ABSTRACT

Title of Document: DESIGN, DEPLOYMENT, AND EVALUATION OF AN INTEGRATED DILEMMA ZONE PROTECTION SYSTEM FOR IMPROVING SAFETY AND MOBILITY FOR HIGH SPEED SUBURBAN INTERSECTIONS

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Despite the fact that both traffic researchers and highway agencies have devoted considerable efforts over the past few decades on improving intersection safety, development of effective strategies to contend with this vital issue remains a challenging task. This dissertation presents the design, deployment, and evaluation of a **d**ilemma **z**one **p**rotection **s**ystem (DZPS) to cope with the safety issues due to the presence of a dilemma zone, a primary factor contributing to rear-end collisions or side-angle traffic crashes, especially at suburban intersections with high-speed traffic flows. The DZPS provides safety improvements from both proactive and reactive perspectives. It also features a dynamic function for speed harmonization with minimal additional hardware to fully utilize each key component for safety and mobility improvements. The dissertation consists of four parts; the first part illustrates the development of a simulation platform, including

step-by-step procedures and details on how all embedded algorithms have been integrated and implemented for pre-deployment analysis. Recognizing that a reliable evaluation of a deployed DZPS's effectiveness requires observation of field data collected over a long time period, the developed simulator will serve the need of identifying potential control and operation issues prior to field deployment with well-calibrated simulation experiments. The second part highlights the DZPS's embedded algorithm for all-red extension, which has been developed to provide additional clearance time to red-light-running vehicles so as to prevent crashes with side-street vehicles. The third part of this study focuses on the design of a speed harmonization module with a variable speed sign using existing hardware for executing the all-red extension. The enhanced system offers additional functions for predicting gap-out timing and calculating the advisory speed for approaching vehicles during the green phase to progress through the intersection. The last part of this research focuses on conducting a field evaluation for the deployed DZPS. The results of extensive analysis show that the system is effective in reducing both the average speed of approaching vehicles and the spatial range of dilemma zones. Most importantly, the developed system can indeed offer full protection to prevent drivers from becoming trapped in a dilemma zone and causing angle-crashes, as expected, at the acceptable preset rate of false alarm.

DESIGN, DEPLOYMENT, AND EVALUATION OF AN INTEGRATED DILEMMA ZONE PROTECTION SYSTEM FOR IMPROVING SAFETY AND MOBILITY FOR HIGH-SPEED SUBURBAN INTERSECTIONS

By

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

I am sure that I could not finish my study without support from my family. My father, Youngjun Park, has always stood by my side and encouraged me to pursue a doctorate. Yinye Kim, my mother, always worries about me and always tries to support me as her top priority. I also want to thank my brother, Junhyuk Park, and sister, Myoungjung Park, for their help. I am so grateful to my wife, Mrs. Pyunghwa Yoon, who has always encouraged me, even when I felt frustrated or like I was under a great amount of pressure. I am sure that I could not have finished my studies without her. She is both a wonderful wife and an incredible mother to our two daughters, Noel Sein Park and Kezia Seah Park. I am very happy for our two daughters who, while I have pursued my degree, have grown into two happy and beautiful kids. I dedicate this work to my wife: thank you, and I will always love you. I appreciate all the support from my parents-in-law (Sungoh Yoon, Myoungsook Park), sisters-in-law, brothers-in-law, and all other family members. I also appreciate CKBC members (especially Pastor Samuel Choi) who pray for me and continue to support my life in the United States. I give God all glory. Lastly, I thank to my roommate MS.

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Chapter 1. Introduction

1.1 Research Background

Since improving traffic safety has long been the priority task of most highway agencies, (e.g., the Maryland Candidate Safety Improvement Location [CSIL] program, 2015), traffic researchers/engineers have placed most attention on reducing accidents at hazardous intersections where accidents often result in injuries and/or fatalities, and consequently, significant traffic delays and property loss. According to the National Highway Traffic Safety Administration, there were 756,570 intersection-related accidents in the United States in 2009, accounting for 36 percent of total accidents (Choi, 2010). The dilemma zone (DZ), a roadway segment where drivers cannot pass the intersection nor stop safely at the stop line during the yellow phase, is one of the main contributing factors to such accidents (Choi, 2010; Brittany et al., 2004; and Hurwitz et al., 2011).

There are two types of accidents that are known to be caused by factors related to the presence of a dilemma zone. The first type of such accidents is the side-angle crash, during which drivers may be trapped in the dilemma zone and unable to stop safely at the stop line. Thus, they are likely to choose to run through the red light, causing a heightened risk of collision with vehicles entering the intersection from the side street during their respective green phase. The second type of accidents is a rear-end collision, which is often incurred when the front vehicle chooses to stop at the stop line during the yellow phase, but the following vehicle decides to pass the intersection. The conflict between these two types of drivers can cause a rear-end collision. Despite the fact that traffic researchers have devoted significant efforts on this vital issue from both the human-factors and design perspectives over the past few decades, development of an effective and reliable Dilemma Zone Protection System (DZPS) for deployment in practice has remained a challenging task (Chang, et al., 2014, Tolani et. al., 2015, MSHA, 2012, MSHA 2014b, FHWA, 2015; USDOT 2014).

To cope with the safety issues associated with the dilemma zone at high-speed intersections, one should first identify the key contributing factors, which are summarized below:

- High approaching speed: As observed in many field studies, drivers driving faster than the posted speed limit are likely to become trapped in the respective dilemma zones, and some may even choose to pass the intersection during the red phase. As such, it is important to reduce the speeds of approaching vehicles for safety improvement.
- Driver response during the yellow phase: It is challenging to predict the decisions that drivers will make during a yellow phase under various traffic conditions. Given the same distance from the stop line and approaching speed, a driver's decision when encountering the yellow phase – whether or not they do so properly – will directly affect whether or not an accident will occur. However, it is difficult to understand the behaviors of different driving populations, and it is also a challenge to monitor and analyze driver behavior from field observations. Similarly, it is very difficult to estimate the compliance pattern of drivers with any traffic information or control strategies.

Hence, any DZPS adopted to improve intersection safety should carry some essential functions to address these vital issues:

- An information component to slow the speed of approaching vehicles: Using information devices such as the variable message sign or advanced warning sign, a DZPS shall be capable of proactively lowering the speed of drivers who approach the intersection at high speeds.

- A prediction module to estimate a driver's reaction to the yellow phase: To reliably capture a driver's response during a yellow phase, the proposed system shall be capable of precisely and continuously monitoring the evolution of speed and location of vehicles in the monitoring zones. In addition, such a DZPS should also have a behavioral mechanism to predict whether or not the target vehicle will run over the all-red phase, based on its speed, location, travel time to pass the intersection, and relation to leading vehicles. Such information should be updated continuously over time for the system's control module to make a proper decision.

- An updated design to prevent side-angle crashes: The DZPS should feature reactive control strategies to prevent accidents caused by non-compliant aggressive drivers or those who improperly change their decisions at the last moment to run over the intersection during the red phase.

Figure 1-1 Example of the variable speed signs

In order to best use available hardware for a DZPS, one may concurrently improve the target intersection's operational efficiency, such as stop delay, with minimized additional components. Figure 1-1 shows an example of variable speed signs, which can be used with other computing modules to exercise speed control and thereby improve mobility and/or overall safety. By harmonizing the speed between the congested and uncongested roadway segments of an intersection, the roadway capacity can be better utilized and consequently reduce the potential for aggressive drivers (Hegyi et al., 2005). Furthermore, by adjusting the speeds of approaching traffic flows to a high-speed intersection, it is likely that the speed variance among vehicles will be reduced, thereby further improving the overall safety (Allaby et al., 2007).

More specifically, by incorporating a Variable Speed Limit (VSL) system into a DZPS, one can use the speed message to proactively advise drivers and prevent them from becoming trapped in the dilemma zone when they approach the intersection at the end of the green phase. Drivers can also be advised to follow the progression speed when they are approaching the intersection during the end of the red phase. Certainly, the challenge for improving both safety and mobility lies in the need to have a function that can reliably predict the gap-out timings with the popular actuated signal control under various conditions.

Despite the potential for a DZPS system to offer both safety and efficiency improvements, most existing studies and practices that contend with dilemma-zone issues focus on altering the green time by either extending beyond or by terminating early the maximum green time. For instance, several field studies have shown the effectiveness of the green extension and green termination strategies to improve intersection safety (Zegger, 1997; Vincent and Pierce, 1988; Peterson, 1986; and Kronborg et al., 1997). One of the prevailing approaches to proactively contend with dilemma zones is to install an advanced warning sign. The sign, “Prepare to Stop,” is placed further upstream from the intersection, particularly when there is a short sight distance. Several field studies also revealed the effectiveness of the advanced warning sign in reducing the number of vehicles that either run over the red phase or become trapped in the dilemma zone (McCoy and Pesti, 2003; Bowman, 1993; Messer et al., 2004; and Sayde et al., 1999). Another alternative remedy for dilemma-zone-related accidents is to provide additional clearance time by extending the all-red phase. One of the major benefits of such a design is to reactively provide protection for potential side-angle crashes. However, an effective strategy that builds on both the preventive and reactive perspectives to improve safety and increase operational efficiency of a hazardous intersection is not yet available.

1.2 Objectives and Scope of Research

The objective of this research is to design, deploy, and evaluate a dilemma zone protection system for high-speed suburban intersections. The proposed system offers both proactive and reactive functions to ensure intersection safety and operational efficiency under both pre-timed and actuated signal control. More specifically, this research has produced a system that can effectively identify potential aggressive drivers who may run over the red-light phase, and prevent such drivers from causing side-angle accidents. In addition, the system is also designed to maximize the efficiency of the intersection with speed harmonization, given the same hardware for safety improvements.

Figure 1-2 shows the process to accomplish the objective of this research. There are three main processes. The development of the system includes identifying expected functions of the system, listing key system components, and identifying contributing factors. The second stage, pre-deployment assessment, consists of field data collection, development of a simulation platform and algorithm, result analysis, and identification of potential issues. The last stage, after deployment of the system in the field, includes field data collection for impact analysis and performance evaluation.

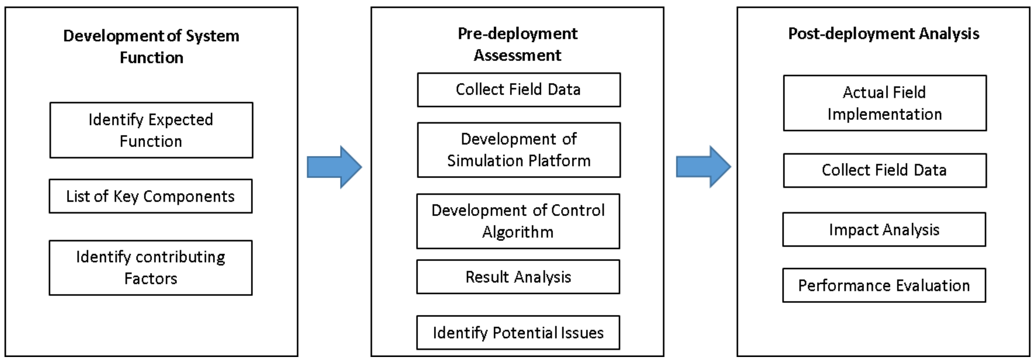


Figure 1-2 Development of the DZPS sequence

1.3 Organization of the Dissertation

Figure 1-3 illustrates the principal tasks and organization of this dissertation, along with its major tasks. A brief description of each chapter is introduced next.

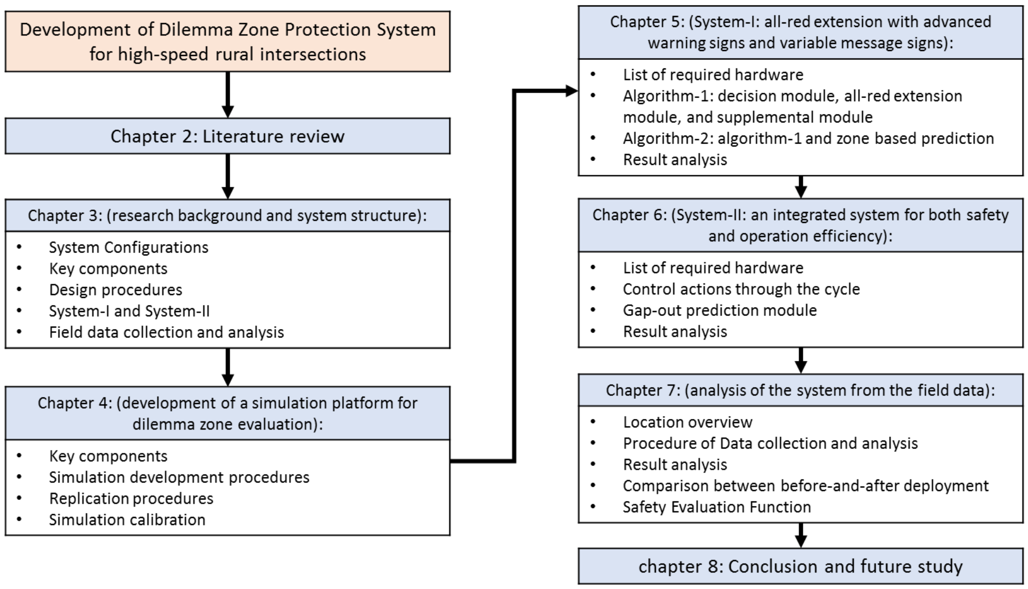


Figure 1-3 Organization of the proposal research

- Chapter 2 presents an in-depth review of existing studies on dilemma zone protection systems, including a green extension and an early termination, an advanced warning sign, a detection and control system, and an all-red extension system. Also included in this chapter are driving behaviors during the yellow phase and a green-light-optimized speed advisory system.

- Chapter 3 describes the research background and system structure. An introduction of the proposed dilemma zone protection system is also provided. There are two systems proposed in this study. System-I features an all-red extension function for improving safety, and System-II, enhanced from System-I, offers both safety protection and speed harmonization with an advisory speed sign. This chapter also illustrates the design process with field data from a real-world intersection.

- Chapter 4 describes the design and calibration process of a simulation platform for pre-deployment evaluation. The main purposes of the simulation platform are to replicate real-world traffic patterns and driver characteristics, and to test the system's performance and the interactions between its key modules in response to the needs of concurrently improving safety and mobility.

- Chapter 5 demonstrates the evaluation result of System-I with the simulation platform. Step-by-step descriptions of the all-red extension algorithm, along with the sensitivity analysis results from the simulation platform, have been presented, based on selected MOEs.

- Chapter 6 describes the key algorithm embedded in System-II to improve not only safety, but also mobility. This chapter also presents all key control actions in a signal cycle, along with evaluation results from the simulation platform.

- Chapter 7 presents the results of extensive traffic data analysis from the deployed DZPS. This chapter describes the data collection procedure, analysis on the short-term impact on driving behaviors, a safety evaluation function, and the detection performance effectiveness of the deployed DZPS, based on the field data.

- Chapter 8 summarizes research findings, lessons, and future works. A summary of the contributions of this research and additional future tasks constitutes the core of this research.

Chapter 2. Literature Review

2.1 Introduction

2.1.1 Type I Dilemma Zone

The study by Gazis, Herman, and Maraduin (1960) first introduced the intersection dilemma zone model, known as the “Type-I Dilemma” or “GHM model,” which defines the dilemma zone as an area in which a vehicle approaching the intersection during the yellow phase can neither safely clear the intersection nor stop comfortably at the stop line.

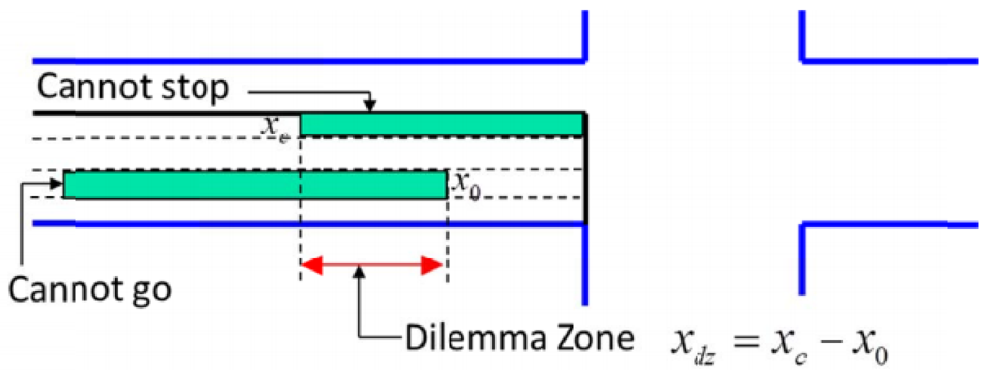


Figure 2-1 A graphical illustration of the Type-I dilemma zone at signalized intersections

Figure 2-1 shows the graphical illustration of the Type-I dilemma zone, an overlapping of “cannot stop” and “cannot go” areas. The existing practice for computing the dilemma zone is based on the following kinematics equation:

$$x_{dz} = x_c - x_0 = v_0\delta_2 + \frac{{v_0}^2}{2{a_2}^*} - v_0\tau + (\,w + L) - \frac{1}{2}{a_1}^*(\tau - \delta_1)^2 \qquad (2\text{-}1)$$

Where:

x_c: Critical distance for a smooth stop under the maximum deceleration rate;

x_0 : Critical distance for intersection clearance under the maximum acceleration rate;

τ: Duration of yellow interval (s);

δ_1: Reaction-time lag of the driver-vehicle complex (s);

δ_2: Decision-making time of a driver (s);

v_0: Approaching speed of vehicles (ft/s);

$a_1{}^*$: Maximum acceleration rate of approaching vehicles (ft/s^2);

$a_2{}^*$: Maximum deceleration rate of approaching vehicles (ft/s^2);

w : Intersection width (ft); and

L : Average vehicle length (ft).

The GHM model is widely used to estimate the yellow or all-red phase duration for intersections. If there is a gap between the end of the "cannot go" area and the start of the "cannot stop" area, the space where drivers have an option to stop at or pass through the intersection is called "option zone." Conversely, Olson and Rothery (1961) conducted field observations at five intersections and found that drivers tend to take advantage of the long yellow phase and consider it an extension of the green phase. Liu et al. (2007) also analyzed driver behaviors during the yellow phase at six intersections. Their study found that driver behaviors vary from location to location, and the resulting dilemma zones are dynamic in nature. The researchers' study also concluded that a longer yellow duration does not affect a driver's decision at the onset of the yellow phase. As shown in Equation 2-1, key model parameters such as reaction time, acceleration, and deceleration rates, are likely to be dependent on driver behaviors and an intersection's geometric features. Several other studies have been conducted to estimate such parameters for the dilemma zone identification (Olson and Rothery, 1961, Crawfoard and Taylor, 1961, Williams, 1977, Chang et al., 1985, and Lin, 1986). In brief, since the approaching speeds of vehicles and responses of drivers are often distributed in a wide range, the resulting dilemma zone for each intersection is not a constant, rather, it is spread over a spatial range.

2.1.2 Type II Dilemma Zone

Parsonson et al. defined the Type II dilemma zone at an ITE annual meeting as a roadway segment from the stop line within which the probability of a driver choosing to stop when encountering a yellow phase drops from 90 percent to 10 percent (Parsonson 1974). Extensive field studies for calibrating such a dilemma zone have also been conducted (Zegeer, 1977; Chang et al., 1985; Bonneson et al., 1994; Papaioannou, 2007; Wei et al., 2009). Figure 2-2 shows the results of their studies where their boundaries vary with vehicle types. For example, trucks often have longer upper boundaries due to the lower deceleration rates compared with other vehicle types. While Type II dilemma zones also vary with location and vehicle type, they have been used for the design of various dilemma zone protection systems, including the green extension system (Zegger, 1977; Tarko et al., 2006;), LHOVRA (Peterson, 1986;), the green early termination system (Krnobogr, 1997;), the detection control system (Bonnenson, et al., 2002;), and the platoon identification and accommodation system (Chaudhary et al., 2006).

The remaining section is organized as follows: Section 2.2 reviews existing dilemma zone protection systems on green extensions, green truncations, the advanced warning signs, and all-red extensions. Section 2.3 presents key studies on driver responses during the yellow phase or red phase. Section 2.4 summarizes the speed harmonization-related development for intersection progression. The chapter concludes with the research needs for developing the dilemma zone protection and speed harmonization system.

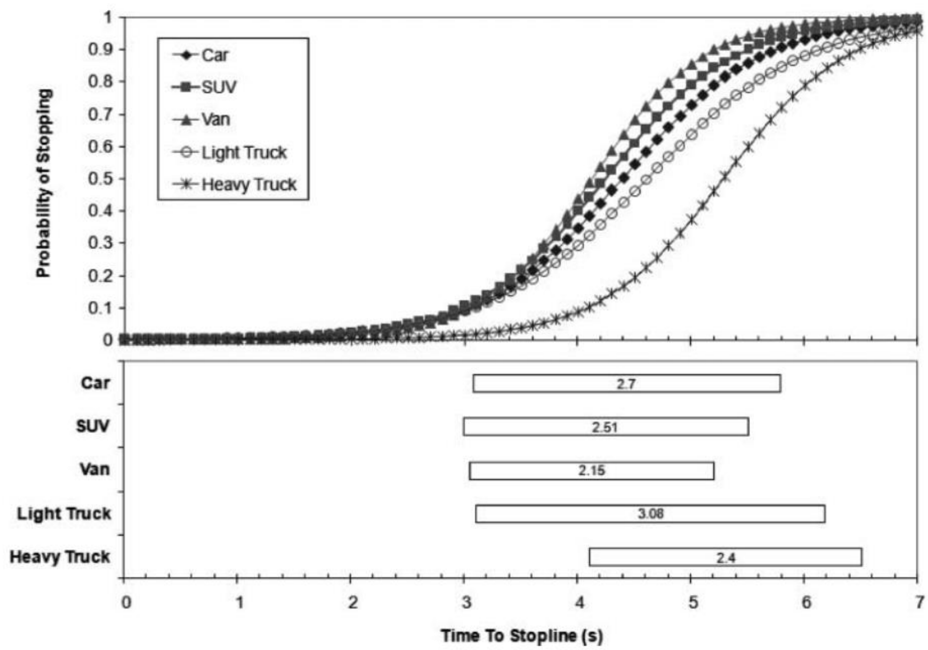


Figure 2-2 Distribution of Type II dilemma zone (Wei et al. 2009)

2.2 Dilemma Zone Protection System

2.2.1 Green Extension or Early Termination Technique

One of the widely used strategies to minimize dilemma zone impact is to alter the maximum green time either with the green extension or the green truncation. The core logic of such a strategy is to either extend the green phase beyond a preset maximum green time to allow vehicles to pass the intersection, or to truncate the green phase to minimize the number of vehicles trapped in the dilemma zone.

Zegeer (1977) conducted a before-and-after evaluation on a proposed Green-Extension System (GES) at three intersections in Kentucky. The proposed GES required two loop detectors (spaced about two to five seconds in advance of the stop bar) where the first is for unit extension for the green phase, and the second detector is for the GES to assure the clearance of vehicles. The field performance results showed a reduction of 54 percent in total accidents and 75 percent in rear-end collisions after deploying the GES.

Along the same line, Tarko et al. (2006) proposed a probabilistic approach to select the optimal green extension to minimize the likelihood function of the Type-I dilemma zone. His proposed method includes the following steps: (1) when the green termination status is warranted, the system will search for all vehicles potentially trapped in the dilemma zone; (2) the system will calculate the dilemma likelihood sum with each extension unit from the identified vehicles; and (3) the system will find a minimized green extension based on the calculated dilemma zone likelihood sums. Simulation results showed that the proposed method can reduce the number of vehicles trapped in the dilemma zone with a short extension to the maximum green.

The Microprocessor Optimized Vehicle Actuation (MOVA) system was developed in the Transportation Research Laboratory in the United Kingdom to improve the signal control system for isolated intersections (Vincent and Peiece, 1988). MOVA is developed primarily for signal timing designs, which vary in response to traffic conditions. Three locations for detectors were proposed in MOVA: IN detector (about 8.0 seconds to the stop line), OUT detector (close to the stop line), and EXIT detector (about 3.5 seconds to the stop line). The end-of-green decision is made based on the comparison of the benefits of preventing vehicles from being trapped in the dilemma zone with the costs of potential delays due to phase changes. The evaluation results from 20 sites showed that such a system provided a reduction of 30 percent in the number of dilemma zone accidents involving injuries (Pierce 1990).

LHOVRA, developed in Sweden (Petersons 1986), consists of six modules: lorry priority (L), major road priority (H), incident reduction (O), variable yellow (V), red light infringement (R), and green-yellow-red-green sequence (A). The signal phase is controlled by six detectors, including five short detectors (e.g. loop detector) and one long detector (e.g., queue detector). Figure 2-3 shows the layout of these detectors for LHOVRA and these functions. The incident reduction module (O), designed for the dilemma zone protection system, is used to reduce the number of vehicles trapped in the dilemma zone. When a vehicle is detected in the dilemma zone, a green extension will be called to provide an additional green time to the target vehicle. Lorry priority module (L) is also part of a dilemma zone protection system, which is used to detect trucks and extend the green duration if needed.

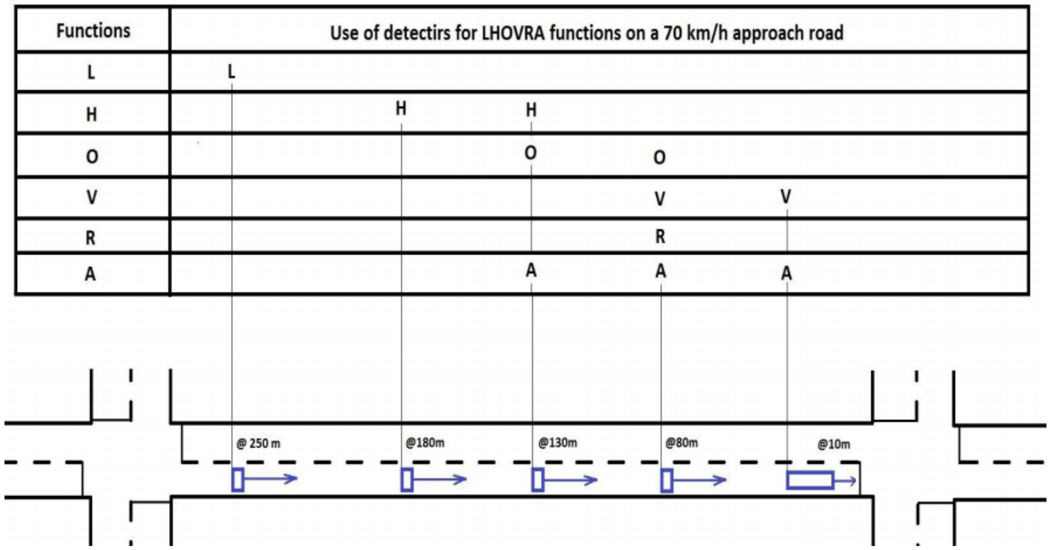


Figure 2-3 Detector layout and relationship on the LHOVRA system

Similar to the incident reduction module (O) in the LHOVRA system, a Self-Organized Signal (SOS) system known as “green termination” was proposed by Kronborg et al. (1997). The locations of detectors are similar to those in LHOVRA, but each detector must cover only one lane, and a detector is placed further upstream from the LHOVRA system. The objective of SOS is to minimize both risk from the dilemma zone and delay in comparison to the other approaches. Based on detector information, the signal controller can estimate vehicle trajectories and find an optimal timing to end the green phase. The embedded optimization algorithm also penalizes the incident reduction module when two or more vehicles are in the same lane within the dilemma zone.

2.2.2 Advanced Warning Sign/Flasher (AWS)

AWSs mainly function to advise drivers of possible phase changes at the downstream intersection. Due to the intricacy of human behavior, implementation of an AWS may affect a driver’s reaction to the yellow phase. There are several types of warning signs reported in the literature (Eck and Sabra, 1985 and Pant and Xie, 1995), such as "Prepare to Stop When Flashing" and "Red Signal Ahead When Flashing." Figure 2-4 shows examples of different types of advanced warning signs.

