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RESEARCH REPORT

Intelligent Dilemma Zone Protection System at High-Speed Intersections

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FINAL REPORT

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16. Abstract

Drivers' actions in an intersection's dilemma zone – the area where the decision to stop at a yellow light or continue through it is not clear-cut – can lead to side-angle and rear-end crashes. In Maryland, researchers developed an intelligent dilemma zone protection system (DZPS) that is reducing these crashes by anticipating drivers' decisions and responding.

The DPZS system was deployed at two high-speed rural intersections (US 40@Western Maryland Parkway and MD 213@Williams/Locust Point Road), and it has three components: (1) two wide-range sensors to track the speeds and locations of all vehicles within the identified dilemma zones; (2) software to predict the response of drivers during the yellow phase and to activate the all-red extension function if needed; and (3) a web-based module for responsible engineers/technicians to monitor the system's performance from a control center. Measured benefits of DZPS include a 30 to 40 percent reduction in dilemma zone length and fewer vehicles approaching the intersection at speeds greater than the posted speed limit. The all-red extensions have helped prevent crashes between through traffic and vehicles entering the intersection from the cross street.

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Executive Summary

The objective of this project was to design, deploy, and evaluate a Dilemma Zone Protection System (DZPS) that can improve intersection safety by reducing side-angle crashes and rear-end collisions. These two types of crashes, plaguing many high-speed intersections, are often due to drivers' decisions when they are trapped in their respective "dilemma zone," defined by the Institute of Transportation Engineers (ITE) as the space between two points on an approach to a signalized intersection, beginning at a point where approaching drivers—when shown a yellow display—will stop at the stop line of the intersection and ending where drivers—again, when shown a yellow display—will proceed through the intersection before the light turns red. Between these two points, drivers are faced with the dilemma of deciding whether to stop or proceed through the intersection. This is a dilemma because they may not be able to stop comfortably at the stop line, nor pass the intersection before the light turns red. Dilemma zones for drivers vary in location and length with vehicle approaching speeds, reaction times, and vehicle deceleration or acceleration constraints.

The DPZS was developed by the University of Maryland and its early version was deployed by the Maryland Department of Transportation State Highway Administration (MDOT SHA) at the intersection of US 40 and Red Toad Road in Cecil County, Maryland in 2012. The system can dynamically extend the all-red phase (every signal in all directions of the intersection is red, to provide additional clearance time, ranging from 0.5 to 3.0 seconds) when it detects a potential red-light running vehicle. It can also proactively alert approaching drivers to reduce speeds with roadside sensors or variable message signs if available.

In this project, an improved version of DPZS was deployed at two high-speed rural intersections (US 40@Western Maryland Parkway, "Intersection-1," and MD 213@Williams/Locust Point Road, "Intersection-2"), and it consists of the following principal components: (1) two wide-range sensors to track the speeds and locations of all vehicles within the identified dilemma zones; (2) software to predict the response of drivers during the yellow phase and to activate the all-red extension function if needed; and (3) a web-based module for responsible engineers/technicians to monitor the system's performance from a control center or a designated remote location.

The Intersection-1, US 40 and Western Maryland Parkway in Washington County, Maryland, is a three-leg intersection where Western Maryland Parkway (three approaching lanes, two for left-turn and one for right-turn vehicles) ends at US 40, a four-lane divided highway with a posted speed limit of 55 mph. The neighboring intersections are about 1,400 feet and 4,500 feet away on either side along US 40 and the target approach has an on-ramp to I-81 700 feet upstream. There were 15 crashes recorded at this intersection between 2010 and 2012, and 12 of them were potentially related to the responses of drivers in the dilemma zone. This intersection's DZPS, activated in October 2016, includes one web-based monitoring module, two sensors on the eastbound US 40 for vehicle detection and all-red activation, and one sensor on westbound US 40 for green extension under actuated control (see Figure 5-1 for exact sensor locations).

The Intersection-2, MD 213 at Williams Street/Locust Point Road in Cecil County, Maryland, is a four-leg intersection. MD 213 is a two-lane undivided highway a posted speed limit of 50 mph and Williams Street/Locust Point Road is a two-lane undivided highway a

posted speed limit of 30 to 35 mph. There were six crashes recorded at this intersection between 2010 and 2013, and four of them were side-angle crashes potentially related to the responses of drivers in the dilemma zone. This intersection's DZPS, activated in early 2017, includes one web-based monitoring module, two sensors each on the northbound and southbound approaches of MD 213 for vehicle detection and all-red activation (see Figure 5-1 for exact sensor locations).

The field data during the "before" period were collected with five camcorders at 200, 300, 500, 700, and 900 feet from the stop line to measure the speed of each approaching vehicle, and one camcorder was used concurrently to record the signal timings. After the DZPS deployments, all essential data for "before-and-after" impact comparison were collected from both the deployed wide-range sensors and the roadside camcorders.

Results

Field evaluations of the deployed DZPS were conducted about one month after the system activation dates, and real-time system monitoring and performance analysis was carried out with respect to the traffic flow characteristics impacts and the all-red extension activations.

