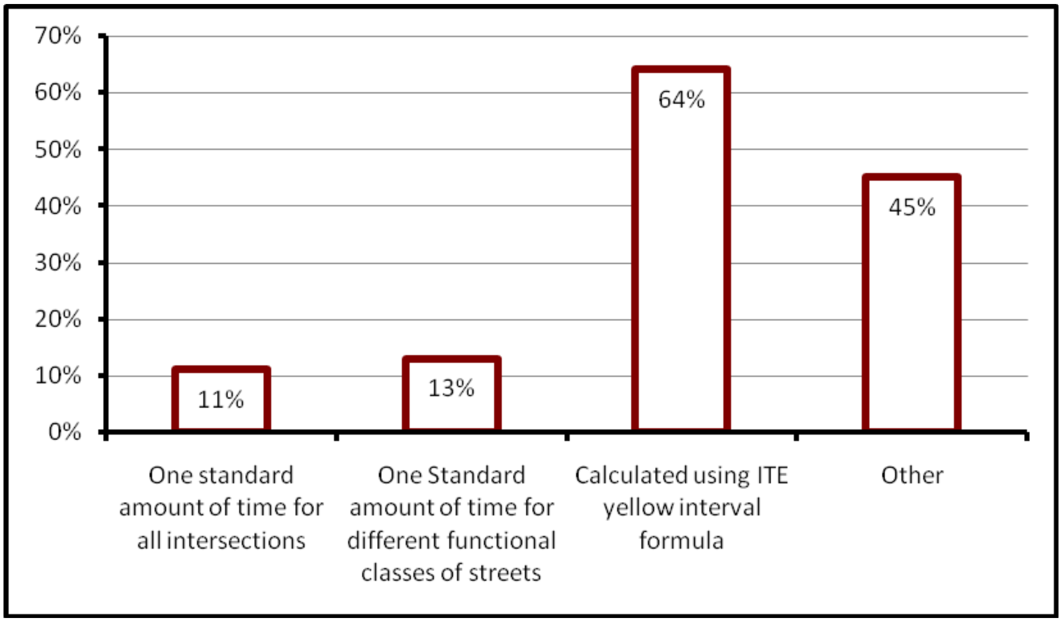

Figure 3 Yellow Change Current Practices (4)

It should be noted that the "other" category for the change interval included yellow times proportional to speed or red interval, values adjusted based on vehicle speeds, increases for high speed or wide intersections, and if yellow abused, add extra all red time. As shown, the most common approach among responding agencies for the determination of change intervals (with 64%) is the ITE recommended equation. It should be noted that there may be a potential for bias towards the ITE approach amongst those responding to an ITE sponsored survey.

Figure 4 displays the results of the survey question 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.

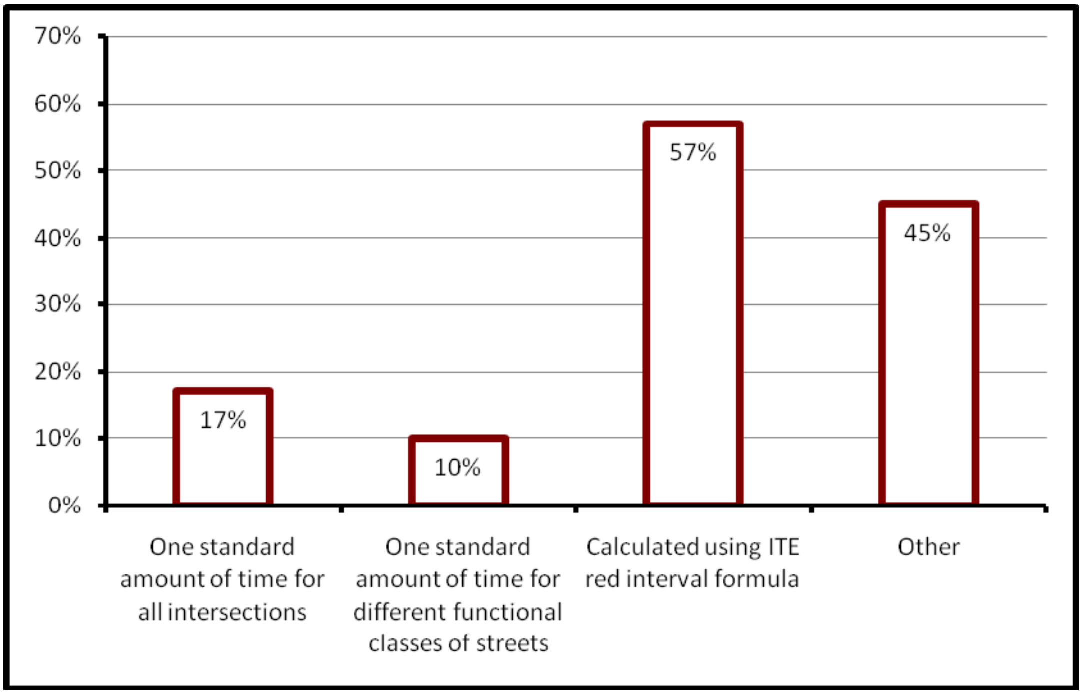

Figure 4 Red Clearance Current Practices (4)

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.

3.3 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 two general classes of dilemma zone conflicts (Type I and Type II). The Type I dilemma zone was first referenced in the literature by Gazis in 1960 (5). Figure 5 shows a diagram of a traditional Type I dilemma zone.

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 (6). Figure 6 shows a diagram of a traditional Type II dilemma zone.