Figure 2-4 Types of warning sign for red signal

In the study by McCoy and Pesti (2003), the researchers conducted field studies for two different dilemma zone protection systems used by the Nebraska Department of Roads. The first is the green extension method used to minimize the number of vehicles trapped in the dilemma zone at the onset of the yellow phase. The second method is to show a "Prepare to Stop When Flashing" sign with one advanced detector. The advanced detector is activated at a pre-determined time before the onset of the yellow signal. McCoy and Pesti's field study showed that both designs performed equally well in reducing the number of vehicles that ran through red lights; however, the AWS resulted in fewer drivers in the dilemma zone during the yellow phase compared with the advanced warning sign. As such, McCoy and Pesti concluded that advanced warning flashers and advanced detection systems can indeed reduce the number of vehicles trapped in the dilemma zone and encourage drivers to stop at the stop line.

Along the same line of research, many studies indicate the effectiveness of advanced warning signs (AWS) from field observations. For example, Bowman showed a reduction of 23 percent (Bowman 1993), and Messer et al. (Messer et al. 2004) evidenced a reduction of 40 percent in red-light-running vehicles. Sayed et al. (Sayde et al. 1999) found that, compared to those intersections that had not deployed an AWS, those that used an AWS saw a reduced rate of accidents. Regarding the type of message displayed via the AWS, some studies indicate that the most commonly used sign for an AWS is “Prepare to Stop When Flashing” (Eck and Sabra 1985, Pant and Xie 1995).

2.2.3 Detection Control System (D-CS)

Texas Transportation Institute developed a Detection Control System (D-CS) that consists of one upstream detection zone to provide the vehicle speed and length, and a second detection zone located close to the stop line for queue detection (Bonneson et al., 2002). The location of the upstream detector is determined by the “look ahead distance,” which is based on travel time prediction accuracy. Such a system can dynamically identify an approaching vehicle’s dilemma zone prior to entering the zone. The objective of the D-CS is to find the minimum duration of a green phase to minimize both the number of vehicles in the dilemma zone and the delays of vehicles in the other phases. Figure 2-5 shows the core concept of the D-CS, which predicts the number of vehicles in the dilemma zone. The D-CS can calculate the time in which each vehicle on the target approach will emerge from its dilemma zone. The D-CS uses a dynamic monitoring approach to end the green phase with a relatively short allowable headway maximum. A field study by

Bonneson et al. (2002) revealed that D-CS reduces the frequency of vehicles trapped in the dilemma zone, and also the total number of red-light-running vehicles while maintaining or reducing the overall delays prior to the system deployment.

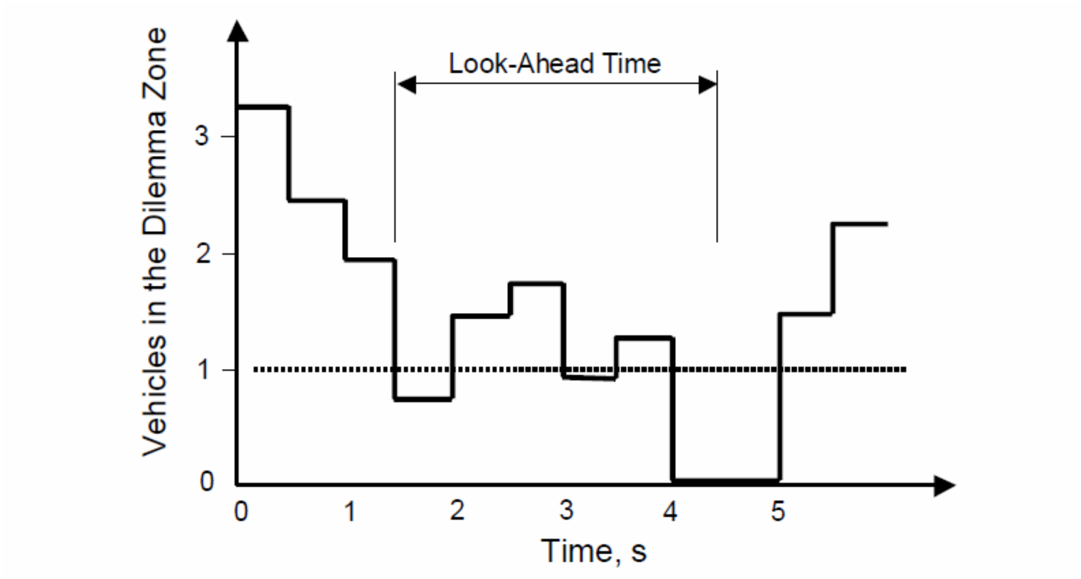


Figure 2-5 Look ahead feature at DC-S

Zimmerman et al. (2014) developed a detection, control, and warning system (DCWS) to use the "vehicle specified in-pavement system" to provide an advanced warning to drivers who will be trapped in the dilemma zone. Figure 2-6 shows the layout of the DCWS. The results of experimental studies indicate that, instead of directly protecting those trapped in the dilemma zone, warning signs that provide more information to drivers in the decision-making stage can prevent drivers from becoming trapped in the dilemma zone in the first place (Zimmerman et al., 2014).

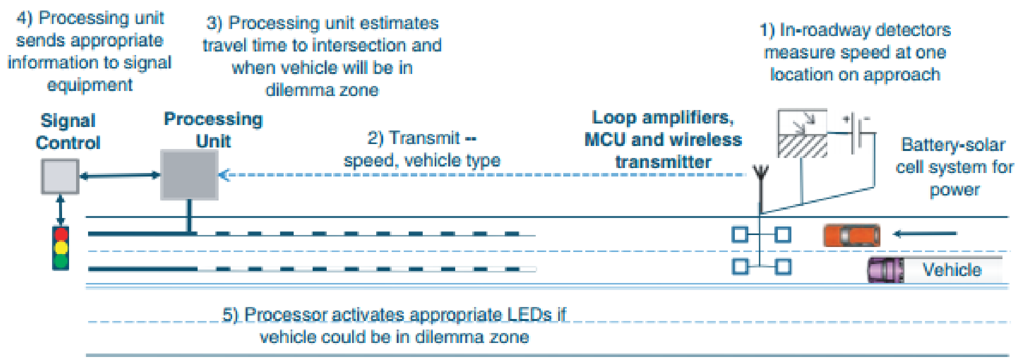


Figure 2-6 DCWS system layout (Zimmerman et al., 2012)

2.2.4 All-Red Extension

An active protection approach to prevent side-angle crashes is to extend the all-red phase. The main objective of this method is to identify vehicles that might run through the red phase and provide additional clearance time for them. The signal controller holds the green phase in the competing approaches until the red-light-running vehicle clears the intersection, so as to prevent a side-angle crash. Figure 2-7 shows the signal phase timing for a normal condition and an all-red extension condition. This all-red extension method requires either the real-time vehicle speed and the location information or predicted information gathered from deployed detectors. An all-red extension can then be adopted based on the identified potential red-light-running vehicles (Gates and Noyce 2015, Chang et al. 2012, Zhang et al. 2012, Park et al.2015 and Gates 2007).

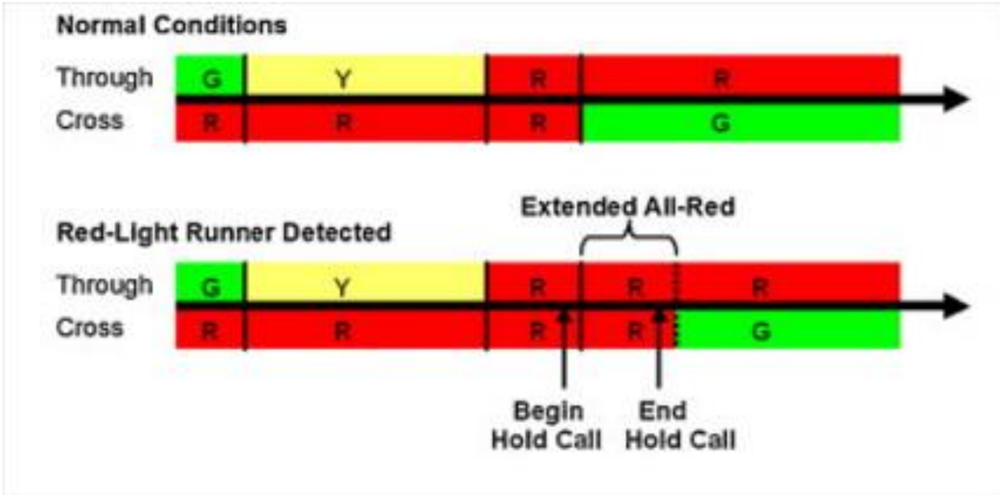


Figure 2-7 Phase diagram for an all-red extension (Gates 2015)

Chang et al. (2012) designed and implemented a dynamic all-red extension system at the intersection of US 40 and Red Toad Road in Cecil County, Maryland, and reported the effectiveness of such a system based on the after-deployment field data. From the evaluation of after-deployment data, the researchers concluded that the all-red extension system can effectively reduce the likelihood of right-angle crashes. Zhang et al. (2012) also developed a probabilistic model for an all-red extension algorithm, DARE (Dynamic All-Red Extension), which can be used to minimize the false alarm rate and maximize the capturing rate based on the speed and the car-following status. The experimental results indicate that DARE has reduced to less than 5 percent of the false-alarm rates and increased to more than 70 percent of the correct-capturing rates.

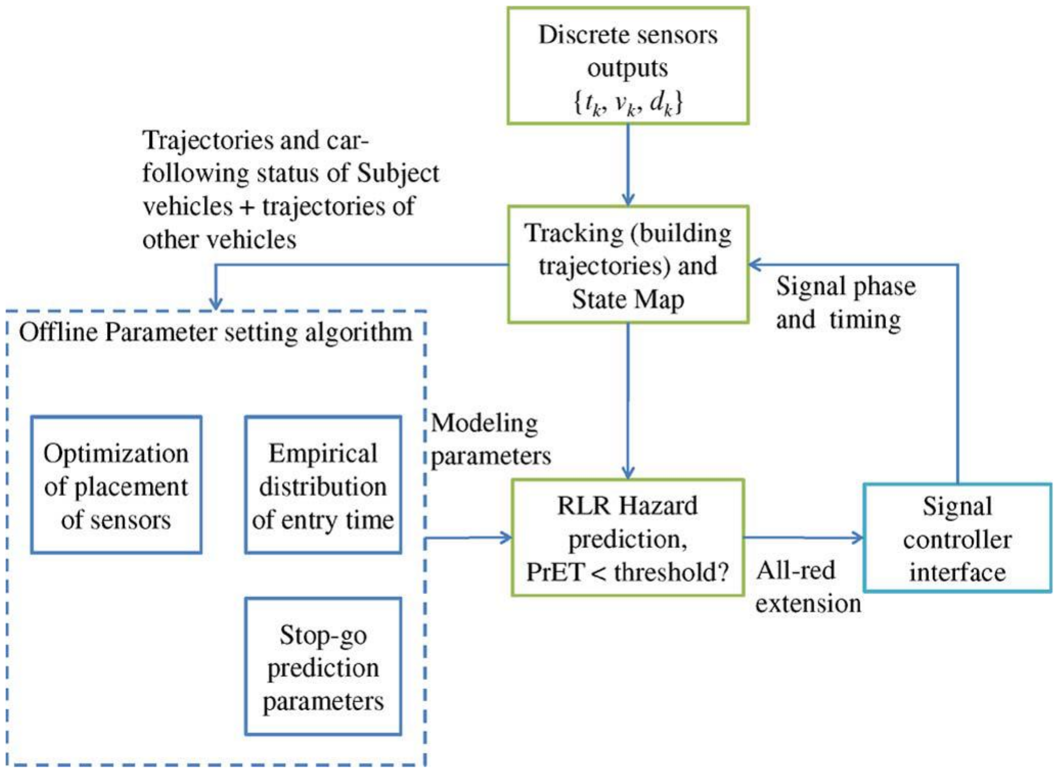


Figure 2-8 DARE system flowchart

2.3 Driving Behavior

To contend with safety issues caused by the intersection dilemma zone, some researchers have conducted field studies to observe the relationships between drivers' decisions during the yellow phase and their decision whether to pass the intersection or to stop at the stop line. For example, Liu et al. (2007) presented an empirical study on drivers' responses to the yellow phase at six signalized intersections in Maryland, reporting that a driver's decision when encountering a yellow phase varies based on the individual behavior and associated factors such as age, gender, presence of passengers, and cell phone usage. The researchers also concluded that extending the yellow phase alone may not be effective in reducing the frequency of accidents. Similar observations on driver behavior conducted in

Greece indicated that gender, age, and platoon leaders and the first-follower are the main factors affecting a driver's reaction to the yellow phase (Papaioannou, 2007). Several other models have been developed to predict a driver's decision at the onset of a yellow phase. (Chang et al., 1985; and Gates and Noyce, 2007). For the same purpose, Yosef and Mahmassani (1981) developed a driver-decision model using a discrete probit modeling method, based on time to intersection and distance to intersection.

2.4 Green Light Optimized Speed Advisory

Green Light Optimized Speed Advisory (GLOSA) is a system used to produce advisory speeds for approaching vehicles so that they can arrive at the intersection during the green phase. GLOSA can convey the message to approaching vehicles either with 1) Connected Vehicle technologies to communicate with individual vehicles, or 2) Variable Speed Signs to broadcast the advisory speed.

The U.S. Department of Transportation has initiated several applications for Connected Vehicle technologies, including the Real-Time Information Synthesis program, in which one of the applications is used to advise an optimized speed to the equipped vehicles (AERIS, 2015). The eCoMove project in the European Union also intends to achieve similar mobility goals by using V2I and V2V communications (eCoMove, 2015). With such technologies, each vehicle can receive signal timings from the roadside infrastructure and select its own speed profile either near an intersection or along an arterial (Barth et al., 2011, Xia et al., 2013) The GLOSA system resulted in a from 7 to 13 percent reduction in fuel consumption compare to the without the GLOSA system (Katsaros et al., 2011; Xia et al., 2012). Xia et al. (2013) further proposed an advisory speed system in which the downstream traffic information is gathered from the preceding connected vehicles.

Unlike Connected Vehicle technologies – which are not yet widely equipped on many vehicles – variable speed signs can broadcast advisory speeds to incoming vehicles. The Optimized Dynamic Speed Advise (ODYSA) system encourages progression by providing advisory speeds for a green wave for far-located downstream intersections (Katwijk et al., 2013). With loop detectors installed on the road, the system can detect a vehicle's approaching speed and provide an individual advisory speed to the target vehicle via a variable speed sign. By maintaining the density of platoons departing from the upstream stop line, the downstream green time can be more efficient in providing traffic progression.

Despite considerable efforts put forth by researchers, design of an effective dilemma zone protection system remains a challenging task. For example, although use of advance warning signs to advise approaching vehicles has produced positive effects on reducing the number of vehicles trapped in the dilemma zone, it does not provide information about the potential downstream hazardous traffic conditions (e.g., a long stop queue under insufficient sight and distance conditions). One may also note that most existing GLOSA systems do not consider the downstream traffic condition when they compute the optimized advisory speed and as a result, they may reduce the level of effectiveness.

2.5 Conclusion

Taking into consideration the stochastic nature of driver responses to a yellow phase and the resulting dilemma zones, there are various studies conducted by the traffic community to reduce accident frequencies, as reported in the literature. While these studies have made significant contributions toward improving intersection safety, some of the following critical issues still need to be addressed;

1. How to improve intersection safety for both preventive and reactive perspectives to minimize both rear-end collisions and side-angle crashes,

2. How to consider the tradeoff between intersection safety and operational efficiency, and

3. How to best use hardware and software devices for intersection dilemma zones to improve signal delay and progression.

The remaining chapters will focus on the development of an all-red extension algorithm, a speed harmonization algorithm, and a simulation platform. Additionally, the chapter will include field data results analysis.

Chapter 3. Research Background and System Structure

3.1 Introduction

This chapter presents the overall development stage for the DZPS. A brief description of the system's configuration, its key components, design procedures, and field implementation constitutes the core of this chapter. To develop and design a DZPS, so as to ensure the success of the system, this research has been conducted with following steps.

Step-1. Collect field data: The collection includes speed, traffic volume, vehicle compositions, and acceleration/deceleration rates. Decisions of drivers during the yellow phase and the resulting distributions of dilemma zones have also been collected.

Step-2. Development of a simulation platform: Based on the field data, the simulation platform has been developed and calibrated to allow the researchers to conduct various tests prior to the field deployment.

Step-3. Development of an all-red extension algorithm for the DZPS (System-I): The main functions of the proposed algorithm are to identify potential red-light-running vehicles and provide all-red extensions to those drivers under the control objectives of maximizing the detection rate and minimizing the false alarm rate. The algorithms for predicting drivers' decisions and executing control actions have been programmed into the simulation platform for analysis of effectiveness.

Step-4: Enhancement of System-I with the minimal hardware changes (named as System-II): System-II is designed to provide an advisory speed to improve both the operational efficiency and safety. System-II's control algorithm, mainly for both speed harmonization and safety improvement, has been evaluated with the developed simulation platform.

Step-5: Collect the field data, including traffic flow data and driver behavior information from the deployed DZPS for system evaluation.

Step-6. Evaluate the deployed DZPS with field data: The evaluation process for identifying changes on traffic flow characteristics, including the spatial distribution of speeds, acceleration/deceleration rates, decision of drivers at the onset of the yellow phase, and distributions of the dilemma zones.

Step-7. Performance evaluation of the DZPS to ensure the effectiveness of the deployed system with respect to safety protection and speed harmonization at high-speed intersections prior to the availability of long-term accident data.

Step-8. Development of a safety evaluation function to facilitate the performance evaluation of the system.

To improve both safety and operational efficiency, this study has proposed two systems for all-red phase extension and speed harmonization with an advisory speed. The first system is designed to offer dilemma zone protection with extension of an all-red interval to drivers running through the intersection during the red phase. The second system, extended for the purpose of improving safety, involves better intersection mobility by minimizing delay or maximizing progression.

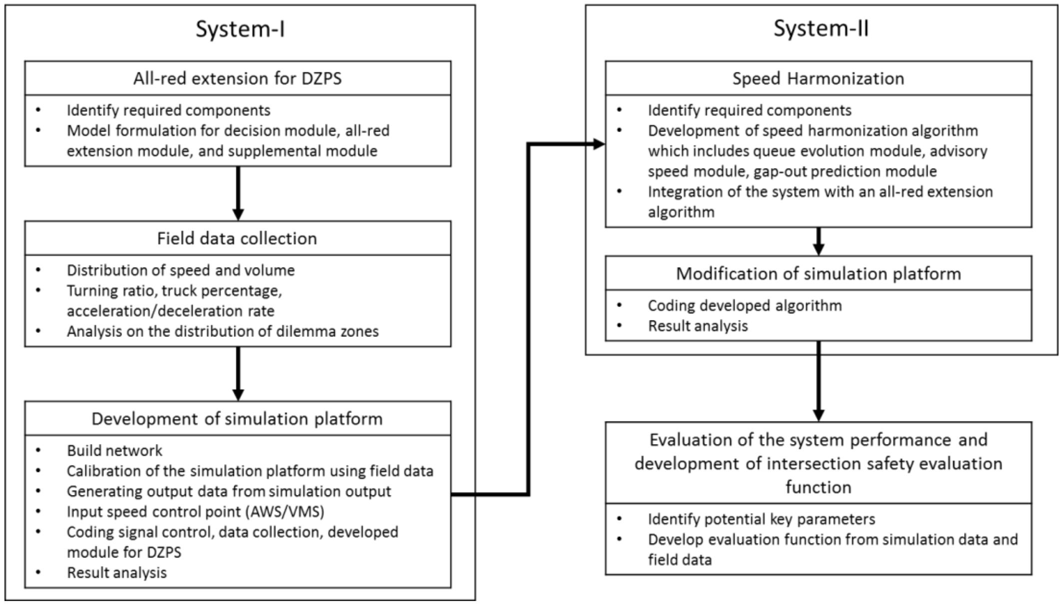


Figure 3-1 Overall research flowchart of the dissertation

Figure 3-1 shows the overall flowchart for developing two such systems. System-I is for a dilemma zone protection with all-red extension with AWS/VMS. The following three major tasks have been conducted during the system construction: design of an all-red extension algorithm, field data collection, and development of a simulation platform. To develop the all-red extension algorithm for DZPS, the key tasks have been conducted, including identification of wide-range traffic monitoring sensors (i.e., Wavetronix Smart Sensor Advanced) to provide real time traffic condition, signal controllers (i.e., Econolite ASC/3) with all-red extension capability, in-cabinet PCs to control VMS/AWS, and VMS/AWS to provide downstream signal status to approaching drivers.

As for the embedded control algorithm using the sensor data, the all-red extension algorithm consists of the following three major modules: identifying potential red-light-running vehicles, minimizing false alarms, and incorporating supplemental modules for enhanced protections. To support the development of DZPS, this study has collected field data such as distribution of speeds and volumes, turning ratios, heavy vehicle percentages, and acceleration/deceleration rates. Such field measurements of traffic patterns provide the information for computing the distributions of dilemma zones. The last task for developing System-I is to construct a simulation platform, which involves building a simulation network, calibrating the simulated system with field measurements, implementing hardware components, coding signal controller and all-red extension algorithms, running simulations, and analyzing the simulation output.

System-II is an enhanced version of System-I, using a speed harmonization module to concurrently minimize the intersection stop queues. Similar to System-I, its core hardware components include wide-range traffic monitoring sensors, signal controllers with all-red extension functions, in-cabinet PCs for computing advisory speed limits, and VMS or variable speed limits. There are several key tasks in the System-II development: a queue estimation module, an advisory speed limit module, and a gap-out prediction module in addition to the all-red extension algorithm from System-I. The simulation platform is modified accordingly to compute the queues and advisory speeds, and to predict the gap-out to evaluate the performance of the proposed systems. The final stage of this research is to analyze the short-term impact of the deployed DZPS on driving behavior based on the field data, and to develop an intersection safety evaluation function to facilitate the evaluation of safety effectiveness. The need of such function is due to the fact that it generally takes a long time period to have sufficient accident data for assessment of safety improvements. Hence, short-term impact analysis and a safety evaluation function are conducted to determine the impact and hazardousness of the intersection. Along with the safety evaluation function, this study has also conducted the detection effectiveness of the deployed DZPS on the field.

3.2 System-I: All-Red Extension

3.2.1 Key System Features and Components for System-I

Figure 3-2 illustrates the developed integrated DZPS and the interrelations between its three principal components: *advanced warning signs, wide-range traffic monitoring sensors, and all-red extension decision modules*. Note that the core notion of the developed dilemma zone protection system is to first inform approaching drivers to prepare a stop during the yellow or the red phase, or to adjust speeds to accommodate slow traffic within the monitoring zone during a green phase. Any positive response from drivers during either of these two scenarios will certainly reduce the likelihood of becoming trapped in the dilemma zone or causing rear-end collisions with, for example, slow queue-dissipating vehicles. If such preventive methods fail to slow aggressive drivers, causing some of them to become trapped in their respective dilemma zone, the proposed system will then activate the reactive protection function; that is, it will extend its all-red phase to prevent any potential angle-crashes with vehicles from side streets.

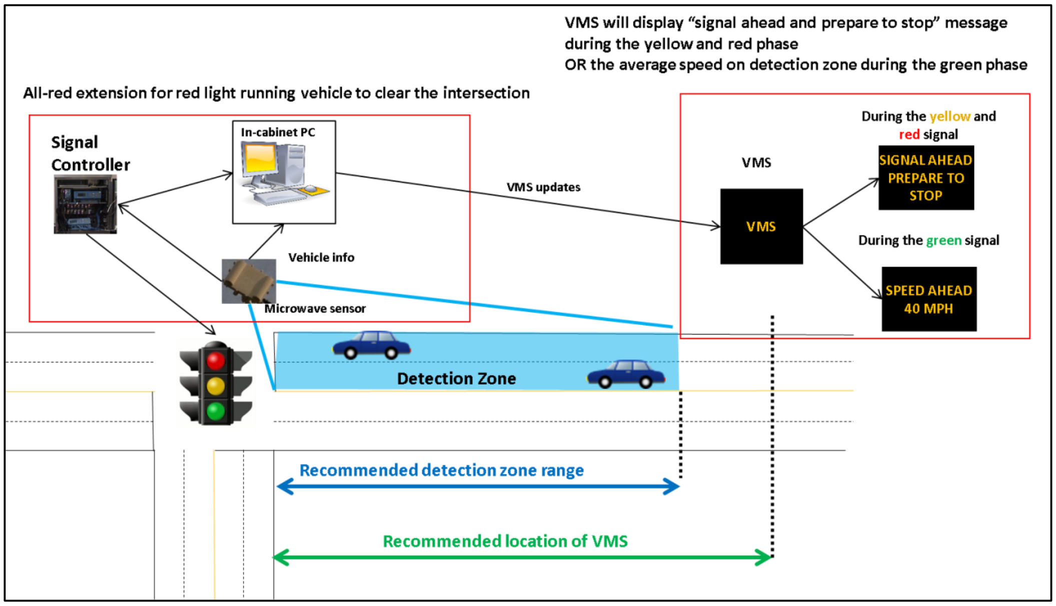


Figure 3-2 Graphical Illustration of the System-I

Hardware Components

- *Long-range Microwave Detectors:* cover the roadway segment from the stop line to the upper boundary of the identified dilemma zone to track the speed and location of individual vehicles. Real-time traffic information offers the basis for the system's computation module to determine the corresponding control actions.
- *In-cabinet Computer:* receives traffic data from the aforementioned detectors and Signal Phase and Timing (SPaT) information from the signal controller. The system will activate VMS/AWS and identify vehicles trapped in the dilemma zone before executing the all-red extension with its embedded computing module.
- *Signal Controller:* extends the all-red phase from the in-cabinet computer. It will provide SPaT information to the in-cabinet computer.

- *VMS/AWS:* receives information from the in-cabinet computer and displays the advisory messages for the incoming vehicles. The messages will help drivers make proper speed adjustments so as to improve either their safety or operational efficiency.

3.2.2 Key Model Algorithms Embedded in the System-I

Advanced Warning Sign (AWS)/Variable Message Sign (VMS)

To inform drivers in advance, the VMS will display, for example, the message of "Signal Ahead Prepare to Stop" during the yellow or red phase and allow them to adjust their speeds in time to ensure a safe stop. If the signal is on the green phase, the VMS can display the average speed of vehicles within the monitoring zone, allowing the approaching vehicles to accommodate the slow speed of intersection discharging flows, especially at the beginning of the green phase or for those sites with a short sight distance. Both types of information can help drivers make proper speed adjustments and thereby reduce potential rear-end collisions.

Decision Module

The decision module consists of two models: one for predicting each individual vehicle's response to the yellow phase when moving into the detection zone, and the second for assessing the necessity of activating an all-red extension and computing the extended duration. Equation 3-1, a function for estimating a detected vehicle's response during the yellow phase, can be calibrated from the field data. The procedures for parameter estimation and calibration will be described in Chapter 4.

$$P_{stop} = \frac{1}{1+e^{-\alpha-\beta_1 v-\beta_2 d}} \tag{3-1}$$

Where d and v are the distance and speed from the intersection, respectively, when the driver perceives the onset of a yellow phase.

3.2.3 Functional Requirements for System-I

To provide all-red extensions to red-light-running vehicles, the designed System-I requires to have the following functions:

- Receive the Signal Phase and Timing information in real time from the traffic signal controller;

- Track the evolution of an individual vehicle's speed and location in the identified intersection dilemma protection zone;

- Assess the need to activate an all-red extension so as to prevent side-angle crashes; and

- Determine the activation time and the advisory speed for the VMS/ASL to display the advisory information.

