New Dilemma Zone Mitigation Strategies

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SCHOLARLY ABSTRACT

Drivers' mistakes in making immediate decision facing yellow signal interval to stop or go through the intersection is one of main factors contributing to intersection's safety. Incorrect decision might lead to a red light running and a right-angle Collison when passing through the intersection or a rear-end collision when failing to stop safely. Improperly timed traffic signal intervals result in the inability of the drivers to make the right decision and can place them in the dilemma zone. Advance warning systems (AWS) have been used to provide information about the downstream traffic signal change prior to approaching the intersection. On the other hand, advance warning systems increase drivers approach speed according to the literature. However, effect of AWS on dilemma zone has not been studied before. The goal of this thesis is to minimize the number of vehicle's caught in dilemma zone by determining more precise boundaries for dilemma zone and to reduce the number of red light violations by predicting the red light runners before arriving to the intersection. Here, dilemma zone boundaries at the presence of AWS has been reexamined with the aid of a large dataset (more than 1870 hours of data for two different intersections). Upper dilemma zone boundaries found to be higher for the intersections with AWS. This is due to vehicles' increasing the speed at the flashing yellow sings to escape the dilemma zone. Moreover, an algorithm for predicting red light runners and distinguishing them from right turners is presented.

PUBLIC ABSTRACT

Dilemma zone, in traffic engineering studies, refers to the area (space or time wise) near the intersection, in which drivers face uncertainty regarding whether to stop or go through the intersection in the yellow traffic signal interval. Failure to make the correct decision might result in a red light running and/or a right angle or rear-end crash at the intersection. Lots of efforts have been done in traffic safety studies to eliminate or reduce dilemma zone problem and increase intersection safety. One of the new methods for this purpose, is using Advance Warning Systems (AWS), prior to the intersection, to inform drivers about traffic signal change status before arriving to the intersection and provide adequate time to make the correct decision and minimize the number of drivers caught in the dilemma zone. This study aims to improve intersection safety by investigating advance warning systems' effect on drivers behavior and dilemma zone, as well as predicting potential red light runners before arriving to the intersection in order to extend the green/yellow light and prevent red light running and possible crashes. The finding of this study revealed that advance warning systems result in an increase in drivers' speed approaching the intersection in order to escape the yellow light, and therefore extending the dilemma zone interval. New dilemma zone boundaries are calculated at the presence of advance warning systems for the first time in the literature. Furthermore, this study introduced an algorithm for finding red light runners before arriving to the intersection, with the ability to separate red light runners from right turners. Findings of this study will improve intersection safety and reduce the number of red light runners and intersection accidents. In addition, this study provides further information regarding considering using advance warning systems at signalized intersections.

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To my parents Azam and Shahrokh,

And to my sister Shadi…

Also to my friend who always pulls the accelerator when seeing the yellow light.

May she understands…

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1 Introduction

Intersection-related crashes account for a major share of all crashes. Right angle crashes and rear-end crashes are two types of crashes associated with dilemma zone, which happen as the result of driver's failure in making a right decision to stop or stopping abruptly, respectively.

Two types of dilemma zone exist in the literature. The Type I dilemma zone, is a result of inappropriately designed intersection and improperly timed clearance intervals that cause vehicles neither safely pass through the intersection or stop prior to the stop bar. The type II dilemma zone, however, deals with driver's perception and the dynamic of driver's decision making. This type of dilemma zone is more complex and finding the boundaries for this type of dilemma zone is difficult due to the dynamic nature of decision making, hence has received more attention during past studies.

Red light running and unexpected stopping vehicles, as results of dilemma zone conflict, are of the main factors for intersection crashes. Based on the literature, right angle crashes cause more severe injuries and damages, hence this type of dilemma zone crash has attracted more attention. Especially as injuries severities increase with the increase in vehicle's speed, dilemma zone problem at high-speed signalized intersections is of the most interest. Providing advance information about the downstream traffic signal change status can help drivers making safer decision regarding passing through the intersection or stopping before the stop bar. Advance Warning Systems (AWS) are used to provide such information for drivers prior to the intersection. The aim of AWS is to minimize the number of vehicles caught in the dilemma zone.

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Many studies in the past have investigate the boundaries for the type II dilemma zone. However, most of these studies are old and have used old data to obtain dilemma zone boundaries values. Furthermore, to this date, research has not been examined the boundaries of dilemma zone with the presence of advance warning system prior to intersections. This study by analyzing a large data set has determined a new dilemma zone boundaries for intersections with advance warning systems. In addition, an algorithm for detecting and predicting red light runners based on the vehicle's trajectory data has been presented. This algorithm helps deploying further dilemma zone mitigation strategies by finding red light violations prior to arriving at the intersection. The presented algorithm is able to distinguish red light runners from right turners in the red signal time.

1.1 Research Objective:

The major objectives of this research are:

- To investigate dilemma zone boundaries at the presence of advance warning systems

- To predict red light running violations before arriving to intersection with precise accuracy

1.2 Thesis Contribution:

This thesis conduct a research by analyzing a large dataset of vehicles trajectory radar data to examine the dilemma zone boundaries for intersections with advance warning systems. The Type II dilemma zone boundaries range at the presence of advance warning systems has been presented in this thesis, for the first time in the dilemma zone protection studies. In addition, in the current research, a new algorithm with a high accuracy is introduced for detecting red

light runners before arriving to intersection. This algorithm discriminates red light runners from right turners in the red signal interval.

1.3 Thesis Organization

The thesis starts with the introduction, research objective, and contribution of the thesis (Chapter 1), followed by a detailed literature review on dilemma zone and red light running at signalized intersections (Chapter 2). Chapter 3 presents finding the Type II dilemma zone boundaries for intersections with advance warning systems. Chapter 4 describes a new algorithm for predicting red light runners based on vehicle trajectory data and distinguishing them from right turners. Finally, the findings of the study and conclusion of the research is presented in Chapter 5.

2 Literature Review

2.1 Dilemma Zone Definition:

Dilemma Zone is the area near (usually time zone, sometimes space zone) the intersection, in which drivers have difficulty deciding stop or go through the intersection. Dilemma zone was first introduced by Gazis, Herman, and Maradudin, studying problems associated with yellow signal setting [1].

May studied vehicles behavior with the various deceleration capability. He reported that yellow signal duration is dependent on acceleration and vehicles can accelerate or decelerate sufficiently to eliminate the dilemma zone [2].

This type of dilemma zone is known as the Type I Dilemma zone. The Type I dilemma zone occurs when the vehicle approaching the intersection in the yellow interval is unable to pass through the intersection safely or stop before the stop bar, due to the intersection's physical characteristics. There exists another type of dilemma zone, The Type II that was identified in 1974 by the Southern Section of ITE [3]. This type of dilemma zone, is defined as the area near the intersection where most of the vehicles decide to stop at the yellow interval and where most of the vehicles pass through the intersection. The Type II dilemma zone is more complex, due to its dynamic structure and dependence on driver decision making. Many studies have been conducted to define the location of Type II dilemma zone. Zegeer et al. stated defined the Type II dilemma zone boundaries as where 90% of the vehicles decide to stop and where 10% of the vehicles decide to stop [4]. Two types of dilemma zone are illustrated in figure 2-1.
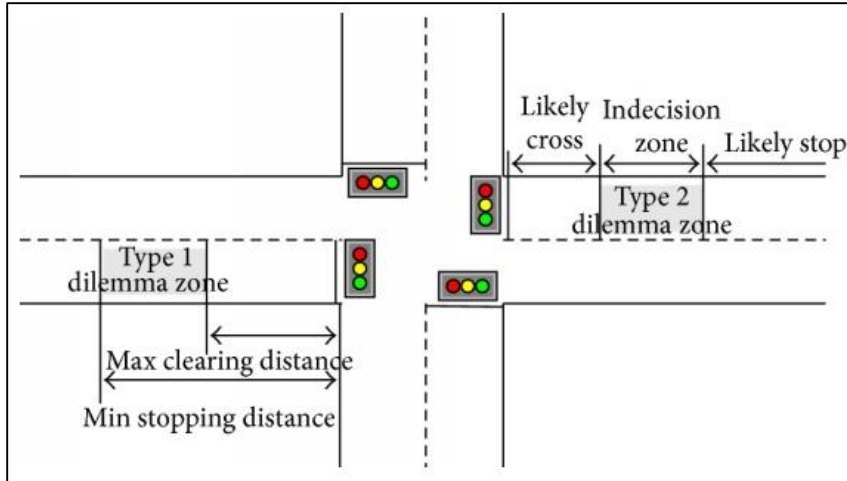
Figure 2-1 Dilemma zone types [5]

2.2 Dilemma Zone Boundaries:

Previous research efforts to find the dilemma zone boundaries indicate that location and size of indecision zone, the area between 10% and 90% of the stopping vehicles, is affected by many factors. However, it is usually assumed that dilemma zone is between 2.5 s to 5.5 s upstream of the intersection at the onset of yellow signal [6, 7]. Dilemma zone boundaries have been reported 2.87 to 4.9 for younger drivers and 1.66 s to 4.81 s for older drivers in a study by Rakha et al. The overall type II dilemma zone found in that study was 1.5 s to 5.0 s [8]. In another study Rakha et al. reported 1.6 s to 5.5 s for 9% and 100% of the stopping probability for a field test with 60 participants. They also state that for the young drivers dilemma zone range was 3.9 to 1.85 s, while for the older participants it was from 3.2 to 1.5 s [9]. Elmitiny et al. by examining a field video data from a high-speed signalized intersection found that vehicle's speed plays an important role in driver's decision to stop or go when vehicle's distance is between 267.5 ft and 372.5 ft from the intersection at the onset of yellow signal. Based on their findings more than 50% of speeding

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drivers would pass the intersection at these distances and more than 50% of speeding drivers would run through red light at the distances between 292.5 ft and 372.5 ft [10].

Sheffi and Mahmassani developed a model for driver behavior to find the length and location of the dilemma zone for speeds greater than 35 MPH in isolated signalized intersections. A probit calculation was used in their study to find dilemma zone boundaries. In their model driver is assumed to stop if their time to intersection at the onset of yellow signal is less than a critical value. However, they failed to consider others options for driver regarding passing through the intersection without considering the caution accelerating option [11]. Other reported ranges for dilemma zone in the literature are 1.7 s to 4.7 s, 2 s to 4.5 s in the studies conducted by Papaioannou by using data of an intersection in Thessaloiki, Greece, and Change et al. by analyzing data obtained from seven intersections [12, 13].