Impact on the traffic flow characteristics-1: A comparison of the before-and-after distribution of the dilemma zones, varying mainly with each individual vehicle's approaching speed and acceleration/deceleration rate, is shown in Figure 5-8, where its maximum length (for vehicles traveling at 75 mph) was reduced from 960 feet to 670 feet for Intersection-1, a 30% reduction. Total length of the dilemma zones weighted by traffic volume in each speed bin also showed a 40% reduction from 73 feet to 44 feet. Similar reduction patterns were also observed at Intersection-2.

Impact on the traffic flow characteristics-2: The percentage of vehicles approaching at a speed over 55 mph for Intersection-1 at 900 feet from the stop bar was dropped from 29 to 16 percent, and the percentage for Intersection-2 at 500 feet from the stop bar dropped from 8 to 1 percent (Tables 5-3 and 5-4). This could be due to the deployment of roadside wide-range sensors that are visible to approaching drivers.

Impact on the traffic flow characteristics-3: More drivers were observed making the conservative decision to "stop" during a yellow phase, compared with the driver decisions observed in the before-deployment period. For example, the percentage of drivers deciding to "pass" through the intersection during yellow phases at the speed of 45-55 mph and 300-400 feet from the stop line, decreased from 50 percent for both intersections in the before-deployment period to 43 percent for Intersection-1 and 18 percent for Intersection-2 in the after-deployment period (see Figure 5-9).

Impact on the traffic flow characteristics-4: The deployment of the DZPS did not have an impact on aggressive drivers, often driving at speeds over the posted speed limit (see Figure 5-9). This seems to justify the need for all-red extensions which, would help prevent crashes between aggressive red-light running vehicles and vehicles entering from the cross street.

Detection rate for all-red extension: The DZPS initiated extension calls in 99 of the 312 observed signal cycles for Intersection-1 and in 78 of the 441 observed signal cycles for Intersection-2 (Table 5-6). The rate of false-positives, i.e., predicting that a passing vehicle would not clear the intersection when it actually did before the light turned red, was 30% for Intersection-1 and 16% for Intersection-2; perhaps because the driver accelerated. More importantly, the video taken at the target approach showed that the DZPS successfully provided all-red extensions to the twelve observed red-light running instances at the two intersections, demonstrating the potential safety benefits to this type of system.

CHAPTER 1: Introduction

1.1 Research Background

Since the early 1960s, traffic researchers (e.g., Gazis, 1960) have recognized that many right-angle or rear-end crashes at high-speed intersections are due to a dilemma zone that often causes a conflict between a driver's desire to comply with a yellow indication and the encountered constraints. As stated in the report from FHWA (1977), there are two types of dilemma zones that can occur at high-speed intersections. The first type is when drivers can neither stop comfortably at the stop line, nor safely clear the intersection when approaching a signal with the yellow indication. The second type of dilemma zone, named "Type II dilemma," arises from drivers' inconsistent behaviors when they can execute both stopping and passing maneuvers. This type of dilemma zone is defined as a range within which 10 to 90 percent of the drivers decide to stop (Zegeer, 1978).

Under either definition both the location and the length of a dilemma zone vary with individual drivers' approaching speeds, reaction times, and vehicle deceleration/acceleration rates. Hence, one high-speed intersection is likely to have several dilemma zones spatially distributed over a wide range. In fact, Liu et al. (2007) in their empirical observations of driver responses during a yellow phase at high-speed intersections confirmed that the dilemma zone is dynamic in nature and varies with the vehicle approaching speed. They also indicated that a driver's response to the yellow phase may be affected by other factors, such as the presence of passengers, the use of cellphones, and the number of through lanes in the approaching direction. The common practice of extending the yellow phase is often not sufficient in protecting drivers trapped in different dilemma zones (Chang, 2012).

Recognizing the imperative need of improving intersection safety, the Maryland Department of Transportation State Highway Administration (MDOT SHA) installed an intelligent dilemma zone protection system at the intersection of US 40 and Red Toad Road in Cecil County in 2012. The system used three sensors to track individual vehicles' trajectories, and activated all-red extensions when certain vehicles were estimated to be trapped in their dilemma zones (Chang, 2012). The preliminary data collected at the target intersection approach seems to support its effectiveness in reducing right-angle or rear-end crashes.

1.2 Research Objectives and Scope

The primary objectives of this project were to design and deploy a dilemma zone protection system (DZPS), similar to the one deployed at US 40 @ Red Toad Road, at two additional high-speed rural intersections. Based on the field observations and key findings from the system deployment, the project would produce operational guidelines for future implementation. The scope of this project included:

- Design and deploy DZPS at the intersections of US 40 @ Western Maryland Parkway, and MD 213 @ Williams/Locust Point Road;
- Construct a web-based module for target users to monitor the system's performance from a control center or a designated remote location; and

- Develop guidelines for the design and operations of the dilemma zone protection system at other hazardous high-speed intersections.