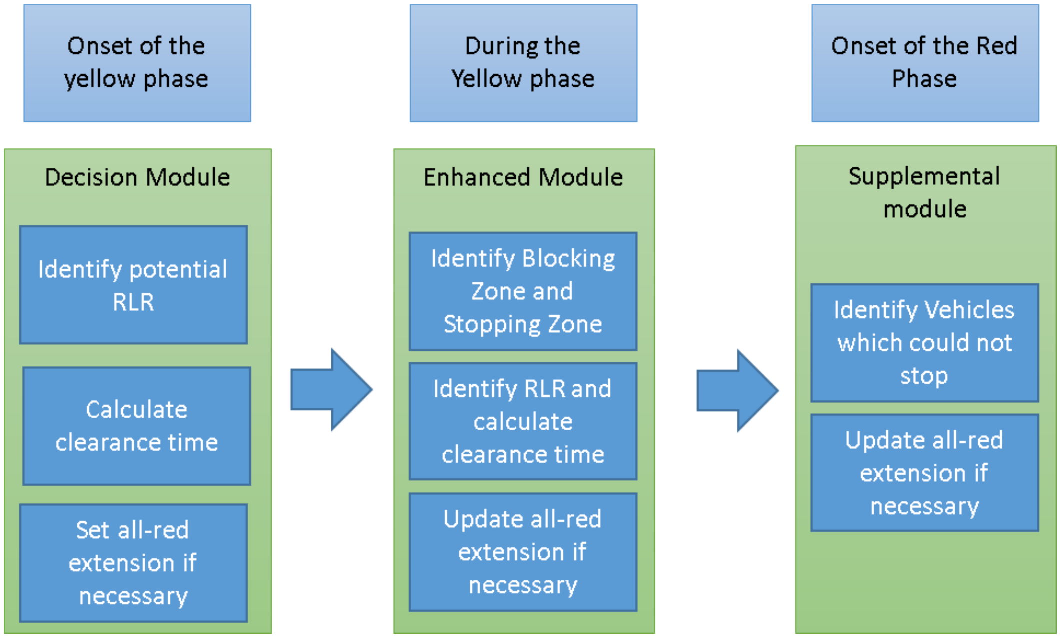


Figure 3-3 Flowchart for all-red extension algorithm

The core logic for an all-red extension decision is illustrated in Figure 3-3. The step-by-step description of Algorithm-I will be presented in Chapter 5.

3.3 System-II: Speed Harmonization

3.3.1 Key System Features and Components for System-II

Figure 3-4 illustrates the operational structure for System-II and the interrelations between its main system components: *long-range microwave detector, in-cabinet computer, signal controller with all-red extension function, variable message sign (variable speed limit sign), all-red extension decision module, queue evolution module, gap-out prediction module (for actuated signal), and advisory speed limit module.* Note that the major objectives of System-II are to reduce side-angle and rear-end crashes for safety improvement and to minimize the stop delay for mobility improvement.

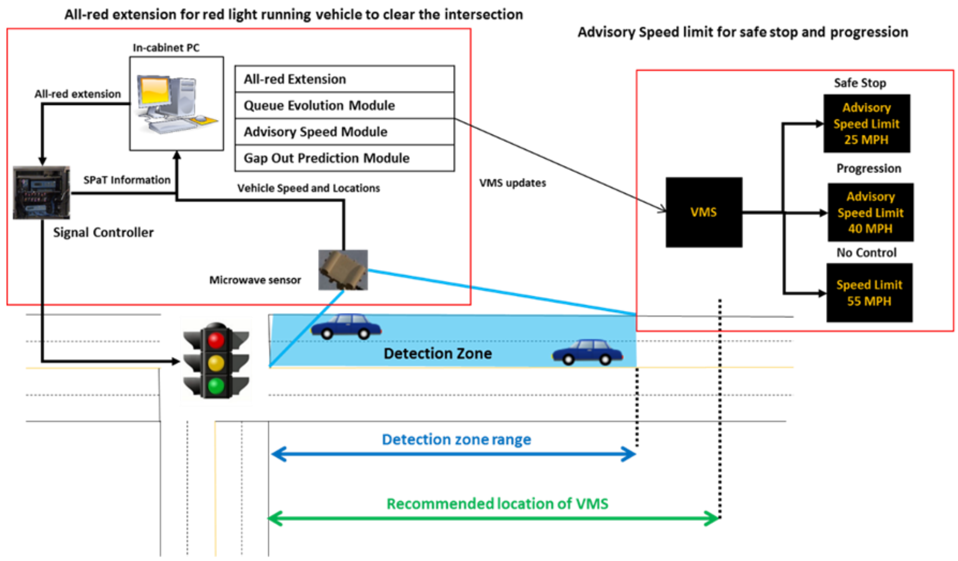


Figure 3-4 Graphical illustration of System-II

The VMS/variable speed limit sign will be activated prior to signal changes. Before the signal changes from green to yellow, the sign will show messages (or reduced speed) to slow the approaching vehicles so as to prevent rear-end crashes and to provide an advisory speed for safe stopping. When the signal changes from the red to the green phase, the VMS will provide an advisory speed for vehicles to progress through the intersection without stop. To provide an advisory speed prior to a signal change, it is essential to have precise SPaT information. Thus, it is important to estimate the remaining phase duration, which can be derived directly from a pre-timed signal controller, but not from the actuated signal controller. Thus, one needs to have a green-phase termination module that can predict both the max-out and gap-out timings under an actuated signal control.

The advisory speed module is designed to predict signal changes, based on the signal status and vehicles in the detection zone. If an aggressive driver does not follow the advisory speed for a safe stop and becomes trapped within the dilemma zone, the system will then activate the all-red phase extension to prevent any potential side-angle crashes with vehicles from the minor street.

Figure 3-4 shows the interrelations between all key components of the proposed System-II. The functions of each system component are summarized below:

Hardware Components

- *Long-range Microwave Detectors:* cover from the stop line to the upper boundary of the identified dilemma zone to track the speed and location of individual vehicles, and to determine the queue length and discharge flow rates during the green phase. Such real-time traffic information offers the basis for the system's computation module to take appropriate control actions.
- *In-cabinet Computer:* receives traffic data from the aforementioned detector and SPaT information from the signal controller. The computer calculates the advisory speed for either a safe stop or progression, executes the *gap-out prediction (for actuated signal),* identifies vehicles trapped in the dilemma zone, and activates the all-red extension.
- *Signal Controller:* same as in System-I, executes the embedded signal timing plan, based on detected traffic conditions, and is capable of providing all-red extensions.
- *Variable Speed Sign:* receives information from the in-cabinet computer and displays the variable advisory speed for the incoming vehicles. The advisory speed helps drivers make proper speed adjustments to improve

either their safety or mobility. During the safe stop and progression process, the VMS displays the proposed speed reduction. During the green phase, it displays the posted speed limit of the arterial.

3.3.2 Key Model Algorithms Embedded in System-II

- *All-red extension module;*
- *Queue evolution module* to predict the queue evolution, based on the phase information and the traffic data;
- *Advisory speed limit module* to calculate the advisory speed limit, based on the predicted duration to the phase change and the current traffic information from the sensor; and
- *Gap-out prediction module* to predict the gap-out timings prior to the signal controller changes a phase.

3.3.3 Functional Requirements for System-II

To account for both the mobility and the safety needs, System-II is capable of executing the following functions in real time in addition to those under System-I:

- Receiving the signal phase and timing information in real time from the traffic signal controller, including the prediction of the signal phase change for actuated signal control;
- Detecting and estimating the intersection's queue length and its evolution within the monitoring zone;

- Measuring the arriving/discharging flow rates to and from the intersection;

- Determining the activation time and the advisory speed for the variable speed sign before the signal changes to yellow so as to prevent rear-end crashes; and

- Estimating the speed for approaching vehicles to minimize the stop delay, or to stay in the progression band before the start of a green phase.

3.4 Field Data from a Target Intersection for Design and Experimental Analysis

To illustrate the design process of the proposed systems and also to evaluate their resulting effectiveness, this study has conducted a field study at a high-speed hazardous intersection. The collected field data is used for both demonstration of the system's features and also to illustrate the evaluation process. The key features of the target intersection and field data collection used in the remaining system development are shown below:

3.4.1 Location Overview

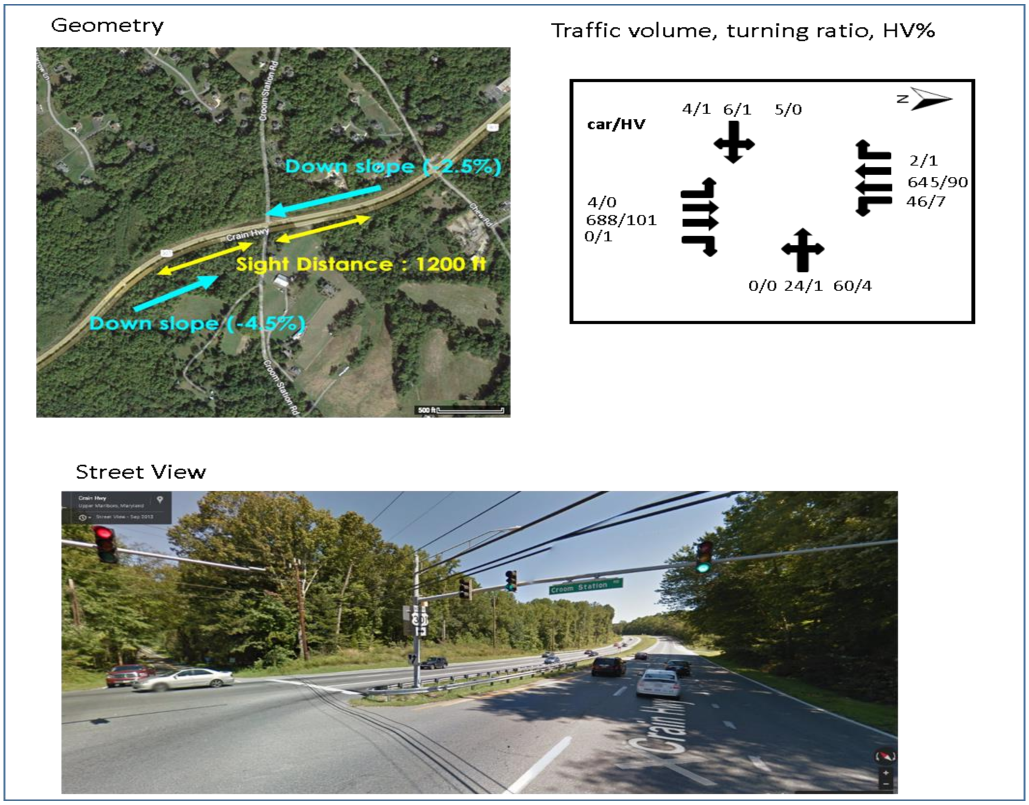


Figure 3-5 Location overview for US 301 at Croom Station Road, Prince George County, MD

Figure 3-5 illustrates an example of a high-speed hazardous intersection, US 301 at Croom Station Road, in the suburb of Prince George's County, Maryland. Between 2009 and 2013, this intersection was plagued by a total of 55 crashes, involving 90 vehicles, 27 injuries, and one fatality. Most of those crashes belong to one of the following three types: left-turn collisions, side-angle crashes, or rear-end accidents. Analysis of the accident data concludes that both the side-angle and rear-end collisions are likely due to the presence of dilemma zones.

Further field investigation of this intersection's geographical and traffic data reveals that key factors contributing to the high-accident frequency include insufficient sight distance from both the main and side streets, high approaching speeds, a high percentage of trucks, and a downgrade slope for vehicles on the main road to the intersection. As such, effective strategies for minimizing the impact of dilemma zones should take into consideration not only the discrepancies of driver responses to an encountered yellow phase, but also the impacts of those accident-contributing factors on the behaviors of the approaching drivers. Moreover, recognizing the dynamic nature of dilemma zones – which may vary due to driving characteristics and approaching vehicular speeds – an effective DZPS should also be capable of proactively warning approaching drivers with proper information, The DZPS should also reactively provide necessary protection for drivers who might become trapped in their respective dilemma zones.

3.4.2 Field Data

Note that the spatial distribution of dilemma zones and potential contributing factors for accidents are location-specific. For this reason, an in-depth analysis of traffic characteristics and intersection geometric features from extensive field data has been collected prior to the design of the system. Key data collected from the field observations for use in the system design are listed below:

- Speed distribution of approaching vehicles at different distances from the intersection stop line (see Table 3-1);

- Distribution of traffic volumes and vehicle types by approach (see Figure 3-1);

- Average acceleration/deceleration rates and variances for trucks and passenger cars, respectively (see Table 3-1); and

- Sample individual drivers' responses to their encountered yellow phases, including the decision and distance to the intersection (see Table 3-2).

Table 3-1 Comparison of Speeds at selected locations between the field data and simulation results

Location	Average(Std.)	Sample Size
Speed @ 1050 ft (mph)	57.4(9.7)	721
Speed @ 650 ft (mph)	39.9(8.2)	705
Speed @ 400 ft (mph)	38.6(11.4)	672
Speed @ 200 ft (mph)	31.3(14.5)	752
Deceleration rate (ft/s^2)	**-9.3(3.5)**	**72**
Acceleration rate (ft/s^2)	**3.6(3.1)**	**62**

Table 3-2 Drivers responses to the yellow phase

Speed of vehicle on set of yellow	**Location of vehicle from stop line onset of yellow**				
	0 - 100 ft	**100 - 200 ft**	**200 - 300 ft**	**300 - 400 ft**	**400 - 500 ft**
30 - 40 mph	100%	86%	21%	2%	0%
40 - 50 mph	100%	100%	74%	50%	20%
50 - 60 mph	100%	100%	88%	50%	0%

Percentage of drivers taking the "Pass" decision from field observations based on the 1123 field data

3.4.3 Distributions of Dilemma Zones

Based on the above data, one can then compute the spatial distribution of dilemma zones for vehicles approaching the intersection at different speeds with the well-established process in the literature (Gazis et al., 1960).

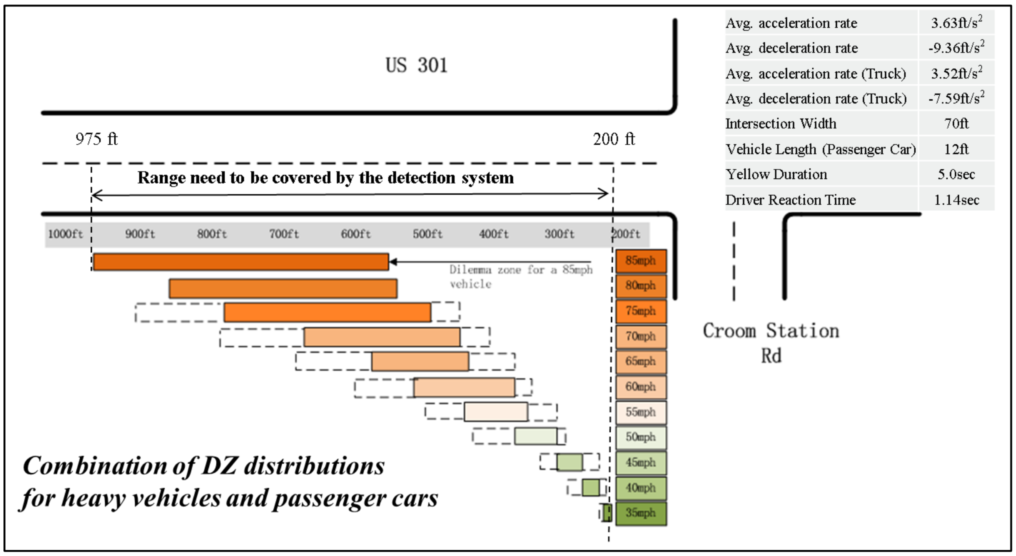


Figure 3-6 Distribution of dilemma zone for passenger cars and trucks for US 301 @ Croom Station Road

Figure 3-6 presents the resulting distributions of dilemma zones for passenger cars and trucks on the target approach link. To cover all possible dilemma zones for vehicles and heavy trucks approaching the intersection at the speed range of 40 to 85 mph, the critical monitoring zone starts anywhere from 200 feet to 975 feet away from the stop line. The proposed DZPS needs to ensure that all vehicles within this monitoring zone can either stop or pass the intersection safely.

Chapter 4. Development of a Simulation Platform for DZ Evaluation

4.1 A Simulation Platform for System Evaluation

This chapter presents the design and calibration of a simulation platform for evaluating the intersections between different key system components and the resulting effectiveness under projected driver behavioral patterns. It is expected that highway agencies intending to deploy the DZPS can fully identify all potential issues and the impacts on the roadway traffic prior to the full-scaled field deployment. The simulation platform helps to understand those issues and to take any necessary adjustments. More especially, the developed simulator for dilemma zone protection operations has offered the following functions:

- Replicate the real-world traffic distributions and driver characteristics,
- Integrate all key components of the proposed system into the simulation platform for experimental analysis, and
- Evaluate the resulting effectiveness on safety and mobility improvement.

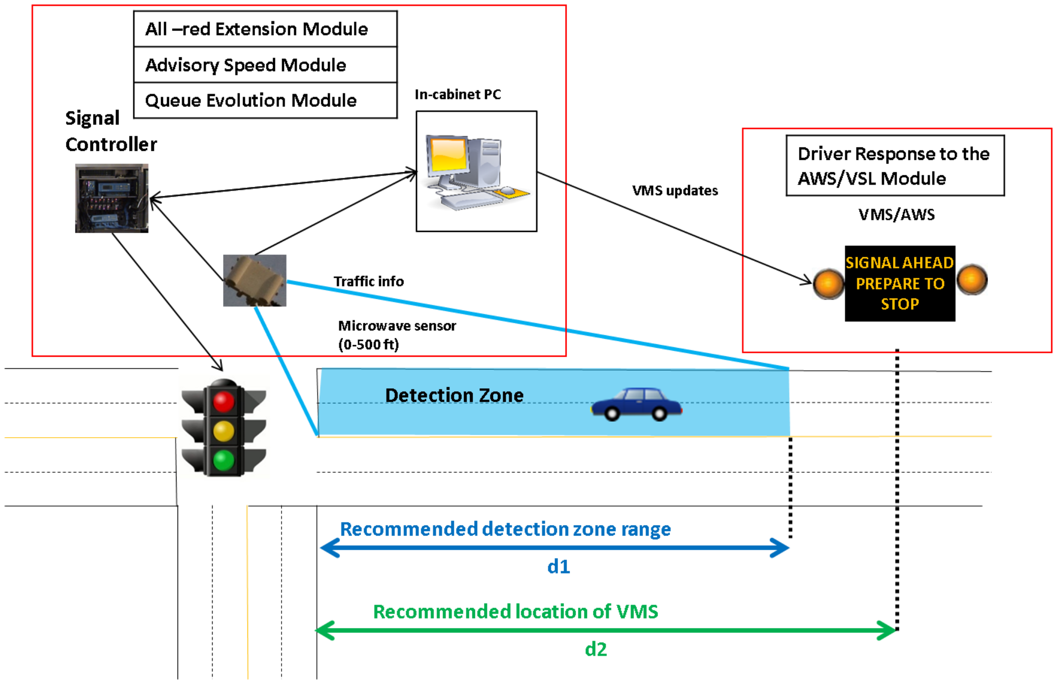


Figure 4-1 Design of the DZPS and key modules

Figure 4-1 shows the overall design of the proposed DZPS, which includes all-red extension, advisory speed, and queue prediction modules. The traffic data from wide-range traffic monitoring sensors serve as the primary input data for the signal controller and the in-cabinet PC to take actions. Note that the all-red extension module is activated by the signal controller, and the advisory speed limit and queue evolution modules are executed by an in-cabinet PC.

Figure 4-2 shows the relationships between the real-world operations of the proposed system and the simulation platform. Through the built-in functions from VISSIM and coded C# programs using COM interface, the simulation platform has been calibrated to replicate both the traffic conditions and their interactions with the deployed DZPS.

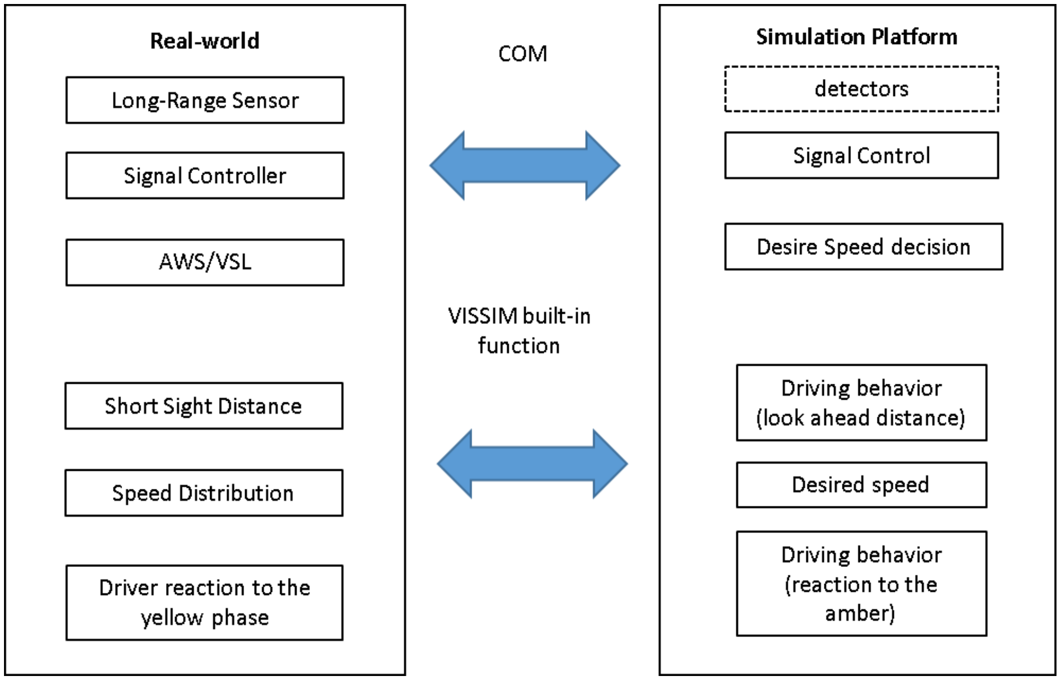


Figure 4-2 Relationship between the DZPS design and a simulation platform

The proposed DZPS algorithm has been implemented and evaluated in a microscopic traffic simulation environment, VISSIM (VISSIM 2011). The following main advantages are provided by VISSIM over other simulation packages:

- Provides the flexible driving behavior models for the users to model the behavior observed from the field data;
- Allows modification of the system operating characteristics in real-time with the developed algorithms; and
- Allows effective interactions of the proposed system with other embedded VISSIM models, using other computer languages, such as C#, C++, Visual Basic.

All listed key components of DZPS have been embedded in the simulation platform by either built-in simulation functions from VISSIM or coded programs in C#. Figure 4-3 shows the framework of the simulation platform. To better replicate a driver's reaction in the traffic simulation, some behavior modules are proposed to replace VISSIM's internal functions using the COM interface. These behavior modules include the driver response to variable speed messages and their perceived sight distances.

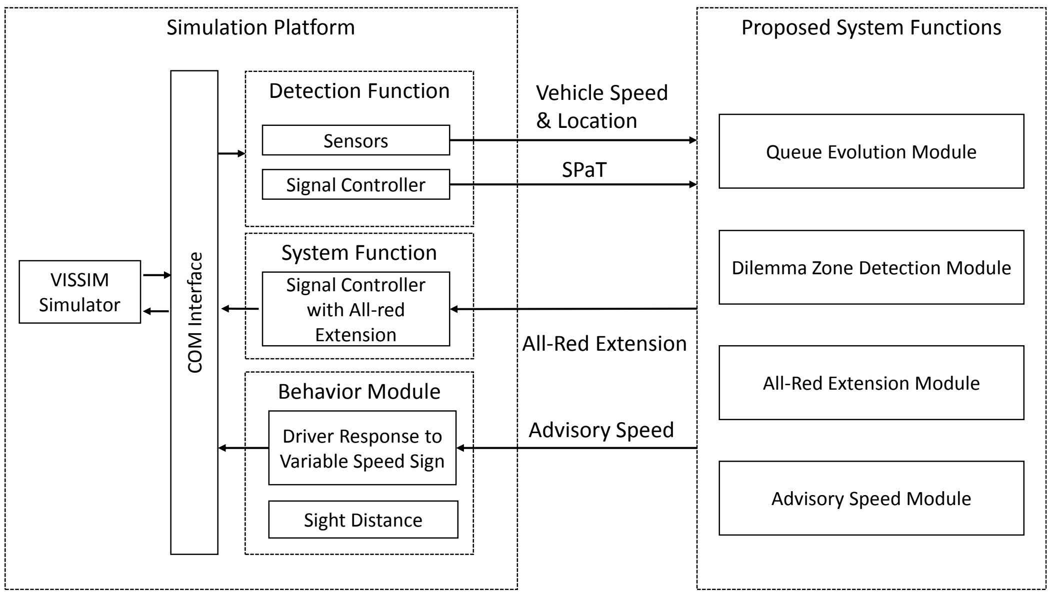


Figure 4-3 Framework of the simulation platform

The simulation platform consists of two major parts. The first part is a VISSIM simulator, which provides traffic data and runs simulations. The second part is a developed program that changes the parameters in VISSIM to affect driver behaviors.

Figure 4-4 illustrates the interrelations between key components in the simulation platform, showing the data flows between the intersection simulated with VISSIM and other system functions developed with the C# program. The intersection with VISSIM after calibration with the collected field data is used to replicate field traffic arriving patterns, their evolutions, and corresponding signal states. The outputs from VISSIM at each time step (e.g., location of each vehicle and its speed) have been fed back to the control module via the customized interface to predict the response to the yellow phase to display the message on the VMS and to determine if the all-red extension should be activated.

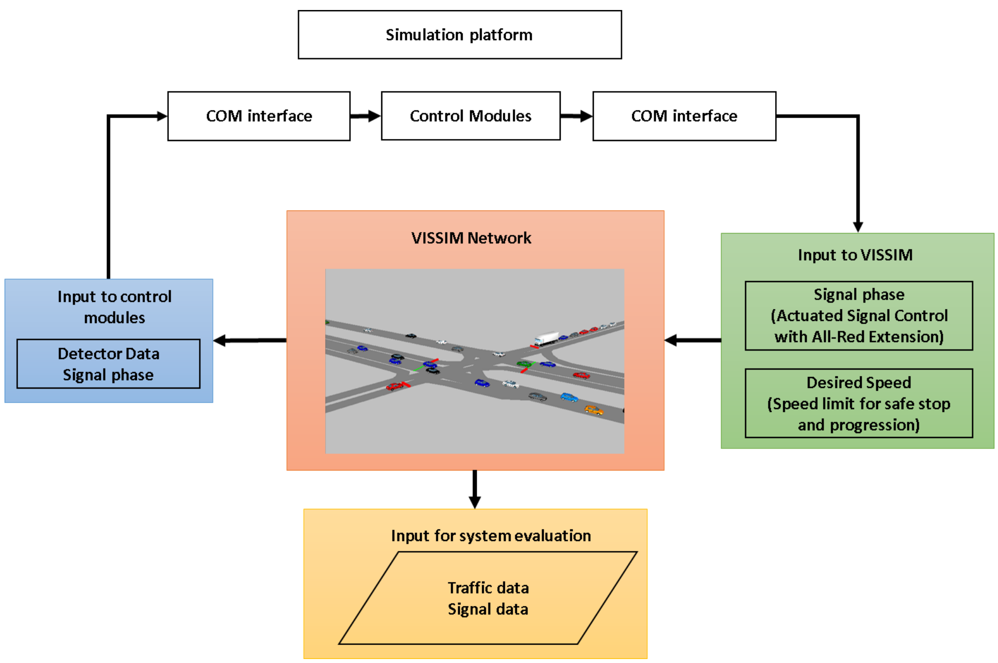


Figure 4-4 Data flows in simulation platform

Figure 4-5 describes all sub-systems in each module. The all-red extension module consists of three sub-modules. Once the system has detected that the current signal phase is changed to the yellow phase, traffic data in the network within the detection zone can be obtained and sent to the decision module. During the yellow phase, the system will run the enhanced module with the detector data to identify the stopping and blocking zones. Finally, the system will execute the supplemental module at the onset of the all-red phase to protect the potential red-light-running vehicles. The queue evolution module and advisory speed limit module are to be activated during the yellow phase, the red phase, and the beginning and end of the green phase. Based on the detected vehicle information from VISSIM, the queue clearance module and VMS for progression will be activated if the vehicle can progress through the intersection. In contrast, if the vehicle cannot pass the intersection, the queue prediction module and VMS for safe stop will be activated to ensure that the approaching vehicles can stop at the intersection safely. Figure 4-6 shows the overall flowchart of the simulation platform.