2.3   Dilemma Zone Protection Strategies:

Yellow Signal Timing Design:
Proper yellow signal timing reduces the number of vehicles caught in dilemma zone and therefore increase the intersection safety. Based on the literature increasing yellow time is especially suggested for intersections with sight limitations. On the other hand, it increases cycle length, delay and queue length, as well as increasing the number of red light running, since drivers might use that to pass through the intersection [14].

Result of a study examining the effect of signal timings on red light running showed that number of red light runners highly reduced by increasing the length of yellow signal. They observed vehicles entering the intersection at the onset of yellow for 10 signalized intersection in New York and compared the number of red light runners with the different signal timings. They

suggested that sufficient yellow interval with the aid of strict penalties for red light violation reduces the number of accidents related to dilemma zone [15].

Liu et al. examined yellow interval duration and reviewed using of a longer yellow duration. They have counted some philosophical objections to longer yellow times like delays to cross the traffic [16].

"All red time" is an alternative for reducing the yellow time, since it might prevent drivers from accelerating and passing through the intersection during the yellow time. A study conducted in Detroit, compared the number of red light running for an intersection before and after implementing all red time. Their results showed that there are significantly lower number of red light runners with all red time [17].

Green extension systems have been used to decrease the dilemma zone problem and the number of rear-end and right-angle crashes. They prevent vehicle from stopping abruptly when passing through the because of getting caught in the red signal intersection in the dilemma zone. They include presence-detection loops before the intersection in the pavement. If a vehicle passes over the detector in the pre-determined dilemma zone interval, a message is sent to the receiver in the signal control box for activating the green extension phase [18, 19].

Zegeer conducted before and after studies at three green-extension intersections for determining the green-extension systems effectiveness. He found that total number of accidents and rear-end accidents, and yellow-phase conflicts were reduced by 54%, 75%, and 62% respectively. Based on his findings, however, there was no significant difference in accident severity and vehicle delays [18]. Li and Abbas developed a multi-objective genetic algorithm for green extension systems. They introduced a new traffic conflict based safety measure-dilemma hazard- to

evaluate the safety performance. Their results from Monte Carlo simulation showed better dilemma zone protection as well as a low control delay level [20].

Dilemma Zone-Advance Warning Systems:

Advance warning systems (AWS) have been used in the past years to warn drivers about the traffic signal changing (usually from green signal to yellow) in order to provide more information to drivers approaching the intersection and assist them make a proper decision in an adequate time. Advance warning flashers (AWF) are the typical type of Advance warning systems. They consist of yellow flashing lights and a symbolic yellow signal sign. "Prepare to Stop When Flashing" (PTSWF), "Flashing Symbolic Signal Ahead" (FSSA), and "Continuous Flashing Symbolic Signal Ahead" (CFSSA) are types of Advance warning flashers. PTSWF consist of two yellow flashers, flashing from few seconds before the onset of yellow to the end of the red signal and a "Prepare to Stop When Flashing" sign. FSSA is similar to PTSWF, just with a schematic traffic signal sign instead of the text sign. Moreover, the difference between CFSSA and FSSA is just that FSSA flash all the time continuously and is not connected to the traffic signal controller [21].

Appiah et al. compared the number of crashes for before and after implementation of advance warning system for 26 intersections in Nebraska. They used a fully Bayesian technique to assure that the results are not affected by any exogenous variables in the long term. They found that advance warning system decreased the number of crashes by 8% and suggested using advance warning systems to improve dilemma zone safety problem at high speed signalized intersections [22]. McCoy and Pesti provided a detailed description of the advanced warning signs design, the lead flash value recommendation for different approach speeds, and the corresponding locations for the advance detectors and warning signs. They reported the warning sign location based on

Manual on Uniform Traffic Control Devices guidelines and location of the advance detector based on a 3.0 s travel time between the detector and the advance warning sign for traveling at the design speed [23]. In another study McCoy and Pesti stated that the effectiveness of advance warning systems might faded with time and their success is for their initial installation time [24]. Advance warning flashers increase drivers approach speed and the number of red light runners. They also increase intersection cost and must be installed carefully based on the site characteristics [44]

A study of 4 signalized intersections in China found that there is a significant relationship between the countdown timers' presence at the intersection and increasing the number of red light runners. They used videotaped data for finding the onset of yellow, the onset of red, driver location, and red light running. Their results showed that countdown timers may cause more vehicles passing through the intersection at the later portions of the yellow and even the red signal [25].

Köll et al. conducted a field study for 10 intersections with a traffic light change anticipation system (flashing green phase) in Switzerland, Austria, and Germany and found that the flashing phase led to longer indecision time intervals and increasing the rear-end crashes rates. However, the number of right-angle collisions were reduces due to the increase in the number of early stops as a result of the system [26]. Quiroga et al. observed more uncertainty, reaction conflicts and number of rear-end crashes in the intersections with flashing yellow change intervals [27].

Dilemma Zone-Driver Behavior:

There are many factors affecting driver's decision to stop or proceed through the intersection. To name some: vehicle's approach speed, vehicles distance to intersection, yellow signal interval, driver's perception reaction time, braking rate, sight distance, intersection clearing time, road

pavement condition and weather condition such as snow, rain and fog. Drivers naturally tend to go through the intersection when caught in dilemma zone [14].

Hicks et al. examined the factors affecting driver's decision to stop or pass through the intersection and their approaching speed in the yellow time. They found that vehicle's distance to the intersection when displaying yellow time, driver's gender, age, and using cell phone are among the most significant factors regarding driver's decision and their speed [28].

Another study also states that the stopping probability at the yellow time is greater for female drivers compared to male drivers. Moreover, at short yellow-indication trigger distances older drivers are less likely to clear the intersection than young drivers [9]. In a field study on two roadways with different surface conditions driver aggressiveness was examined and a new parameter for predicting driver aggressiveness was introduced to be used in modeling driver's stop or go behavior [29].

Caird et al. measured the performance of 77 old and young participants approaching signalized intersection at the onset of yellow. Based on their findings at the longest TTI, the older drivers were significantly less likely to stop compared to the younger drivers and they were more likely to be in the intersection at the onset of yellow [30].

Dilemma Zone Red Light Running:

Intersection and intersection related crashes consists 27% of all crashes [31]. Quiroga et al. in a study in Texas Transportation Institute reviewed red light violations and factors affecting red light running. Based on their findings fatal red light running crashes mostly occur in daylight hours, however, other environmental factors impact like weather condition were insignificant in

red light running crashes. They also stated that red light violations are higher for young drivers compared to older drivers and for male drivers than female drivers [27].

Regardless of the dilemma zone definition, both types of dilemma zone result in both rear-end and right-angle crashes at the intersections. The higher the vehicle's approaching speed, the more severe the crash would occur. Hence, there is more emphasis on preventing vehicles from getting caught in the dilemma zone at high-speed signalized intersections [32].

Numerous studies have tried to reduce the dilemma zone issue by deploying new technologies. Green signal countdown displays (GSCD) are used to provide information about green countdown timing to the drivers to improve their decision making to stop or pass through the intersection. Lum et al. evaluated different drivers' response in the intersections with GSCD in a before and after study. They reported 65% reduction in number of red light runners after installing GSCD, however, its effectiveness tended to dissipate over time as drivers gradually committed the red light running as before installing GSCD [33]. However, another study conducted in Taiwan, that compared rates of fatal and injury accidents before and after the GSCD is strongly opposed installing GSCD [34]. Similar to this finding a study in China found vehicle stop rate was decreased at the end of the green phase at the presence of countdown timing. They also reported that dilemma zone was increased for intersections with countdown timers resulting in more rear-end crashes and did not significantly improve intersection safety [35]. Puan et al. also in their study of 6 intersections in Malaysia observed inadequate yellow signal time as a result of countdown timer and failure to reduce the dilemma zone problem [36].

3 Revisiting Dilemma Zone Boundaries at the Presence of Advanced Warning Signs—Cases Deserving Further Investigation

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3.1 ABSTRACT

One of the main factors contributing to crash occurrence at high-speed signalized intersections is the dilemma zone: an area in which drivers face uncertainty regarding whether to continue through an intersection or to stop when the yellow signal is presented. Prior research has sought to reduce the uncertainty in the dilemma zone by studying the different factors affecting it. Providing a sufficient yellow signal interval, extending the green signal time and in advance warning systems are of methods that have been used to reduce the dilemma zone issue. Advance warning systems were originally used with the aim of providing adequate time for stopping in advance of intersections before the onset of the yellow signal. However, according to previous studies advance warning systems cause vehicles to increase their speed when approaching the intersection. Few studies have been done to examine the effect of advance warning systems on the dilemma zone. In this study, we reexamine the dilemma zone boundaries in the presence of advance flashing yellow signs. By analyzing more than 1,870 hours of data for two different intersections and for different directions we present new boundaries for the dilemma zone. We found that dilemma zone boundaries (with the presence of advance warning systems) are different at different sites and also different for different directions at the same site. Moreover, we found that upper dilemma zone boundaries were higher than previously reported upper boundaries in the literature. The much larger values of the dilemma zone boundaries that we found in this study is due to vehicles speeding up during the flashing yellow light signs before the onset of the yellow signal in order to escape the dilemma zone. Hence, we argue that intersection characteristics and drivers' behavior should be taken into account in the design of traffic signals, rather than assuming a pre-defined value for the dilemma zone boundaries

Key words: Dilemma Zone, Dilemma Zone Boundaries, Advance Warning Systems, High-Speed Intersections

3.2 INTRODUCTION

Intersection and intersection-related crashes contribute to a vast majority of all road crashes. Based on the National Highway Traffic Administration's data (NHTSA), these crashes makeup 27% of overall crashes [31]. Red light running and unexpected stopping of vehicles are some of the main factors for intersection crashes. Red light running violations accounted for 638 deaths and an estimated number of 133,000 injuries in 2012 [37].

Dilemma Zone is a time-zone (sometimes defined in space) that becomes relevant at the onset of the yellow signal interval, in which a driver goes through uncertainty deciding whether to stop or proceed through the intersection. Inappropriate decision to continue through the intersection or to stop may result in a right-angle or a rear-end collisions, respectively. Hence, a large body of research in the past decades has focused on the dilemma zone problem and how to prevent approaching vehicles from being caught in the dilemma zone [11, 19, 38-50]. Dilemma zone conflict is one of the main contributors in intersection crashes, especially at high-speed signalized intersections.