1.3 **Locations overview**

The intersection of Western Maryland Parkway and US 40 in Washington County, Maryland, is a three-leg intersection and the posted speed limit on US 40 is 55 mph. The nearest eastbound and westbound intersections are about 1400 feet and 4500 feet, respectively, apart from the target site. There are on/off ramps from I-81 between these two intersections, where the ramp lane of 700 feet becomes a right-turn exclusive lane. On westbound US 40, there is an exclusive left-turn lane at about 400 feet from the intersection. The candidate site's northbound (i.e., on Western Maryland Parkway) has three approaching lanes, two for left-turn and one for right-turn vehicles.

Figure 1-1 shows the accident records reported by MDOT SHA. Note that there were 15 accidents recorded between 2010 and 2012, and 12 of them were potentially related to the responses of drivers in a dilemma zone. Seven out of those 15 accidents were angled crashes between the eastbound and northbound vehicles. Judging from the accident types and frequencies at this candidate intersection, one may expect that traffic safety in its eastbound approach can be improved with a well-designed dilemma zone protection system. Figure 1-2 shows the satellite image of the candidate intersection from Google Earth.

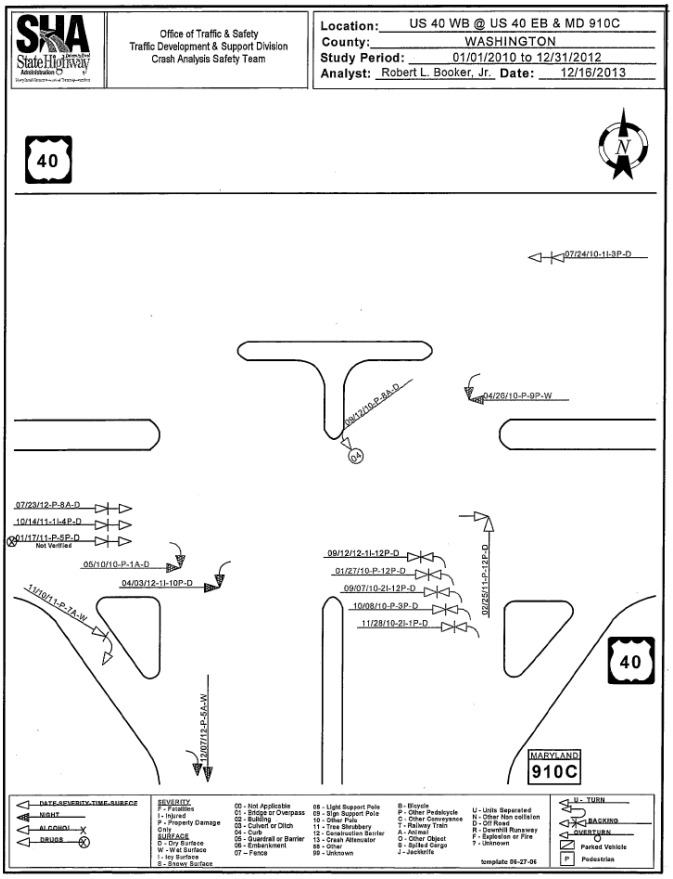


Figure 1-1 Accident records at the intersection of Western Maryland Parkway on US 40

Figure 1-2 Satellite Image for the intersection of Western Maryland Parkway on US 40

The second candidate location was the intersection of Williams Street/Locust Point Road and MD 213 in Cecil County, Maryland. It is a four-leg intersection, where MD 213 is a two-lane undivided highway with a speed limit of 50 mph. The nearest northbound and southbound intersections are about two miles and one mile, respectively, from the target site. Williams Street/Locust Point Road is also a two-lane undivided roadway with a speed limit of 30 to 35 mph.

As shown in Figure 1-3, both the northbound and southbound approaches of the intersection have two lanes, one for exclusive left turns and the other for shared use between the through and right-turn vehicles. Both its eastbound and westbound approaches have only one lane to accommodate vehicles exercising through, right, and left movements. Figure 1-4 shows the second candidate site's accident records from 2010 to 2013. All accidents were potentially caused by aggressive driving behaviors in the dilemma zone since five of them are angled crashes. A customized dilemma zone protection system could improve traffic safety at this hazardous intersection.