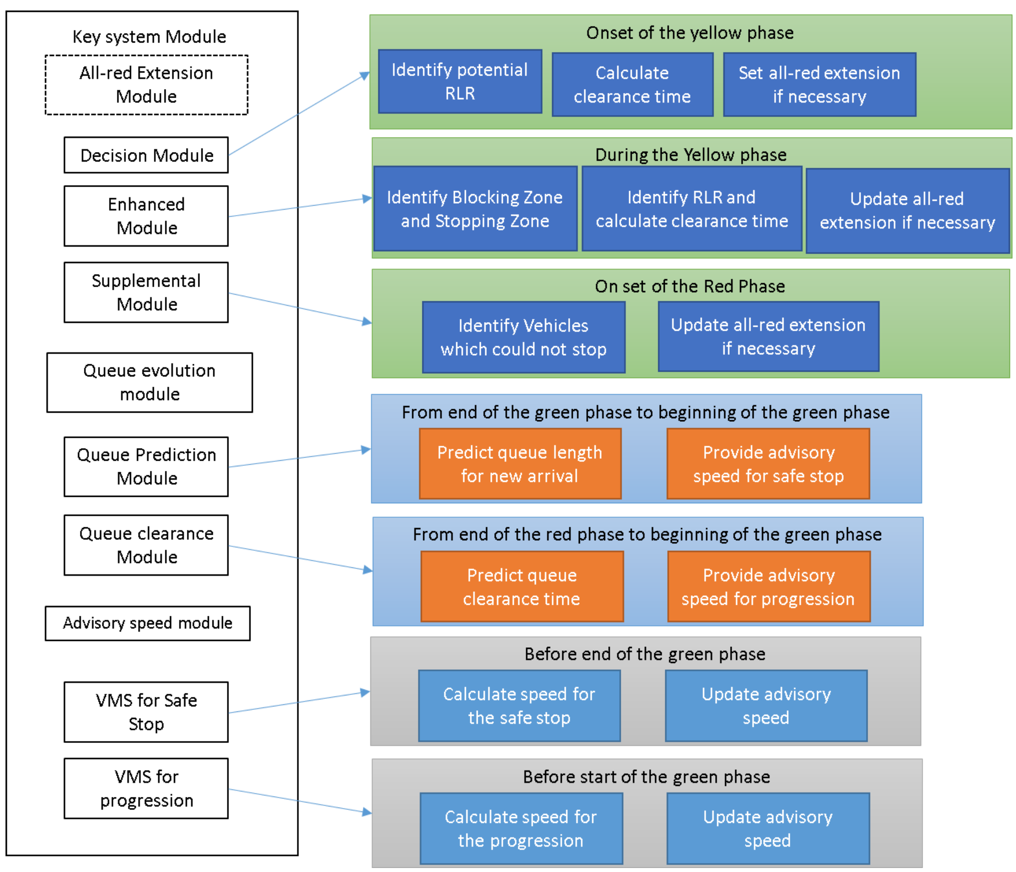


Figure 4-5 Key system modules

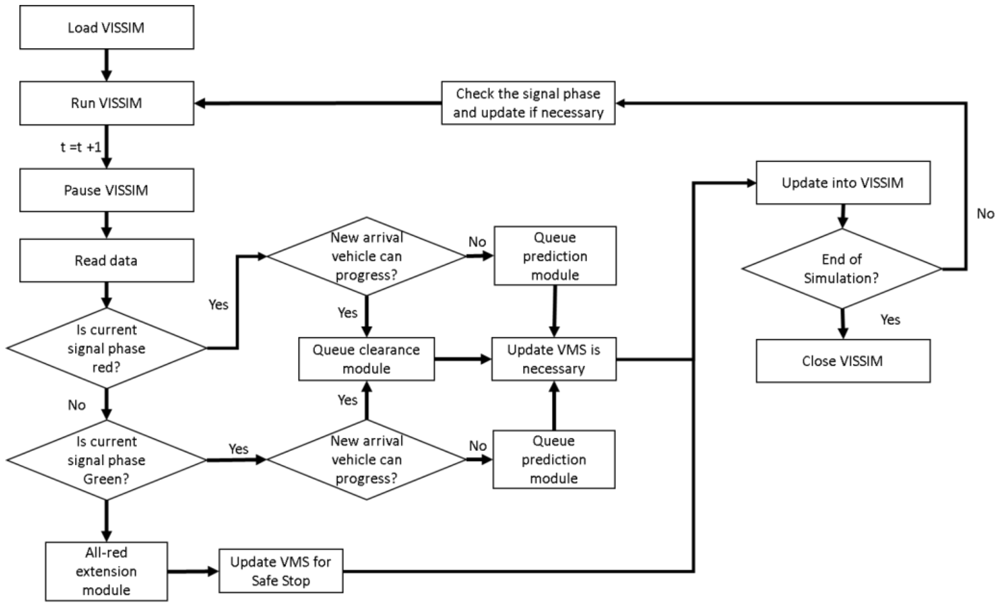


Figure 4-6 Simulation Platform operational flowchart

A queue evolution module and an advisory speed limit module are tied together to calculate the advisory speed, but not necessary to activate the VMS every cycle. Once a vehicle has been detected, the simulator will identify its advisory speed based on the minimal acceptable speed (i.e. 35 mph with a speed limit of 55 mph) to free-flow speed. If the arrival vehicle can progress over the intersection without any speed adjustment, the advisory speed will remain on the "OFF" state, and vehicles shall travel at their speeds approaching to and over the intersection.

Note that, for the developed simulator to have the fidelity of replicating the response of traffic patterns under the proposed DZPS operations, it shall be capable of providing the following functions:

- Replicating the detection capability of the deployed wide-range sensors;

- Simulating the functions of the signal controller in executing the all-red extension;
- Reliably simulating the arriving traffic flow patterns, including the distributions of flow rate, speed, and acceleration/deceleration rate, and vehicle composition; and
- Reflecting the responses of drivers to the VMS message and to the encountered yellow phase.

The procedures used to develop and calibrate the above functions are described next.

4.2 Key Components in the Simulation Platform

There are several key components in the simulation platform for use in replicating real-world traffic conditions. Since VISSIM can provide several types of driving behaviors and take programmed models from the .NET framework in real time, the simulation platform has been developed with the following features to evaluate the DZPS's performance prior to its field development.

- Wide-range traffic monitoring sensors
  - Provides traffic data (speed and location) within the monitoring zone (i.e. 900 feet) with a short time interval (i.e. 0.1 second)
- Geometric features
  - The number of lanes, and length of the turning bay, grade, and sight distance
- Traffic flow rate

- Traffic flow rate with the turning ratio from the field data collection

- Driving behaviors
  - Vehicle approach speed, and acceleration and deceleration rate from the field data collection
- Reactions to the yellow signal
  - Drivers' reactions to the yellow signal from the field data
- Advanced warning sign/advisory speed
  - Provides the information to drivers when the signal changes to the yellow or the red phase, or provides the advisory speed to vehicles to progress through the intersection
- Response to the AWS/VSL
  - Drivers' reactions to the AWS/VSL when they encounter the activated AWS/VSL
- Signal Controller (signal phases, logic, and all-red extension)
  - Fully actuated signal controller with an all-red extension function (i.e. Econolite ASC/3)
- Advisory speed module
- Queue evolution module

4.3 Key Components Embedded into the VISSIM Simulator

The VISSIM simulation allows users to set up the key parameters to realistically reflect the actual field conditions. The following built-in functions from VISSIM provide the basis for simulating the field observed traffic characteristics:

Geometry/Traffic flow

The geometric characteristics, such as the short sight distance from the major or minor streets and downgrades, are major contributing factors to the intersection safety. The geometric features of the intersection were obtained from satellite images and site visits. In addition to the geometric features, the traffic flow data, obtained from field observations, includes volumes, turning fractions, and percentages of vehicles that can be classified as “heavy vehicles.” Figure 4-7 shows the target intersection’s geometric features from the satellite imagery, traffic flows from the field data, and the network built with VISSIM for the US 301 and Croom Station Road intersection in Prince George’s County, Maryland. As shown in Figure 4-7, it has a short-sight distance and a downgrade toward the intersection, and a high percentage of heavy vehicles was observed during the field data collection.

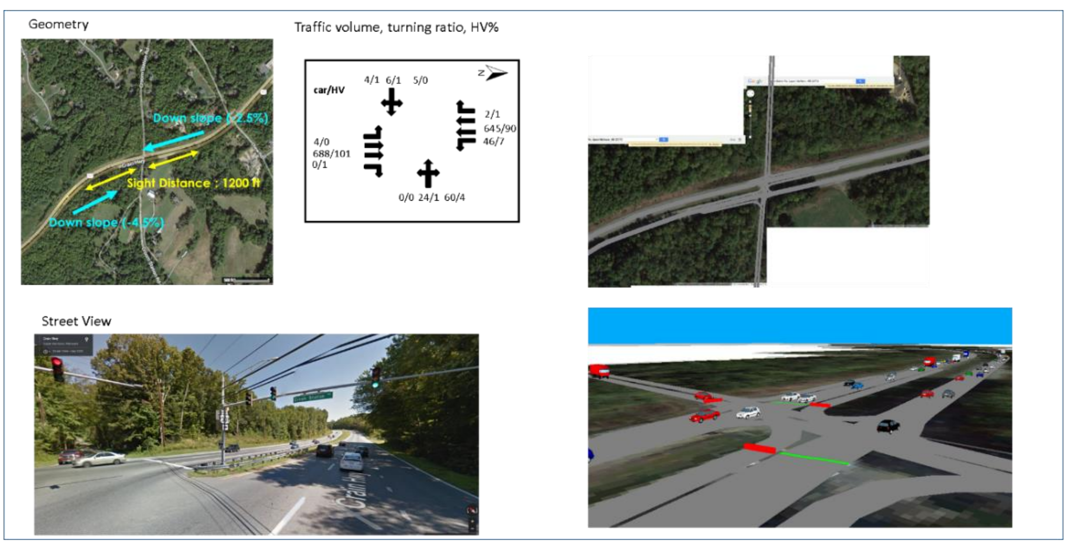


Figure 4-7 Location Overview for US 301 @ Croom Station Road and simulation network, Prince George County, MD

Driving behavior – spatial distributions of speed, and acceleration, and deceleration rates

Driving behavior data – such as the spatial distribution of speeds, acceleration and deceleration rates during the yellow and red phases – were collected during field measurements for calibration of the simulation platform. Four locations (200, 400, 650, 1050 feet from the stop line) were selected for field data with videos.

Table 4-1 shows a comparison of the field observations and simulation results. Notably, the simulation key parameters have been calibrated to a sufficient level of fidelity.

Table 4-1 Comparison of Speeds at selected locations between the field data and simulation results

	Field		Simulation	
	Average(Std.)	Sample Size	Average(Std.)	Sample Size
Speed @ 1050 ft (mph)	57.4(9.7)	721	59.68(7.5)	740
Speed @ 650 ft (mph)	39.9(8.2)	705	41.8(8.1)	689
Speed @ 400 ft (mph)	38.6(11.4)	672	42(9.4)	690
Speed @ 200 ft (mph)	31.3(14.5)	752	32.8(14.2)	679
Deceleration rate (ft/s^2) Passenger car / truck	**-9.3(3.5)/-7.5(2.12)**	**72/14**	**-9.7(5.4)**	**87**
Acceleration rate (ft/s^2) Passenger car / truck	**3.6(3.1)/3.5(2.4)**	**62/7**	**3.05(2.6)**	**107**

Reactions to the yellow signal

To simulate the responses of the target driving population in a scenario of encountering a yellow phase, the study has taken the following steps:

1. Collecting the actual responses of drivers during the yellow phase at the target intersection;
2. Calibrating the collected data with a behavioral model referenced in the literature (Chang et al., 1985);
3. Embedding the calibrated behavioral model in the traffic simulator and executing the experiments over the same period as the duration during the field data collection; and
4. Comparing the simulated driver response patterns with those observed from field responses to determine if any model parameters should be revised.

A total of 1,123 individual drivers' responses over the yellow phase at six intersections have been collected and used as the basis for a model calibration (Liu et al., 2007). The function, "Reaction to amber" from the VISSIM, has two parameters – the vehicle's location and its speed at the onset of the yellow phase. The field data has been calibrated for the equation embedded in VISSIM with two observable variables shown in Equation 4-1, where v and d_x denote the speed and distance of vehicles, respectively, at the onset of the yellow phase.

$$P_{stop} = \frac{1}{1+e^{-\alpha-\beta_1 v-\beta_2 d_x}} \qquad (4\text{-}1)$$

The initial set of parameters was programmed into the VISSIM simulator to map the response of drivers during the yellow phase at the target intersection after all other calibration tasks have been completed. By comparing the distribution of driver responses to the yellow phase under the simulated environment with the field-observed results from the target intersection, one can further update the model parameters in the revised model until they can realistically replicate the observed distribution of driver responses during a yellow phase. Equation 4-2 shows the model with the data for the initial six intersections, and Equation 4-3 presents its updated parameters calibrated with field data for a target intersection.

$$P_{stop} = \frac{1}{1+e^{-0.798+0.288v-0.043d}} \tag{4-2}$$

$$P_{stop} = \frac{1}{1+e^{-0.798+0.35v-0.455d}} \tag{4-3}$$

The purpose of calibrating the parameters is to minimize the total differences between the field and the simulation on the percentage of drivers passing the intersection, as shown in Equation 4-2.

$$\text{Minimize} \sum \left| P_{stop\ in\ simulation} - P_{stop\ in\ filed\ data} \right| \tag{4-2}$$

To capture the response of the target driving population when drivers encounter a yellow phase, Table 4-2 summarizes the percentage of drivers from the field data collection and the simulated output (using the embedded VISSIM function) who choose the “Pass” decision during a yellow phase at different speeds and distances from the intersection. Noticeably, for those simulation-generated drivers at speeds of 30 to 60 mph and distances from 0 to 400 feet, their responses to the yellow phase are sufficiently similar to the data from the field observation, offering a reasonably reliable basis for experimental analysis with the simulator.

Table 4-2 The percentage of drivers taking the "Pass" decision during a yellow phase between the field data and simulated results

Speed of vehicle on set of yellow (sample size)*4	Location of vehicle from stop line onset of yellow														
	0 - 100 ft			100 - 200 ft			200 - 300 ft			300 - 400 ft			400 - 500 ft		
	Field *1	Initial *2	Final *3	Field	Initial	Final	Field	Initial	Final	Field	Initial	Final	Field	Initial	Final
0 - 40 mph	100% (203)	100% (234)	100% (227)	86% (276)	100% (212)	61% (243)	21% (158)	100% (223)	21% (231)	2% (92)	89% (273)	0% (214)	0% (6)	18% (189)	0% (197)
40 - 50 mph	100% (78)	100% (100)	100% (84)	100%(100)	100% (100)	93% (114)	74% (73)	100% (124)	76% (117)	50% (24)	100% (209)	26% (164)	20% (5)	100% (175)	8% (187)
50 ++ mph	100% (9)	100% (35)	100% (24)	100%(20)	100% (25)	100% (33)	88% (47)	100% (23)	80% (33)	50% (16)	100% (35)	48% (27)	0% (16)	100% (25)	21% (29)

*1: Field: percentage of drivers taking the "Pass" decision from the field observations
*2: Initial: percentage of drivers taking the "Pass" decision generated from the simulator with the initial set of model parameters ($\alpha = 0.798, \beta_1 = -0.288, \beta_2 = 0.043$)
* 3: Final: percentage of drivers taking the "Pass" decision generated from the simulator with the updated set of model parameters ($\alpha = 0.798, \beta_1 = -0.35, \beta_2 = 0.455$)
*4: the number in each parenthesis denotes the sample size.

4.4 Key Components Developed for Simulating DZPS

Wide-range Traffic Monitoring Sensors and Advanced Warning Sign/Advisory Speed Sign

The wide-range traffic monitoring sensor is one of the major key components in the developed DZPS, which tracks vehicles in the monitoring zone. Such sensors (e.g., SmartSensor Advanced from Wavetronix®) are tasked with tracking the speed and location of each individual vehicle over short intervals (i.e. 0.1 second) within the detection zone until the vehicle either makes a complete stop or passes through the intersection. Such real-time information, regarding the temporal and spatial distributions of vehicles, offers the basis for the proposed system to execute the all-red extension and queue evolution module. The data from such sensors is also used to determine which vehicles are likely to be trapped in their dilemma zones, whether or not to execute an all-red extension, and whether or not newly arriving vehicles require advisory speeds for progression through the intersection or for a safe stop. Figure 4-8 shows how the wide-range traffic monitoring sensors have been placed in the simulation platform, where a series of small detectors has been deployed along the link and data also have been retrieved at every time step. The advisory speed and advanced warning signs have also been programmed in the simulation platform with a "Speed Limit Sign" in VISSIM that can be changed dynamically during the simulation through COM interface, and that allows the user to test various compliance rates of drivers.

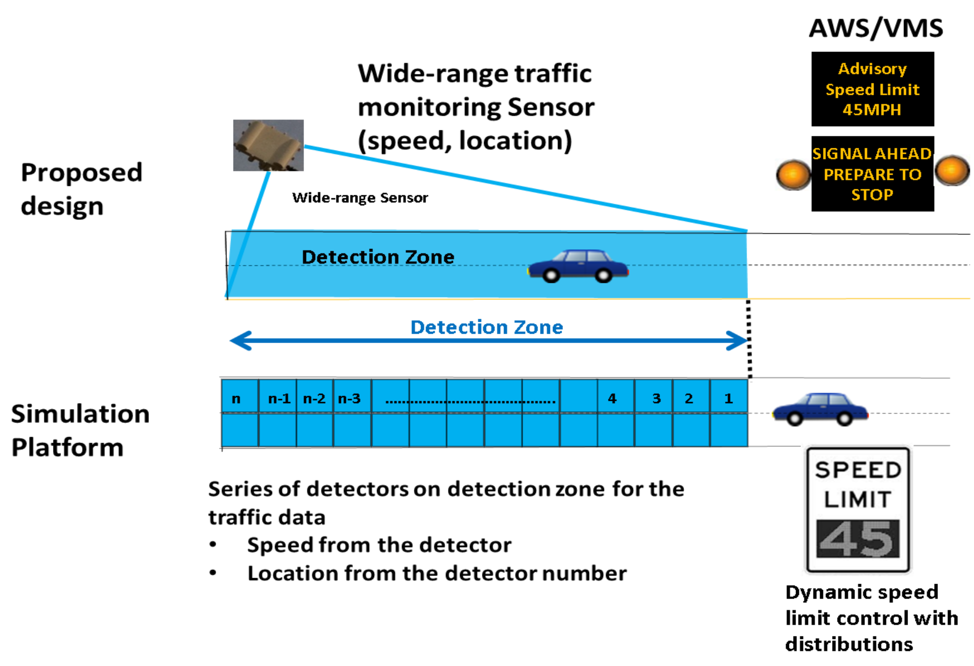
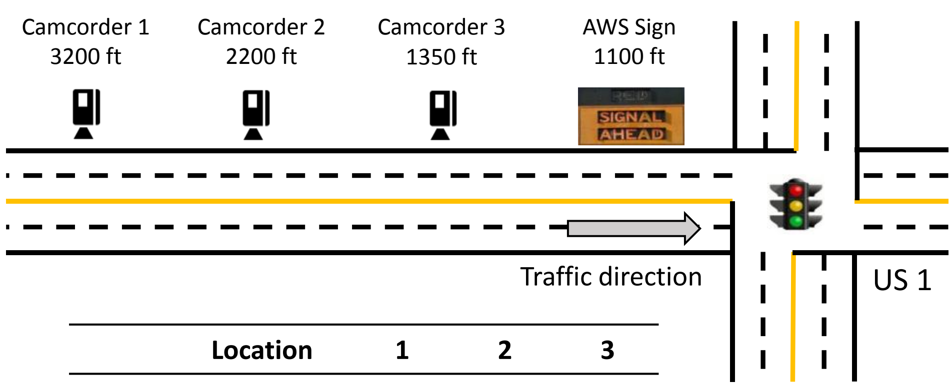


Figure 4-8 Wide-range traffic monitoring system and Advisory speed limit in the simulation platform

Driver response to the AWS/VSL (from the field data)

Once the drivers of approaching vehicles notice the advisory speed limit or advanced warning sign, they react to the sign by either changing their speeds to be in conformity with the advisory speed or to slow down their speeds as a response of the activated AWS. It should be mentioned, however, that the impacts of the AWS on drivers approaching the target intersection cannot be observed under the simulation development process, because such a device has not been deployed at the assessment stage. Hence, this study has adopted the data observed from other similar intersections as the basis for the simulation modeling and the sensitivity analysis.



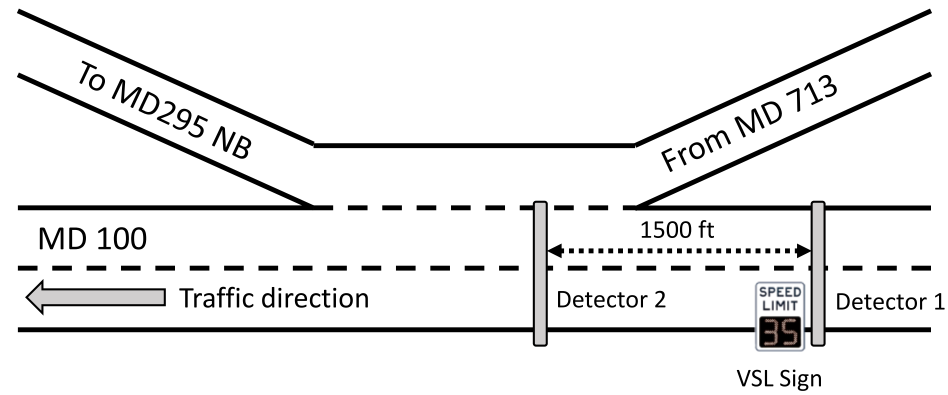
	Location	1	2	3
AWS OFF	Avg. Speed	54.6	49.0	36.4
	Std. Speed	4.3	5.7	3.3
AWS ON	Avg. Speed	52.8	44.7	33.5
	Std. Speed	4.5	5.2	3.4

Figure 4-9 Impacts of Impacts of the AWS from field studies

Figure 4-9 presents the field data collected at the intersection of US 1 and Contee Road in Maryland, illustrating the average traffic flow speeds with and without encountering the AWS at different distances from the signalized intersection. Recognizing that the field data are too limited to quantify the impact of the AWS on the approaching vehicles, this study has adopted the following method to model the simulated drivers' responses to the developed AWS:

- Identifying the speed of each simulated driver generated in the experimental analysis, and assigning the mean value for speed reduction from Figure 4-9 (e.g., 5 mph if in the range of 40-49 mph);
- Randomly generating an adjustment term within the interval of two standard deviations from the assigned mean value to reflect the variation of drivers' responses to an AWS.

To overcome the same data limitation, this study has analyzed the field data collected from MD-100 (Chang et al., 2011) to approximate the impact of a displayed advisory speed sign on the prevailing traffic flow speed, and has applied a random term from the simulation to capture the potential variance among different drivers (Figure 4-10).



Approaching Speed (from Detector 1)	**> 60 mph**					**50 ~ 60 mph**				
Posted VSL Speed	**50**	**45**	**40**	**35**	**30**	**50**	**45**	**40**	**35**	**30**
Avg. Speed Drop (from Detector 2)	0.9	1.4	1.2	1.4	3.2	0.4	0.9	0.6	1.2	3.4
Std. Speed Drop	1.7	1.9	1.9	1.5	1.5	1.9	2.4	1.9	1.6	7.6

Figure 4-10 Impacts of the VSL control from field studies

As demonstrated in Figure 4-11, the average speed reduction due to the displayed average traffic speed in the downstream dilemma zone can be modeled with the same method as for the AWS. The robustness of assessment results with respect to such data limitations can be analyzed with a sensitivity analysis and a generation of various driving populations with the developed traffic simulator. To account for drivers' responses to the AWS or VSL, different traffic compositions and different levels of speed distributions have been created for simulation experiments as shown in the Figure 4-11.

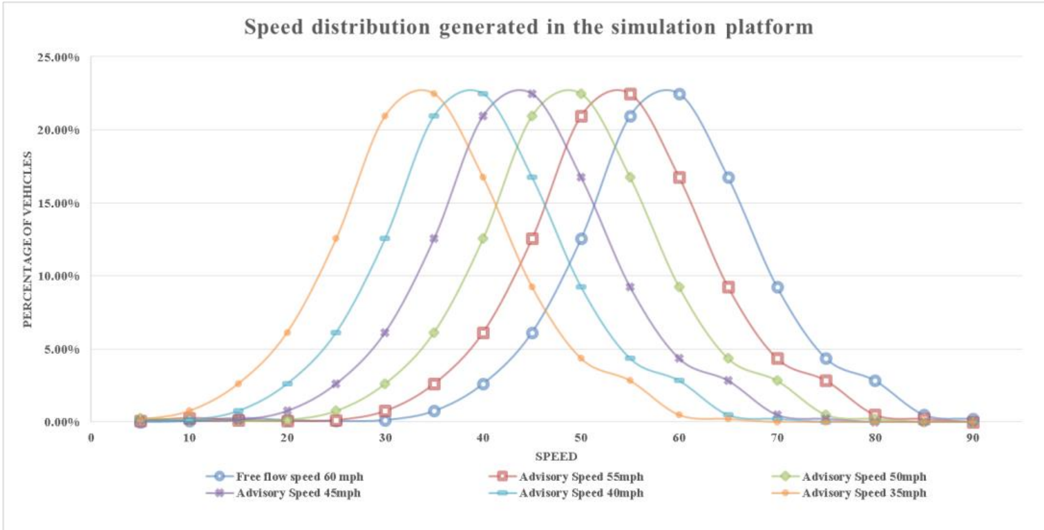


Figure 4-11 Speed distribution generated for drivers' response to the AWS/VSL

The following presentation shows the step-by-step procedure used to produce the impact of the VMS/VSL in the simulation environment.

Step 1: Identify vehicles reacting to the variable speed sign
Step 1-a: Define the boundary of the variable speed sign reaction zone
Set the lower/upper bound (S_{LB}/S_{UB}) of the speed reaction zone as the location of the variable speed sign and the farthest location that drivers can read the variable sign, respectively.
Step 1-b: Identify vehicles located in the reaction zone by their location (i.e., $S_{LB} < X_i < S_{UB}$).
Step 1-c: For those vehicles identified in Step 1-b, decide whether or not to comply with the advisory speed.

i. *Set a decision threshold using the inputted compliance rate (e.g., 0.5).*

ii. *Generate a random number p ~ U(0, 1) for each identified vehicle.*

iii. *If the random number is less than the preset threshold, then*

Set the vehicle as comply

Step 2: Adjust the approaching speed for the complying vehicles

For the complying vehicles, assign the advisory speed as their average free flow speed while keeping their speed multipliers unchanged.

Signal Controller

One of the core techniques in the dilemma zone protection system is to extend the all-red phase to the drivers who run over the red phase. The signal controller should be capable of extending the all-red phase to provide an additional clearance time to those vehicles. Since the signal controller in VISSIM cannot provide an all-red extension with proposed algorithms, the actuated signal controller (such as Econolite ASC/3) with an all-red extension function has been programmed in the simulation platform. Figure 4-12 describes the flowchart for the customized signal control logic. In order to replicate the actuated signal controller, every time the simulation is paused, the system will check the current signal status and calls for executing necessary modules. Based on the preset minimum green, maximum green, and unit extensions, the signal controller in the simulation platform can alter the phase accordingly.