Based on the literature, two types of dilemma zones are defined. "Type I Dilemma Zone," is the type defined as the area in which drivers are unable to have a safe stop or comfortable and safe continuing through the intersection. Providing a proper clearance interval can eliminate this type. "Type II Dilemma Zone," on the other hand, shift the focus to the driver's perception on whether they should stop or go [51]. This type cannot be eliminated, since most of the drivers would not know in advance when the signal would turn red. The boundaries of this type are therefore determined based on statistical distributions of drivers' decisions.

Regardless of the dilemma zone definition, both types of dilemma zone result in both rear-end and right-angle crashes at the intersections. The higher the vehicle's approaching speed, the more severe the crash would be. Hence, there is a larger emphasis on preventing vehicles from getting caught in the dilemma zone at high-speed signalized intersections [32]

Advance warning systems (AWS) are used at intersections with a high speed profile to provide additional information about the changing of the traffic signal in advance of yellow signals to assist drivers in making a safer decision while approaching the intersection.

One of the essential problems in dealing with the dilemma zone issue, is defining its boundaries. Prior research has determined the boundaries for dilemma zone. However, there still exists inconsistency between the values derived by this research as they have been presented in the literature review section. In addition, little research has examined the effect of flashing yellow signs on the dilemma zone boundaries. In this study we analyze a large dataset (more than 1,870 hours) of vehicles trajectory radar data to present more precise boundaries for the dilemma zone at the presence of advance warning flashers. This provides an edge over previous studies in this area.

In the following sections, we first review related research. Second, we explain our data collection procedure. Third, we describe our methodology for obtaining boundary values. Fourth, we discuss analysis and results of our study. At last, the conclusion and future work is presented.

3.3 LITERATURE REVIEW

Dilemma zone was first defined in the literature by the Gazis, Herman, and Maradudin [20], their model is now well known as the GHM model. Based on their model, dilemma zone is the distance between the minimum stopping distance (Xs) (the distance between the nearest vehicle that can completely stop and the stop line) and maximum crossing distance (Xc) (the distance between the farthest vehicle that can cross the intersection at the onset of yellow and stop line), when Xs is greater than Xc. Formulas for Xs and Xc calculation are presented below in equations 1 and 2, respectively.

$$X_s = v\tau + \frac{v^2}{2a_1} \tag{1}$$

$$X_c = = vY + \frac{1}{2}a_2(Y - \tau)^2 - L - W \tag{2}$$

Where v_0 = vehicle's initial speed at the start of the yellow signal (ft/s); a_1 = vehicle's maximum acceleration (ft /s^2); a_2 = vehicle's maximum deceleration (ft /s^2); τ =driver's perception-reaction time (PRT) (s); L = vehicle's length (ft); w = intersection's width (ft); and Y = yellow signal duration (s).

This type of dilemma zone is known as Type I Dilemma Zone. This type of dilemma zone is indicative of a range, in which vehicle's approaching the intersection can neither have a safely comfortable stop or passage through the intersection[19, 38, 39]. Type I Dilemma Zone happens as a result of poor signal clearance timing design and inappropriate detector placement [38, 52].

One problem with the GHM model and Type I Dilemma Zone is that it fails to take into account the randomness and differences in drivers' behavior. The GHM model is based on the assumption that all the vehicles, if it is possible, will stop at the onset of yellow. This assumption, however,

was not consistent with the observation of Olson et al.'s study, where they were using the yellow signal time as the green extension for some of the vehicles [53]. This issue has limited the use of Type I Dilemma Zone in dilemma zone protection systems.

Another type of dilemma zone, known as Type II Dilemma Zone, was introduced in 1974 by Parsonson et al [3]. Type II Dilemma Zone begins where 90% of vehicles stop and ends where only 10% of vehicles will stop when the yellow is presented. Type II Dilemma Zone is currently vastly used in dilemma zone protection systems like the green extension systems [4], the green termination system [54], LHOVRA [55], the detection control system [6], and the platoon identification and accommodation system [56]. This type of dilemma is the indicator of a range, in which vehicles' approaching the intersection are both able to stop or to go through the intersection (which has also been referred to as the "Indecision Zone" in the literature) that reflects the drivers' difficulty in decision making as well as the probabilistic and dynamic nature of this type of dilemma zone [57-62]. Prior research has sought to determine the features of type II dilemma zone under different conditions.

Rakha et al. conducted a study to find drivers' decision based on their time to intersection (TTI) at the onset of yellow time. In their study they analyzed field test data of 60 participants and concluded that older drivers experience a larger dilemma zone ranging from 1.66 s to 4.81 s, while these values for younger drivers were 2.87 s to 4.90 s. They also reported that dilemma zone boundaries for female drivers are closer to intersection and they tend to stop more compared to male drivers. They built a logistic type linear model for probability of vehicles stopping by assuming a binomial distribution for data, and reported a final values of 1.5 s to 5.0 s as Type II Dilemma Zone boundaries [8]. Papaioannou by analyzing 84 hours of traffic data at an intersection in Thessaloiki, Greece and collecting their speed, distance from stop line when yellow presents

and their age and gender group, presented a binary choice model for calculating the probability of vehicle stopping and reported 1.7 s to 4.7 s for boundaries of dilemma zone [12]. Chang et al. by using the data collected from seven intersections analyzed driver behavior to signal changes and suggested 2 s to 4.5 s dilemma zone boundaries [13].

Zegeer, in 1977 in a study for determining the effectiveness of green-extension systems, by the observation of arriving vehicles' speed and yellow time indication at 9 intersections found the lower limit of 2.5 s and an upper limit of 5.0 s for dilemma zone [4]. Zimmerman et al. by analyzing 32 hours of data collected at two intersections as a part of their study for evaluating Detection-Control System (D-CS), calculated dilemma zone boundaries as 2.5 s to 5.5 s [63]. Gates et al. by recording vehicles' behavior such as brake response time and deceleration rate for first-to-stop ones at six intersections, with 463 first-to-go and 538 last-to-go vehicles, reported 2.5 s to 5.5 s as dilemma zone boundaries. Their study also showed that drivers were more likely to go through the intersection rather than to stop with shorter time at intersections at the onset of the yellow signal, longer yellow duration, if they were driving a heavy vehicle, or in the absence of side-street vehicles, pedestrians and bicycles. However, they found time to intersection to be the most affective factor in drivers' decision to go through the intersection or to stop [57]. Bonesson et al. presented 3.0 s to 5.0/6.0 s for dilemma zone boundaries calculated assuming a logistic distribution for the probability of stopping vehicles [64].

Advanced warning systems are traffic warning devices that are used prior to the intersection to provide advance information about traffic signal status to drivers in order to improve drivers' decision and intersection safety. There are two types of advance warning systems. A typical advance warning system is consisted of an Advance warning flasher (AWF) with yellow flashing lights and a sign of symbolic yellow signal ahead.

There are different types of AWFs according to the literature. "Prepare to Stop When Flashing (PTSWF)" that is warning sign with the "Prepare to Stop When Flashing" text and two yellow flashers that flash from a few seconds before the onset of yellow signal to the end of the red signal interval. "Flashing Symbolic Signal Ahead (FSSA)" that have a schematic traffic signal sign instead of the text in PTSWF, but their function is the same as the PTSWF sign. "Continuous Flashing Symbolic Signal Ahead (CFSSA)" that are similar to FSSA except for the fact that they flash all the time and are not connected to the traffic signal controller [21]

A Study on various types of warning signals showed that CFSSA and Passive Symbolic Signal Ahead (PSSA)'s effect is the same in speed reduction. On the other hand, PTSWF and FSSA increase vehicle's speed since drivers try to escape through the yellow signal time. The study suggested that the benefits of AWS depends on road geometry and recommended installing CFSSA before PTSWF. This study discouraged using PTSWF at tangent approach of high speed signalized intersection and states that PTSWF is more desirable than FSSA [65]

Gibby et.al in a study of high speed isolated signalized intersections found that AWSs improves these intersections' functionality compared to similar intersections without AWSs. They had significantly lower accidents rates. Their study suggests installation of flashing beacons on AWSs in more than 2000 feet from the intersection [66]

Previous research conducted by The Ministry of Transportation in Ontario evaluates advance warning systems' effectiveness by comparing accident rates, red light violations, speed distribution, and the number of vehicles caught in the dilemma zone. They found that AWS reduced the overall accident rates but that it was ineffective in reducing vehicle speed for high speed intersections [14]. Research conducted by Messer et.al. found that advance warning flashers increase drivers approach speed and the number of red light runners [67].

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3.4 METHODOLOGY

As discussed in the literature review section, the idea behind the identification of the DZ

boundaries is to find the time to intersection (TTI) values where 90% and 10% of vehicles stop,

when the yellow signal is presented, for defining the beginning and end of the DZ, respectively.

To this aim, we use vehicles' trajectory data at two instrumented sites. We first capture all

vehicles at the onset of yellow. Next, we divide the set into stopping and non-stopping vehicles.