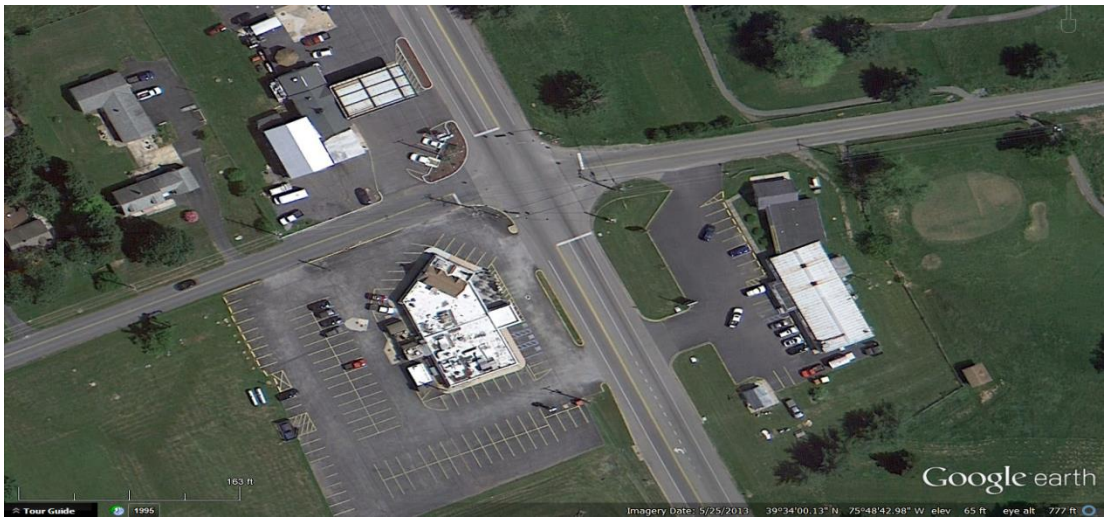


Figure 1-3 Satellite Image for the intersection of William Street/Locust Point Road on MD 213

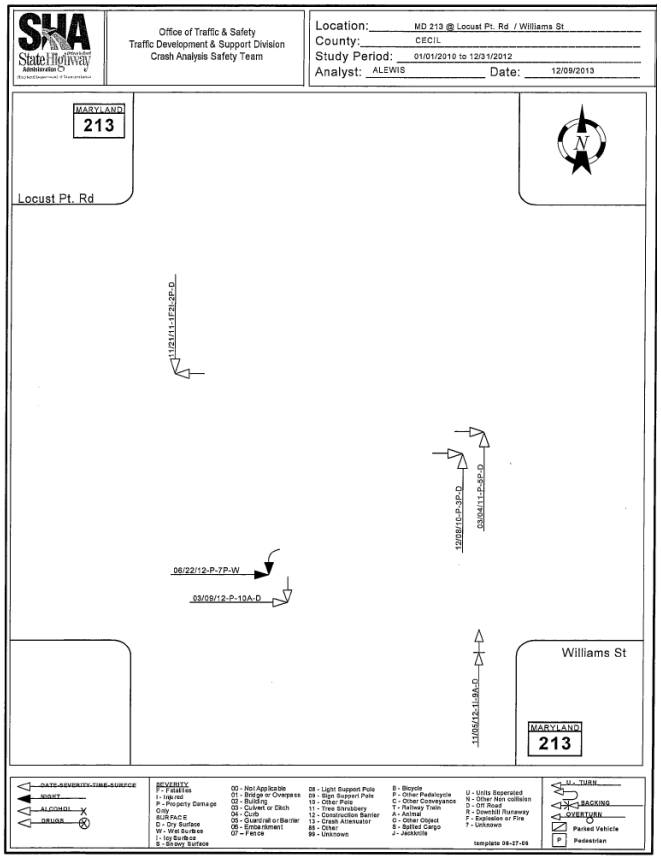


Figure 1-4 Accident records for the intersection of William Street/Locust Point Road on MD 213

1.4 Report organization

The research findings of this project along with additional works for future studies are presented into five chapters. A brief description of information reported in each chapter is summarized below:

Chapter 2: Literature review of related studies and designs for improving intersection safety. This chapter presents some key studies on dilemma zone related issues, including the design of various control plans and state-of-the-art practices for improving intersection safety. The critical role of driver behavior on the design of operational strategies for prevention of angled crashes and read-end collisions is also discussed. Section 2.2 reviews existing dilemma zone protection systems on green extensions, green truncations, advanced warning signs, and all-red extensions. Section 2.3 presents key studies on driver responses during a yellow phase. Section 2.4 summarizes the speed harmonization-related development for intersection progression. The last section concludes with the research needs for developing dilemma zone protection and a speed harmonization system.

Chapter 3: Description of DZPS for high-speed intersections: This chapter presents a dilemma zone protection system, using 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. The system first uses the VMS to inform approaching drivers of a yellow or red phase ahead and advises 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 helps compliant drivers adjust their speeds in a timely manner to avoid possible rear-end collisions. In instances involving aggressive/non-compliant drivers, the system's wide-range sensors track the evolution of their speeds and locations within the dilemma zone (i.e., every 0.1 seconds), and determine whether or not an all-red extension call should be granted to prevent such vehicles from incurring potential side-angle crashes.

Chapter 4: Development of a DZPS simulator for pre-deployment 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 make necessary adjustments. The developed simulator offers the following functions: (1) replicate the real-world traffic distributions and driver characteristics; (2) integrate key components of the DZPS into a simulation platform for experimental analysis, and (3) evaluate the effectiveness on safety and mobility improvement.

Chapter 5: Performance evaluation using before-and-after field data. This chapter presents the performance evaluation results of the DZPS deployed at the two high-speed intersections: US 40 at Western Maryland Parkway and MD 213 at Williams/Locust Point Road. The evaluation comprises the following tasks: (1) before-and-after comparison of the dilemma zone distribution; (2) before-and-after comparison of drivers' responses to the yellow phase at different approaching speeds and distances from the intersection stop line; (3) before-and-after

comparison of the approaching speed distribution and average acceleration/deceleration rate; and (4) the detection rate of potential red-light running vehicles and the success rate of all-red extension provisions.