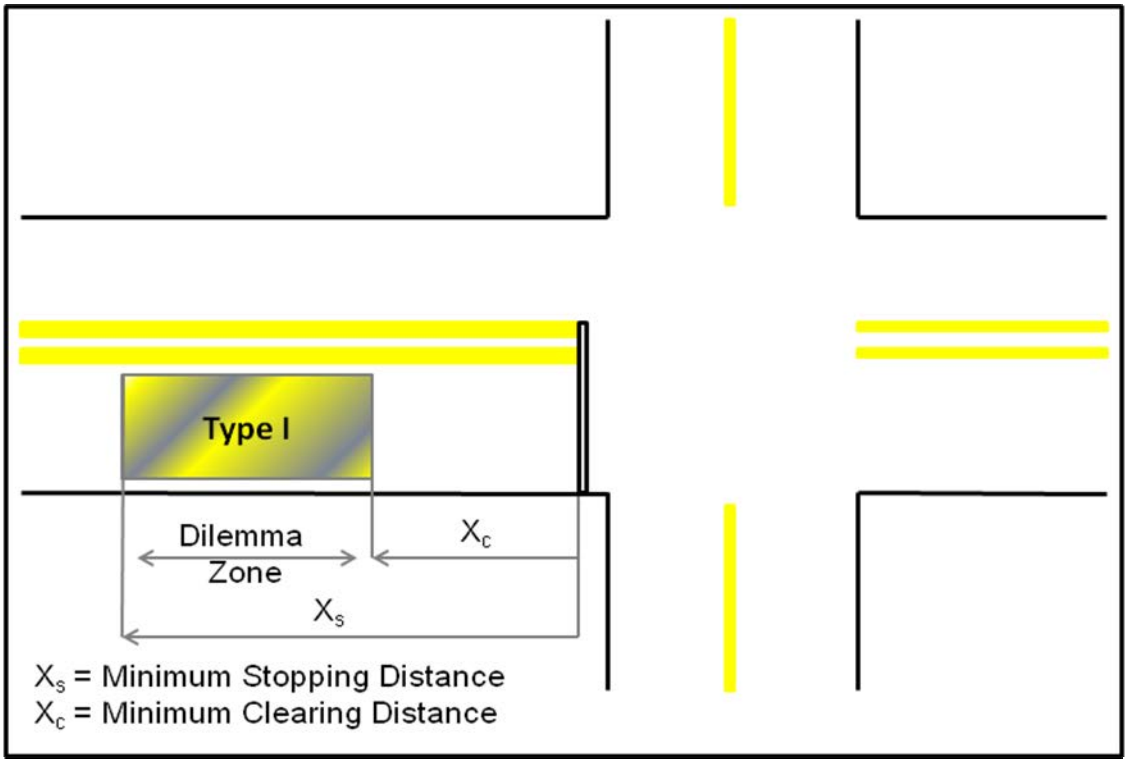

Figure 5 Type I Dilemma Zone Diagram

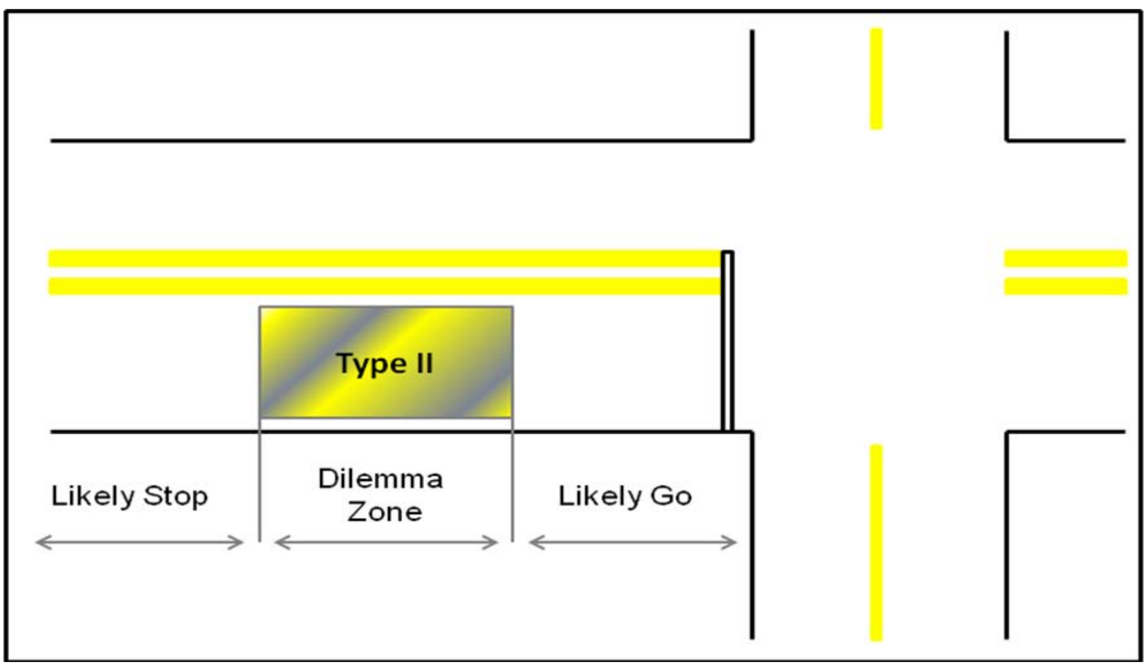

Figure 6 Type II Dilemma Zone Diagram

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 driver 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 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 (7). 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 three 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 (8). 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.

3.4 Mitigation

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

3.4.1 Signal Timings

The impact of signal timing methods and practices are of critical concern in any discussion of signalized intersection safety. In prior sections, this document has 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 and a concern of lengthening all-red times, the North Carolina Department of Transportation (NCDOT) prepared a formal request to investigate traditional signal timing practices and recommend timing practices for the determination for change and clearance intervals (9,10). 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* (11). They also recommended rounding any calculated yellow time up to a minimum time of 3.0 seconds, and holding a stakeholders meeting before accepting any yellow time greater than 6.0 seconds (9, 10). Figure 6 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 second 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 (9, 10). 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 (seconds)
W = width of intersection (ft)
V = 15^{th} 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 second threshold, requires stakeholder meeting prior to approval

Figure 8 Sample Red Intervals (9, 10)

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 Carolina 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 also 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 (12).

In 1998, Sacramento County, California, strayed from the commonly adopted ITE equations for the establishment of change and clearance interval timings (13). 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 an assumed deceleration rate of 10 ft/sec^2 and 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 CA.

Speed (mph)	Far Dilemma Zone Boundary (ft from stop bar)	Travel Time from Far Dilemma Zone Boundary to Stop Bar = Recommended Yellow Clearance (seconds)	Minimum Yellow Clearance per California MUTCD (seconds)
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

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

3.4.2 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 (7). 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 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 designed by the Texas Transportation Institute. The D-CS system is comparable with previous detector systems used to eliminate potential dilemma zones, however one major improvement was that it considered a vehicles speed and size in it is estimation of whether a vehicle would in fact be in a dilemma zone. (14). 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 distance 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 (15). Additional information about the Wavetronix SmartSensor Advance is included in Chapter 5.

Figure 10 Installation of Wavetronix SmartSensor Advance in Vermont

As with any new intelligent intersection strategy, the Wavetronix SmartSensor Advance technology has not had 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.

3.4.3 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, taken on Route 7 south of Route 103 in Vermont, of a typical AWS configuration. This particular AWS 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 sing 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"*(16).

The myriad of previous research effort 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 (17).

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 (17).

This preferred AWEGS provided less delay due to stoppages at the traffic signal and provided 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 (17).

4.0 Driver Behavior in Vermont

4.1 Introduction

A field assessment of current VTrans high-speed signalized intersection design and control was conducted to quantify the existence and impact of Type I or Type II dilemma zone. The operational field evaluation considered existing intersection approach speeds, current change and clearance interval timing, maximum green times, unit extensions, detection zone, and the positioning of motorists approaching the intersection to determine the likelihood of a dilemma zone creation. Additionally, drivers' reactions were recorded (i.e., proceed or stop). The number of vehicles observed varied by intersection volume; however it should be noted that the selection of appropriate intersections was completed in consultation with VTrans staff.

4.2 Current VTrans Design & Operations Strategies

Several design and operational strategies are currently implemented by VTrans to promote the safe and efficient operation of 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 typically 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 released into the intersection.

Several locations are also equipped with static AWFs. These sign/signal systems are composed of a signal ahead sign positioned at the roadside in advance of a signalized intersection and are affixed with a pair of amber flashing lights which always remain on. This warning system is designed to alert approaching drivers that there is a signal ahead and they may be required to stop.

4.3 Methodology

The project methodology was developed to address the aforementioned research goal of 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 Clarendon, 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 to provide insight into individual vehicle behavior. Figure 12 shows a completed installation of an ATR in Berlin, Vermont.

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, a researcher on a ladder in a safety vest mounting a camera (top left), a completed camera installation on a lighting fixture (right), and a zoomed in image of the camera attachment (bottom left).

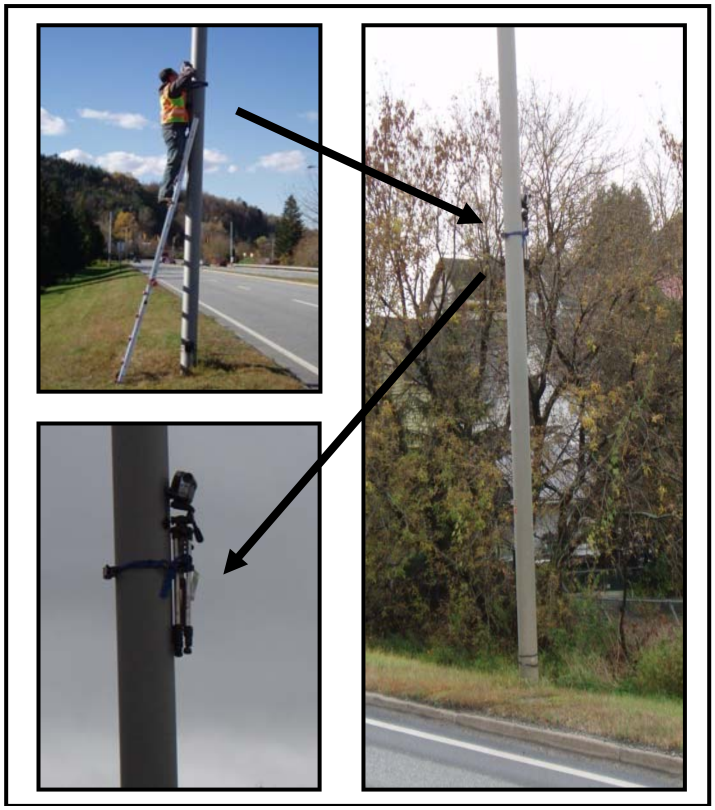

Figure 13 Example of Typical Video Camera Installation

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 researchers were trained, 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. The compiled data set was then used for further analysis as described in the following section.

4.4 Results

The field experiment included the observation of traffic signal operation, vehicle approach speeds, and resulting driver behavior. This section describes the information which was gleaned from this effort.

4.4.1 Speed

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, 85^{th}, and 95^{th} 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 85^{th} percentile speeds on Route 7 ranged from 56 mph to 60 mph while the 85^{th} 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	40	40	50	50
ADTs	7458	7440	6662	3840	7396	8773	6958	5400	7120	8434

Once the speed data was reduced, different critical speed values (e.g., posted speed, mean speed, 85^{th} and 95^{th} 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 distances traversed can be observed on the northbound approach to the intersection of Route 7 and Route 103 at a distance of 526 ft.

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, further examination of the sensitivity analysis displayed in Table 5 was compared with the evidence provided in Figure 15. As shown the application of four 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.