We used a MATLAB script for this purpose. Examining video recordings showed that some

vehicles do not necessarily stop before the stop bar, rather they pass the stop bar with a low

cruising speed and stop before the intersection. Hence, a discriminant analysis was conducted to

determine the speed at which vehicles are stopping and separate the stopping vehicles from the

passing ones. Discriminant analysis is a statistical analysis used to separate two or more groups

from each other and determine to which known groups a new observation belongs based on

measured characteristics. Figure 3-1 shows the canonical plot for discriminating stopping

vehicles and passing vehicles after the stop bar based on their speed. The blue dots indicate

stopping vehicles, and the red dots indicate passing vehicles. Our discriminant analysis results

show that if the vehicle's speed is less than 12 MPH the vehicle is a stopping vehicle.
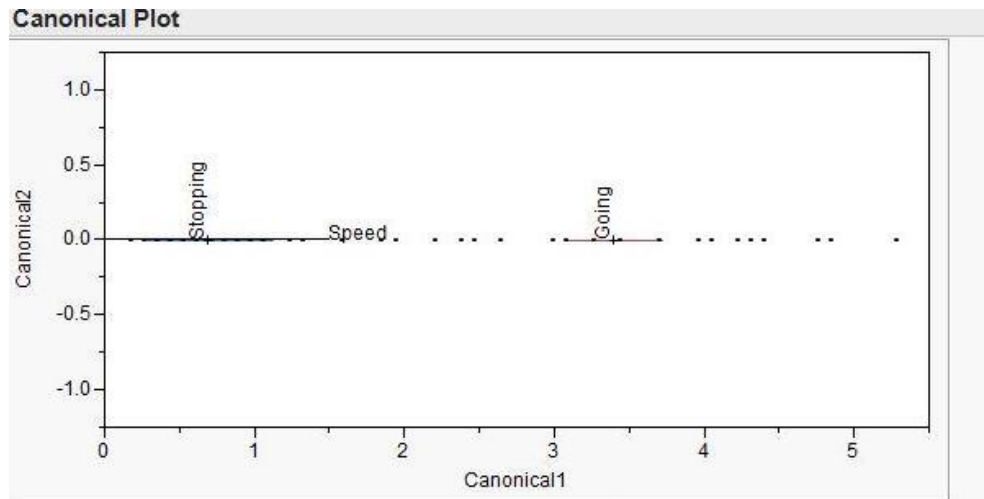
FIGURE 3-1 Canonical Plot for finding the stopping vehicles based on their speed

$$\text{Status} = 0.0880594 \times \text{Speed (MPH)}$$

$$\text{Stopping Vehicle} = \begin{cases} \text{Yes} & \text{Status} > 1.1 \\ \\ \text{No} & \text{Status} \leq 1.1 \end{cases}$$

Then, for each vehicle based on its distance to intersection and its speed at that moment (start of the yellow signal), we calculate the TTI (time to intersection is the time that is needed to arrive at the intersection if driver continues with the same speed as the speed at the measured point). Then, we categorize vehicles based on 0.1-second increments in TTI and we calculate the percentage of stopping vehicles for each TTI. These percentages are plotted based on the corresponding TTI. A regression model was fitted for the data. Finally, based on the fitted model corresponding TTIs, for 10% and 90% of stopping vehicles were calculated.

The procedure was conducted separately for each site, to observe the changes (if any) in the values of dilemma zone boundaries between different directions and different sites. The

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procedure for finding the dilemma zone boundaries is illustrated in the Figure 3-2 below.

```
┌─────────────┐
│    Start    │
└──────┬──────┘
       │
       ▼
┌──────────────┐      ◇────────────◇   No    ◇────────────◇
│ Find all the │─────▶│ Vehicle's last │──────▶│Vehicle's Speed >│
│ vehicles at  │      │point > Stop bar│       │    12 MPH      │
│the onset of  │      ◇────────────◇          ◇────────────◇
│  yellows     │            │ Yes      No         │ Yes
└──────────────┘            ▼                     ▼
┌──────────────┐     ┌──────────────┐      ┌──────────────┐
│Calculated TTI│◀────│   Stopping   │◀─────│   Passing    │
│based on      │     │   Vehicle    │      │   Vehicle    │
│distance to   │     └──────────────┘      └──────────────┘
│intersection  │
│and speed     │
└──────┬───────┘
       │
       ▼
┌──────────────┐          ┌──────────────┐
│Find the      │─────────▶│Draw the      │
│percentage of │          │diagram of the│
│stopping      │          │percentage of │
│vehicles in   │          │stopping      │
│each TTI (with│          │vehicles based│
│0.1s increment│          │on TTI        │
│in TTIs)      │          └──────┬───────┘
└──────────────┘                 │
                                 ▼
                          ┌──────────────┐
                          │Find the 90%  │
                          │and 10%       │
                          │stopping      │
                          │vehicles based│
                          │on the diagram│
                          └──────┬───────┘
                                 │
                                 ▼
                          ┌──────────────┐
                          │ Dilemma Zone │
                          │ Boundaries   │
                          └──────┬───────┘
                                 │
                                 ▼
                          ┌──────────────┐
                          │     End      │
                          └──────────────┘
```

**FIGURE 3-2 The Methodology for Finding Dilemma Zone Boundaries.**

3.5 DATA COLLECTION

Site Description:

Two T-intersections in Ridgeway (US220 site) and Blacksburg (US460 site), Virginia, with advanced flashing yellow signs were selected for the study. The US220 site is located at US 220 and US 87, and has a speed limit of 45 mph. The US460 site is located at US 460 and Southgate and has a speed limit of 65 mph that is reduced to 55 mph in the vicinity of the intersection (although most traffic continues with the same speed). The AADT for US220 and US460 are 16,000 and 32,000, respectively [68]. Figure 3-3 shows these two site locations.


| (a) | (b) |
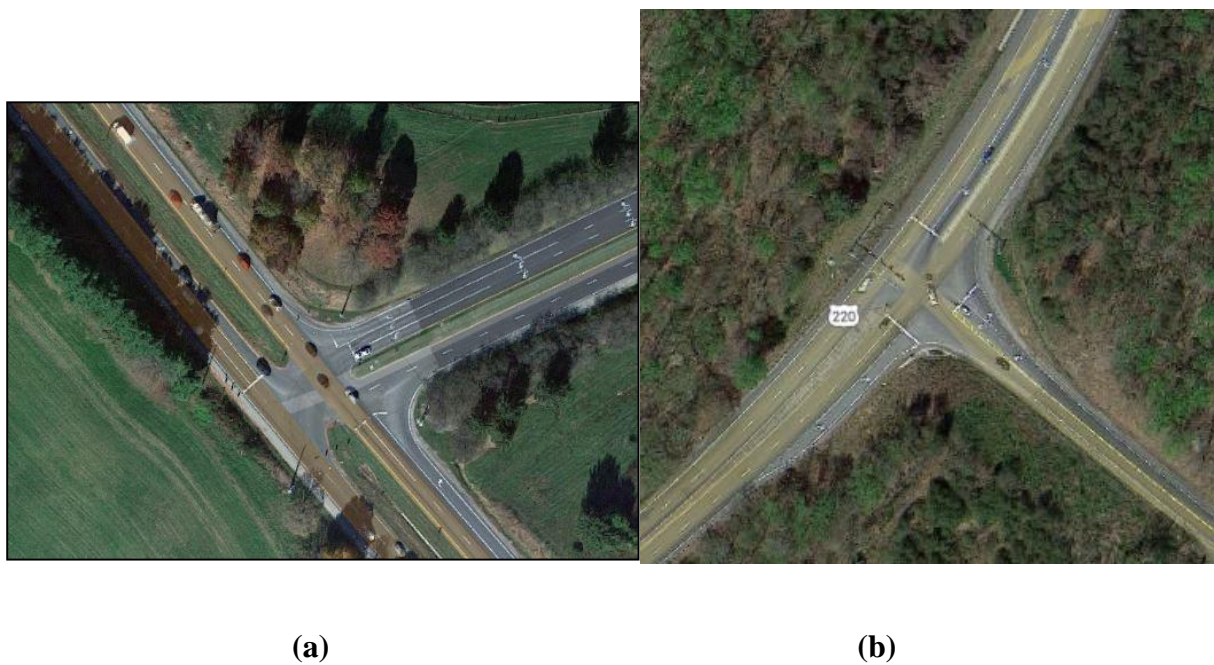
Figure 3-3 Study sites: (a) US460 site, (b) US220 site.

Data Collection and Preparation

Real time field measurements of vehicle trajectories were collected using the second-generation of the intersection safety data collection and evaluation system developed at the Virginia Tech

Signal Control and Operations Research and Education System's (VT-SCORES) lab. The system

uses Wavetronix radar system combined with signal phase, video and detector data to create a

more complete safety assessment of the intersection [69]. Figure 3-4 illustrates the system. The

system was installed at the T intersections of both US220 site and US460 site to collect their

traffic data. It consists of a hardened field computer, two advanced Bus Interface Unit (BIU), a

Sierra wireless modem, two Wavetronix click 304 units, and up to four camera streams. Data is

collected and stored through the data stream between the controller and other cabinet

components using the two BIUs (Terminal and Facilities (TF1) BIU for signal phase status and

detector BIU for detectors status). The Wavetronix system is capable of simultaneously keeping

track of up to 25 vehicles per approach. Vehicles were detected as they approached the

intersection from about 250 ft away. Data was collected continuously for months May 2014 to

July 2014, for all vehicles approaching the intersection and was output as csv files with vehicle

track, speed, range and time, phase data for one hour, and a video file with images of vehicles

approaching the intersection [70]. In total, More than 1,870 hours of data (continuously for the

24 hours a day) was used for this study. A MATLAB script was used for the reduction and

manipulation of the data like tracking vehicles, determining cycles, phases and calculating the

traffic signal intervals, i.e., start and end time of green, yellow and red signal.
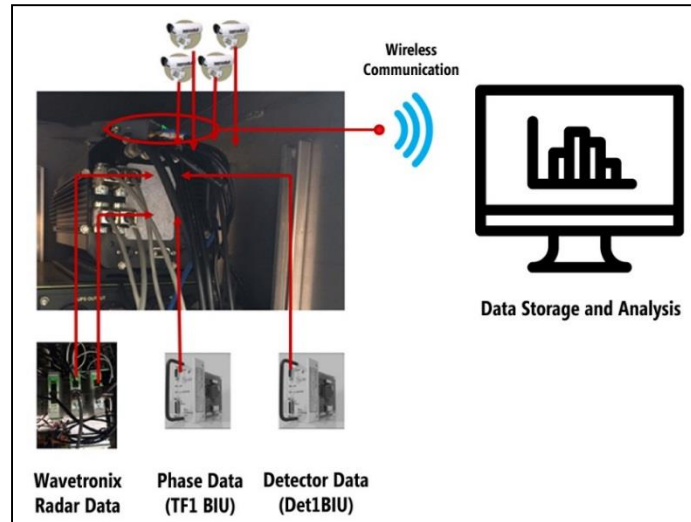
Figure 3-4VT-SCORES safety data collection and evaluation system.

3.6 Analysis

Dilemma zone boundaries found in this paper are significantly higher than previous findings.

One explanation found when examining the vehicle's trajectory diagrams is that some vehicles,

even far from the intersection, noticeably accelerate and speed up at the flashing light (before the

start of the yellow signal) and at the onset of yellow signal in order to escape the dilemma zone.