Chapter 6: Conclusions of research and deployment findings. This chapter first summarizes the DZPS key functions, and then highlights the benefits of DZPS on improving intersection safety. Some future system enhancements, such as integrating with variable message signs (VMS) or connected vehicles, are also explored in this chapter.

CHAPTER 2: Literature Review

2.1 Introduction

This chapter presents some key studies on dilemma zone-related issues, including the design of various control plans and state-of-the-art practices for improving intersection safety. The critical role of driver behavior on the design of operational strategies for the prevention of angled crashes and read-end collisions is also discussed.

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.

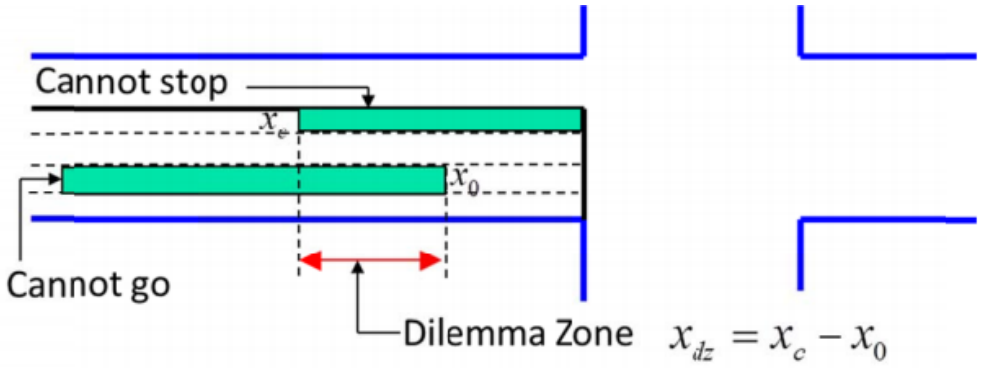


Figure 2-1 A graphical illustration of the Type-I dilemma zone at signalized intersections

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:

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

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. They 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 intersection geometric features. Several other studies estimated such parameters for dilemma zone identification (Olson and Rothery, 1961; Crawfoard and Taylor, 1961; Williams, 1977; Chang et al., 1985; and Lin, 1986). In brief, since the vehicle approaching speeds and driver responses are often distributed in a wide range, the dilemma zone for an intersection is not a constant; rather, it spreads over a spatial range.

Type II Dilemma Zone

Parsonson et al. defined the Type II dilemma zone 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 were also conducted (Zegeer, 1977; Chang et al., 1985; Bonneson et al., 1994; Papaioannou, 2007; Wei et al., 2009). Figure 2-2 shows that the dilemma zone boundaries vary with vehicle types. For example, trucks often have longer upper boundaries due to the lower deceleration rates compared with other vehicle types. The Type II dilemma zones were 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 (Kronbogr, 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, advanced warning signs, and all-red extensions. Section 2.3 presents key studies on driver responses during the yellow phase. Section 2.4 summarizes the speed harmonization-related development for intersection progression. The last section concludes with the research needs.

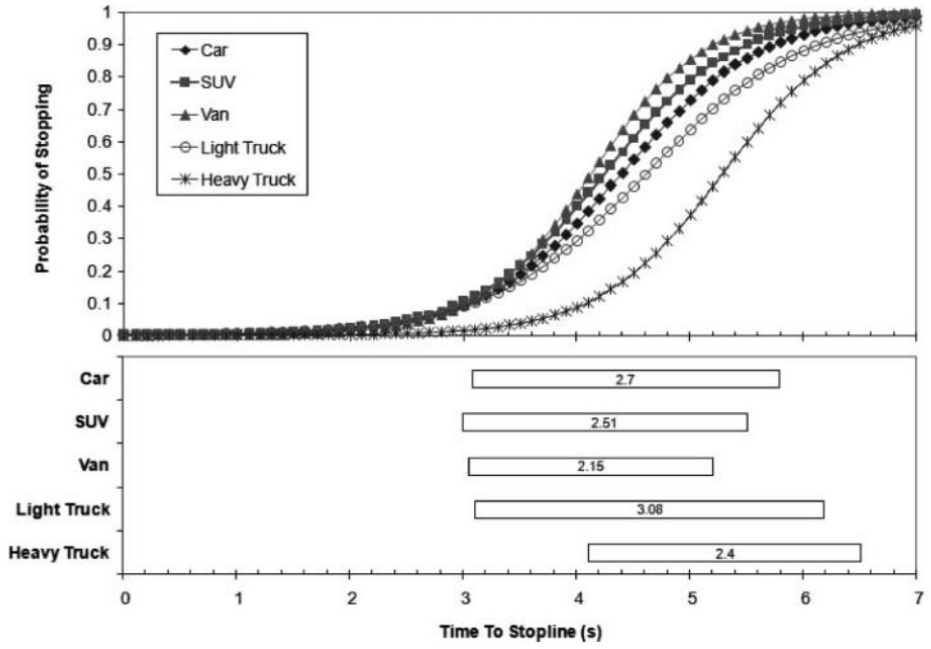


Figure 2-2 Distribution of Type II dilemma zone (Wei et al. 2009)