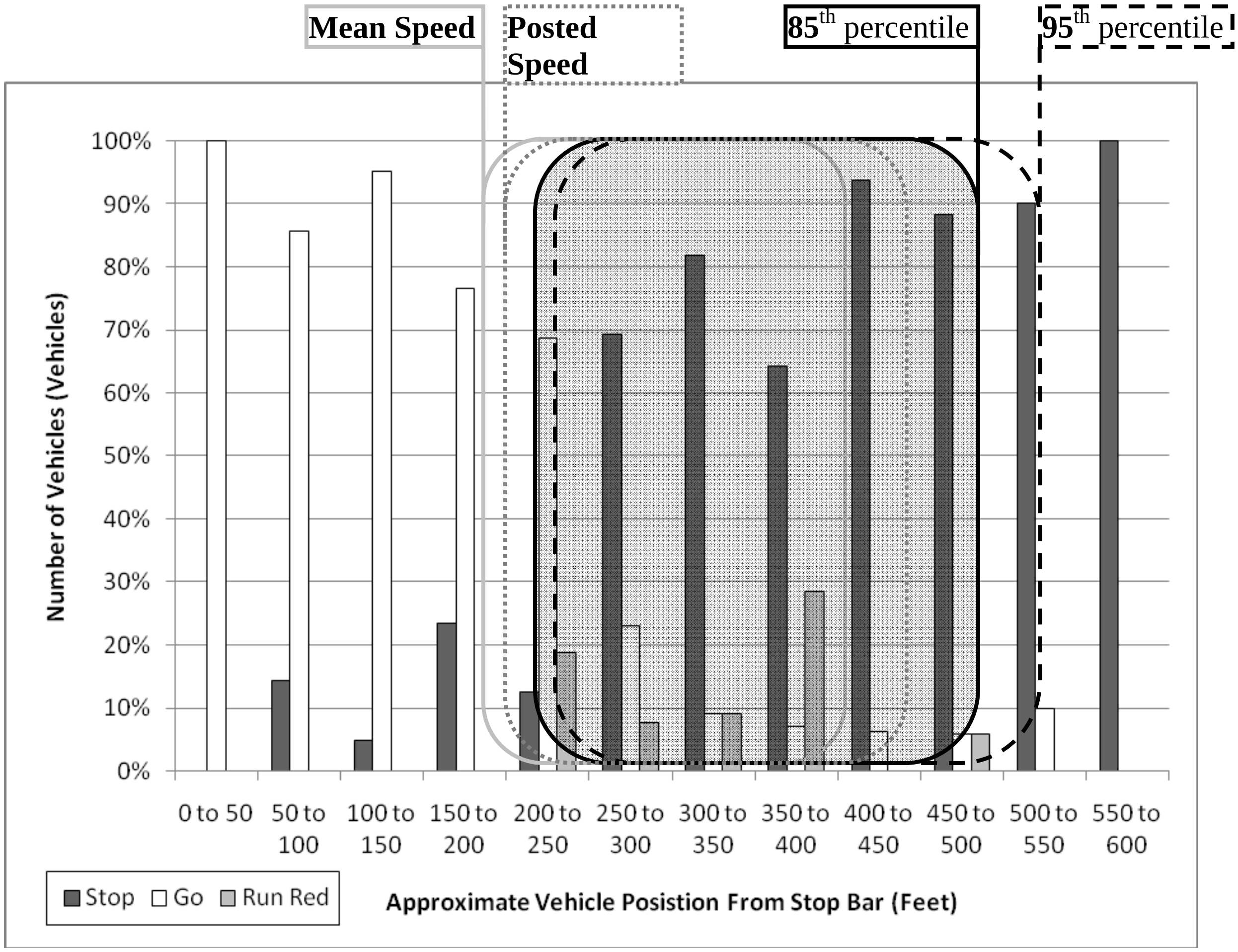

Figure 15 Influence of Selected Approach Speed on Type II DZ Boundaries

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.

4.4.2 Position & Behavior

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 16 through Figure 24 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 approach. These figures were also used to describe the existing 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 seconds to 5.5 seconds 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.

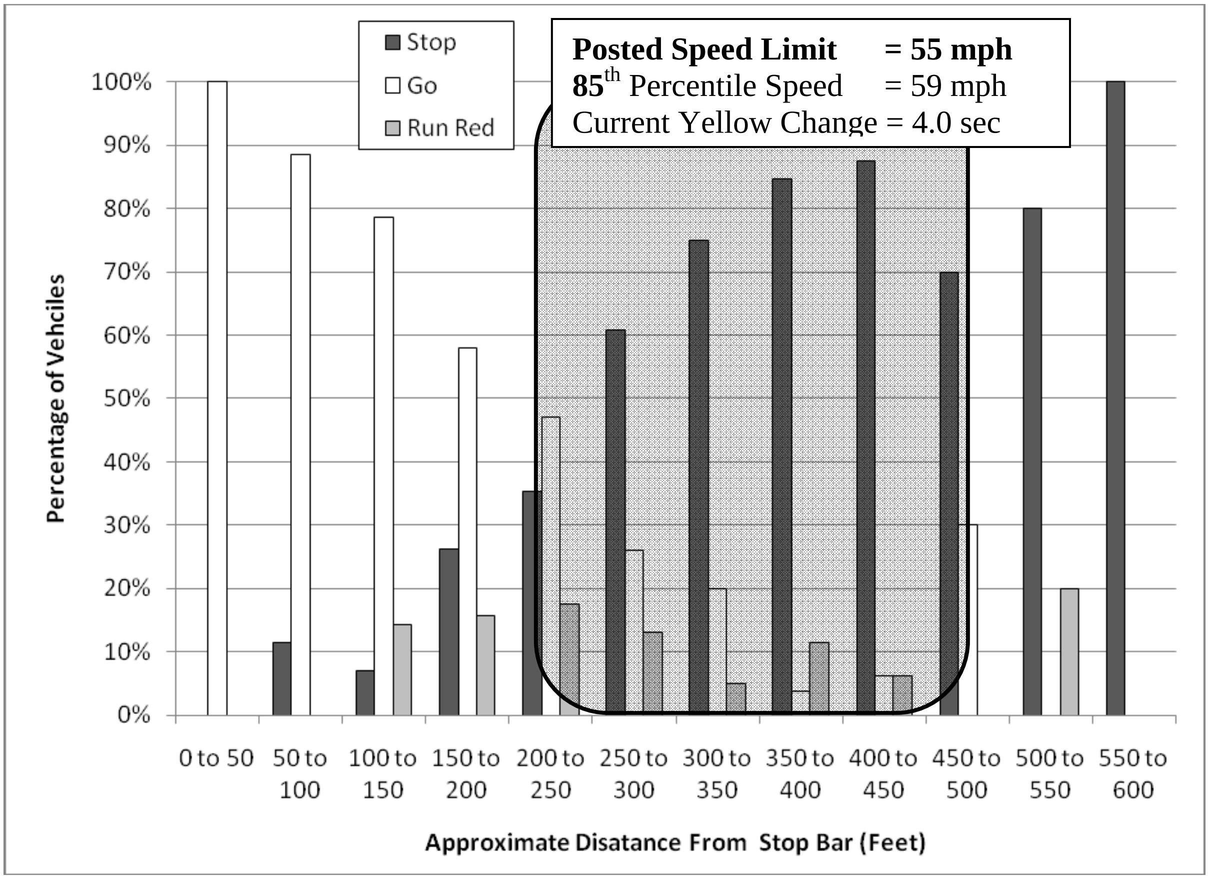

Figure 16 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication North Shrewsbury @ Route 7 (Southbound Approach)

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 is a larger than may be expected tendency for drivers to run the red light from the 500 to 550 ft back from the stop bar. Based on the 85^{th} 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 RLR, although it seems that there is some RLR in the 100 to 200 ft region that 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.