This results in more vehicles passing even in greater TTIs like 7 and 8s, hence shifting the 90%

of stopping vehicles to a greater value. This finding was consistent with the results of studies that

showed vehicles accelerate/decelerate severely at the intersections with advanced warning signs

to avoid getting caught in the dilemma zone [2, 14, 65, 67].

Figures 3-5 and 3-6 show samples of a vehicle passing through and stopping before the

intersection in the yellow interval, respectively. The left column shows video recording of the

vehicles with the corresponding timestamp. Subtracting the start timestamp (3817287) gives the

time in 0.1 seconds. The right column shows the vehicle trajectory with the passing vehicle and

stopping one in the video record pointed by the arrow. The vertical axis is the vehicle's distance to the intersection (ft), and the horizontal axis is time (s). Phase cycles are drawn on the time axis and speed is color-coded.

Additionally figures 3-7 and 3-8 show corresponding yellow signal time and detector status for the passing and stopping vehicle indicated above from the csv raw data. Stopping Vehicle (driving on the first lane) passes on detector 2 and the passing vehicle (driving on the second lane) passes on detector 3 and 9. Passing vehicle passes the detector before the start of yellow and passes detector 9 in the yellow time. Stopping vehicle does not pass detector 10 in the yellow time. There is 0.3 second difference between timestamps of the video recording file and the csv file.
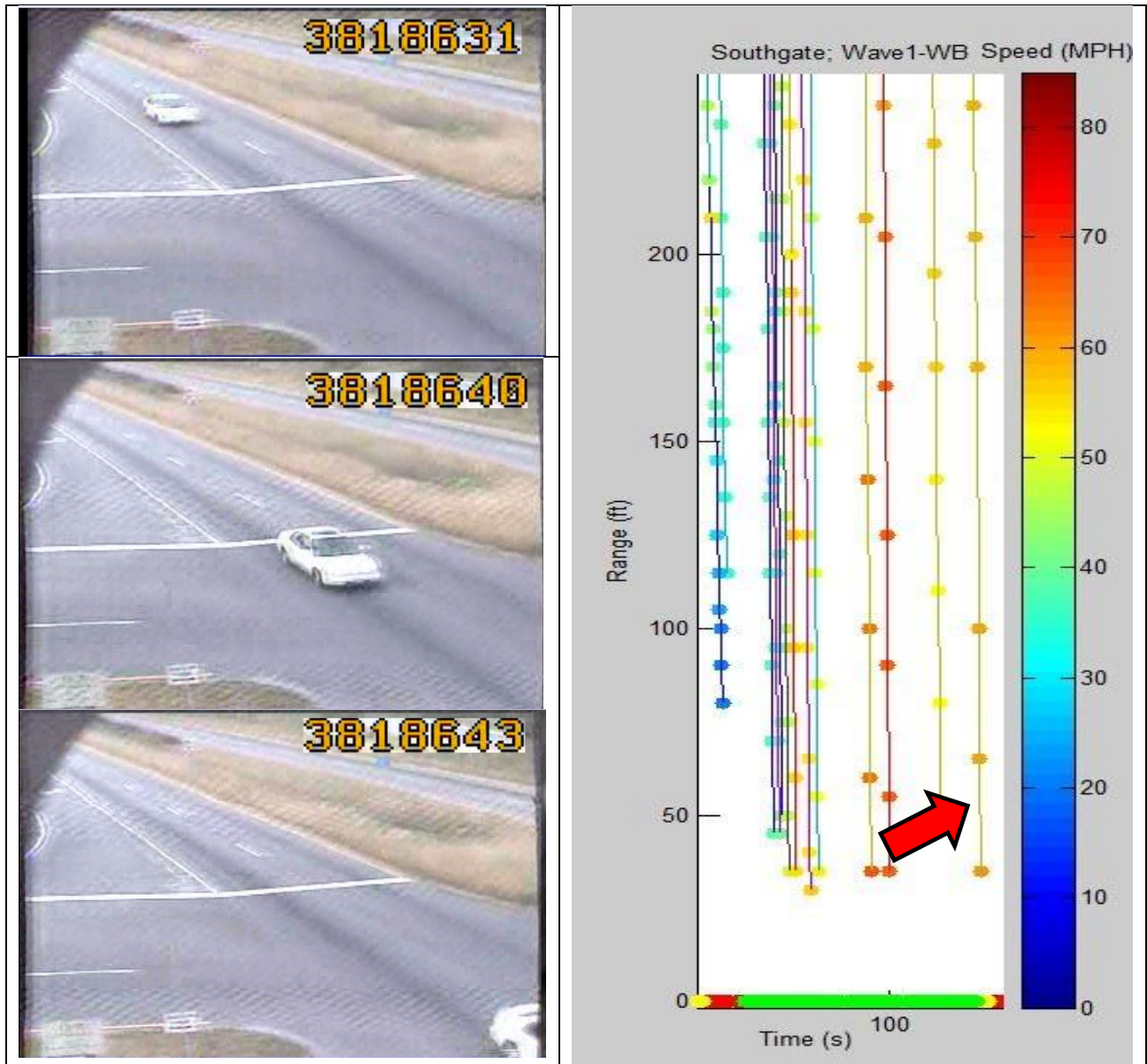
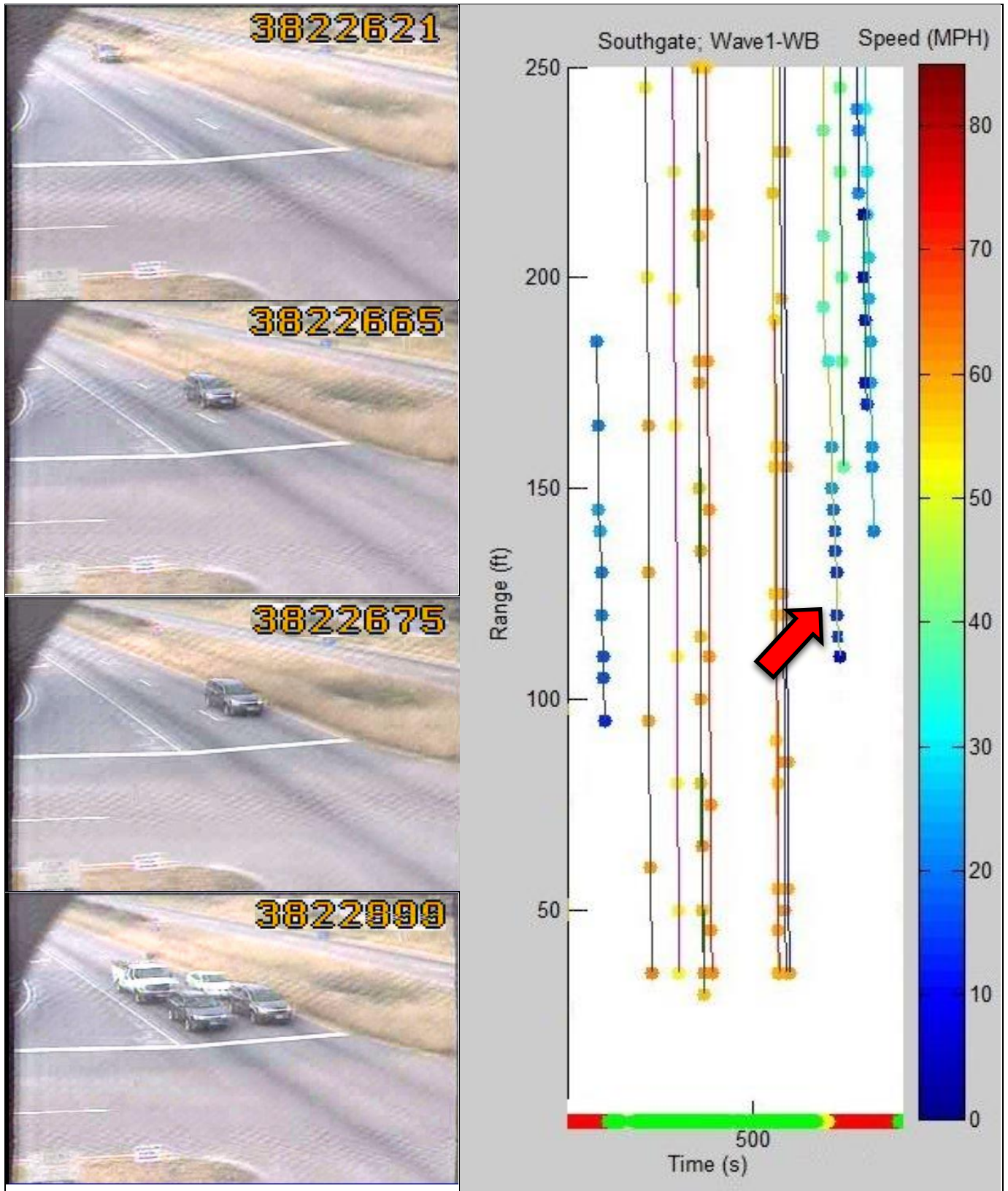**Figure 3-5 A Sample of a Vehicle Passing through the Intersection in the Yellow Interval**