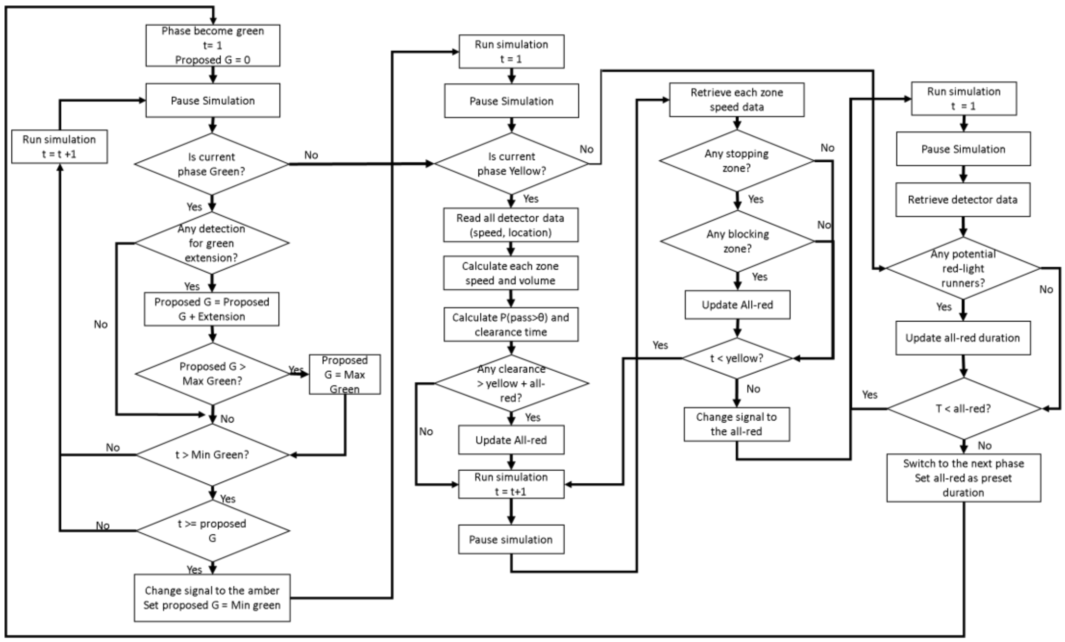


Figure 4-12 Flow chart for signal controller

Advisory speed module/Queue evolution module

The simulator retrieves detector data within the detection zones whenever the simulation pauses (i.e., 0.1 second). Once the advisory speed or the queue evolution module is called, the retrieved data is used to calculate a queue length and an advisory speed.

Chapter 5. System-I: All-Red Extension with Advanced Warning Signs/Variable Message Signs

5.1 Introduction

This chapter presents a dilemma zone protection system (DZPS), based on the all-red extension method and the advanced warning sign/variable message sign. The developed DZPS consists of three principal modules: variable message signs (VMS) for advanced warning or speed display, wide-range sensors to track individual vehicles' speeds and locations in the dilemma zone, and a decision module to execute the all-red extension. Based on a proactive design notion, the proposed system can first use the VMS to inform approaching drivers of a yellow or red phase ahead and advise them to prepare to stop; or the VMS can display the speed of the discharging traffic flows from the stop line during a green phase. Such information will help compliant drivers adjust their speeds in a timely manner so as to avoid possible rear-end collisions. In instances involving aggressive/non-compliant vehicles, the system's wide-range sensors will function to track the evolution of their speeds and locations within the dilemma zone (i.e., every 0.1 seconds), and then determine whether or not an all-red extension call should be granted to prevent such vehicles from incurring potential side-angle crashes.

Figure 5-1 shows the key components and their interrelations in real-world operations. The key function of each component and its embedded algorithm are reported in sequence in this chapter.

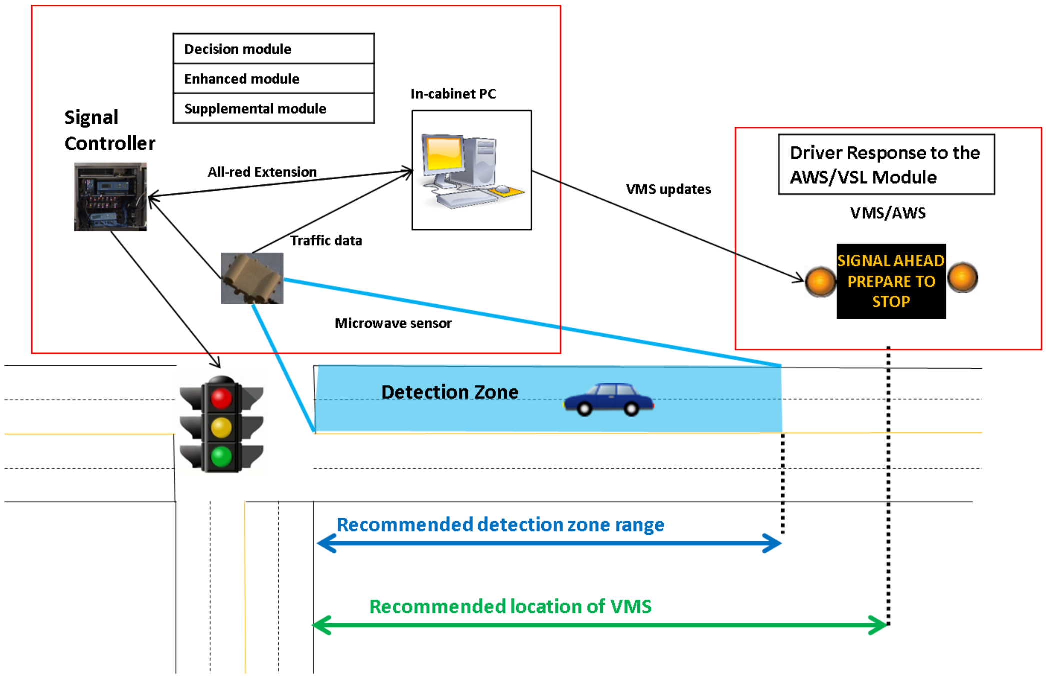


Figure 5-1 Illustration of System-I

Note that the proposed DZPS is not only designed to maximize the protection to red-light running vehicles with the all-red extension, but also to minimize the false alarm rate and improve operational efficiency. To prevent what the system misses in providing protection to red-light-running vehicles, the system will track all vehicles' speeds and locations in the predetermined monitoring zone and determine if the all-red phase needs to be extended. The DZPS will activate an all-red extension if any vehicle's speed in the monitoring zone at the onset of the red phase exceeds the preset thresholds from the intersection. To properly execute such a function, the developed DZPS contains two extension algorithms. Algorithm-1 for all-red extension is based on a behavior module to assess the speed and the location of each vehicle at the onset of the yellow phase, and then to predict its decision as to having a stop or pass action. Algorithm-2 employs a zone-based approach to compute the optimal duration of the all-red extension based on the spatial-temporal evolution of vehicles in the monitoring zone covered by the wide-range traffic monitoring sensors.

5.2 All-Red Extension Algorithm-1

The core logic of Algorithm-1 is to identify potential red-light-running vehicles and then calculate the required duration for an all-red extension, based on the current speed and location of each vehicle within the monitoring zone. Algorithim-1 takes each vehicle's location and speed from the sensor, and identifies any potential red-light-running vehicles based on the estimated probability yielded by the behavioral decision module and the preset probability to pass the intersection during the red-light. Figure 5-2 shows the operational flowchart of Algorithm-1, and its step-by-step description below:

Step 1

- *Identify which vehicles are trapped in their respective dilemma zones based on their speeds and locations, detected by the deployed wide-range sensors*

Step 2

- *Calculate the required clearance time for each vehicle trapped in its DZ to pass the intersection*

Step 3

- *Estimate the probability for vehicles identified in step 1 to take the passing decision (using Equation 4-1)*

Step 4

- *Identify vehicles with a passing probability greater than the preset threshold (e.g. > 0.5)*

Step 5

- *Find the maximum required clearance time among all vehicles identified from step 4*

Step 6

- *Set the all-red extension based on the maximum clearance time calculated from step 5*

Step 7

- *At the onset of the red phase, identify vehicles that cannot stop safely, and*
- *Consider the all-red extension duration and update if necessary*

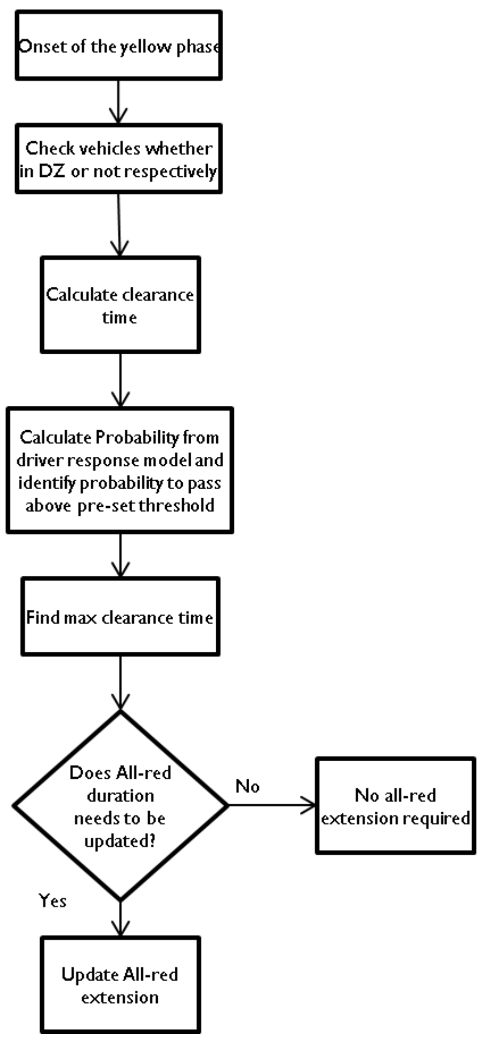


Figure 5-2 Operational flow chart for the decision module

Note that a decision of whether or not to execute an all-red extension during the yellow phase can result in a missed call (i.e., vehicles should be protected, but the system does not call an all-red extension) or a false alarm rate (vehicles do not need be protected but the system calls an all-red extension). However, some drivers may change from their initial decision when they face the yellow phase. Thus, a supplemental module is developed to ensure that all such drivers will be protected by the deployed system.

5.3 All-Red Extension Algorithm-2 (Zone-Based)

As shown in Figure 5-3, the monitoring zone under Algorithm-2 is divided into four sub-zones, and the decision module will view the entire monitoring zone as a series of spatially connected sub-zones. Hence, whether or not a decision is made to grant the all-red extension will depend on the average speed of these vehicles in the leading and following sub-zones. More specifically, it is assumed that the following vehicle's decision will be affected by its leading vehicle within the same sub-zone. Also, all leading and following vehicles are assumed to behave according to the following rules:

- *If vehicles in the leading zone(s) decide to stop at the intersection*

  AND

  If the vehicles traveling on the leading zone(s) occupy both lanes, then
- *The following vehicles are predicted to select the "stop" decision.*

During the yellow phase, the DZP system will collect each vehicle's speed and location and then compute the average zone speed and total number of vehicles in each zone. If the average speed of a zone is below the preset threshold and decreasing over time, that zone is identified as a "Stopping Zone." Depending on the number of vehicles in that zone, a "Stopping Zone" may be reclassified as a "Blocking Zone." The criteria for defining a "Blocking Zone" are given below:

- *If total number of vehicles in the stopping zone is more than a certain value*

  AND

- *If total length required for those vehicle is greater than the length of the zone*
- *The zone is marked as a "Blocking Zone"*

If a "Blocking Zone" is identified, the system will search for potential red-light-running vehicles from the vehicles ahead of the "blocking zone," and then extend an all-red phase if necessary. If no blocking zone has been identified, the system will search for potential red-light-running vehicles over the entire monitoring zone and execute an all-red extension if necessary.

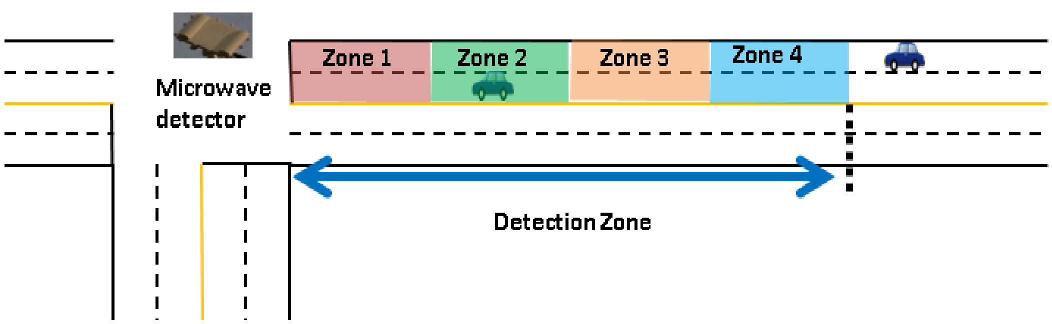


Figure 5-3 Zone based all-red extension

In brief, the focus of the zone-based all-red extension method is to compute the optimal duration of the all-red extension from a macroscopic perspective, based on the spatial-temporal evolution of vehicles in the monitoring zone, to minimize the potential false alarm rate. A step-by-step description of Algorithm-2 for the all-red extension is given below:

Initialize

Set t = 0; onset of the yellow phase

Set AR = 0; the initial all-red extension.

Step 1. Collect traffic data in the monitoring area

a. Obtain the speeds and locations for all vehicles in each sub-zone

b. Set Zone ID: z = 1 (nearest to the intersection)

Step 2. Identifying if any sub-zone shall be classified as a "Stopping Zone"

Step 2-a: Checking the speeds of all vehicles in the target zone z (z=1,…,4)

If all speeds are less than the predefined threshold, then

Set zone z as a "stopping zone"

Go to Step 3.

Else

Go to Step 2-b.

Step 2-b: Checking the evolution of average zone speed

Calculate the average speed in a zone z and zone z+1 over time (i.e. $\bar{V}_{j,t} - \bar{V}_{j+1,t-1}$ *)*

If the speed is decreasing over time t (i.e. $\bar{V}_{j,t} - \bar{V}_{j+1,t-1} < \boldsymbol{\theta'}$ *) AND no outliers (i.e.* $max\{v_{i,t}\} - \bar{V}_{j,t} < \boldsymbol{\theta''}$ *) exist in zone z, then*

Set the zone z as a "stopping zone"

Go to Step 3.

Else

Go to Step 4.

Step 3. Identifying "Blocking Zone"

Calculate the total length occupied by vehicles in the zone without any outliers

If the calculated total length is greater than the length of the zone AND without any outliers, then

Set the zone z as a "Blocking zone"

Go to Step 5.

Else

Go to Step 4.

Step 4. Proceed the same blocking-zone identification for all detection zones

If all zones have been checked, then

Go to Step 5.

Else

Go to Step 2. for a upstream zone z +1

Step 5. Identifying passing vehicles

Identifying all vehicles whose decisions are passing (i.e. P(passing) > 0.5)

If there exists any "Blocking zone", then

Identifying those "passing" vehicles between the stop line and the closest "blocking zone"

Else

identify all vehicles in the detection zone whose decisions are passing

Step 6. Calculate the clearance time

a. Calculate the required clearance time for vehicles identified from step 5.

b. Convert the required clearance time to the required all-red extension

Step 7. Update All-red extension

Update AR if necessary

Step 8. Finalization

If t < end of the yellow phase

t = t +1

Go to Step 1.

Else

Onset of the red phase, identify vehicles cannot stop

Compare all-red extension duration and update if necessary

5.4 Pre-Deployment Process and Assessment

This section is focused on illustrating the pre-deployment process and the essential assessment. To facilitate the presentation, the illustration uses the intersection at US 301 and Croom Station Road as an example. The pre-deployment process generally includes the following steps:

- Developing the simulation platform for the DZPS to be deployed as discussed in Chapter 4,
- Selecting the MOEs and performing extensive simulation experiments, and
- Performing sensitivity analysis with respect to key model parameters embedded in the simulation platform.

Each of these steps is described below.

Step 1 - Simulation platform

As evidenced by the final design (see Figure 5-4), the simulator for experimental analysis is capable of replicating both the DZPS and traffic characteristics, especially the response of drivers during a yellow phase and the arriving traffic patterns (see Chapter 4 for more details).

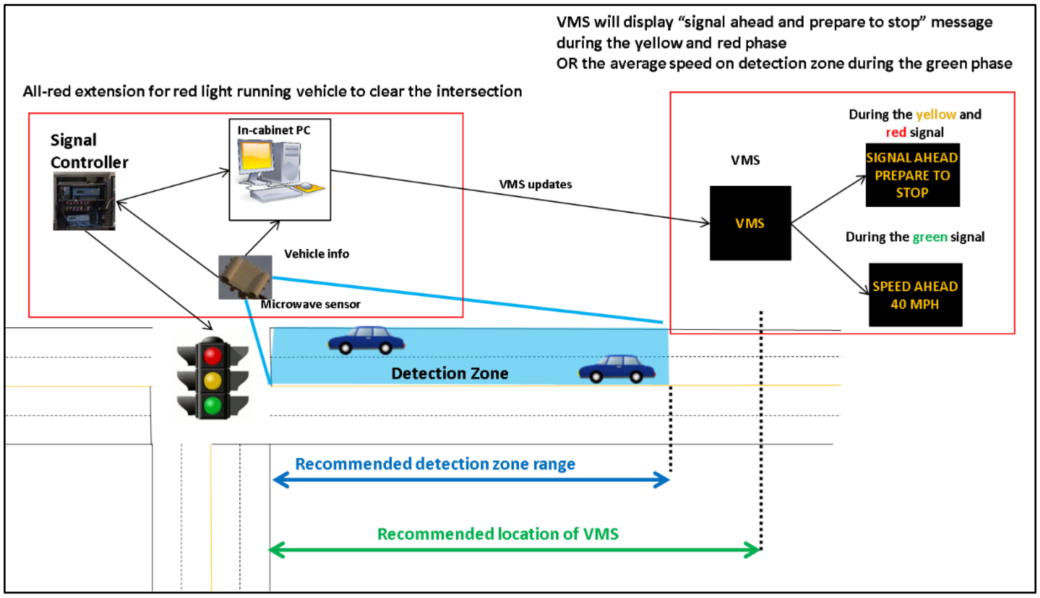


Figure 5-4 Graphical Illustration of System-I

The main functions in this simulation platform to be customized for a target intersection include:

- Advanced warning signs, and the appropriate activation logic;
- The function of wide-range traffic monitoring sensors to track both the speed and the location of each vehicle;
- The signal controller of Econolite ASC/3, which can offer an extended all-red phase, based on the instructions from the monitoring sensors;
- The all-red extension and computing algorithm;
- The real-time communicating relationships between the sensors, advanced warning messages, and the all-red computing algorithm, and the signal controller; and

- The signal phase and timing plan.

Table 5-1 shows the signal phase plan on the target intersection. The DZPS is implemented on both the northbound and southbound through movements. The minimum green phase duration is 35 seconds, the unit extension is six seconds, and the maximum green phase is 90 seconds for both the north and the south through movements. The total simulation periods are 40 hours long, with different random seeds for each hour.

Table 5-1 Signal Phase plan

	Phase 1	Phase 2	Phase 3
Direction	N/S	N/S	E/W
Movement	Left	Through	Left/Through
Min. Green	5	35	8
Unit Ext	3.5	6	4
Max. Green	40	90	40
Yellow	5	5.5	5
All-red	2	3	2

Four simulation scenarios have been built for experiments to compare the effectiveness of the proposed DZPS. The base scenario represents the condition in which no DZPS is provided. The base scenario serves as the base line for comparing the performance of different DZPS algorithms. The second scenario consists of a default algorithm that divides the detection zone into two zones. The first zone is the distance from the stop line to 500 feet beyond the line, and the second zone is from the line at 500 feet to the end of the detection zone. If a speed of greater than the 27 mph is detected in the first zone, or if a speed of greater than 56 mph is detected in the second zone during the all-red phase, the signal controller will extend the all-red phase. The third scenario is based on Algorithm-1 that uses the decision module and the supplemental module. The last scenario is built in Algorithm-2, which uses the zone-based all-red extension as well as the decision and supplemental module.

Step 2 -Selection of MOEs

As in most evaluation tasks, the assessment of the proposed DZPS with field-calibrated parameters is focused on the following critical aspects:

- The total number of red-light-running vehicles (RLR);
- The total number of extension calls;
- The detection rate based on the thresholds preset in each all-red extension algorithm; and
- The false-alarm rate in each cycle under each all-red extension algorithm.

Table 5-2 MOEs under different all-red extension algorithms and impacts from the VMS

MOE	No Control	Default [1]	Algorithm-I	Algorithm-II
Red-light-running rate [2] (RLR) (RLR / cycle)	8.9%	8.9%	9.5%	9.1%
Extension call rate (extension call / cycle) [3]	-	52%	30%	25%
Detection rate (protected RLR) [4]	-	56%	100%	100%
False alarm rate (false alarm / cycle)	-	47%	21%	16%

1 The default algorithm embedded in the SmartSensor.
2 The total red-light-running vehicles divided by the total number of cycles
3 The total number of all-red extension calls divided by the total number of cycles
4 The total number of protected red-light-running divided by the total number of red-light running.

Recognizing that the top priority is to prevent red-light-running vehicles from potential crashes, this study has tuned the proposed system to offer 100 percent detection and protection, which naturally results in a relatively high false-alarm rate. As shown in Table 5-2, Algorithm-1 produces a 21 percent false-alarm rate, (if given the target of protecting all red-light-running vehicles) which is about 9 percent of red-light-running vehicles on the average under the current traffic patterns. Algorithm-2 slightly outperforms Algorithm-1 and yields a false-alarm rate of 16 percent – an acceptable rate from the operational perspective despite the fact that excessive extensions will increase the loss time per cycle. Table 5-2 compares the results between these two candidate algorithms. Further performance enhancements can be achieved if factors to improve intersection safety and increase operational efficiency are weighted early in the design process.

Step 3 -Sensitivity analysis

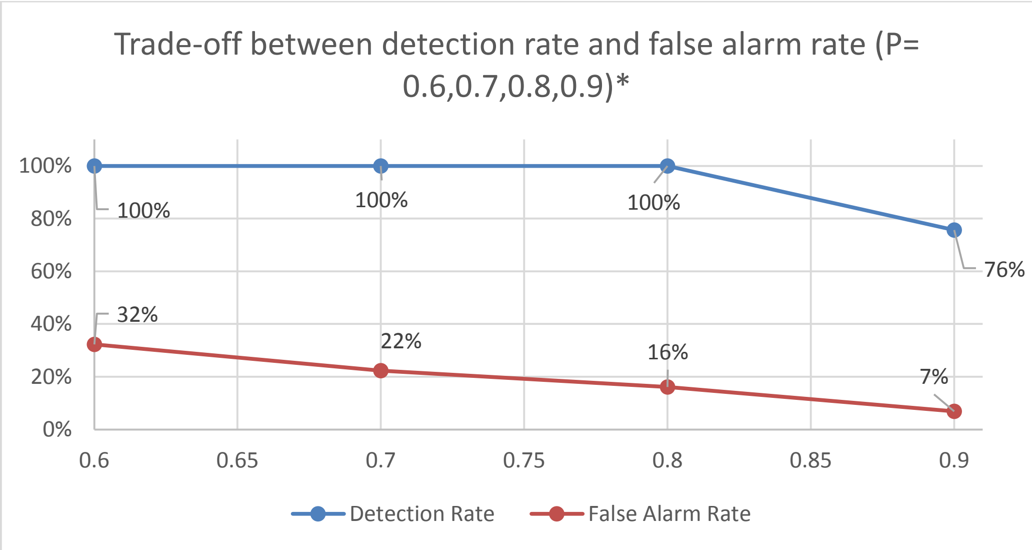


Figure 5-5 Trade-off between capturing rate and false alarm rate using different thresholds of probability

(* P is the probability threshold to determine if the detected drivers will take the "Pass" action during the yellow phase)

Figure 5-5 illustrates the trade-off between the false alarm rates and the detection rates under the same traffic conditions, where **P** denotes the preset probability of which the target driver will be viewed as taking the "Pass" action. As shown in Figure 5-5, by raising the threshold to a level of 0.9, the rate of offering an excessive all-red extension would fall to 7 percent, but at the cost of providing the all-red extension only to 76 percent of red-light-running vehicles. Ideally, one would deploy a system that can maximize the detection rate and minimize the number of false alarms. Recognizing that the cost of one missed detection, however, far outweighs additional delay due to a false all-red extension -- particularly at high-speed and generally low-volume intersections -- any such system should aim for a 100 percent detection rate as the foremost function.

Table 5-3 also demonstrates the red-light-running rate and average speed for the simulated traffic flows in cases where the impact level due to AWS is different from the field data. It is apparent from the results in the table that the RLR rate is likely to be reduced if the AWS produces more pronounced reduction in the speed of approaching vehicles. For instance, the resulting RLR rate will drop from 7.4%to 2.3%if the actual impact of the VMS on prevailing speed is increased from 5 mph to 15 mph.

Table 5-3 Impact of the VMS from different speed reduction rates

VMS impacts	**Without VMS**	VMS with 5 mph impact	VMS with 10 mph impact	VMS with 15 mph impact
1000 ft from the stop line Avg speed	59.3(7.1) [1]	60.3(6.9)	58.4(7.9)	57.8(9.4)
400 ft from the stop line Avg speed	54.4(7.6)	48.6(10.1)	42.3(12.1)	36.7(14.7)
Red-light-running rate (RLR) (RLR / cycle)	8.9%	7.4%	4.2%	2.3%
1 The number in the parenthesis shows the standard deviation.				

5.5 Conclusion

To contend with rear-end collisions and side-angle crashes caused mainly by the existence of dilemma zones at high-speed intersections, this chapter has presented an integrated dilemma zone protection system that offers protection to drivers via both preventive and reactive measures. By displaying the information of a yellow/red phase ahead or the average speed of downstream queue discharging flows, the proposed system can exercise its AWS to alert approaching drivers of their need to reduce speeds so as to prevent them from incurring rear-end collisions. For aggressive or non-compliant drivers, the system uses monitoring results from wide-range sensors and detection algorithms to exercise its all-red extension in order to protect these drivers from causing side-angle crashes.

To evaluate the effectiveness of the developed system, this study involves field data collected from a candidate intersection, and demonstrates the procedures for conducting a pre-deployment assessment with a well-calibrated simulator. Through extensive simulation experiments, the proposed system has demonstrated its effectiveness in offering 100% protection to red-light-running vehicles at the acceptable false alarm rate.

Further research on this subject will focus on the following issues: (1) collecting the arrival traffic patterns (e.g. speed and acceleration/deceleration rates) and driver responses during the yellow phase after the system deployment, and (2) extending the system's control algorithm to concurrently optimize the detection rate and false alarm rate so that safety improvement for an intersection will not come at the cost of operational efficiency. In addition, considering the likelihood of having connected vehicles under various penetration rates in the traffic flows, it will be imperative for traffic researchers to investigate how to use information from such vehicles to minimize the deployment cost and improve the system's effectiveness.

Chapter 6. System-II: An Integrated Intersection Control System for Both Safety and Operational Efficiency

6.1 Introduction

This chapter presents the enhanced DZPS (System-II) illustrated in the previous chapter, along with a speed harmonization function developed with the all-red extension module and variable advisory speed sign instead of the VMS/AWS sign from System-I. The integrated system, for improving the safety and the operational efficiency, consists of several major modules: a variable advisory speed sign to display the advisory speed, wide-range sensors to track individual vehicles' speeds and locations in the dilemma zone and estimate a queue length, a gap-out prediction module for predicting gap-out timing, and an all-red extension module to offer protection. System-II, with a minimal hardware enhancement to the reactive dilemma zone protection system (i.e., the All-Red Extension), utilizes the traffic information from wide-range traffic monitoring sensors to provide advisory speeds to advise either a safe stop or a progression through the intersection. The improvement on the safety and the mobility brings more benefits at the same deployment cost as the developed System-I, while avoiding competition for resources among these vital intersection traffic issues.

6.2 System Objectives and Control Actions

Figure 6-1 illustrates the operational process of System-II. This system functions to select the control objective based on the signal status and detected traffic conditions, and then execute control actions with embedded models. A brief description of the control process under different signal phases and traffic conditions is presented in Figure 6-1.