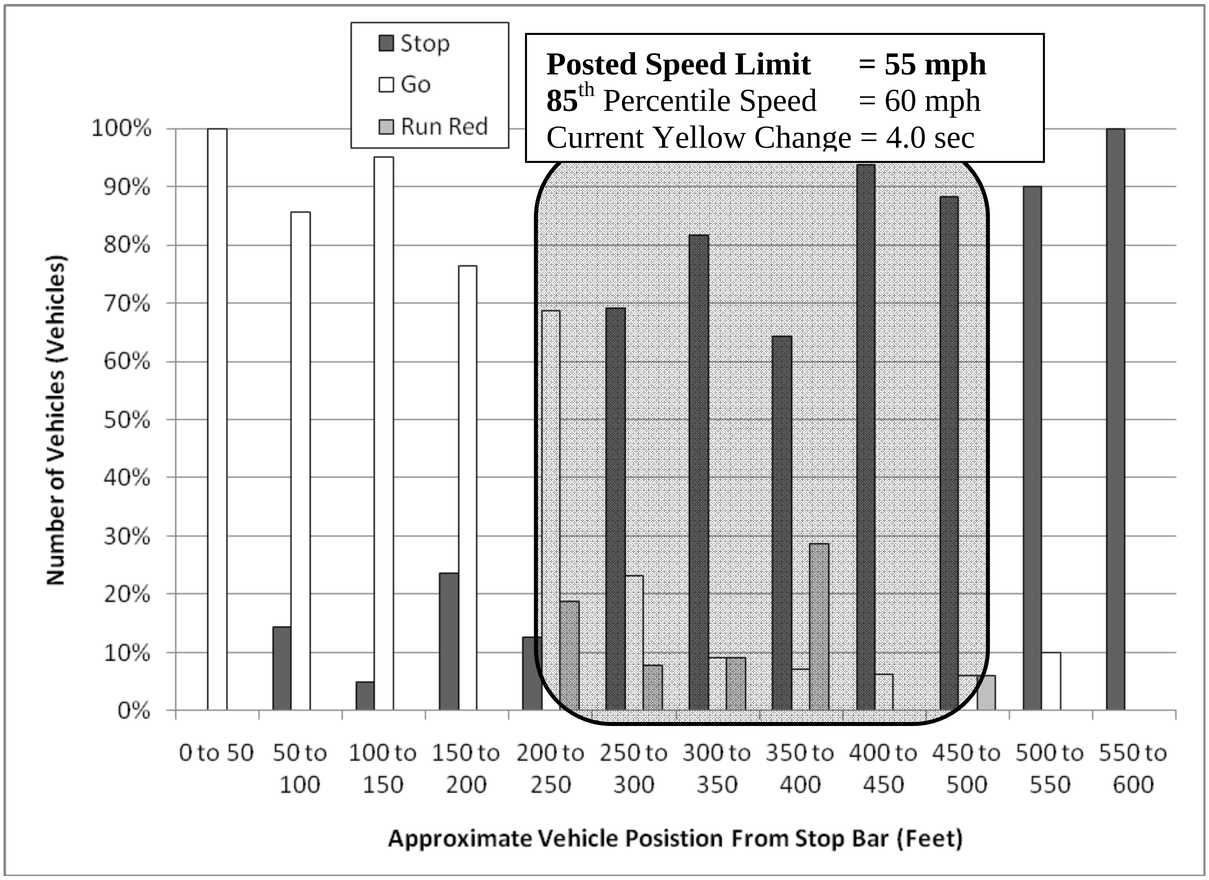

Figure 17 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Route 103 @ Route 7 (Northbound Approach)

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 RLR. 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.

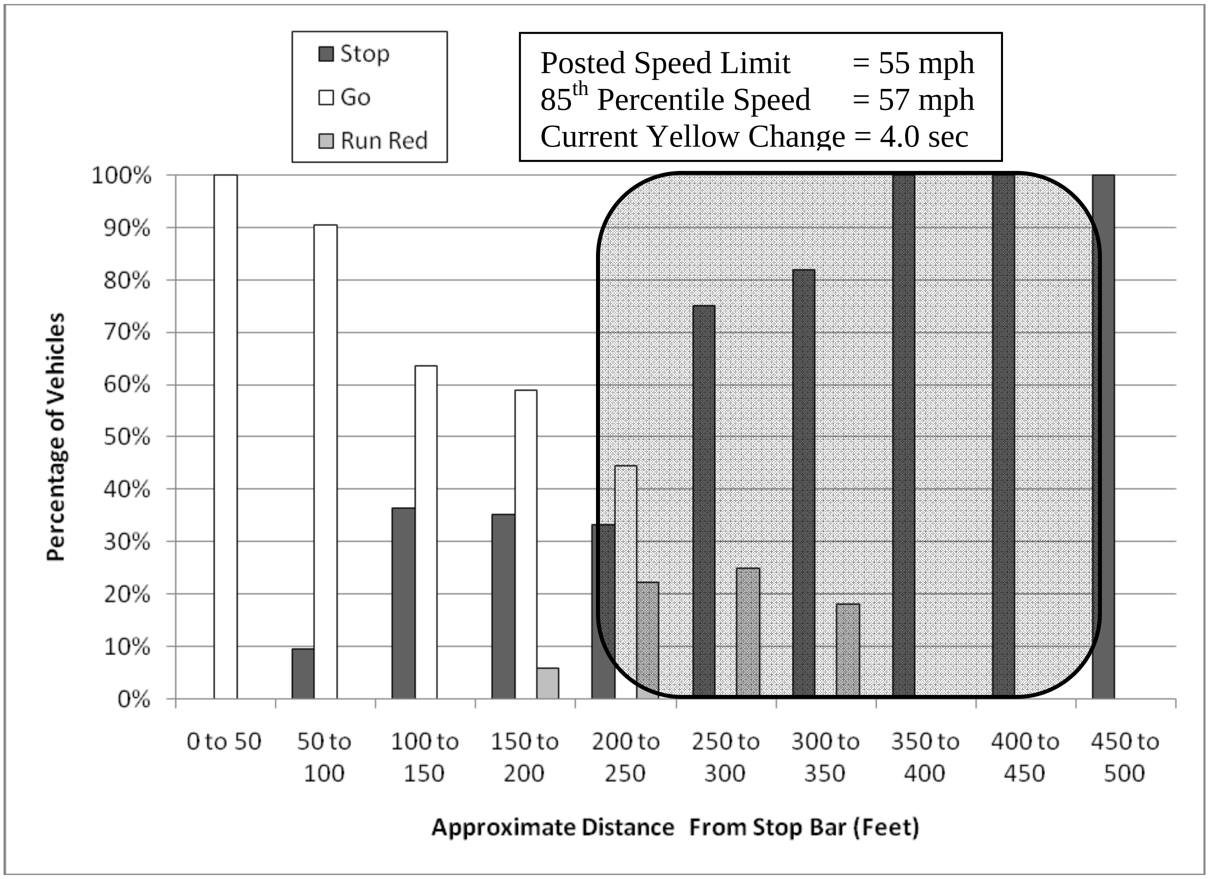

Figure 18 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Route 103 @ Route 7 (Southbound Approach)

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 RLR, 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.

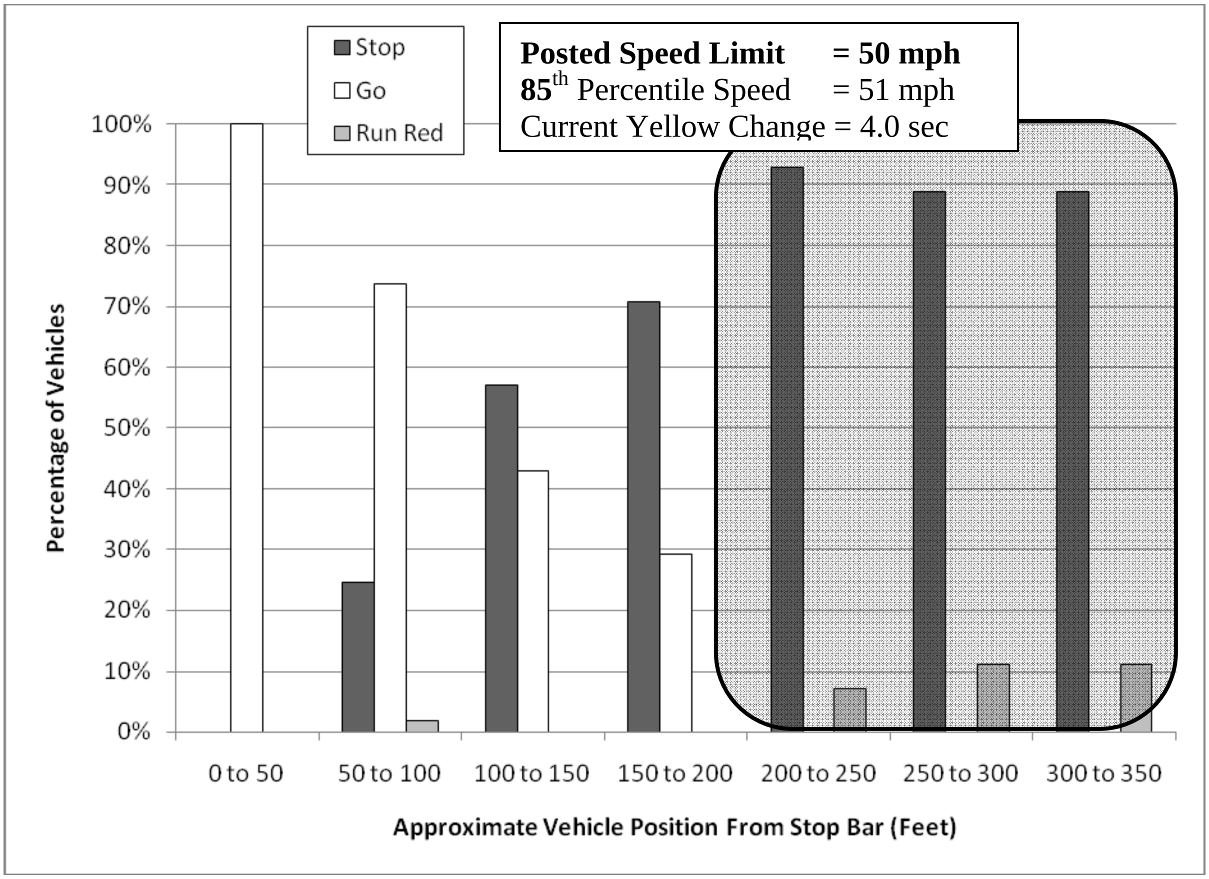

Figure 19 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Paine Turnpike @ Route 62 (Eastbound Approach)

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 85^{th} 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. Nevertheless, this region seems to correlate relatively nicely with the presence of increased percentages 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 4.85 seconds in duration.