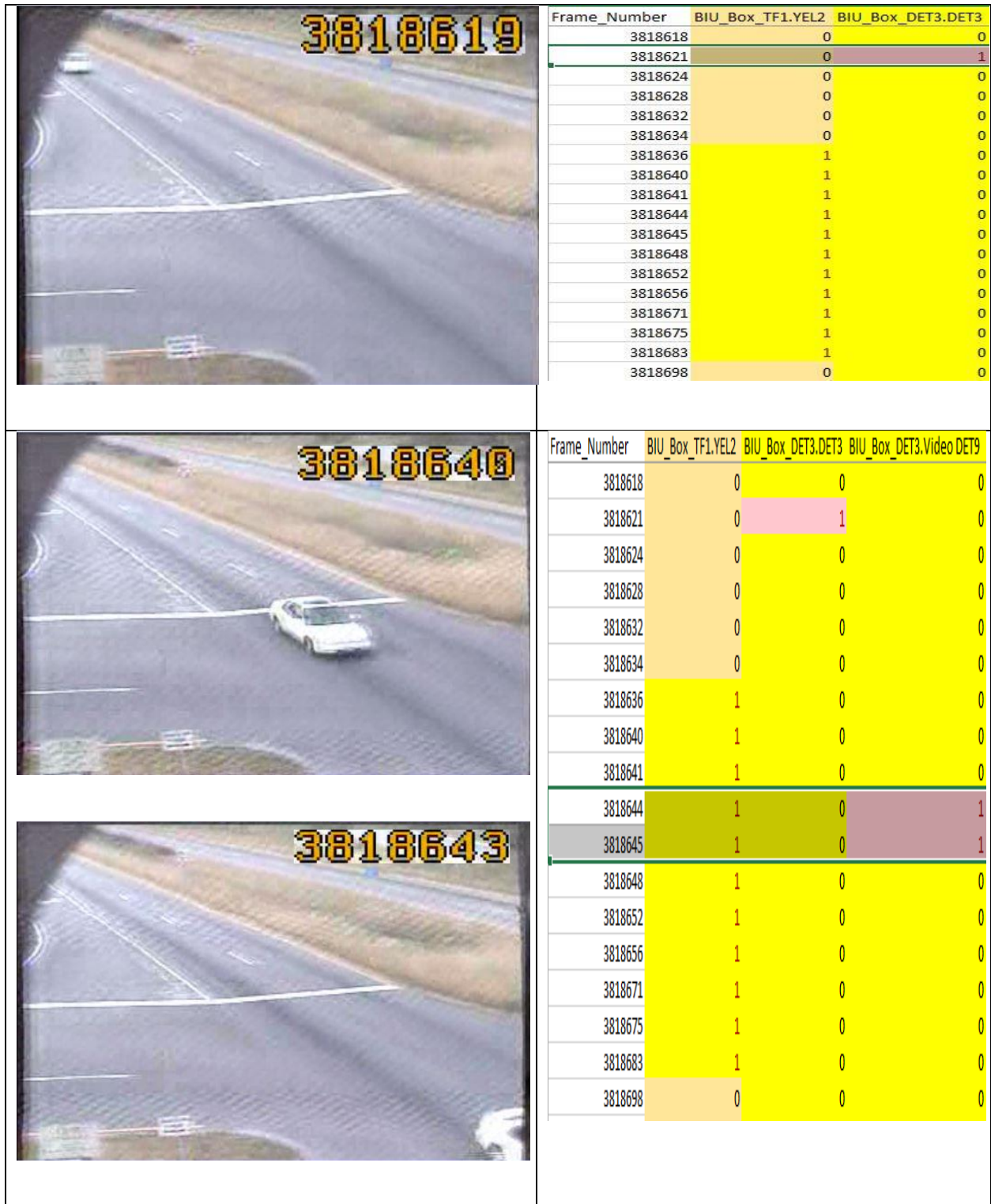**Figure 3-6 A Sample of a Vehicle Stopping before the Intersection in the Yellow Interval**

Figure 3-7 Corresponding Yellow Signal Time and Detector Status for the Passing Vehicle

Frame_Number	BIU_Box_TF1.YEL2	BIU_Box_DET3.DET2
3822586	0	0
3822589	1	0
3822593	1	0
3822597	1	0
3822601	1	0
3822605	1	0
3822609	1	1
3822610	1	1
3822613	1	0
3822617	1	0
3822621	1	0
3822625	1	0
3822628	1	0
3822629	1	0
3822633	1	0
3822635	1	0
3822636	0	0

Frame_Number	BIU_Box_TF1.YEL2	BIU_Box_DET3.DET2	BIU_Box_DET3.Video DET10
3822586	0	0	0
3822589	1	0	0
3822593	1	0	0
3822597	1	0	0
3822601	1	0	0
3822605	1	0	0
3822609	1	1	0
3822610	1	1	0
3822613	1	0	0
3822617	1	0	0
3822621	1	0	0
3822625	1	0	0
3822628	1	0	0
3822629	1	0	0
3822633	1	0	0
3822635	1	0	0
3822636	0	0	0

Figure 3-8 Corresponding Yellow Signal Time and Detector Status for the Stopping Vehicle

3.7 RESULTS

We calculated percentages of stopping vehicles based on the TTIs, for different sites and different directions. Different distributions were used to fit each plot and the distribution with the best goodness of fit was selected for each of them. Based on the plotted diagram and the fitted distribution, 10% and 90% of the stopping vehicles were extracted from the fitted lines. The distance range for West bound direction, the Southgate site was close to the intersection, therefore this direction was not considered in the analysis, due to the lack of data for ranges far from the intersection and thus greater TTIs. Table 3-1 presents the corresponding TTIs for 10% and 90% of the stopping vehicles for Southgate site for East bound direction. Similarly, corresponding TTIs for 10% and 90% of the stopping vehicles for Ridgeway for different directions are shown in table 3-2. As shown in these two tables, the 10% of the stopping vehicles is 2.6 and 1.1 (mean=1.85, Std=1.06, variance=1.12) for different directions for the Ridgeway site and 1.7 for East bound direction the Southgate site. 90% of the stopping vehicles also is 8.9 and 7.8 (mean=8.35, Std=0.78, variance=0.60), and 8.7 for different directions for the Ridgeway and the Southgate site, respectively. The statistical results for comparing Southgate site, with mean number for the Ridgeway site are mean=1.47, Std=0.53, variance=0.28, and mean= 8.525, Std= 0.247, variance= 0.061 for the lower and upper boundaries respectively.

Table 3-1 Corresponding TTIs for 10% and 90% of Stopping Vehicles, Southgate Site

Direction	10 % of the Stopping Vehicles (s)	90% of the Stopping Vehicles (s)
East Bound	1.7	8.7

Table 3-2 Corresponding TTIs for 10% and 90% of Stopping Vehicles for Each Direction, Ridgeway Site

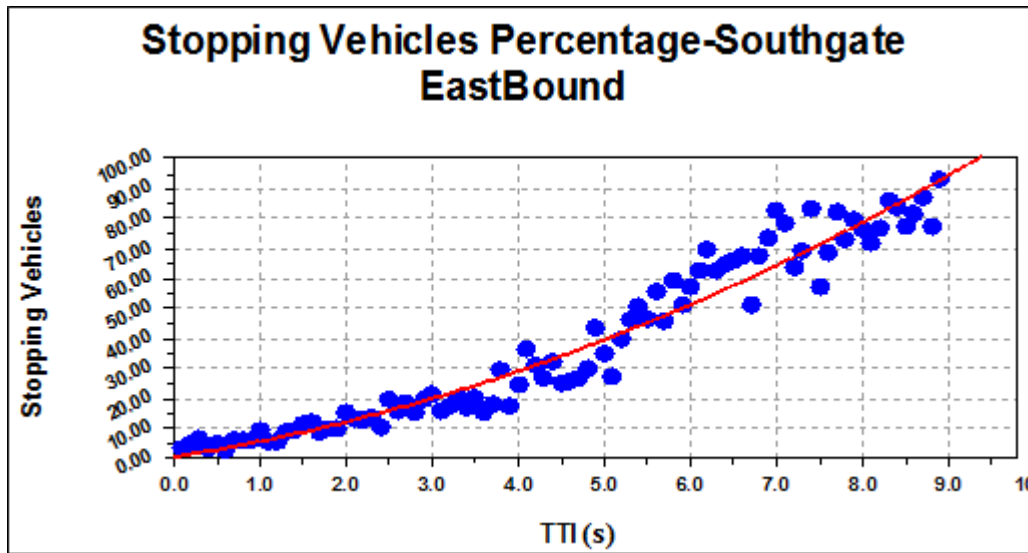| Direction	10 % of the Stopping Vehicles (s)	90% of the Stopping Vehicles (s)
North Bound	2.6	8.9
South Bound	1.1	7.8
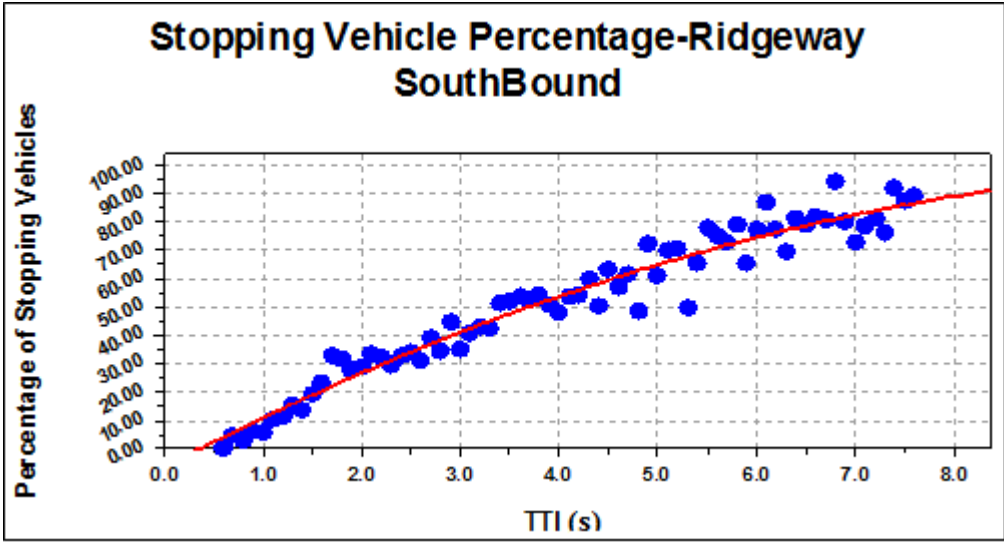
(a)
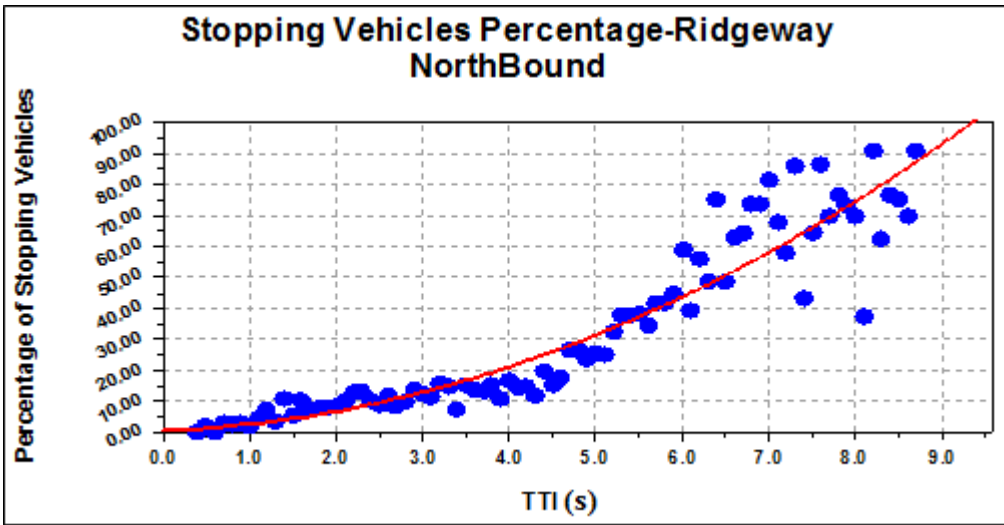
(b)

Figure 3-9 (a) The Percentage of Stopping Vehicles Based on Their Time to Intersection for the southbound direction, the Ridgeway Site (b) The Percentage of Stopping Vehicles Based on Their Time to Intersection for the northbound direction, the Ridgeway Site

Figure 3-10 The Percentage of Stopping Vehicles Based on Their Time to Intersection for the Eastbound direction, the Southgate Site

Moreover, based on the results, South bound direction of the Ridgeway site has smaller

boundaries compared to North bound direction, with almost the same range for the dilemma

zone.