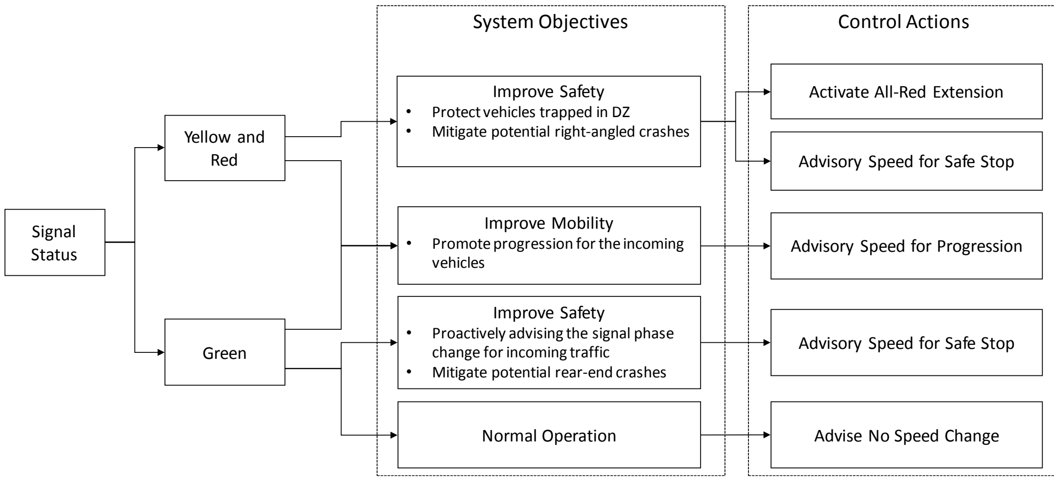


Figure 6-1 Operational flowchart of System-II

Figure 6-2 shows the vehicle trajectory over a cycle with and without an advisory speed control. The solid line and dashed lines represents vehicles without and with advisory speed control, respectively. The advisory speed will reduce the approaching vehicle's speed to achieve either a safe stop or a progression.

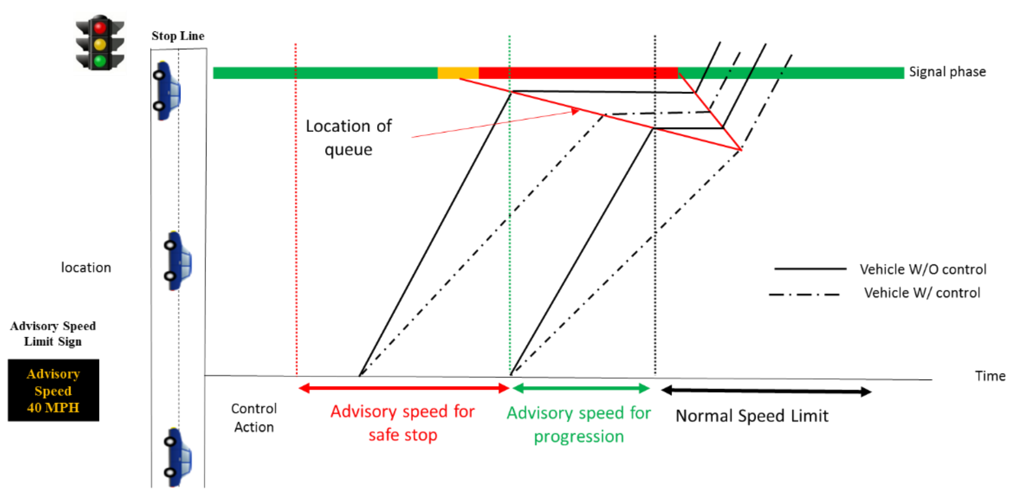


Figure 6-2 Vehicle trajectory with and without the advisory speed control

6.2.1 Data Flows for the Computation Modules

Figure 6-3 illustrates the interrelations of data flows and computation modules. The wide-range sensor is used to provide each individual vehicle's location and speed, queue length at the intersection, and discharge and arrival flow rates in the detection zone. The signal phase and the timing information, provided by the signal controller, are fed back to the in-cabinet computer (see Figure 6-4). If the intersection is operated under actuated signal control, a supplemental module to estimate green termination timing will be used to compute the remaining phase duration. The computation modules function to estimate a vehicle's passing decision -- a queue evolution -- and estimate a number of vehicles within the control boundaries with the information from the data source module. Either reactive or proactive actions are activated in response to the detected traffic conditions and the signal status.

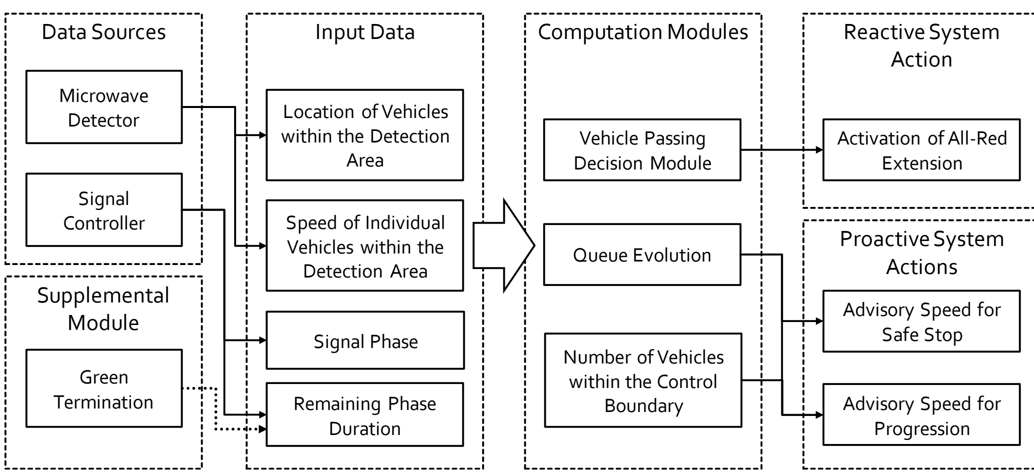


Figure 6-3 Data flows within the developed System-II

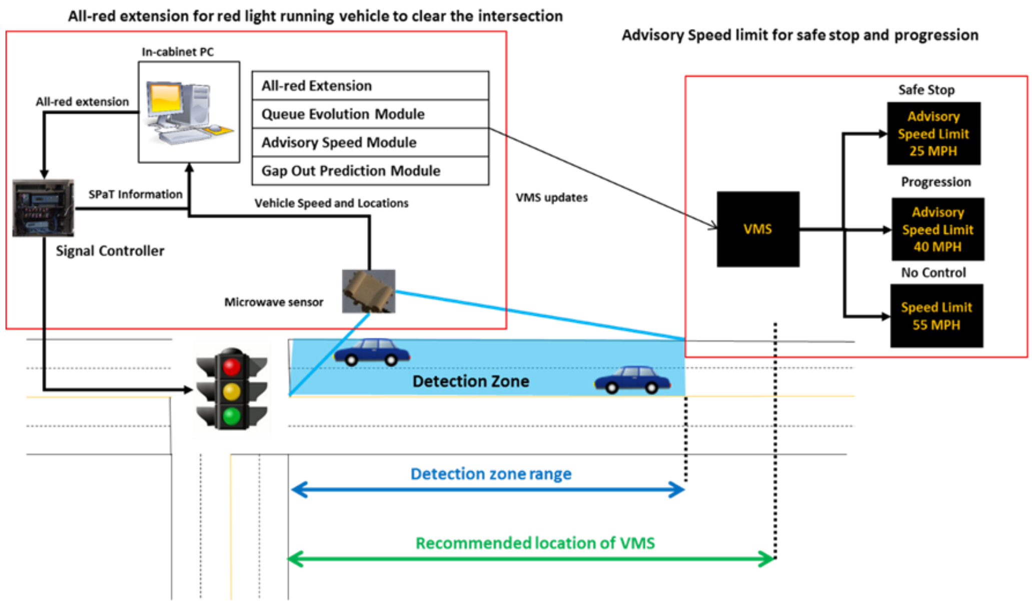


Figure 6-4 Design of the developed intelligent intersection system

Module 1: Estimate the number of vehicles within the control boundaries

This module is used to estimate the number of vehicles from the intersection stop line to the advisory speed sign. With the advisory speed sign placed beyond the dilemma zone, the number of vehicles within the control area may not be detected directly with the system sensors. By using the long-range sensor, one can directly compute the traffic density within the detection zone; this traffic density is then used to estimate the number of vehicles between the stop line and the advisory speed sign in real-time. The module is shown as follows:

Step 1: Retrieve data from the sensor

> *At current time t, derive speed ($v_i[t]$) and location ($X_i[t]$) of all vehicles (i) within the detection area. Let $N[t]$ be the number of vehicles within the detection area.*

Step 2: Determine the location of the end of stop queue ($L[t]$) with a pre-defined speed threshold

Step 3: Calculate the traffic density within the detection area ($K[t]$) by:

$$K[t] = N[t] / \left(L_D - L[t]\right) \qquad \text{6-(1)}$$

where L_D is the length of detection area and $L[t]$ is the queue length at time t.

Step 4: Estimate the number of vehicles between the stop line and the location of advisory speed sign ($N_A[t]$) by:

$$N_A[t] = K[t] \times \left(L_A - L[t]\right) \qquad \text{6-(2)}$$

where L_A is the distance between the stop line and the advisory speed sign.

Step 5: Approximate the queue length that arriving vehicles may experience by:

$$L_Q[t] = L[t] + N_A[t] / \left(n_L \times K_{jam}\right) \qquad \text{6-(3)}$$

where K_{jam} is the field-observed jam density and n_L is the number of through lanes.

Module 2: Estimate the probability for an observed vehicle to take the passing action during a yellow phase

The system will track each individual vehicle's trajectory within the monitoring area, and estimate a vehicle's pass/stop probability at the onset of a yellow phase with the concept as developed in Chapter 4:

Step 1: Identify vehicles with a passing decision using the following equation:

$$P_{pass}(i,t)=\frac{1}{1-e^{-\beta_0-\beta_1 v_i(t)-\beta_2 d_i(t)}} \quad 6\text{-}(4)$$

where v_i *and* d_i *are the vehicle's speed and the distance from stop line at time t, respectively;* $\beta_0, \beta_1,$ *and* β_2 *are parameters calibrated from the field data.*

Step 2: If $P_{pass}(i,t)\geq 0.5$*, then*

Identify vehicle i as a passing vehicle.

Else,

Identify vehicle i as a stopping vehicle.

Module 3: Predict the stop queue evolution

Vehicles, arriving at the intersection at the end of a red phase, may be able to progress through the intersection by delaying their arrival times until queues being discharged. With the limited detection ability on discharging vehicles as pointed out by (Sharma et al., 2011), this study uses the notion of detecting shockwaves to predict the time-varying queue size in advance for executing the speed advisory task. The module for predicting queue evolution is described as follows, where the entire detection zone is viewed as a series of spatially connected cells (each of 5 feet long, according to the sensor specification):

Step 1: Retrieve data from the sensor

Derive speed ($v_i[t]$*) and location (*$X_i[t]$*) of all vehicles (i) within the monitoring area*

Step 2: Update traffic speed for each cell in the monitoring zone

a. *For all vehicle i within the monitoring zone, derive its current* *(* $X_i[t]$*)* *and previous (* $X_i[t-1]$*) locations*

b. *Set the speed (*$u_j[t]$*) of cell j as the speed of vehicle passing cell j during current time step t by:*

$$u_j[t]=v_i[t],\ \ for\ X_i[t-1]\le j\le X_i[t] \qquad 6\text{-}(5)$$

c. *If multiple vehicles traveling through the same cell during time step t, set the cell speed as the average of all passing vehicles.*

d. *If no vehicles passing cell j at time t, set* $u_j[t]=u_j[t-1]$

Step 3: Search for the backward queue formation shockwave

a. Determine the location of the end of queue ($L[t]$*) from the sensor by setting a speed threshold on* $u_j[t]$.

b. For each moving vehicle in the monitoring area, estimate their time-to-arrival (at the end of queue) by assuming constant speed and build an arrival table.

c. Predict the location of the end of queue ($\hat{L}[t]$*) with the arrival table.*

Step 4: Search for the backward queue discharging shockwave

d. Determine the location of the queue discharging shockwave ($D[t]$*) from sensor by setting a speed threshold on* $u_j[t]$.

a. Calculate the speed of discharging shockwave (υ_d *)*

If signal phase is green, then

Calculate υ_d *with the detected* $D[t]$ *by:*

$$\upsilon_d = \sum_{G \le t' \le t} \frac{D[t'] - D[t'-1]}{\Delta t} \qquad 6\text{-}(6)$$

where Δt *is the sensor update interval and G is the start of green phase.*

If signal is red, then

Set υ_d *using data from the previous cycle.*

b. *Predict the location of the discharging shockwave (* $\hat{D}[t]$ *) by:*

$$\hat{D}[t] = D[t_{now}] + \upsilon_d \times (t - t_{now}) \qquad 6\text{-}(7)$$

where t_{now} *is the current time step*

Step 5: Estimate queue clearance time

Determine the queue clearance time (t_{clear} *) by solving* $\hat{L}[t_{clear}] = \hat{D}[t_{clear}]$

6.2.2 Control Objectives and Actions during Yellow and Red Phases

For vehicles arriving during yellow and red phases, the proposed system shall determine the control objectives by using both dilemma-zone-detection and queue-evolution modules. The design to select the control objective depends on the following scenarios, which drivers are likely to encounter:

- Scenario 1: Arriving at the intersection during the yellow and the all-red phases
- Scenario 2: Arriving at the intersection during the red phase

- Scenario 3: Arriving at the intersection during the end of the red phase

Figure 6-5 shows the flowchart of the control process for during the yellow and red phases.

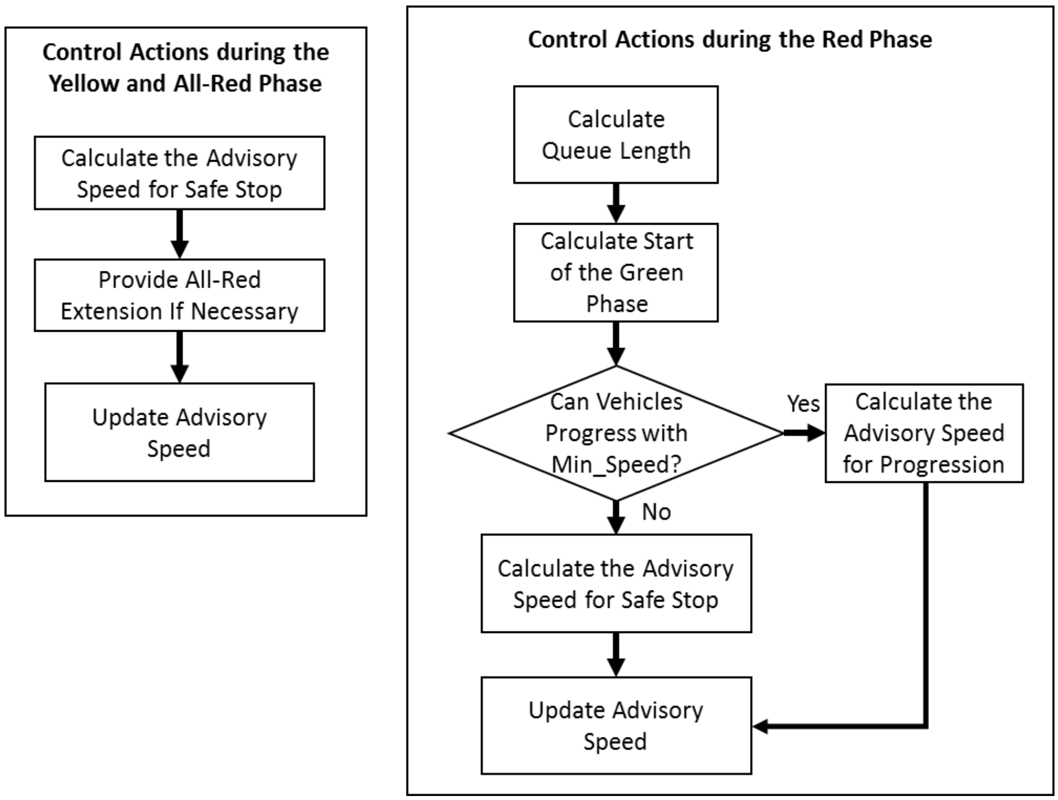


Figure 6-5 Control action during the yellow and the all-red phase

<u>Scenario 1: Arriving at the yellow and the all-red phases</u>

Vehicles arriving at the yellow and the all-red phases should stop at the stop line. However, those trapped within their respective dilemma zones may not stop nor pass safely. To improve traffic safety, System-II proactively informs incoming drivers of the yellow and the red phase with an advisory speed and reduces the likelihood of them becoming trapped in their dilemma zones. In addition, the system also protects those vehicles failing to stop at the stop line with an all-red extension function. Such control actions capable of mitigating hazardous scenarios are described below:

Control Action 1: Calculate the advisory speed for upstream incoming vehicles

Step 1: Estimate the queue length that incoming vehicles may encounter (L_Q) when they arrive at the stop line by:

<u>*Computation Module 1: Estimate the number of vehicles within the control boundary*</u>

Step 2: Solve the advisory speed by the available braking distance from the variable speed sign to the stop line by solving (v_S):

$$L_A - L_Q = \frac{v_s^{\,2}}{\alpha_{dec}} + \frac{1}{2} \times \alpha_{dec} \times \left(\frac{v_s}{\alpha_{dec}} \right)^2 \qquad 6\text{-}(8)$$

where L_A is the location of the advisory speed sign, and a_{dec} is the field-observed deceleration rate.

Step 3: Activate the advisory speed sign and display $\boldsymbol{v_s}$

Control Action 2: Protect the vehicles trapped in their dilemma zones using an all-red extension

In order to protect all vehicles trapped in their respective dilemma zones, the system tracks all vehicles' speeds and locations in the monitoring zone and determines if an all-red phase extension is needed. To effectively detect these vehicles unable to stop and to also reduce the false alarm rate, the entire monitoring zone is viewed as a series of spatially connected sub-zones, where a vehicle's decision in the following zone will be affected by those in the leading zone. The all-red extension algorithm is identical to that referenced in Chapter 5.

<u>Scenario 2: Arriving at the intersection during the red phase</u>

Intersections plagued with an insufficient sight distance are particularly hazardous for drivers who experience a long stop queue. The wide-range sensors, which provide vehicles' locations and speeds in the detection zone, can monitor the queue length and offer the essential information for the system to calculate the advisory speed and then inform the incoming vehicles so as to prevent or mitigate potential rear-end crashes. The control actions aimed at improving safety are described as follows:

Control Action 3: Advisory speed for preventing or mitigating rear-end crashes due to insufficient sight distance

Step 1: Estimate the queue length that incoming vehicles may encounter (L_Q) when they arrive at the stop line by:

<u>Computation Module 1: Estimate the number of vehicles within the control boundary</u>

Step 2: Solve the advisory speed by the available braking distance from the variable speed sign to the end of queue by solving ($\boldsymbol{v_{SM}}$):

$$L_A - L_Q = \frac{v_{SM}{}^2}{\alpha_{dec}} + \frac{1}{2} \times \alpha_{dec} \times \left(\frac{v_{SM}}{\alpha_{dec}} \right)^2 \qquad 6\text{-}(9)$$

where a_{dec} is the field-observed deceleration rate.

<u>Scenario 3: Arriving at the intersection at the end of the red phase</u>

Vehicles arriving at the intersection at the end of the red phase may be able to progress through the intersection by delaying their arrival times until the queue dissipates during the subsequent green phase. Such vehicles can be identified and provided with an advisory speed for improving mobility with the following control actions:

Control Action 4: Advisory speed for vehicles arriving at the end of the red phase

Step 1: Estimate the queue clearance time

Estimate the queue clearance time with: <u>Computation Module 3: Queue Evolution Module</u>

Step 2: Identify the possible progressing vehicles

a. *Calculate the potential arrival time with a preset lower bound on advisory speed:*

$$\hat{t}_p = t + L_A \times v_{LB}^{-1}, \quad \text{6-(10)}$$

where L_A is the location of advisory speed sign and v_{LB} is the preset lower bound of advisory speed

b. *If the potential arrival time is prior to the queue clearance time (i.e., $t_{clear} > \hat{t}_p$), then*

Set the incoming vehicles as "blocked"

Else,

Set the incoming vehicles as "progressing"

Step 3: Calculate the advisory speed

If the incoming vehicles are "blocked", then

Calculate the advisory speed for safe stop by solving:

$$L_A - L_Q = \frac{v_{SM}{}^2}{\alpha_{dec}} + \frac{1}{2} \times \alpha_{dec} \times \left(\frac{v_{SM}}{\alpha_{dec}} \right)^2 \text{ (similar to Control Action 3)}$$

Else,

Calculate the advisory speed for delaying vehicles' arrival until queue clearance by:

$$v_p = D[t_{clear}] \times (t_{clear} - t)^{-1} \quad 6\text{-}(11)$$

6.2.3 Control Objectives and Actions during the Green Phase

When detecting vehicles approaching the intersection during the green phase, the proposed System-II uses traffic evolution module to evaluate which of the following scenarios those vehicles may encounter:

- Scenario 1: Arrive at the beginning of the green phase and encounter the stop queue.

- Scenario 2: Arrive at the end of the green phase and encounter the yellow and the red phases.

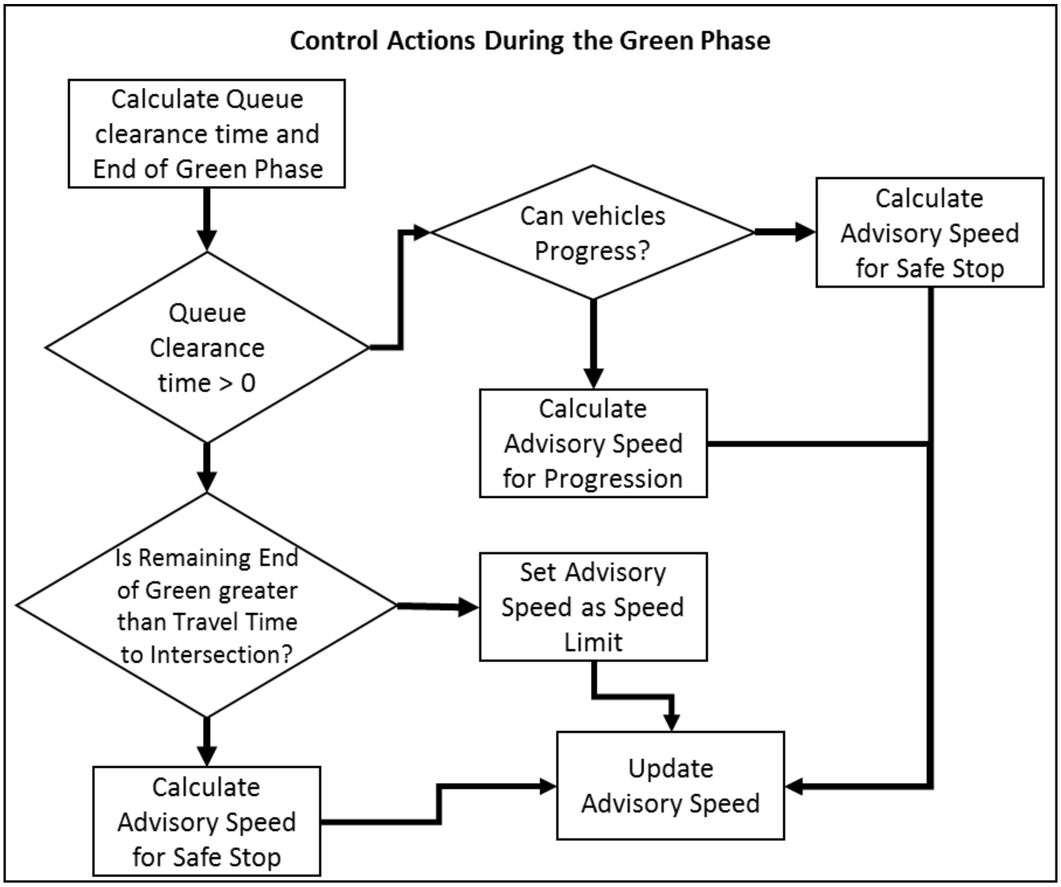


Figure 6-6 Control actions during the green phase

Figure 6-6 shows the flowchart for control actions during the green phase. The system's control actions and the computing functions to be executed in each scenario are presented below:

<u>Scenario 1: Arriving at the beginning of the green phase and encountering the stop queue</u>

Vehicles arriving at the beginning of the green phase may either be i) blocked by the dissipating stop queue or ii) able to progress through the intersection by delaying their arrivals until queue clearance. For the first group of vehicles, an advisory speed is conveyed to prepare them to join the end of queue safely. Unlike most existing AWS systems, which would be turned off during the green phase, the developed system uses the queue length information derived from the sensor to protect incoming vehicles from rear-end crashes. As for the second group of vehicles, an advisory speed is provided to improve the traffic mobility by advising them to adjust arrival times so as to meet the progression band. Note that the intersection traffic departure rate during the green phase can be directly derived from the wide-range sensors. The identification of such a scenario and its corresponding control actions are described below:

Control Action 5: Advisory speed for early stage of the green phase

Step 1: Determine whether or not the stop queue is discharged

> *If all vehicles within the monitoring area has a speed higher than the pre-defined threshold,*
>
> > *Go to Step 4.*
>
> *Else*
>
> > *Go to Step 2.*

Step 2: Estimate the queue clearance time

> *Estimate the queue clearance time using <u>Computation Module 3: Queue Evolution Module</u>*

Step 3: Determine the advisory speed

> *Set the advisory speed using the same step as of Control Action 4.*

Step 4: Deactivate advisory speed

> *All stop queue is cleared, set the advisory speed sign as the speed limit.*

Scenario 2: Arriving at the end of a green phase and encountering the yellow and the red phase.

The incoming vehicles, entering upstream from near the end of the green phase, may encounter either a yellow or a red phase when arriving at the stop line. Under such scenarios, the developed system detects the approaching speeds and the signal timing for those incoming vehicles, and then takes the following actions to prepare drivers for stopping at the intersection safely. Key steps in the control action are described below:

Control Action 6: Advisory speed for vehicles arriving at the end of the green phase

Step 1: Collect the approaching speed (v_0 *) of the incoming vehicles from the traffic sensor*

Step 2: Calculate the arrival time to the stop line

$$t_{arr} = t + L_A \times v_0^{-1}$$

where t_{arr} *is the arrival time for the incoming vehicles at the variable speed sign to arrive at the stop line*

Step 3: Calculate the advisory speed

If the arrival time is prior to the end of green phase (i.e., $t_{arr} < G_{end}$*), then*

Post the speed limit on the variable speed sign

Else,

Calculate the advisory speed by using Control Action 1

6.2.4 Supplemental Module for Intersections with Actuated Traffic Signal Control

Signal Phase and Timing (SPaT) information, (e.g., remaining phase duration), are crucial for predicting the traffic evolution. While most existing studies on GLOSA (Green Light Optimize Speed Advisory) are based on pre-timed signal operations, there are numerous actuated signals implemented in real-world practices (Alsabaan et al., 2013, De Nunzio et al., 2013, Erdmann, 2013, and Seredynski et al., 2013). Without accurate SPaT information, some studies conclude that GLOSA may be less effective under the actuated signal control (by using the average phase durations as system inputs) (Xiang et al., 2015). The ability to predict the gap-out time prior to the actual change represents a major advantage since it would allow the advisory speed to be displayed prior to the phase change. The logic of the proposed gap-out prediction algorithm based on the traffic data gathered from the sensor is presented below:

Signal Module: Estimating the green termination time for the actuated signal control intersection

Step 1: Detect vehicles in the detection zone

a. *Obtain the locations (* $X_{i,T}$ *) and speeds (* $V_{i,T}$ *) for all vehicles (i) at current time step T*
b. *For each vehicle i, determine if an update is required by checking if its current location and speed deviates from the prediction using the following equation*

$$\left|\hat{X}_{i,T} - X_{i,T}\right| > \varepsilon_x \quad or \quad \left|\hat{V}_{i,T} - V_{i,T}\right| > \varepsilon_v \qquad 6\text{-}(12)$$

If vehicles i deviates from the prediction or is a new vehicle in the detection zone, then

Add vehicle i to the update list (I)

Step 2: Calculate vehicle trajectories

a. *Calculate the average acceleration rate (A_i) for vehicle $i \in I$ by*

$$A_i = \frac{1}{n \times \Delta t}\left(V_{i,t} - V_{i,t-n}\right) \qquad 6\text{-}(13)$$

where n is a given parameter and Δt is the duration of detection time interval

b. *Calculate the preliminary trajectory ($x_{i,\hat{t}}$) for vehicle i by*

$$x_{i,t} = X_{i,T} + V_{i,T} \times (t-T) \times \Delta t + \frac{1}{2} A_i \times \left[(t-T) \times \Delta t\right]^2 \quad \forall t > T \qquad 6\text{-}(14)$$

Step 3: Identifying potential blockage

a. *For each vehicle i in the detection zone, check if its preliminary trajectory ($x_{i,\hat{t}}$) cross that of any leading vehicles j ($\forall j < i$)*

b. *If the trajectory of vehicle i does not cross any leading vehicles, set the predicted trajectory by $\hat{X}_{i,t} = x_{i,t} \quad \forall t > T$.*

c. *If the trajectory of vehicle i cross that of leading vehicle j at the location and time (X^*_{i,t^*})*

i. *If a leading vehicle (i') also exist nearby at the same time, i.e., $\left|\hat{X}_{i',t*} - X^*_{i,t*}\right| < \varepsilon_b$, then*

Set the predicted trajectory by

$$\hat{X}_{i,t} = \begin{cases} \hat{X}_{i',t} + \delta, & for\ t > t^* \\ x_{i,t}, & for\ t \le t^* \end{cases} \quad 6\text{-}(15)$$

where δ *is a safe following distance*

ii. *If no other leading vehicles exist nearby, set the predicted trajectory by*

$$\hat{X}_{i,t} = x_{i,t} \quad \forall t > T . \quad 6\text{-}(16)$$

Step 4: Determine the Estimated Actuation Time

Calculate the estimated actuation time (ET_i *) for each vehicle i by* $ET_i = \arg\min_t \left(\left| D - \hat{X}_{i,t} \right| \right)$

where D is the location of the signal actuation sensor

Step 5: Determine the gap-out time

Given the 95th *percentile arrival speed* $\bar{V}$ *, the detection range L, and the time of last actuation (* $ET_{MAX} = \max\left(ET_i\right)$ *).*

If the 95% of the arriving vehicles cannot reach the actuation sensor before the given unit extension (γ *), i.e.,* $T + \left(\frac{L-d}{\bar{V}} \right) > ET_{MAX} + \gamma$ *, then set the gap-out time* $G_p = ET_{MAX} + \gamma$ *.*

Step 6: Determine green termination time

Determine the green termination time (G_{end} *) by comparing the gap-out time with the maximum and minimum green, i.e.,* $G_{end} = \min\left\{ \max\left\{ G_p, G_{MIN} \right\}, G_{MAX} \right\}$ *.*

6.3 Pre-Deployment Assessment

The pre-deployment evaluation aims to assess the effectiveness of System-II and to detect potential deployment issues. The entire pre-deployment evaluation includes the following two stages:

1. Develop a traffic simulator to replicate the field surveyed traffic characteristics, intersection geometries, and system functions (in Chapter 4).