2.2 Dilemma Zone Protection Systems

Green Extension or Early Termination

One of the widely used strategies to minimize the 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 through the intersection, or 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 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 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. Their proposed method included the following steps: (1) when the green termination status is warranted, the system searches for all vehicles potentially trapped in the dilemma zone; (2) the system calculates the dilemma likelihood sum with each extension unit from the identified vehicles; and (3) the system finds a minimized green extension based on the calculated dilemma zone likelihood sums. Evaluation results with simulation experiments showed that Tarko's

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 Peirce, 1988). MOVA was developed primarily for signal timing designs responsive to traffic conditions. Three detection locations were included 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 was determined by comparing the benefits of preventing vehicles from being trapped in the dilemma zone with the costs of potential delays. The evaluation results from 20 sites showed that such a system provided a 30 percent reduction 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 was controlled with 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 their functions. The incident reduction module (O) was used to reduce the number of vehicles trapped in the dilemma zone. When a vehicle was detected in a dilemma zone, a green extension was called to provide additional green time to the vehicle. The lorry priority module (L) was used to detect trucks and extend the green duration if needed.

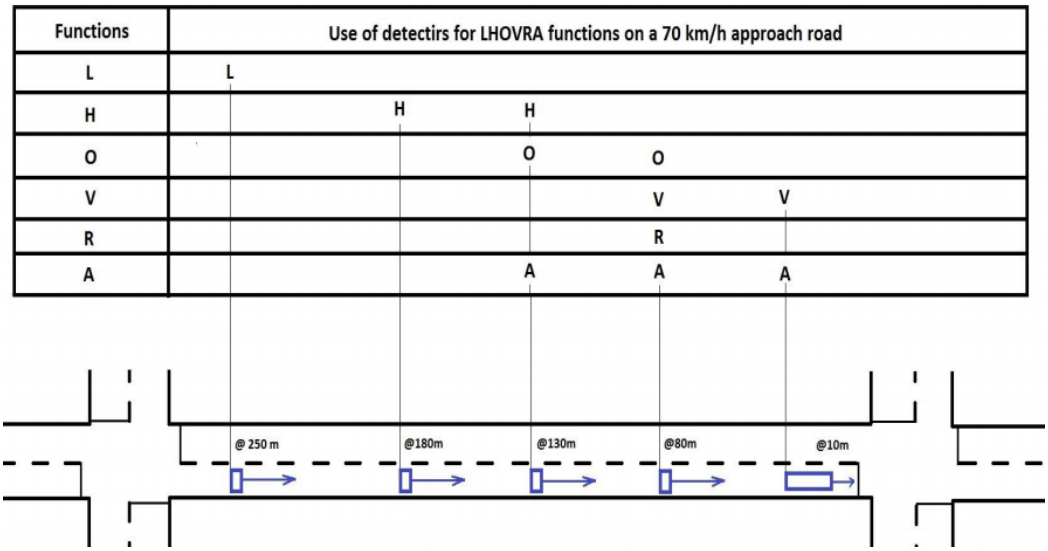


Figure 2-3 Detector layout and relationship on the LHOVRA system

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 were similar to those in LHOVRA, but each detector covered only one lane and an additional detector was placed further upstream from the LHOVRA system. The objective of SOS was to minimize both risk from the dilemma zone and delay, i.e., to improve both safety

and mobility. Based on detector data, the signal controller estimated vehicle trajectories and selected an optimal timing to end the green phase. The embedded optimization algorithm would increase the incident cost by two times when two or more vehicles were in different lanes within the dilemma zone, and by four times when they were in the same lane.

Advanced Warning Sign/Flasher (AWS)

The AWSs advise drivers of possible signal phase changes at the downstream intersection, and they 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; Pant and Xie, 1995), such as "Prepare to Stop When Flashing" and "Red Signal Ahead When Flashing." Figure 2-4 shows AWS examples.

Figure 2-4 Types of warning sign for red signal

McCoy and Pesti (2003) conducted field studies of two DPZS systems deployed by the Nebraska Department of Roads. The first was the green extension method and the second method was to show a "Prepare to Stop When Flashing" sign with one advanced detector that is to be activated at a pre-determined time before the onset of the yellow signal. The study showed that both designs performed equally well in reducing the number of vehicles that ran through red lights. The AWS, however, resulted in fewer drivers in the dilemma zone compared with the green extension or green early termination method. They concluded that AWS with advanced detection reduced the number of vehicles trapped in the dilemma zone and encouraged drivers to stop at the stop line.

Several other studies indicated the effectiveness of AWS based on field observations. For example, Bowman (1993) showed a reduction of 23 percent and Messer et al. (2004) evidenced a reduction of 40 percent in red-light-running vehicles. Sayed et al. (1999) found that those intersections deployed with an AWS showed a significant reduction in crash rates. Studies indicated that the most commonly used sign for an AWS is "Prepare to Stop When Flashing" (Eck and Sabra 1985; Pant and Xie 1995).