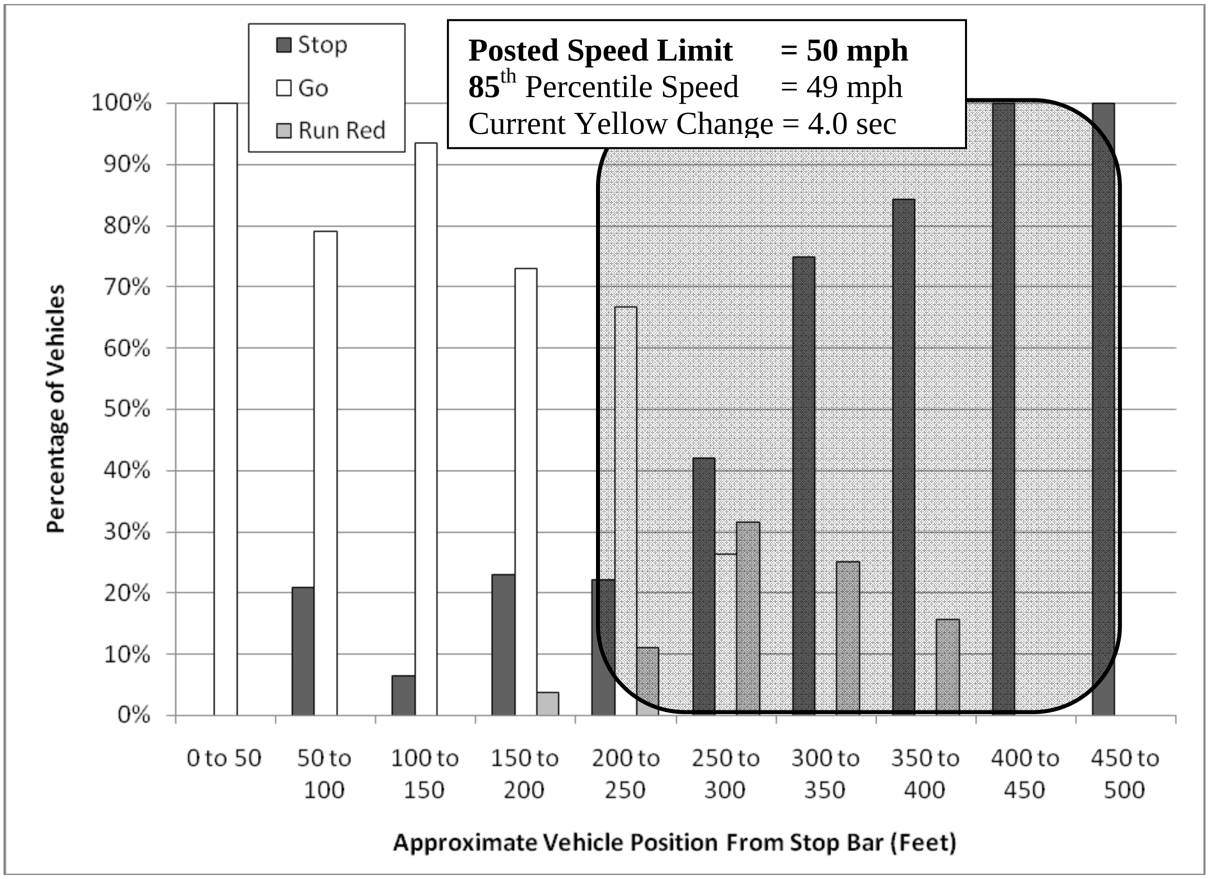

Figure 20 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Paine Turnpike @ Route 62 (Westbound Approach)

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. This region seems to correlate relatively nicely with the presence of increased percentages 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.

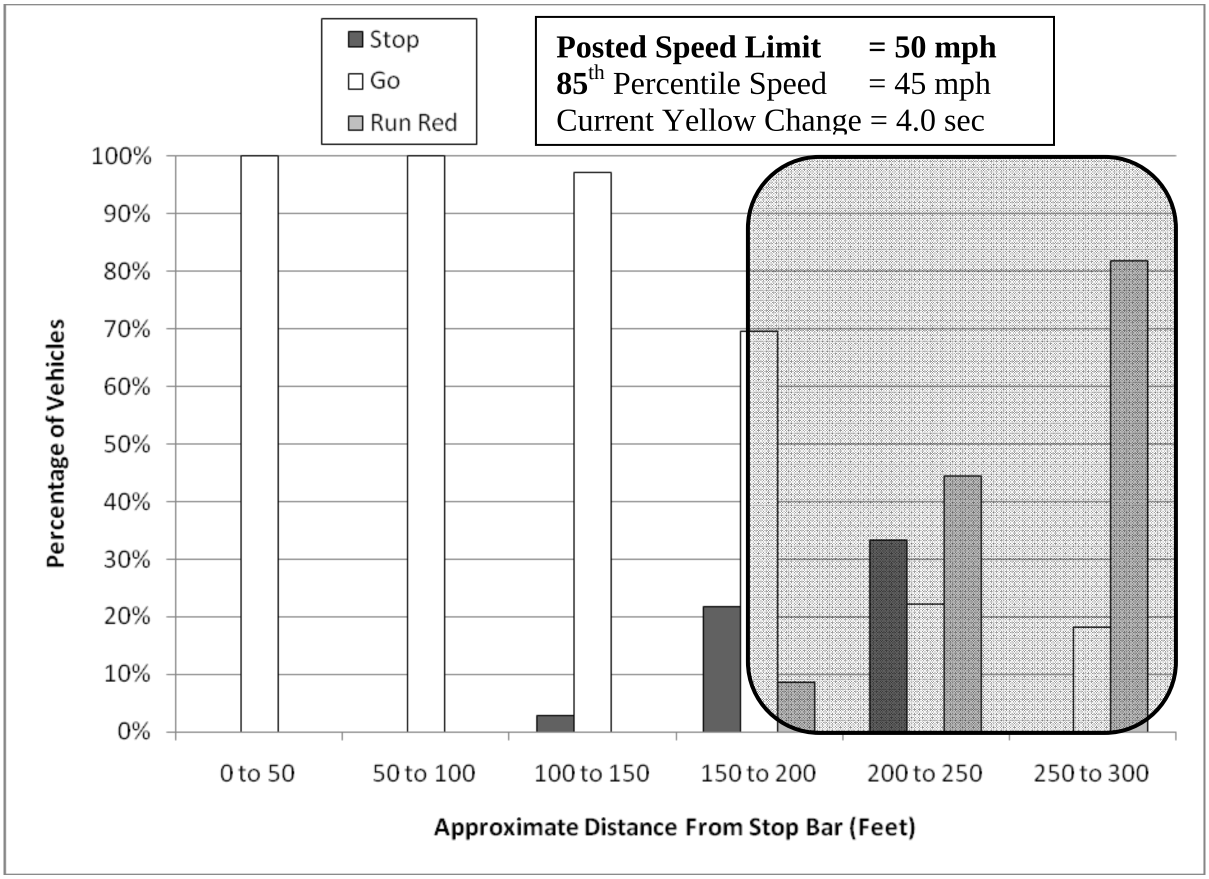

Figure 21 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Airport Road @ Route 62 (Eastbound Approach)

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 85^{th} 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. This region seems to correlate relatively nicely with the presence of increased percentages 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 4.87 seconds in duration.