2. Conduct numerical experiments to evaluate the performance of the developed system under different scenarios.

6.3.1 Simulation Platform Settings and Scenarios

As described in Chapter 4, the traffic simulator replicates the function of key components in the system (see Figure 6-4). The evaluation with extensive simulation experiments have been set up to address the systems' effectiveness on the following issues:

Improve safety and efficiency, including (same as Chapter 5):

a. Protecting red-light-running vehicles by using the All-Red Extension method, and

b. Minimizing the number of false alarms and maximizing the detection rate.

Enhance the intersection safety, including:

a. Mitigating the potential for rear-end crashes (i.e., reduce the number of hard-braking vehicles),

b. Decreasing the number of vehicles trapped in the dilemma zone, and

c. Reducing the number of red light running vehicles.

Improve the intersection mobility, including:

a. Reducing the number of stops,

b. Minimizing stop delays, and

c. Lowering fuel consumption.

Three scenarios are generated to evaluate system performance. The first scenario serves as the base line for a comparison, whereas the second scenario consists of only a reactive protection function (i.e., all-red extension function.) Scenario 3 replicates the system with both all-red extensions and advisory speed functions; three different driver compliance rates, 100%, 50%, and 25%, have been evaluated to address the effectiveness of System-II. More specifically, these test scenarios are summarized below:

- Base Scenario: Without any proactive/reactive protection system;
- Scenario 1: With only reactive protection function (i.e., all-red extension function); and
- Scenario 2: The full system with both proactive/reactive safety and mobility functions.

- Scenario 2-1: Set driver compliance rate to 100%
- Scenario 2-2: Set driver compliance rate to 50%
- Scenario 2-3: Set driver compliance rate to 25%

6.3.2 Result Analysis

As protecting vehicles from crashes is the top priority of the integrated DZPS, this study has tuned the all-red extension module to offer a 100% detection rate, which is expected to result in a relative high false-alarm rate (14% and 16% in the pre-timed and actuated signal control, respectively.) Table 6-1 and 6-2 (the base scenario) shows that the average number of hard-braking vehicles per cycle is 0.66; whereas the advisory speed sign reduces such rate from 0.66 to 0.15 (0.75 to 0.18 for actuated signal control) when driver compliance rate is 100%. One may also note that, the system even with low driver compliance rates is still effective in reducing potential rear-ended crashes. As for the number of vehicles trapped within the dilemma zone, the result shows a reduction of nearly 33-40% (i.e., from 892 to 540 for the pre-time signal control and 792 to 525 for actuated signal control).

Table 6-1 The System Performance for Different Test Scenarios with Pre-timed Signal Control.

<table>
<tr><td colspan="2" rowspan="2">Scenarios
MOEs</td><td rowspan="2">Base Case</td><td rowspan="2">All-Red Extension Only</td><td colspan="3">All-Red Extension and Advisory Speed4</td></tr>
<tr><td>100% compliance</td><td>50% compliance</td><td>25% compliance</td></tr>
<tr><td rowspan="4">Safety MOEs</td><td>Average number of hard-braking vehicles per cycle 1</td><td>0.66</td><td>0.66</td><td>0.15</td><td>0.24</td><td>0.29</td></tr>
<tr><td>Total number of vehicles in dilemma zone</td><td>892</td><td>862</td><td>540</td><td>702</td><td>790</td></tr>
<tr><td>The average number of red-light running vehicles per cycle (RLR / cycle) 2</td><td>0.11</td><td>0.11</td><td>0.06</td><td>0.08</td><td>0.09</td></tr>
<tr><td>Detection rate for red-light running vehicles</td><td>-</td><td>100%</td><td>100%</td><td>100%</td><td>100%</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td rowspan="4">Mobility MOEs</td><td>Average number of stops per cycle</td><td>6.4</td><td>6.5</td><td>4.2</td><td>4.5</td><td>4.6</td></tr>
<tr><td>Average stopped delay for all vehicles per cycle (second)</td><td>45.7</td><td>48.6</td><td>38.0</td><td>40.5</td><td>42.1</td></tr>
<tr><td>Average fuel consumption per cycle (Gallon)</td><td>0.239</td><td>0.226</td><td>0.132</td><td>0.158</td><td>0.167</td></tr>
<tr><td>False alarm rate for the all-red extension3</td><td>-</td><td>14%</td><td>5%</td><td>10%</td><td>12%</td></tr>
<tr><td colspan="7">1 Total number of hard-breaking vehicles divided by the total number of cycles (Deceleration rate > 10ft/s2)

2 Total number of red-light running vehicles divided by the total number of cycles

3 Total number of false all-red extension divided by the total number of cycles

4 Advisory Speed: limited to the range of 30 ~ 50 mph with an increment of 5 mph</td></tr>
</table>

Table 6-2 The System Performance for Different Test Scenarios with Actuated Signal Control.

MOEs \ Scenarios		Base Case	All-Red Extension Only	All-Red Extension and Advisory Speed4		
				100% compliance	50% compliance	25% compliance
Safety MOEs	Average number of hard-braking vehicles per cycle 1	0.76	0.77	0.18	0.21	0.26
	Total number of vehicles in dilemma zone	792	770	525	596	622
	The average number of red-light running vehicles per cycle (RLR / cycle) 2	0.094	0.097	0.064	0.081	0.087
	Detection rate for red-light running vehicles	-	100%	100%	100%	100%
Mobility MOEs	Average number of stops per cycle	6.4	6	4.5	5.1	6.89
	Average stopped delay for all vehicles per cycle (second)	76	77	54	59	63
	Average fuel consumption per cycle (Gallon)	0.24	0.22	0.14	0.15	0.17
	False alarm rate for the all-red extension3	-	16%	4%	7%	7%

1 Total number of hard-breaking vehicles divided by the total number of cycles

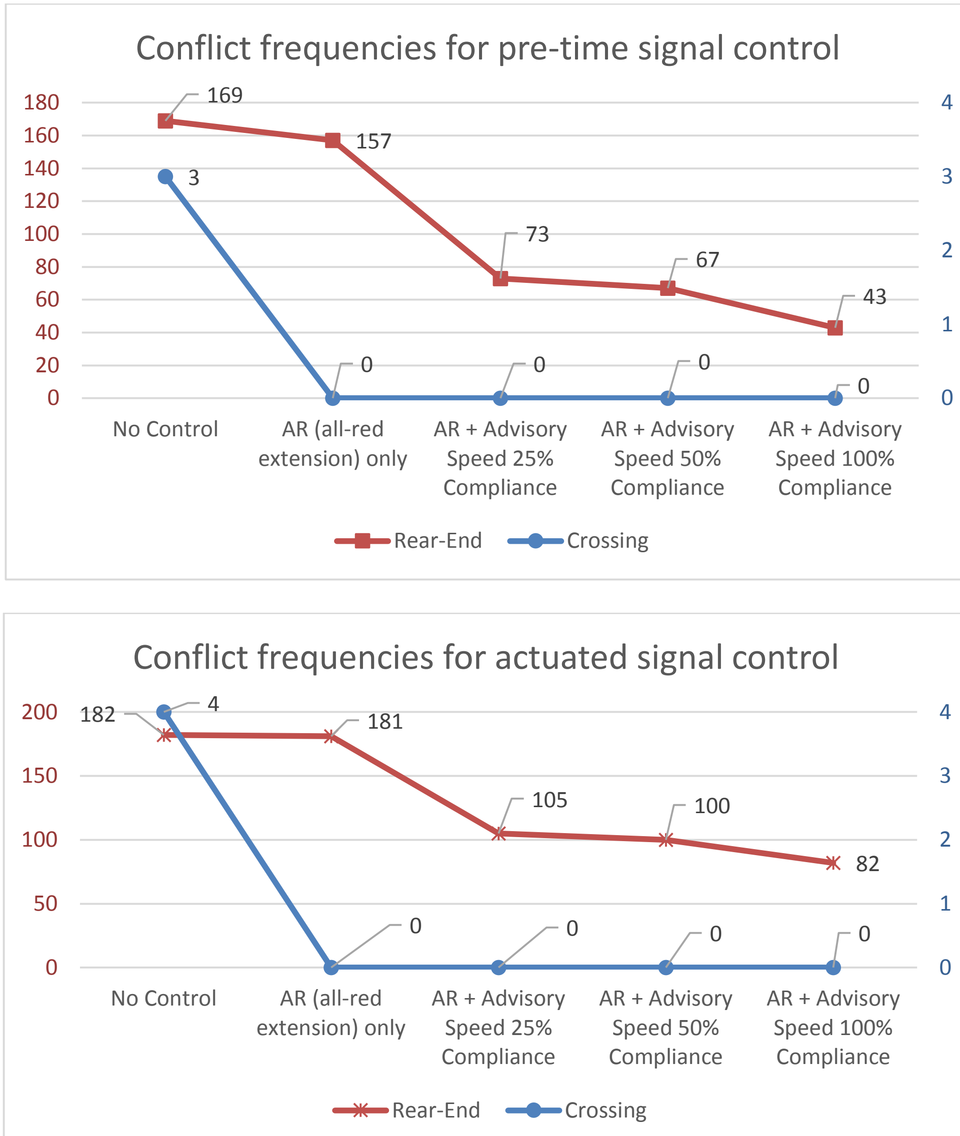
2 Total number of red-light running vehicles divided by the total number of cycles

3 Total number of false all-red extension divided by the total number of cycles

4 Advisory Speed: limited to the range of 30 ~ 50 mph with an increment of 5 mph

System-II is also effective on improving traffic mobility. As shown in Table 6-1 and 6-2, the average number of stopped vehicles per cycle reduces from 6.4 to 4.2 (6.4 to 4.5 for actuated signal control), whereas the average stop delay per cycle reduces from 45.7 to 38 (76 to 54 for actuated signal control) seconds. With the improved mobility, the fuel consumption shows a significant improvement from 0.239 to 0.132 (0.24 to 0.14 for actuated signal control) gallons per cycle. One may also notice that the false alarm rate with the advisory speed can be reduced from

14% to 5% (16% to 4% for actuated signal control), which improves traffic mobility by reducing unnecessary all-red extension calls.



(a) (b)

Figure 6-7 Conflict frequencies during 40 hours of VISSIM simulation with (a) pre-time signal control, and (b) actuated signal control

In addition to analyzing the simulation output with VISSIM, Surrogate Safety Assessment Model (SSAM) has been conducted for further conflict analysis (Gettman et al., 2008). SSAM utilizes the trajectory file created from VISSIM to evaluate intersection safety (i.e., rear-end, crossing, and lane-changing conflicts) with MOEs such as time-to-collision (TTC), post-encroachment (PET), deceleration rate (DR), maximum speed (MaxS), and speed differential (DeltaS).

Figure 6-7 compares rear-end and crossing (side-angle) conflict frequencies, resulting from 40 hours of simulation results with the aforementioned scenarios. As shown in Figure 6-7, crossing conflicts have been reduced to zero under those scenarios with a dilemma zone protection function (under both pre-time and actuated signal control); which is consistent with results shown in Table 6-1 and 6-2. One may also note that rear-end conflicts have also been significantly reduced in the presence of advisory speeds.

Intersections Plagued with Short Sight Distances

Intersections plagued with short sight distances are particularly hazardous and likely to result in either rear-end crashes or red-light-running vehicles. To evaluate the effectiveness of the developed system under insufficient sight distance, three test scenarios have been generated with the pre-timed signal control, which are:

- Scenario 1: Sufficient sight distance (i.e., a sight distance of 1000 feet);
- Scenario 2: A sight distance of 100 feet shorter than the recommended value; and
- Scenario 3: A sight distance of 250 feet shorter than the recommended value.

Table 6-3 Safety Improvement under Insufficient Sight Distance Conditions.

Scenarios	Total number of hard-braking vehicles			Total number of red light running vehicles		
	No protection	The proposed system	Reduction	No protection	The proposed system	Reduction
Scenario 1	760	116	644 (84.7%)	154	102	52 (33.8%)
Scenario 2	1030	234	796 (77.3%)	171	108	63 (36.8%)
Scenario 3	1643	296	1347 (82.0%)	176	116	60 (34.1%)
* Note that the values are calculated under 100% driver compliance rate.						

Table 6-3 compares the total number of hard-braking vehicles to the total number of red-light-running vehicles under different sight-distance scenarios from 40 hours of simulations. One may note from Table 6-3 that the total number of hard-braking vehicles under insufficient sight distance increases significantly compared to that of sufficient sight distance. Notably, the number of red-light-running vehicles also increases under insufficient sight distances. System-II prepares the incoming vehicles to stop and join the queue safely by providing advisory speeds that reduce the number of hard-braking vehicles significantly. One may also note from Table 6-3 that the system is also effective in reducing the number of red-light running vehicles.

Based on the results of extensive simulation evaluation, one can conclude that enhanced DZPS has the potential to effectively perform the following functions:

- Its all-red extension module can effectively provide protections to those vehicles running on the red phase. With the all-red extension function, the intelligent intersection can prevent side-angle crashes by holding side street traffic.

- Its advisory speed sign, activated before the onset of the yellow phase, can effectively reduce the number of vehicles trapped in the dilemma zone and mitigate rear-ended crashes.
- Intersection mobility, e.g., the number of stops, stop delays, and fuel consumptions, can be improved with smoother traffic propagation guided by the advisory speed sign under either pre-timed or actuated signal controls.
- The advisory speed, accounting for the intersection queue evolution, can effectively reduce the potential for rear-end crashes for intersections plagued with an insufficient sight distance.

6.4 Conclusion

This chapter presented an innovative intelligent intersection control system to improve both safety and mobility for high-speed intersections. System-II which can exercise either proactive or reactive actions to prevent accidents, and also advise drivers in real time to facilitate their progression during the green phase or minimize delay at the intersection. The system is to extend the functions of control devices designed for the DZPS to speed harmonization of vehicles approaching the intersection during the green phase. The share utilization of deployed hardware devices and control components allows responsible agencies to best use available resources for improving safety and operational efficiency.

From the extensive simulation experiments with a well-calibrated simulator, the developed system has demonstrated its effectiveness in offering 100% detection rates to red-light-running vehicles and in effectively reducing potential rear-ended crashes. The results also show improved traffic mobility with fewer stops, reduced stop delays, and less fuel consumption as the result of smooth traffic flows guided with dynamic advisory speed signs.

After complete analysis of System-II, further study on this subject will focus on the following issues: (1) including a more robust traffic evolution module to accommodate different types of traffic sensors, and (2) the information provided by the presence of connected vehicles may also enrich inputs of traffic data and improve the system's effectiveness. In addition, a fail-safe mechanism to prevent posting an inadequate advisory speed shall also be explored before field deployment.

Chapter 7. Field Evaluation after System Deployment

7.1 Introduction

This chapter presents the field evaluation results with respect to the short-term effectiveness of the DZPS after deployment. This is due to the low frequency of crashes and their stochastic nature. Hence, a reliable evaluation of the DZPS's long-term impact on traffic safety can be conducted only after having several years of field data.

The main analysis results presented in this chapter are the impact assessment of the deployed DZPS on driving behaviors, including drivers' decisions during the yellow phase, deceleration rates, and distributions of speeds and dilemma zones. Additionally, the detection effectiveness of the DZPS in preventing side-crashes due to red-light-running vehicles has also been evaluated with field data.

The evaluation processes include the following tasks:

- Identify the impacts of the wide-range traffic monitoring sensors on each approaching driver's speed (roadside unit): The installed roadside sensors which are visible to drivers, may have impacts on the distribution of drivers' speeds, deceleration rates, and decisions during the yellow phase.

- Compute the dilemma zone distributions before and after system deployment.

- Observe drivers' decisions during the yellow phase before and after system deployment, and their likelihood of running over the intersection during the red light.

- Conduct performance evaluation with respect to protecting side-street drivers against red-light-running vehicles from the main street.

7.2 Location Overview of the Deployed DZPS

The intersection of US 40 and MD 910C located in Washington County, Maryland has been deployed with the proposed DZPS system, and selected for field data analysis. It is a T-intersection, consisting of two lanes on US 40 eastbound and westbound with a speed limit of 55 mph. The side street also has two lanes, one for left turns and the other for right turns only. Figure 7-1 shows the areal map of the intersection and locations of the deployed roadside sensors. The intersection suffered 15 accidents from 2011 to 2013. Seven of those 15 accidents were side-angle crashes, resulting in a total of three injuries. Each of the side-angle crashes was related to eastbound traffic only since there is no westbound side street. Based on the field data collected prior to DZPS design, the distribution of dilemma zones was calculated and shown in Figure 7-2. The upper limit of the dilemma zone is 960 feet from the stop line for vehicles approaching the intersection at 75 mph. Two wide-range sensors from the DZPS were deployed to cover the entire spatial distribution of the dilemma zones. Another sensor on WB is used for the actuated control to extend or terminate the green interval.

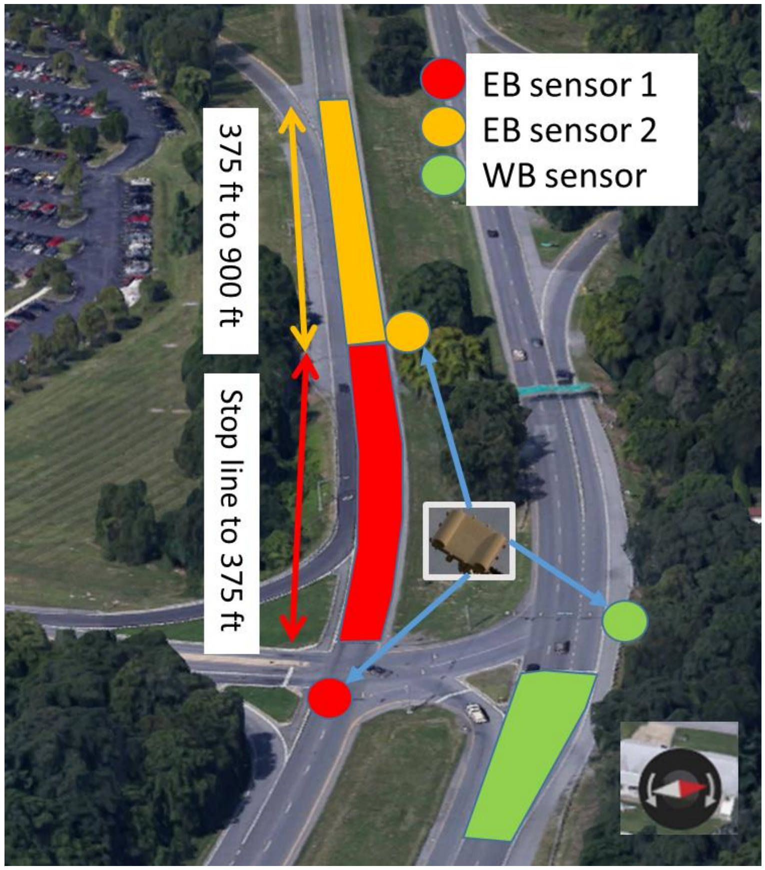


Figure 7-1 Design of the DZPS at US 40 and MD 910C in Washington County, Maryland

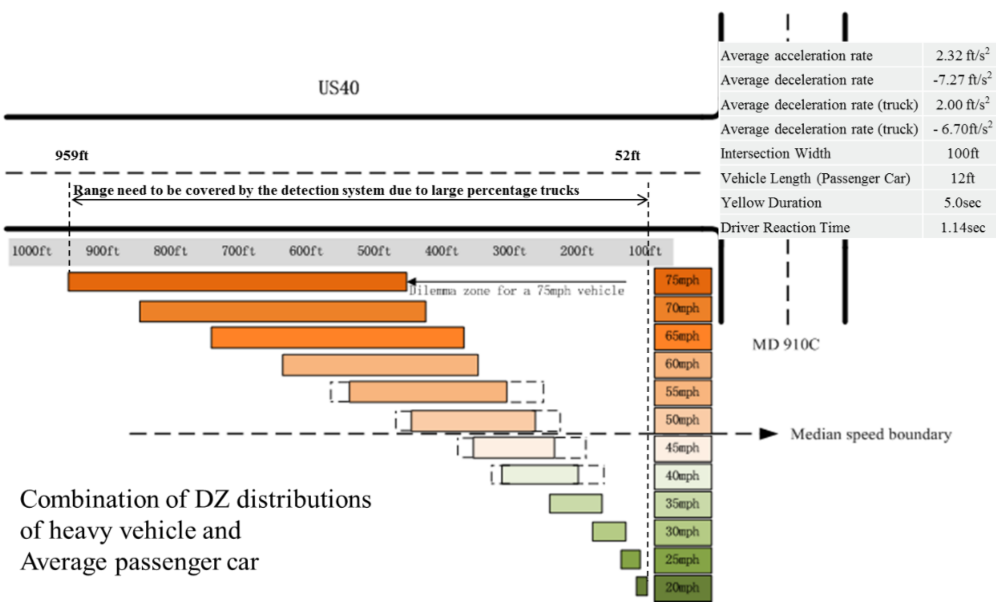


Figure 7-2 Distribution of the dilemma zones before the system deployment

7.3 Evaluation Procedures and Results

The field evaluation process was conducted with the following steps: field data collection, analysis of impacts on traffic flow speeds, computing the acceleration/deceleration, the resulting spatial distribution of the dilemma zones, assessing the effectiveness of detecting red-light running vehicles and executing all-red extensions.

Step1: Data collection procedures

The "Before" data were collected on October 7th and 8th, 2014, with five camcorders at 200, 300, 500, 700, and 900 feet from the stop line to measure the speed of the approaching vehicles, and one camcorder was used to record the signal timings. After implementation of the DZPS, the same level of effort has been devoted to the data collection for impact comparison.

"After" traffic data were collected from both the sensors and field camcorders. Figure 7-3 shows screen data captured from the recorded information, featuring signal timing and the stop line to determine whether a vehicle may violate the signal or not. The signal timing data was retrieved with a customized program. Figure 7-4 shows one vehicle's trajectory data detected by the deployed sensors. Note that text colors represent the signal status such as a yellow color for the yellow phase, and a red color for the red phase.

In one example, there was a vehicle traveling at 49 mph at 455 feet from the stop line at the onset of the yellow phase (Figure 7-4). The approaching vehicle speed, shown in the figure, was reduced to 46 mph at 115 feet from the intersection at the onset of the red phase, but it kept the same speed to go through the intersection during the all-red phase. This vehicle actually entered the intersection 1.7 seconds after the start of the all-red phase. (Figure 7-3).

Figure 7-3 screen capture on a red light running vehicle from the camcorder

Date	Time	Veh ID	Speed	Location	Signal	Date	Time	Veh ID	Speed	Location	Signal
10/14/2016	57:55.9	28168	49	510	Green	10/14/2016	57:59.7	28168	48	245	Yellow
10/14/2016	57:56.1	28168	49	500	Green	10/14/2016	57:59.8	28168	48	235	Yellow
10/14/2016	57:56.3	28168	49	490	Green	10/14/2016	58:00.0	28168	48	225	Yellow
10/14/2016	57:56.4	28168	49	480	Green	10/14/2016	58:00.1	28168	48	220	Yellow
10/14/2016	57:56.5	28168	49	465	Green	10/14/2016	58:00.3	28168	48	205	Yellow
10/14/2016	57:56.7	28168	49	455	Yellow	10/14/2016	58:00.5	28168	47	195	Yellow
10/14/2016	57:56.9	28168	49	445	Yellow	10/14/2016	58:00.6	28168	47	185	Yellow
10/14/2016	57:57.0	28168	49	430	Yellow	10/14/2016	58:00.7	28168	47	175	Yellow
10/14/2016	57:57.2	28168	49	420	Yellow	10/14/2016	58:00.9	28168	47	160	Yellow
10/14/2016	57:57.3	28168	50	410	Yellow	10/14/2016	58:01.1	28168	47	150	Yellow
10/14/2016	57:57.5	28168	50	395	Yellow	10/14/2016	58:01.2	28168	46	140	Yellow
10/14/2016	57:57.6	28168	50	385	Yellow	10/14/2016	58:01.4	28168	46	135	Yellow
10/14/2016	57:57.8	28168	50	375	Yellow	10/14/2016	58:01.5	28168	46	120	Yellow
10/14/2016	57:57.9	28168	50	360	Yellow	10/14/2016	58:01.7	28168	46	115	Red
10/14/2016	57:58.1	28168	50	350	Yellow	10/14/2016	58:01.8	28168	46	105	Red
10/14/2016	57:58.3	28168	49	345	Yellow	10/14/2016	58:02.0	28168	46	90	Red
10/14/2016	57:58.4	28168	48	335	Yellow	10/14/2016	58:02.2	28168	45	80	Red
10/14/2016	57:58.6	28168	48	325	Yellow	10/14/2016	58:02.3	28168	45	70	Red
10/14/2016	57:58.7	28168	48	315	Yellow	10/14/2016	58:02.5	28168	45	65	Red
10/14/2016	57:58.9	28168	48	305	Yellow	10/14/2016	58:02.6	28168	45	55	Red
10/14/2016	57:59.1	28168	48	290	Yellow	10/14/2016	58:02.8	28168	45	40	Red
10/14/2016	57:59.2	28168	48	280	Yellow	10/14/2016	58:02.9	28168	45	30	Red
10/14/2016	57:59.3	28168	48	270	Yellow	10/14/2016	58:03.1	28168	45	20	Red
10/14/2016	57:59.5	28168	48	260	Yellow	10/14/2016	58:03.3	28168	45	10	Red

Figure 7-4 Sample data of a vehicle's trajectory from the wide-range monitoring sensors

The collected data, before-and-after the deployment of DZPS, were used for investigating its impacts on the following critical aspects:

- Speeds of approaching vehicles by locations, and their distribution;
- Deceleration rates of vehicles when approaching the intersection;
- Distributions of the dilemma zones and their impact on safety; and
- Decisions of drivers during the yellow phase.

Further analyses were also conducted to study the change in total dilemma zone length, and to develop a safety evaluation function for such a design. Lastly, field observations of red-light runners were also conducted to make sure that the system can provide all-red extensions to protect side-street vehicles from crashing with those aggressive drivers.