Detection Control System (D-CS)

Detection Control System (D-CS), developed by Texas Transportation Institute, consists of one upstream detection zone to provide the vehicle speed and length, and a second detection zone 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," derived from the predicted travel time to the stop line. 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 in predicting the number of vehicles in the dilemma zone. The D-CS calculates the time in which each vehicle on the target approach emerges from its dilemma zone and uses a dynamic monitoring approach to end the green phase with a short allowable headway. A field study by Bonneson et al. (2002) revealed that the D-CS reduced both the frequency of vehicles trapped in the dilemma zone and the total number of red-light-running vehicles.

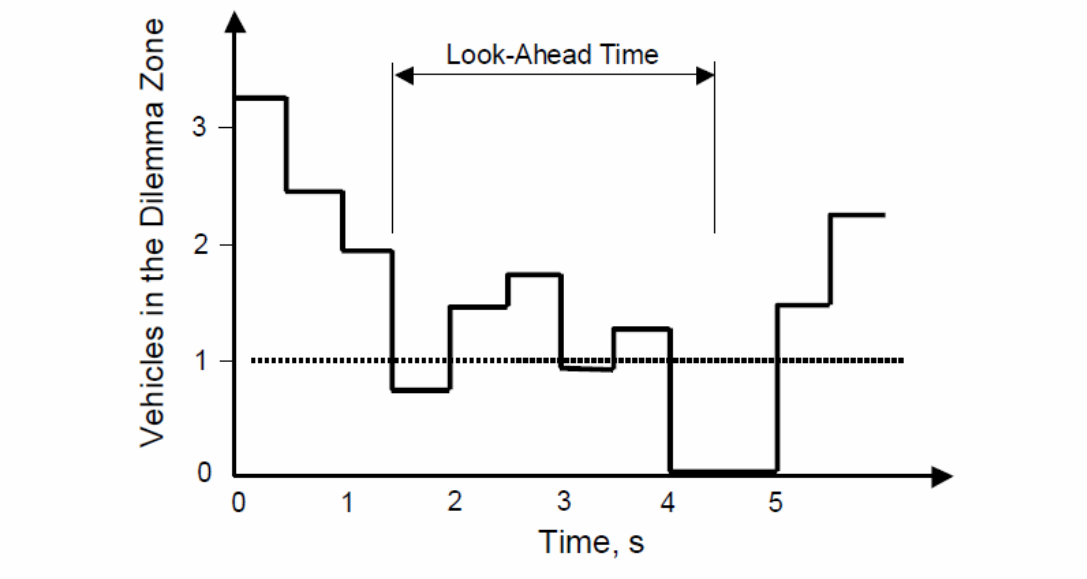


Figure 2-5 Look ahead feature at DC-S

Zimmerman et al. (2014) developed a Detection, Control, and Warning System (DCWS) using the "vehicle specified in-pavement system" to provide advanced warnings to drivers. Figure 2-6 shows the layout of the DCWS. The results of experimental studies indicated that instead of directly protecting those trapped in the dilemma zone, by providing more information to drivers in the decision-making stage warning signs can prevent drivers from becoming trapped in the dilemma zone in the first place (Zimmerman et al., 2014).

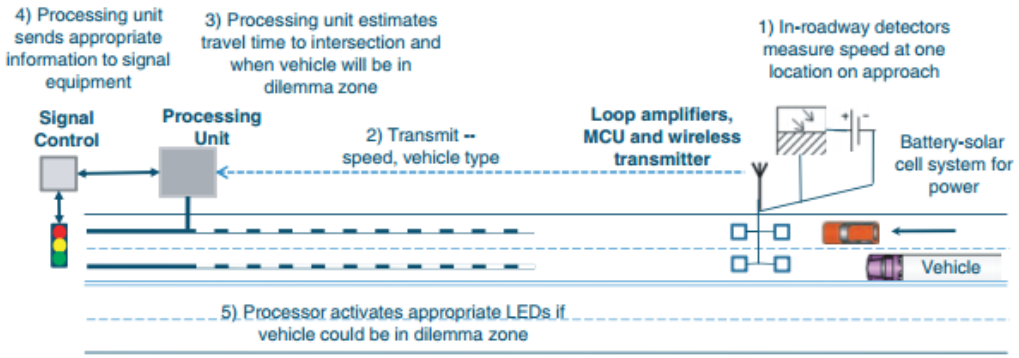


Figure 2-6 DCWS system layout (Zimmerman et al., 2012)

All-Red Extension

An active protection approach to prevent side-angle crashes is to extend the all-red phase. The main objective of such a method is to identify potential red-light-running vehicles and provide additional clearance time for them. The signal controller with such a function can postpone the green phase in the competing approaches until a red-light-running vehicle clears the intersection in order to prevent a side-angle crash.

Figure 2-7 shows the signal phase timing for a normal condition and an all-red extension condition. The all-red extension method requires either the real-time vehicle speed and location information, or a prediction based on information collected with deployed detectors (Gates and Noyce 2015, Chang et al. 2012, Zhang et al. 2012, and Gates 2007).