These findings indicate that the dilemma zone boundaries are sensitive to drivers' behavior,

speed distribution and intersection characteristics, and are not constant among all intersections

and directions. Intersections with advance warning signs have significantly higher upper

dilemma zone boundary due to their impact on drivers to increase their speed and they should not

be considered the same as other intersections when designing signal operations. Hence, these

values should be defined for each intersection separately by considering the intersection's type

and traffic characteristics like speed distribution and drivers' behavior, rather than assuming a

pre-defined boundaries when designing intersections and traffic signal operations.

3.8   CONCLUSION AND FUTURE RESEARCH

New values for Type II Dilemma Zone boundaries in the presence of advanced flashing yellow signs were presented in this paper by analyzing more than 1,870 hours of data, which was rarely used in the previous studies. The lower and upper boundaries of dilemma zone were calculated for each direction for two different sites. This study found new boundaries for the intersections with advanced flashing signs. Results of the founded boundaries also showed that dilemma zone boundaries are significantly different at the presence of advanced flashing signs compared to other intersections. Moreover, there is a significant difference between boundaries between the two intersections, also dilemma zone boundaries are not always constant and they change for different directions and with different intersection characteristics. Thus, the final finding of this study suggests that dilemma zone boundaries should be defined differently for intersections with advanced flashing signs and for each intersection with special consideration of its characteristics.

The above finding for the boundaries of dilemma zone in this paper is wider than previous boundaries reported in the literature because of changes in some drivers' behavior before starting the yellow light. Therefore, dilemma zone boundaries are not always constant and authors suggest selecting dilemma zone boundary values considering drivers' behavior and intersection's characteristics.

Future research may investigate differences in dilemma zone boundaries under different conditions such as different weather conditions (data used in this study was collected during summer, possible changes in boundaries may be examined for rainy or snowy days like during fall or winter), difference in dilemma zone based on vehicle's type (passenger cars vs. heavy vehicles), or different traffic volumes and speed limits.

3.9 ACKNOWLEDGEMENT

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4 An Algorithm for Identifying Red Light Runners from Radar Trajectory Data

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4.1 Abstract

Drivers often experience uncertainty when traffic signals change from green to yellow, and they must quickly decide whether to stop at an intersection or continue driving. This situation is called the "dilemma zone," and a great deal of research has been performed to minimize the uncertainty in that zone. The goal is to have the minimum number of vehicles caught in the dilemma zone and reduce red light runners while maximizing the green light period. In order to determine how well dilemma zone protection systems perform, we need to measure the frequency of red light runners. This frequency is closely correlated with crashes, but is difficult to collect. Recent algorithms utilize radar for dilemma zone protection. However, verification of the number of red light runners requires additional video detection. In this study, we propose a new algorithm to predict red light runners and distinguish them from right turners on red. We used Canonical analysis to exclude right turners from red light runners. Our model has 96% accuracy.

Keywords— Dilemma Zone, Red Light Running, Violation Prediction, Video Detection, Signalized Intersection

4.2 Introduction

Intersection and intersection-related crashes form the vast majority of all road crashes. Based on the National Highway Traffic Administration's (NHTSA) data, these crashes make up 27% of all crashes [31]. Red light running is one of the main factors in intersection crashes. Red light running violations accounted for 638 deaths and an estimated number of 133,000 injuries in 2012 [12]. In a nationwide survey (2000) involving 880 licensed drivers, one in five drivers declared that they made at least one red light violation in the last 10 signalized intersections they passed through [71]. A study of red light running violations conducted at five high-volume intersections in Fairfax, Virginia, showed an average of three red light runners per intersection per hour [72]. A travel safety study in three Southeast Virginia cities showed that red light running violations were more frequent at larger intersections and at higher traffic volumes [73].

Prior research has identified factors affecting red light violations as: longer yellow intervals, absence of side street vehicles, opposing left turners, bicycles and pedestrians, presence of vehicles in adjacent lanes going through the intersection, heavy or not heavy vehicle, and driver age, gender, and ethnicity [74].

Based on this literature, we propose that analyzing statistics regarding red light runners' will lead to more informed prevention and mitigation strategies for reducing their number and improving overall intersection safety.

A dilemma zone, one of the historic problems in traffic safety, is defined as the area when traffic signals turn from green to yellow and drivers in that area face uncertainty regarding whether to choose to stop or proceed through the intersection. If they decide to stop, and the vehicle behind them proceeds, a rear-end crash will occur. If they decide to proceed and the signal turns red, they are a red light runner, and there is a risk of collision with conflicting vehicles. Research has shown that a major factor causing red-light running is the dilemma zone [10, 75-77]. A vast number of intelligent transportation system (ITS) strategies, including basic green-extension time, enhanced green extension time, and green termination, have been deployed to solve the

dilemma zone problem [9, 42, 78]. Among these ITS strategies, Detection-Control System (D-CS), which uses advanced loop detectors [79], and a Wavetronix system using radar detectors [69], are the two best known real time dilemma zone protection systems. Radar detectors can continuously monitor vehicles approaching intersections, and therefore give more accurate information about vehicles, so they are one of the most commonly used technologies for providing dilemma zone protection. However, video detection is needed for monitoring and detecting red light runners. Data from radar detectors installed on US 460 at Southgate Rd. in Blacksburg, Virginia, revealed that a high percentage of red light runners flagged using video detection equipment were not real red light runners. Some of these drivers where simply turning right on red. Hence, there was a need to use the video detector data to devise a methodology that can be used to detect and predict red light runners with higher accuracy.

In the paper, we present a new method for detecting and predicting red light runners using vehicle speed and trajectory data. The model distinguishes red light runners from right turners. Drivers' decisions on whether stop or proceed is a function of their mean cumulative speed, mean cumulative acceleration, time to intersection, and their time-lost-gain [39, 41, 43]. In our algorithm, first the driver's decision to stop or go is predicted [41], then, if they were going to continue through the intersection, based on their arrival time and their speed at the intersection, the algorithm will determine whether they are red light runners. Detecting red light runners with high accuracy is critical, because it has implications for devising strategies and algorithms to reduce crashes in the dilemma zone.

4.3 Methodology

Data Collection

Real time field measurements of vehicle trajectories were collected using the Virginia Tech Signal Control and Operations Research and Education System's (VT-SCORES) lab intersection safety data collection and evaluation system (second generation). The system uses Wavetronix radar and was installed at the T intersection of US 460 and Southgate Rd., in Blacksburg, Virginia, to collect

data for US 460 traffic. Figures 4-1 and 4-2 show pictures of the study site. The second generation of the intersection safety data collection and evaluation system integrates Wavetronix radar data with signal phase, detector, and video data to create a more complete safety assessment of the intersection [70]. Vehicles were detected as they approached the intersection from about 75 m (250 ft) away. Data were collected continuously for all vehicles approaching the intersection and were output as a csv file with vehicle track, speed, range and time, phase data for one hour, and a video file with images of vehicles approaching the intersection.



Figure 4-2 Site location

Proposed Model

The first step in identifying red light runners was to determine whether a vehicle would stop or go. To that end, the model presented by Ghanipoor, et al. for predicting drivers' decision based on the mentioned factors was used [41]. This model was initially proposed for simulator data. In this research, we deployed the model for field data and modified it to predict the correct number of red light runners. The parameters for this model were mean cumulative speed, mean cumulative acceleration, time to intersection, and time-lost-gain (time that vehicle obtain or loose when accelerating or decelerating compared to driving with a constant speed). The validation was performed by comparing the results with the recorded video files from the field.

Figure 4-1 West bound view of the intersection

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The algorithm for identifying red light runners is shown in figure 4-3. This algorithm first determines whether the vehicle is going to stop or continue. If the vehicle is going to continue, it then extrapolates the vehicle's time and distance to the intersection, and its speed, to find the arrival time to the intersection. If vehicle's speed is less than 17.06 mph, it is categorized at a right turner; otherwise it was categorized as a red light runner. The MATLAB smoothing spline method was used to extrapolate vehicles' trajectories based on their previous ranges, speeds and times. Only westbound traffic on US 460 were analyzed, because that traffic had right turning vehicles. For separating right turners from red light runners, discriminant analysis was performed and a model was produced to exclude right turners (N=14, Mean=0.25, Std Dev=0.44) from red light runners (N=40, Mean=0.74, Std Dev=0.44) counting (1) (figure 4-4). Discriminant analysis is a statistical analysis used to separate two or more groups from each other and determine to which known groups a new observation belongs based on measured characteristics.

$$\text{Status} = 0.0937555 \times \text{Speed (MPH)} \quad (1)$$

$$\text{Red Light Runner} = \begin{cases} \text{Yes} & \text{Status} > 1.6 \\ \text{No} & \text{Status} \leq 1.6 \end{cases}$$
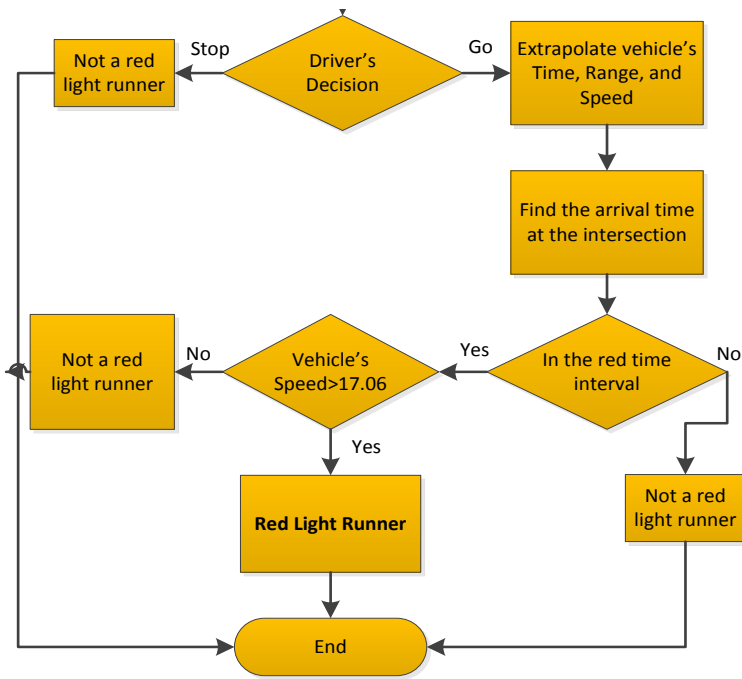
Figure 4-3 The algorithm for identifying red light runners.