Step2: Impacts on the traffic flow speed

After the data have been collected for before-and-after comparison, the first step for the impact assessment is to compare any change on speeds. The videos for analyzing the speed data before the deployment were compared with the speed data retrieved from wide-range sensors at different locations (200 feet, 500 feet, and 900 feet)

Figure 7-5 and Table 7-1 show the spatial distribution of the speeds computed from the field data. As shown on their patterns, the maximum speed detected at different locations does not seem to be impacted by the deployed system. However, the average traffic speeds after the deployment were detected to decrease significantly, compared to the same data observed before the deployment (for example, from 49.7 mph to 44.6 mph at 900 feet from the stop line, from 46.4 mph to 45.3 mph at 500 feet, and from 40 mph to 34.9 mph at 200 feet). Hence, one can conclude that the deployment of DZPS sensors has some impacts on most drivers. Most drivers they tend to reduce their speeds --except those who are considered aggressive drivers -- when approaching the intersection.

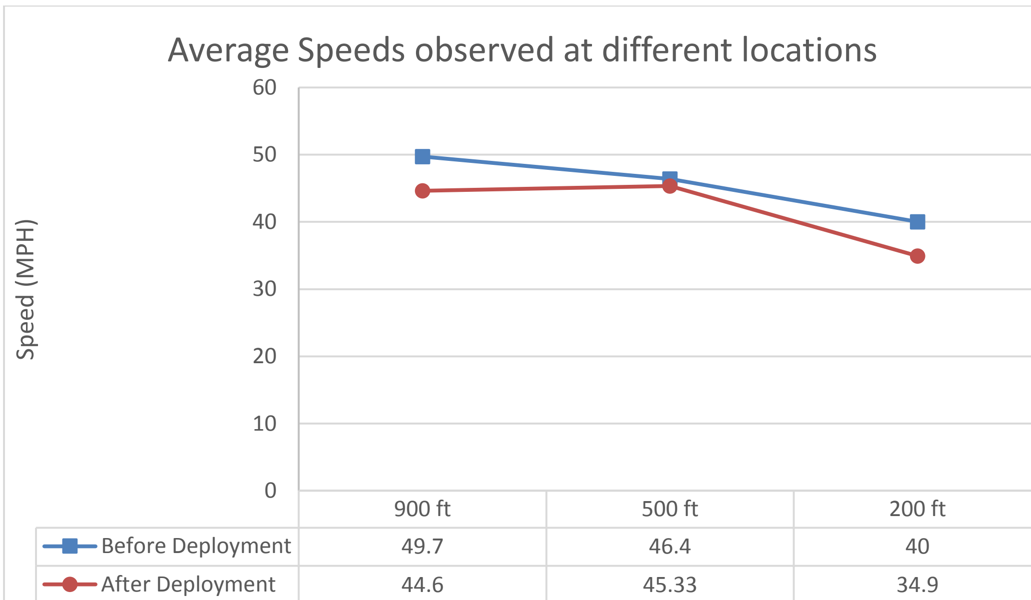
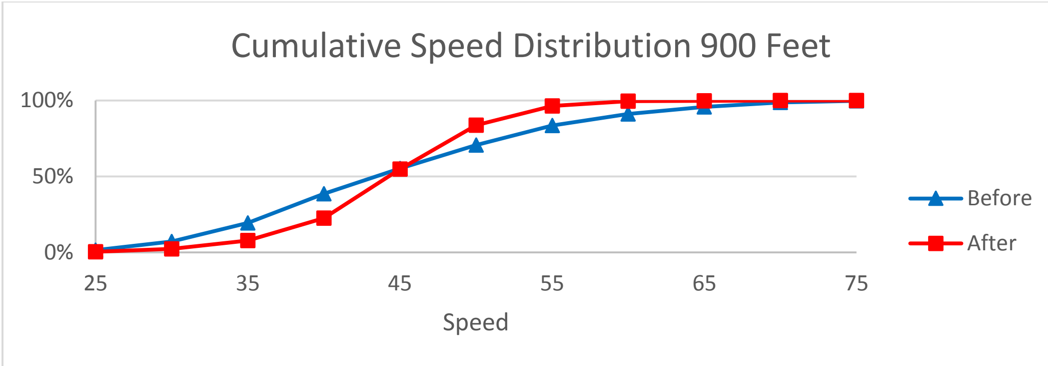


Figure 7-5 Comparison of the spatial distribution of speeds before-and-after the DZPS deployment

Table 7-1 Distribution of the speeds before-and-after the DZPS deployment

Location	900 feet		500 feet		200 feet	
Data Collection Period	Before	After	Before	After	Before	After
Average speed (mph)	49.7	44.6	46.4	45.33	40	34.9
Standard Deviation	10.6	6.24	6.7	6.95	9.07	10.48
Minimum speed (mph)	18.9	23	10.9	12	4.58	4
Maximum speed (mph)	72.1	70	69.4	67	61.2	60
Sample Size	1233	2943	1371	3000	1343	3000

Figure 7-6 shows the cumulative distribution of the speeds before and after system deployment at different locations, and Table 7-2 summarizes the percentage of vehicles within each speed bin. Note that the speed limit at the location for DZPS deployment is 55 mph. After system deployment, field traffic flow data show that the percentage of high-speed vehicles in the traffic flows has been reduced. As shown in Table 7-2, the percentage of high-speed vehicles has been reduced from 29% to 16%, a 13% reduction. The deployment of roadside sensors indeed has some impact on drivers, as reflected in their reduced intersection approaching speeds. For example, the cumulative distributions of drivers at different speeds at the location of 900 feet and 500 feet clearly show that the deployed system can increase the percentage of drivers who typically approach the intersection around the speed limit. However, for those aggressive drivers at 500 feet (i.e., over 55 mph), the deployed system does not seem to impact their approaching speeds to the intersection, as shows in the cumulative distribution patterns. This actually justifies the need to implement some reactive control strategies such as the all-red extension to prevent those drivers from causing crashes with side-street vehicles.



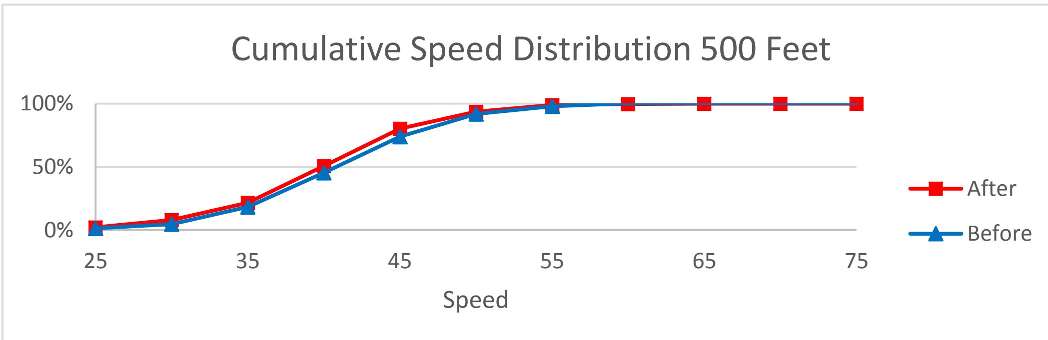


Figure 7-6 Cumulative distribution of the approaching speeds for before and after the DZPS deployment (900ft and 500ft)

Table 7-2 Frequency with different speed bins for approach vehicles before and after deployments (900 feet)

Speed	Before		After	
	Frequency	Percentage	Frequency	Percentage
75+	14	1%	0	0%
70-75	36	3%	3	0%
65-70	58	5%	6	0%
60-65	92	7%	94	3%
55-60*	160	13%	375	13%
50-55	189	15%	850	29%
45-50	206	17%	951	32%
40-45	236	19%	432	15%
35-40	153	12%	166	6%
30-35	68	6%	56	2%
25-30	19	2%	10	0%
Over the Speed Limit (total)	360 (1231)	**29%**	478 (2943)	**16%**
* Speed limit: 55 MPH				

Step3: Impacts on the deceleration rate and the distribution of dilemma zones

Deceleration rates of approaching vehicles after deployment has also been calculated. From the recorded video data, vehicles, stopped during the yellow phase and the all-red phase, have been identified, and their speeds and locations are calculated from both the videos and the sensor log files. It is noticeable that the deceleration rate was changed from -7.28 ${ft}/{s^2}$ to -11.27 ${ft}/{s^2}$ after system deployment. It shows that the same drivers who choose to take the "Stop" decision at the onset of the yellow phase are willing to take a higher braking rate than they were before the deployment to take a "stop" action. Based on the new calculated deceleration rate, one can then compute the distribution of dilemma zones after the system deployment. Figure 7-7 shows the distributions of dilemma zones before and after deployment. Note that the upper limit of the dilemma zone was reduced from 960 feet to 670 feet for vehicles traveling at 75 mph, and 840 feet to 580 feet at 70 mph, and so forth. Clearly, the length of the dilemma zones for each speed bin has been reduced, compared to those exhibited before deployment.

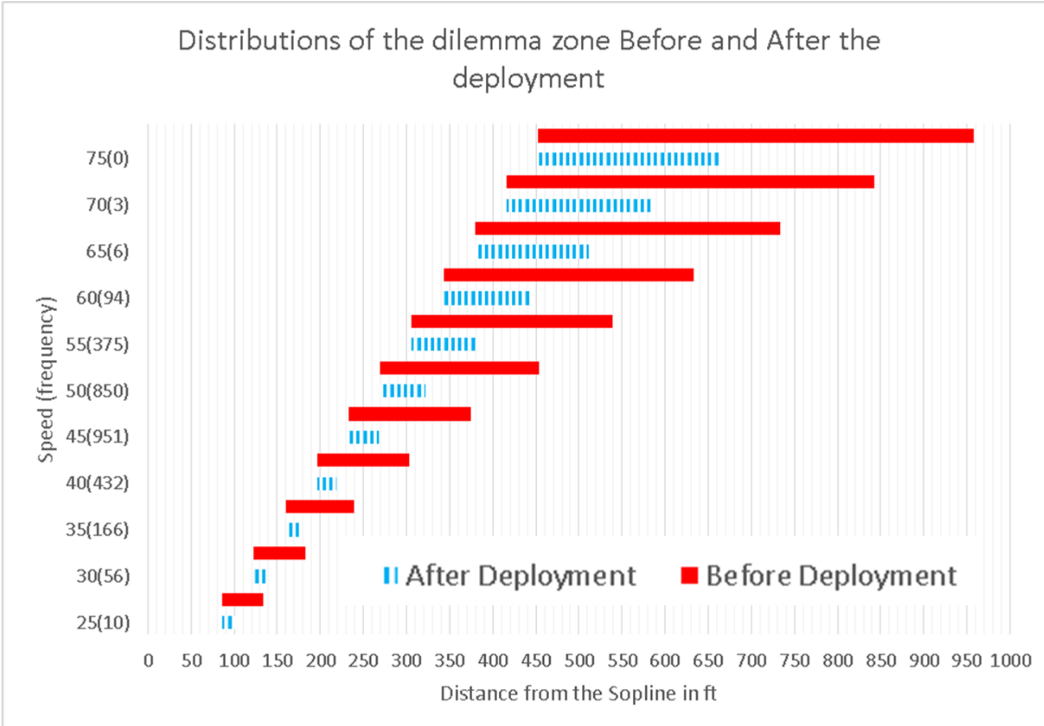


Figure 7-7 Distributions of dilemma zone (frequencies are in the parenthesis)

Step4: Impacts on a driver's reaction to the yellow signal

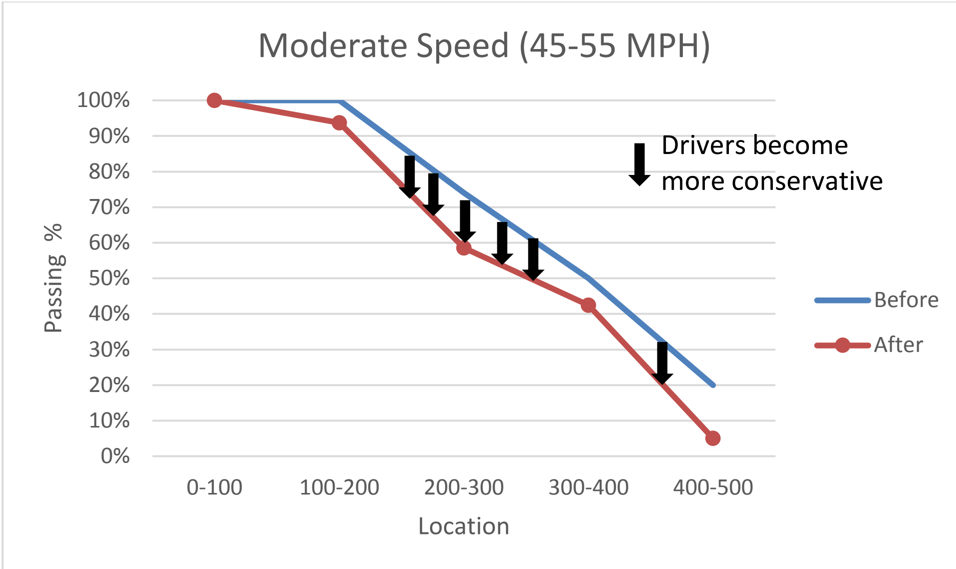
Table 7-3 summarizes the decision of drivers during the yellow phase. As reflected in those statistics, the percentage of drivers choosing the "Pass" decision at the onset of the yellow phase has decreased for those approaching the intersection at a moderate speed (i.e., 45-55 mph with speed limit of 55 mph). For example, when vehicles travel at 45-55 mph and encounter the yellow phase between 300-400 feet from the stop line, about 50% of such drivers choose to pass the intersection before DZPS deployment. However, the percentage for drivers taking such a decision decreased to 43% for those during the "After" period. The reduction in such decision varies between 6% and 15%, depending on the location of the vehicles.

For vehicles traveling at a speed higher than the speed limit, their decisions in response to the yellow phase were less affected by the deployed system. As shown in the Figure 7-8, compared to those at the moderate speed, the differences for high-speed vehicles between the before period and after the deployment are not significant. Hence, one can conclude that the roadside sensors may discourage most non-aggressive drivers, traveling at less than or around the speed limit, to choose the "Pass" decision during a yellow phase. However, overall the total number of vehicles traveling at a high speed (i.e., over 55 mph) has been reduced due to the presence of the roadside sensors.

Table 7-3 Driver choose the "pass" decision during a yellow phase

Speed of vehicles at the onset of a yellow phase (sample size)	**Location of vehicles from the stop line at the onset of a yellow phase**									
	0 - 100 ft		**100 - 200 ft**		**200 - 300 ft**		**300 - 400 ft**		**400+ ft**	
	Before	After	Before	After	Before	After	Before	After	Before	After
45 - 55 mph	100% (78)	100% (24)	100% (100)	94% (32)	74% (73)	59% (41)	50% (24)	43% (40)	20% (5)	5% (59)
55+ mph	100% (9)	100% (7)	100% (20)	100% (9)	88% (47)	91% (22)	50% (16)	54% (13)	10% (20)	9% (44)

*1: Field: percentage of drivers taking the "Pass" decision from the field observations
*2: the number in parenthesis denotes the sample size.



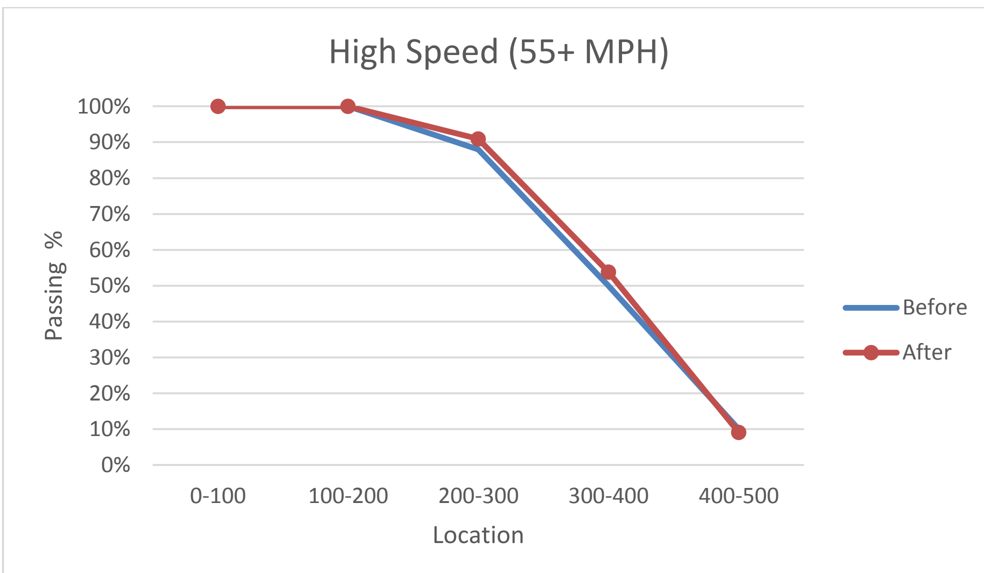


Figure 7-8 comparison of driver decision on the yellow phase with approaching speed

Step 5: Safety evaluation function

Since it needs a long duration for any agency to evaluate the safety improvement from the field data, this step is to compute a surrogate function that allows traffic engineers to perform safety evaluation with short-term field data. Instead of comparing the accident frequencies over time, the dilemma zone distributions before and after the deployment have been used to assess the improvement on safety.

Figure 7-9 shows the dilemma zone length under different speeds from the field data before-and-after the deployment. The equations shown in the Figure 7-9 are a simplified presentation of standard equations for dilemma zone computation, and it has been calibrated with the field data. As shown in the equation 7-(1) the length of the dilemma zone shows a polynomial relation with each vehicle's approaching speed.

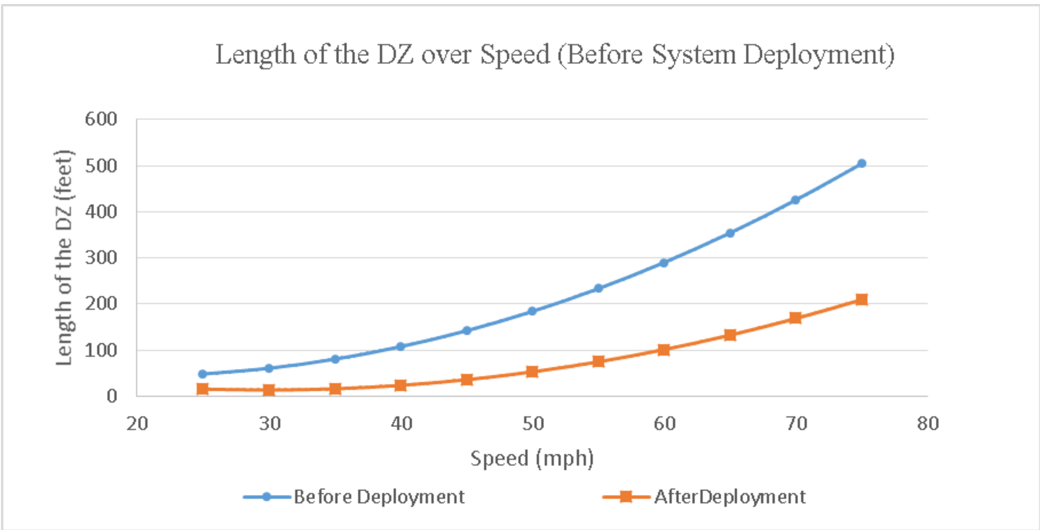


Figure 7-9 Length of the dilemma zone over the speed (before and after the deployment)

$$L_{DZi} = \alpha * {v_i}^2 + b * v_i + \mathrm{c} \qquad \text{7- (1)}$$

Note that the length of each dilemma zone is weighted by the volume ratio associated with each speed bin to reflect the impact of such changes on the speed distributions. The following equation is used to calculate the weighted total length of the dilemma zones.

$$DZ_L = \sum L_i * \frac{Vol_i}{Vol_{Total}} \quad 7\text{- }(2)$$

Where, L_i is the length of the dilemma zone for the i^{th} speed bin;

Vol_i is the number of vehicles in the i^{th} speed bin; and

Vol_{Total} is the total number of vehicles.

The total weighted dilemma zone length for the periods before and after the deployment is 73 feet and 44 feet, respectively. The ratio between these two dilemma zone lengths is 0.374, implying that the total dilemma zone length can be shortened by 37% after deploying the DZPS.

Step 6: System performance evaluation

The performance evaluation with respect to the detection rate for the all-red extension includes the following steps:

Step1: Sync the times between the video and log data from the sensors.

Step2: Identify any red light running vehicles from the videos.

Step3: Identify each all-red interval from the videos.

Step4: Determine whether or not the all-red interval was extended for each identified red light running vehicles.

Step5: Calculate the detection rate, extension rate, and false alarm rate.

Table 7-4 shows the performance evaluation results. The selected MOEs for the evaluation are:

- Extension-call rate: the number of all-red extensions over the total number of cycles;
- Detection rate: the number of detected red light running vehicles over the total number of red light running vehicles; and
- False alarm rate: the number of all-red extensions without red-light-running vehicles over the total number of cycles.

During the data collection period, there were 312 cycles, 5 red light running vehicles, and 99 all-red extensions. The system has detected all red-light running vehicles, and executed all-red extensions. However, there were 30 percentages of false alarms. Note that, the main objective of the system is to provide the highest protection for side-street vehicles when detecting the red light running vehicles so as to minimize the likelihood of having accidents. From the perspective of ensuring the safety, the system is designed to maximize the detection rate and at the cost of some false alarms. During the period of field observations, the system has been observed to execute the intended all-red extension in time to provide additional clearance time to prevent the potential side-angle crashes.

Table 7-4 Evaluation of the system performance

MOE	Simulation	Field Operation*
Red-light-running rate (RLR) (RLR / cycle)	9.50%	1.60%**
Extension call rate (extension call / cycle)	30%	31.7%
Detection rate (protected RLR)	100%	100%
False alarm rate (false alarm / cycle)	21%	30.1%
* Based on the 6 hours field observations, total of 312 Cycles. ** Five red light running vehicles during the data collection.		

7.4 Conclusions

This chapter has presented the field evaluation results using data from a DZPS deployed at the intersection of Western Maryland Parkway and US 40. Since it requires a longer period to compare its impacts on reducing accident frequency, this study has focused on its short-term impacts on driving behaviors, including approaching speeds, deceleration/acceleration rates, and decisions during a yellow phase. The results of extensive field observations show that the deployed DZPS can indeed reduce the average approaching speed, the percentage of high-speed-vehicles, and the probability of passing the intersection during the yellow phase, particularly for those traveling at or near the speed limit.

The impacts on driving behaviors are reflected in reducing the spatial distribution of the dilemma zones. The upper limit of the re-calculated dilemma zone distribution is 670 feet from the stop line after the deployment, compared to 960 feet during the before deployment period. Safety improvement has also been presented as a function of the total dilemma zone length weighted by the volume ratio. The deployed system has reduced the total length of dilemma zones by 37%. The deployed system also has also demonstrated its effectiveness on yielding a 100 % detection rate on detecting red-light-running vehicles, and activating the all-red extension in time to prevent any potential side-angle crash.

Grounded on short-term evaluation results, further research along the same line should focus on the long-term impacts of the DZPS on the driving behaviors and on the reduction of the accident frequency. Additional field data from different deployment locations shall also be collected to further confirm the effectiveness of such a DZPS design.

Chapter 8. Research Summary and Future Tasks

8.1 Research Findings and Conclusions

This research features the design, deployment, and field testing of a dilemma zone protection system (DZPS) for improving intersection traffic safety. The developed system comprises wide-range traffic monitoring sensors, a driver behavior module, variable message sign (or roadside sensors), and an all-red extension controller to proactively slow the speed of approaching vehicles and reactively extend the all-red phase to prevent potential side-angle crashes. Field observations at a high-speed suburban intersection, based on experimental findings from the pre-calibrated traffic simulator, have concluded that the developed DZPS can indeed accomplish the following development objectives:

- Reducing the speed of approaching traffic flows to a signalized intersection;
- Eliminating or narrowing the range of dilemma zones for vehicles approaching the intersection at different speeds;
- Pressuring moderate drivers to take conservative actions during a yellow phase; and
- Activating the all-red extension phase in time to hold vehicles from the side street.

The results from extensive field observation also reveal that it is essential to deploy such a system at intersections plagued by aggressive drivers, who often ignore warning messages and are likely to run over the all-red phase, potentially causing side-angle crashes.

Additional findings from the design and development of the DZPS are summarized below:

- Design of any system to cope with safety issues at any intersection should be based on behaviors of driving populations because high-speed approaching vehicles are most likely to become trapped in their respective dilemma zones at the onset of the yellow phase;
- Extensive field observations are essential for understanding key factors contributing to accidents as well as for designing essential functions to improve intersection traffic safety. Additionally, the effectiveness of any system to improve intersection safety often varies with driving populations;
- A set of robust behavior models will be needed for estimating and predicting driver response to any available message or to an encountered yellow phase;
- The behavior of aggressive drivers is unlikely to change significantly with advanced warning signs or any roadside messages so that some reactive design, such as the developed DZPS, will be needed to protect other drivers;
- To ensure the success of a developed system and to identify any potential issues prior to system deployment, it is beneficial to have a well-calibrated traffic simulator that includes all key system functions,

traffic patterns, and their interactions in real-world conditions for analysis and enhancement;

- A well-designed all-red extension algorithm can effectively predict potential red-light-running vehicles to prevent potential side-angle crashes by holding the side street traffic;
- Enhancement of an all-red extension function from the DZPS with speed harmonization can be implemented with minimal additional hardware;
- A properly designed module for speed harmonization can be beneficial for improving both intersection safety and mobility;
- The function to track each individual vehicle's speed and location over a wide-range detection zone is the essential input for the proposed system's computational module;
- Effective monitoring of the evolution of intersection traffic queues is critical in order for the proposed DZPS to compute advisory speeds for approaching vehicles to exercise smooth stops and to join the end of the queue, and/or to progress over the intersection;
- It is critical to predict gap-out timing under the actuated signal control because providing information prior to the signal change is one of the main required functions for executing speed harmonization;
- The effects of intersection mobility, such as number of stops, stop delays, and fuel consumptions, can be improved with smoother traffic

propagation, guided by the advisory speed sign under either the pre-timed or the actuated signal control;

- A proper display of the VMS/VSL, which will be activated before the onset of the yellow phase, can effectively reduce the number of vehicles trapped in the dilemma zone and thereby reduce the number of rear-end collisions;
- The advisory speed sign, which accounts for the intersection queue evolution, can effectively advise drivers to slow down and to join the end of the queue so as to reduce potential rear-end crashes for intersections plagued with insufficient sight distance; and
- A higher compliance rate under the displayed message/advisory speed will often result in a safer and more efficient traffic environment.

8.2 Further Research Tasks

Despite the successful use of the developed DZPS for intersection safety improvement and speed harmonization, much remains to be researched prior to its comprehensive deployment. Some critical tasks to be conducted in the future study are summarized below:

- **Impacts of the VMS and AWS on driver behaviors:** Extensive field studies and development of behavior models shall be conducted to reflect the discrepancies of driver behaviors under different VMS and AWS.
- **Integration of the system with connected vehicles:** In recognition of the emergence of connected vehicles in the traffic flows, it is essential

to integrate the proposed DZPS under different penetration rates of connected vehicles so as to improve the reliability of the system's operational functions.

- **More field studies on the impacts of roadside sensors on the driving behaviors:** Despite the observed impacts of roadside sensors on traffic flow speeds, its impacts, are likely to vary with different driving populations. Hence, more field studies will be essential to quantify such impacts so that the results can be used for the design of proper locations for sensor deployment.
- **Development of an intersection safety evaluation function:** Due to the low frequency and stochastic nature of accidents, a safety evaluation of an intersection generally needs a long-period of deployment to have sufficient data for performance evaluation. As such, a reliable evaluation of any deployed system on reducing traffic accidents becomes a challenging task. To promote the deployment of such systems from the cost/benefit perspective, one shall focus on developing a reliable function with critical data associated with accidents to facilitate short-term performance analyses.
- **Long-term analysis on safety:** This study has focused on short-term impacts on driving behavior from the deployed roadside sensors. However, the learning impacts (i.e., any changes on short-term impact discussed in Chapter 7) of driving populations over time with respect to

the roadside sensors or any deployed system deserve further understanding with more field studies.

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