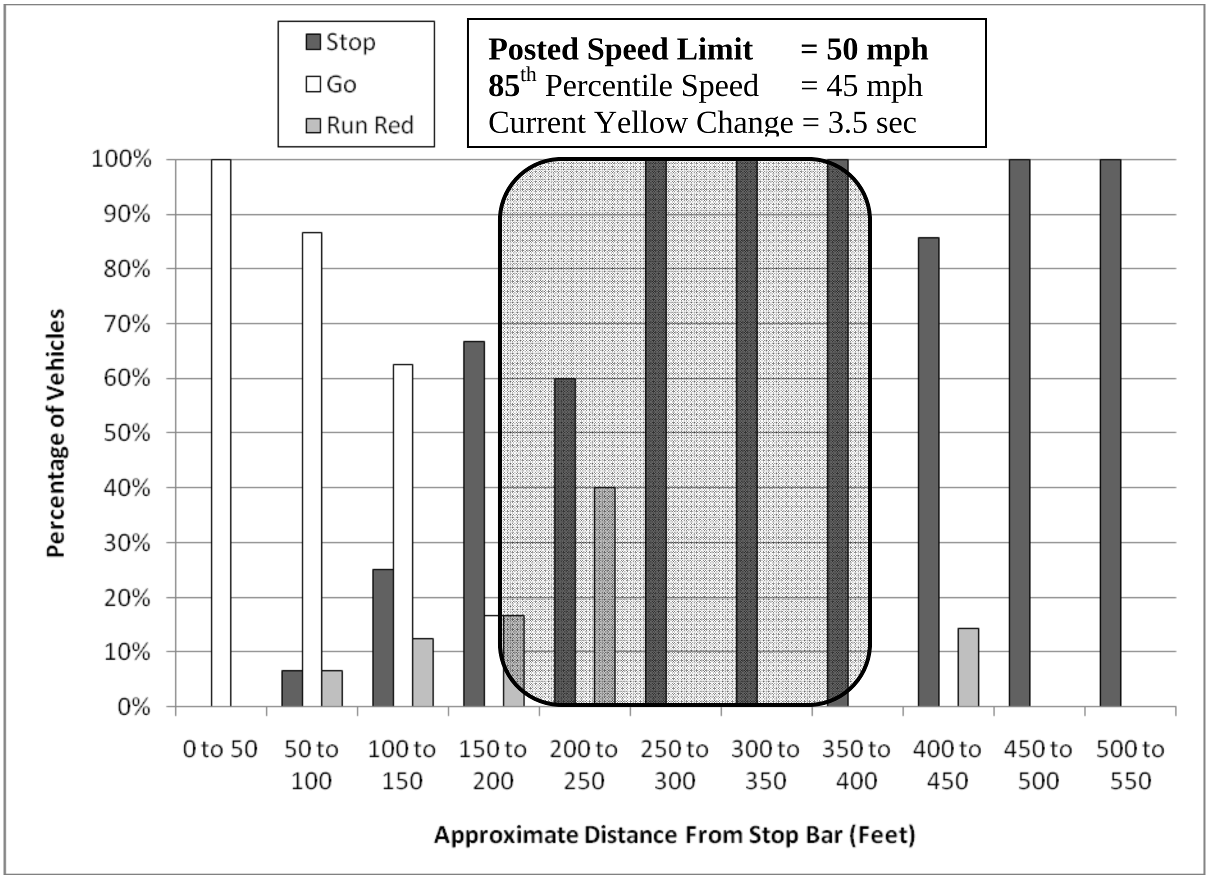

Figure 22 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Airport Road @ Route 62 (Westbound Approach)

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 85^{th} percentile speed of 45 mph, the predicted dilemma zone region exists between 169 feet to 371 feet. This region seems to correlate relatively nicely with the presence of increased percentages 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.

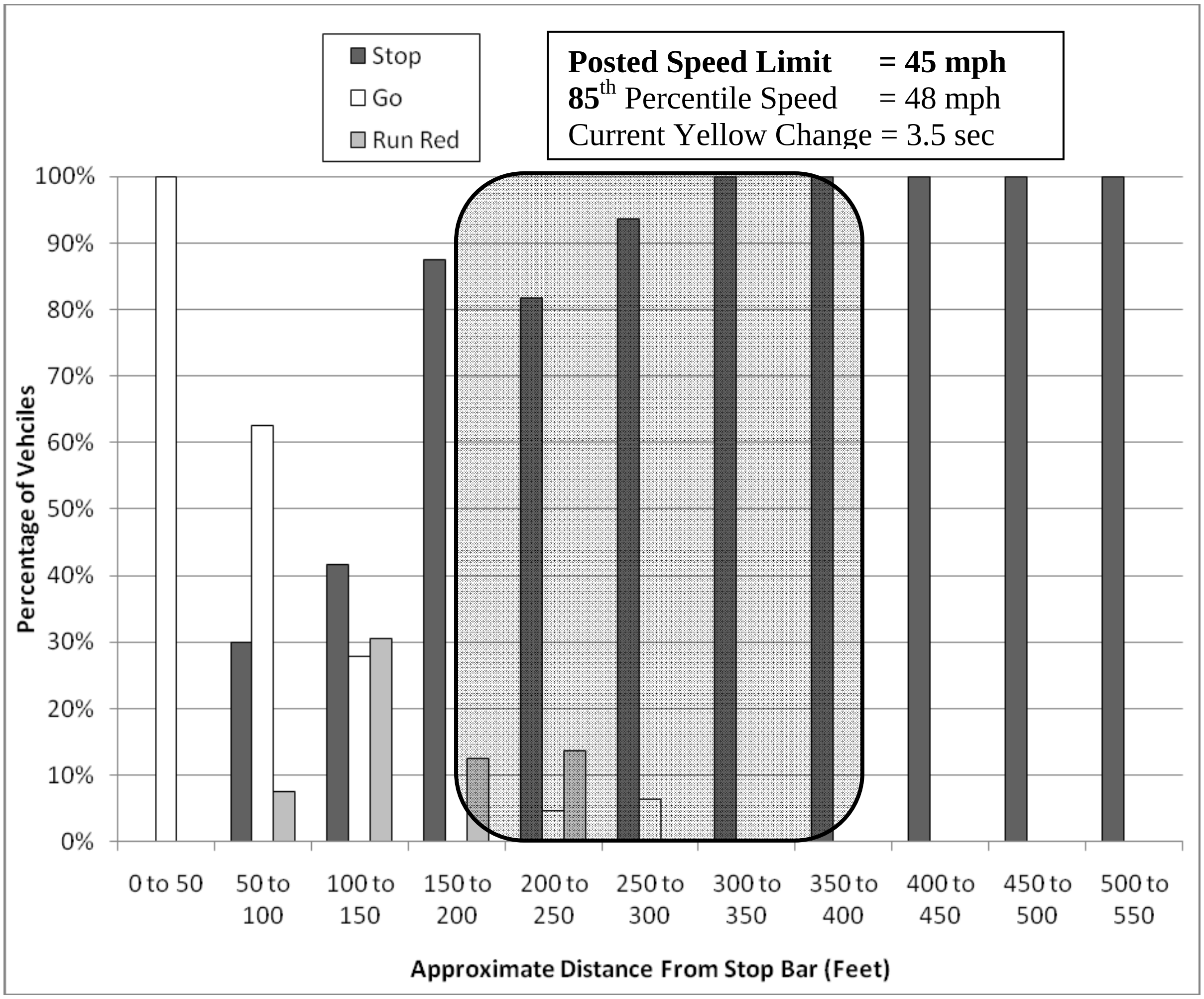

Figure 23 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Berlin Street @ Route 62 (Eastbound Approach)

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 85^{th} 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 full capture the RLR 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.

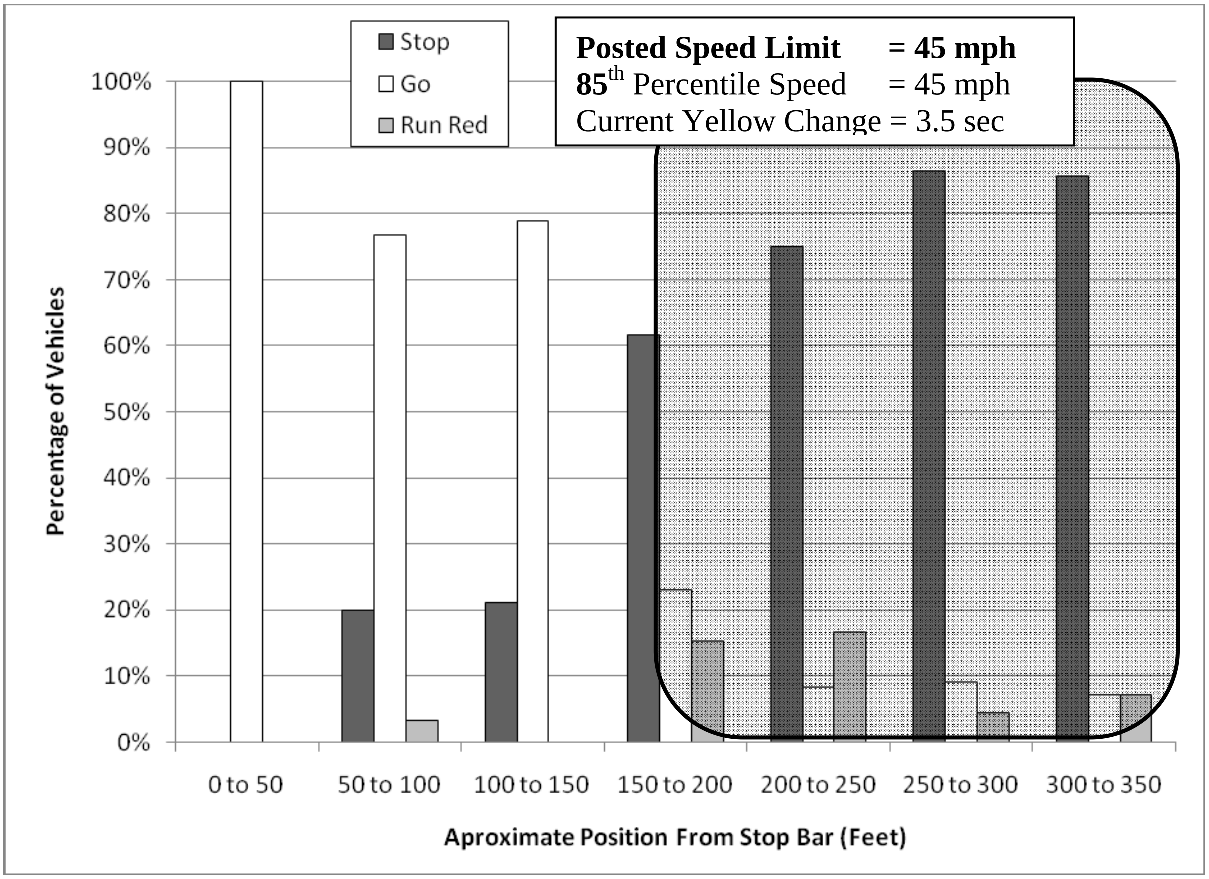

Figure 24 Relative Position and Driver Action of Vehicles at Onset of Yellow Indication Berlin Street @ Route 62 (Westbound Approach)

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 correlate relatively nicely with the presence of increased percentages of RLR. 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.