Figure 4-4 shows the canonical plot for discriminating red light runners from right turners. The blue dots indicate right turners, and the red dots indicate red light runners. Based on the figure (and canonical analysis), if the canonical result (status) is greater than 1.6, the vehicle is a red light runner.
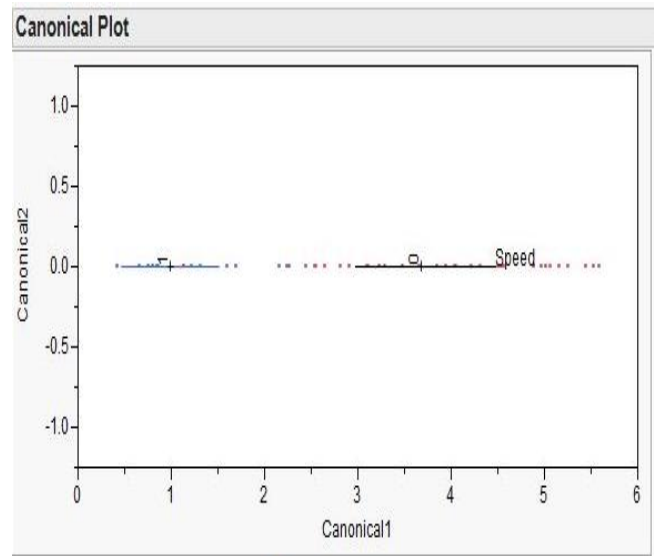
Figure 4-4 Canonical discriminant analysis

In figure 4-5, sample vehicle trajectory data are shown. The vertical axis is vehicle distance to the

intersection in feet, and the horizontal axis is time in seconds. Speed is color coded and phase cycles are drawn on the time axis. A red light runner, right turner, and a vehicle which decided to stop are boxed in the figure with a red rectangle. Vehicle 3 was a red light runner and had a speed between 30-40 mph when approaching the intersection. Vehicle 2 stopped and had a speed equal to zero. Vehicle 1 continued and was a right turner with a speed less than 10 mph.
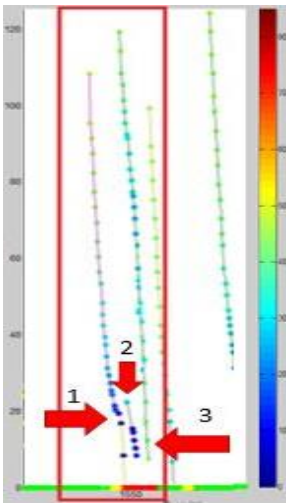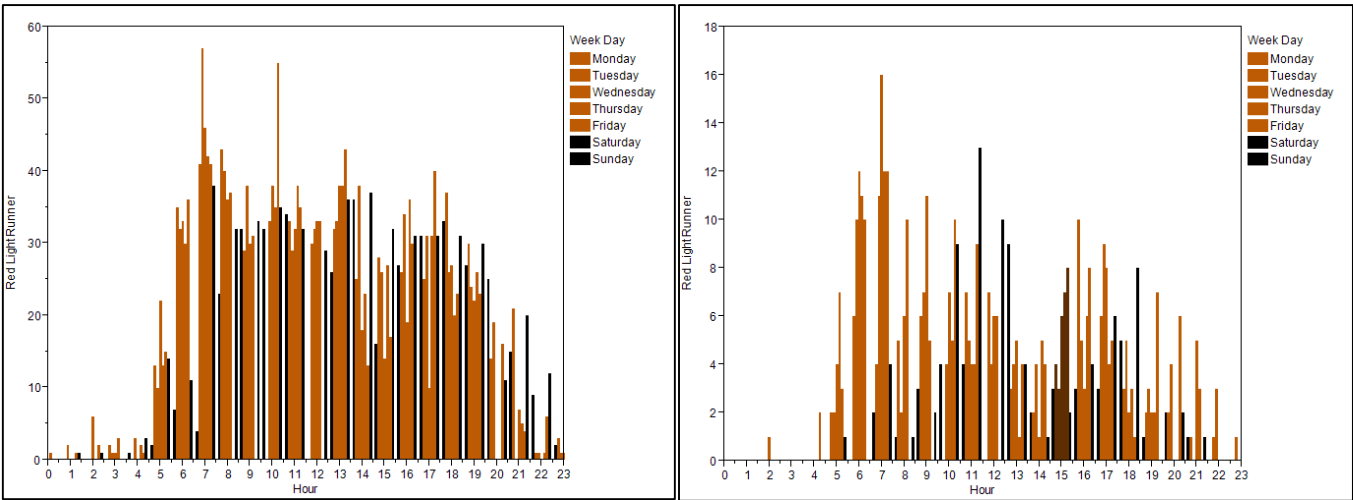

Figure 4-5 Vehicle trajectories

4.4 Analysis and Results

Data from one month were selected for analysis. A Matlab script was written to process the data and deploy the algorithm for identifying red light runners. The result of the analysis is shown below (figure 4-6).

a) Eastbound

b) Westbound

Figure 4-6 Number of red light runners per hour for each weekday

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Results of the red light running findings showed that there were an average of 19.91 (N=185, Std Dev=15.30) and 3.41 (N=185, Std Dev=3.49) red light runners per hour in one week for the eastbound and westbound directions, respectively. As shown in figure 6, most of the red light running occurred in the early morning when drivers usually go to work or at night when they go home. Those times also had higher traffic volumes. Furthermore, weekends had a higher rate of red light violations. An alternative method for finding red light runners was loop detectors, which are not highly reliable. To statistically compare the results regarding red light runners based on radar and on loop detectors, a t-test was conducted. Results showed that there was a statistically significant difference between red light runners per hour in a week based on measurement type for both eastbound ($p < 0.0001$) and westbound traffic ($p < 0.0001$). Red-light runners measured using radar for eastbound traffic (N=185, Mean=19.91, Std Dev=15.30) and westbound traffic (N=185, Mean=3.41, Std Dev=3.49) had far lower means and standard deviations than those measured

using loop detectors for eastbound traffic (N=185, Mean=55.22, Std Dev=41.811) and westbound traffic (N=185, Mean=70.44, Std Dev=50.08).

To validate the model and find its percent accuracy, 100 samples were randomly selected (using the MS Excel random function) and checked against video files. The results are presented in table 4-1. The mean absolute error was 0.04, and was based on a confusion matrix and calculating true positive, true negative, false negative, and false positive amounts. The overall accuracy of the model was 96%.

Number of Errors	Turning Right	Red Light Runner	Emergency Vehicle
Misclassification	0	0	0
False-Positive	3	0	1

Table 4-1 Misclassification and False-Positive errors for 100 samples

4.5 Conclusions and Future Research

In this study, we proposed a new method for finding red light runners to be used as a substitution for video detection methods. This model is based on driver's

decision prediction, and it excludes right turners on red to determine the number of red light runners in each cycle and hour. The algorithm was 96% accurate when compared to video records.

Future research can focus on implementing a similar method for identifying red light runners among emergency vehicles, trucks, and busses based on their unique characteristics. Moreover, more research can be conducted on providing more precise detection.

4.6 Acknowledgements

4.7 References

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5 Conclusion

This thesis conducted two dilemma zone protection studies with the aim of increasing signalized intersections safety. The Type II dilemma zone boundaries were reexamined at the presence of advanced flashing yellow signs and new values for boundary range were presented by analyzing more than 1870 hours of vehicle trajectory radar data. Dilemma zone boundaries found to be significantly different for intersections with advance warning systems compared to other intersections. The upper dilemma zone boundaries found to be greatly higher for these intersections. The reason for these higher values is vehicle's speeding up during the yellow flashing signal before the onset of yellow signal when approaching the intersection, in order to escape the intersection. . This indicates that some drivers, even far from the intersection, accelerate more to escape from dilemma zone. Examining the vehicle's trajectory data showed that some vehicles change their speed during yellow time before arriving to intersection, therefore the assumption of constant speed, when calculating TTI is not always correct for the intersections with advanced warning signs. Findings of this research reveal that advance warning systems influences drivers' behaviors, hence advance warning systems and their impact need to be carefully examined for dilemma zone mitigation systems and intersection safety analysis. Findings of this research complies with the previous studies which had been indicated that the presence of advance warning systems increases drivers approaching speed to the intersection. This research is expected to be a valuable source for calculating the Type II dilemma zone boundaries for signalized intersections with advance warning systems.

The study's finding shows that dilemma zone boundaries are different for different directions of an intersection as well as for different intersections. Hence, dilemma zone boundaries depend on

intersection's characteristic and should not be assumed the same when designing traffic strategies for intersections.

Moreover, this thesis presents a new method for detecting red light violations based on driver's decision prediction, which is able of excluding right turners from red light runners at the red traffic signal interval. The results of finding red light runners for different directions of the selected intersection showed that number of red light runners is significantly different for different directions. And these numbers are higher early in the morning or at night when drivers are going to or coming back from work with the higher traffic volumes as well as weekend hours. This method for finding red light runners is preferred over using loop detectors because of its higher reliability.

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