The most critical failure typically attributed to the dilemma zone is RLR. Table 7 displays the rates of yellow indication incursion as well as RLR along each approach. Depending on the approach, vehicles were exposed to the change interval at an average rate of 26 veh/hr with a high of 53 veh/hr (Rte 62 at Paine Tpke EB) and a low of 10 veh/hr (Rte 7 at Rte 103 SB). Of the vehicles exposed to the change interval, approximately 120 entered the intersection during the clearance interval. Red light running generally occurred at a rate of 1.7 veh/hr with a high of 3.0 veh/hr (Rte 62 at Airport EB) and a low of 0.9 veh/hr (Rte 62 at Berlin WB).

Table 7 Calculated Rates of Change Interval Incursion and RLR

Approach	Reduced Video (Hours)	Yellow Incursion (Veh)	Rate of Yellow Incursion (Veh/Hr)	Driver Reaction			Rate Red Running (Veh/Hr)
				Stop	Go	Run Red	
Rte 7 @ N. Shrew (NB)	1	35	35	35	9	2	0.5
Rte 7 @ N. Shrew (SB)	13	335	26	135	162	25	1.9
Rte 7 @ Rte 103 (NB)	8.5	195	23	95	87	11	1.3
Rte 7 @ Rte 103 (SB)	11	114	10	42	54	13	1.2
Rte 62 @ Airport (WB)	3.5	86	25	36	44	6	1.7
Rte 62 @ Airport (EB)	5	133	27	9	107	15	3.0
Rte 62 @ Berlin (WB)	9.5	162	17	67	84	9	0.9
Rte 62 @ Berlin (EB)	8.0	314	39	184	111	20	2.5
Rte 62 @ Paine Tpke (WB)	10.5	346	33	113	213	18	1.7
Rte 62 @ Paine Tpke (EB)	4.2	222	53	81	136	4	1.0
Totals	73.2	1907	26	578	887	101	1.5

5.0 SmartSensor Field Trial

5.1 Introduction

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.

5.2 Methodology

The identification of an adequate experimental site was of crucial importance. A regional provider for traffic signal equipment, HighwayTech, 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 approximately 2 feet wide and the right shoulder is 11 feet wide. Figure 25 displays an image of the aforementioned intersection approach.

Figure 25 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 is also tangent with no obstructions, which allowed for both the sensor to work effectively and the approach to be observed via video.

Figure 26 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 27 is an image of the SmartSensor Software program connected to the sensor hardware in the traffic cabinet.

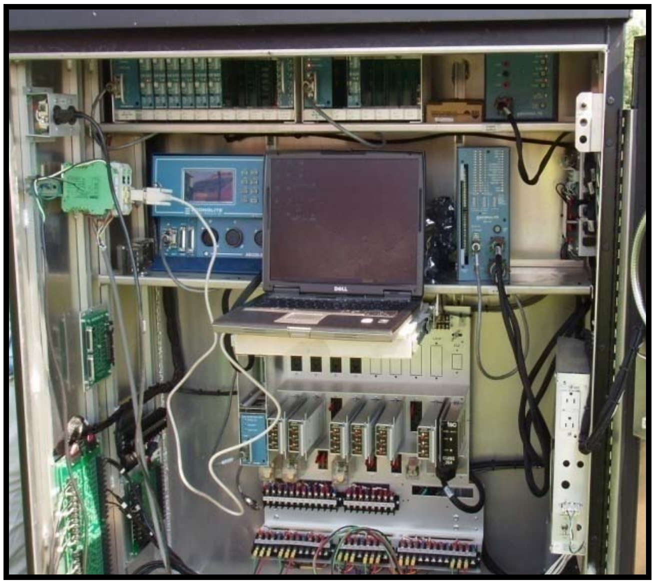

Figure 27 SmartSensor Configuration in Traffic Cabinet

The 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 28 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.

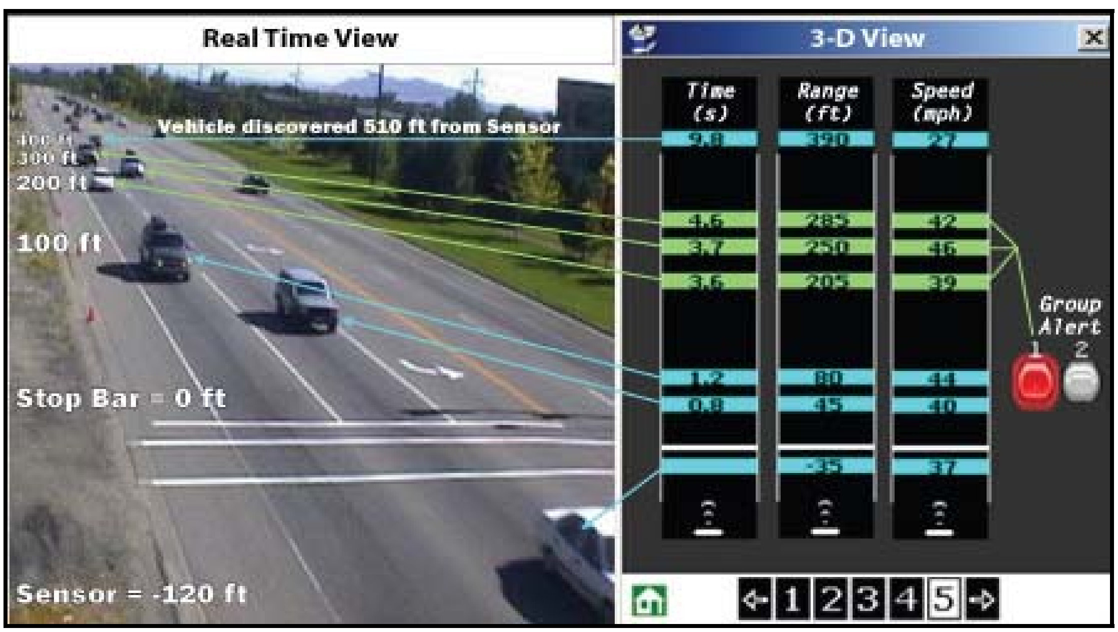

Figure 28 Image of SmartSensor Vehicle Detection

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.

This begs the question, "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 29 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 29 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 Chapter 4 used to identify the dilemma zone conflicts that exist under the current change interval timings and inductive loop advance sensors used in Vermont.

5.3 Results

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 reduce 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 30 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 seconds) is highlighted in grey. The frequency of vehicles caught within the dilemma zone is also identified as being 12.3 vehicles per hour.

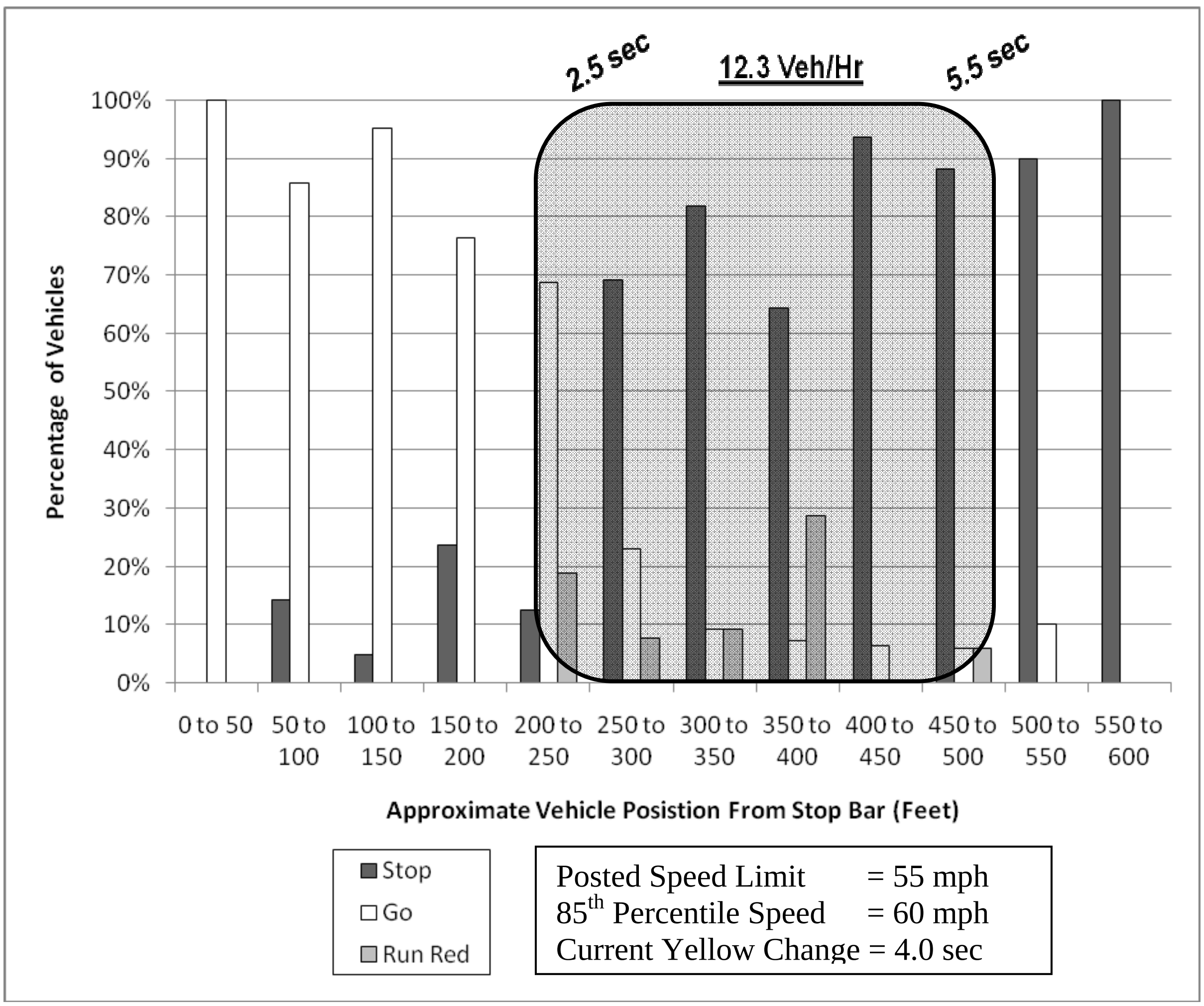

Figure 30 In-Pavement Inductive Loop DZ Protection

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 seems to correlate nicely with the presence of increased percentages 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 5.0 seconds in duration.

Figure 31 displays the driver behavior observed with advance vehicle protection provided from Smartsenor Advance. The position of the Type II dilemma zone (time to stop bar 2.5 to 5.5 seconds) is highlighted in grey. The frequency of vehicles caught within the dilemma zone is also identified as being 9.8 vehicles per hour.

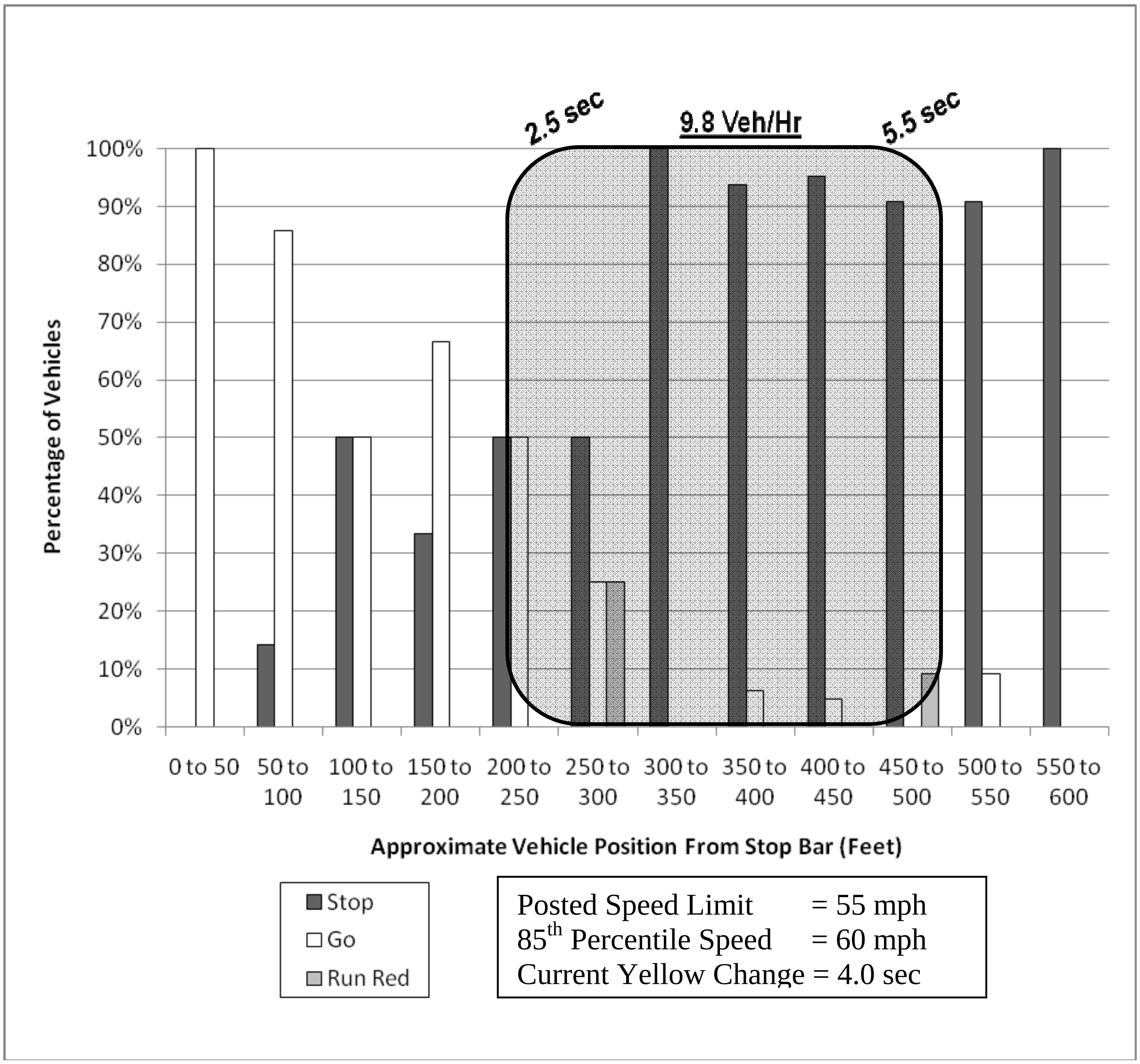

Figure 31 SmartSensor Advance DZ Protection

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 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 forward beyond the dilemma zone. The distribution of vehicles in each condition was compared with a chi-squared test, resulting in a statistical 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. Table 8 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 8 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-squared 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). The Pearson chi-squared value was determined to be 3.467, with a degree of freedom of 1, and a P-value of 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.

6.0 Conclusions and Implementation

The overarching objectives of this research project were to evaluate the effectiveness of current dilemma zone practices currently utilized within the State of Vermont at high-speed signalized intersection. Similar to many agencies, the typical strategy includes a combination of signal timing and advanced detection technology. Yet, the perception was that at similar locations with a similar dilemma zone strategy, one intersection may operate safely and efficiently while another may not. To address this issue, the extent to which dilemma zone issues exist was evaluated in the field in an effort to identify factors that may be contributing to the creation of a dilemma zone. A secondary objective was to review the current state of the practice with regards to dilemma zone protection and identify existing approaches and technologies that may be applicable at high speed signalized intersections in Vermont. One such technology identified during this process was implemented in Vermont and included within this evaluation as a result. Overall, the following conclusions were drawn:

- 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 a 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 range of possible dilemma zones along the intersection approaches, which provides valuable information in the resulting strategies that will be used to eliminate and / or shorten the range.

- Based upon the field results it is recommended that consideration be given to lengthening the yellow interval times for intersection approaches where the existing yellow interval is shorter than the current ITE calculation values. Given the nature of interest in this topic and the potential for lengthening yellow intervals at reducing RLR, it is recommended that a similar data collection and analysis be completed after lengthening the yellow intervals for the intersection approaches included in this study.

- The application of the field results, can be employed in determining the extent of existing dilemma zone problems as well as to provide insight on possible mitigation, including the potential benefits associated with signal timing changes (i.e., lengthening the yellow interval) and detection strategies (i.e., detector placement). Specifically, the measured distribution of speeds will provide some information on the optimal location and likely effectiveness of a signal inductive loop detector system. Specifically, if the distribution of speeds has little variability then the effectiveness of the loops will theoretically increase and the appropriate location of the detector is more easily identified.

- 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.

- 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 RLR 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 some mechanism for determining suitable locations and the associated benefits should be established.

- Given the identification of this baseline data, it is recommended that future strategies and / or changes at these intersections be evaluated in a similar manner. A specific example may include the resulting impact from lengthening of change intervals at selected locations. Additionally, the impact resulting from installation of additional Wavetronix units as well as the impact of varied settings should also be evaluated.

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