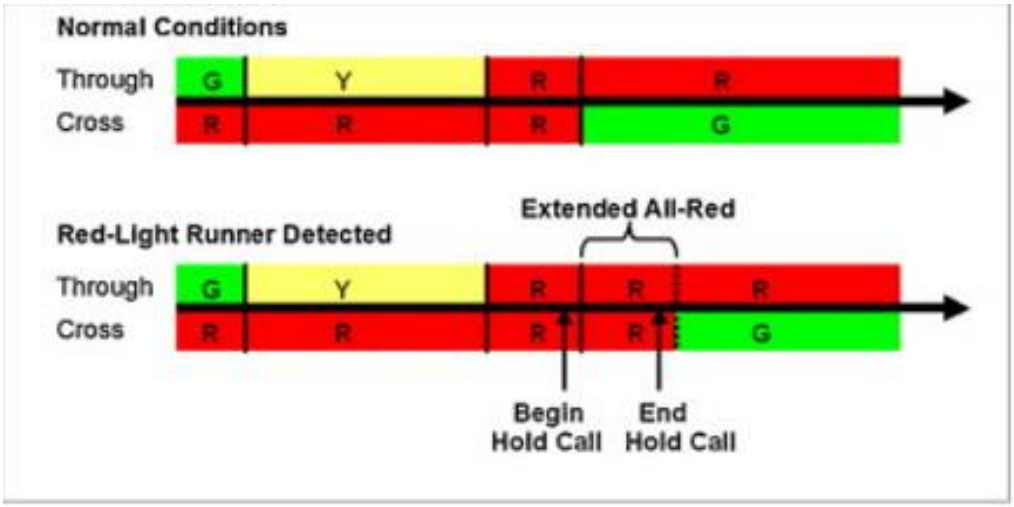


Figure 2-7 Phase diagram for an all-red extension (Gates 2015)

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 their field evaluation. They concluded that the all-red extension system can effectively reduce the likelihood of side-angle crashes. Zhang et al. (2012) developed a probabilistic model for an all-red extension algorithm, Dynamic All-Red Extension (DARE), to minimize the false alarm rate and maximize the capturing rate based on the vehicle speed and the car-following status. The experimental results indicated that DARE reduced about five percent of the false alarms and achieved a 70 percent correct-capturing rate.

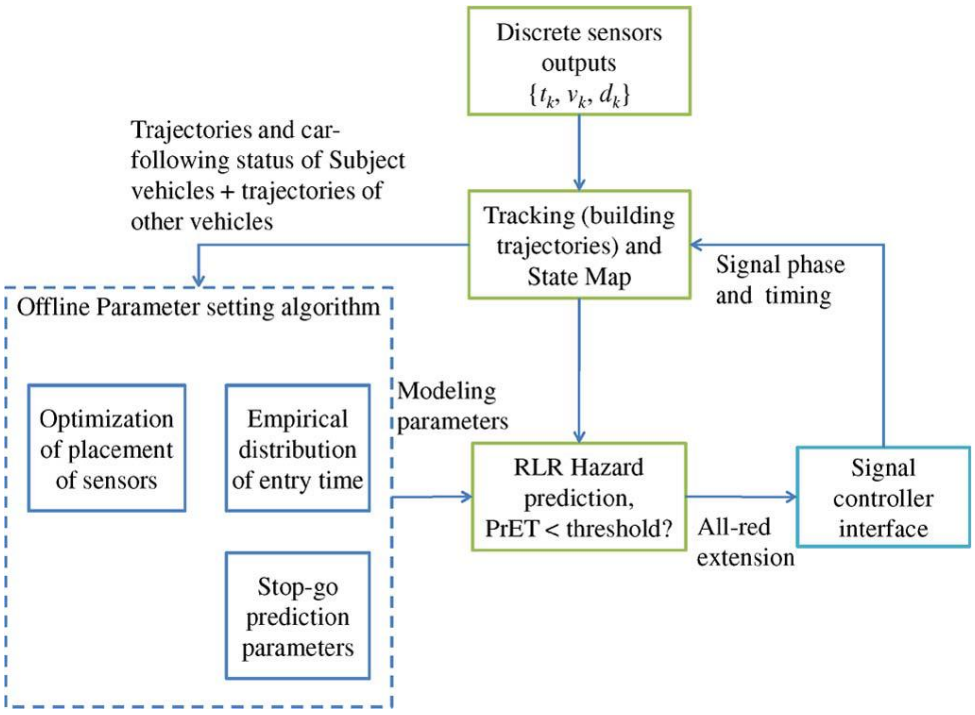


Figure 2-8 DARE system's flowchart

2.3 **Driving Behavior**

Researchers conducted field studies to observe drivers' behavior during the yellow phase and their decision to pass the intersection or to stop at the stop line. For example, Liu et al. (2007) presented an empirical study at six signalized intersections in Maryland and reported that a driver's decision when encountering a yellow phase varies with factors such as age, gender, presence of passengers, and cell phone usage. They concluded that extending the yellow phase alone may not be effective in reducing the frequency of accidents. Similar observations on driver behavior in Greece also indicated that gender, age, and platoon leader or first-follower indicators are the main factors affecting a driver's reaction to the yellow phase (Papaioannou, 2007).

Several similar models were developed to predict a driver's decision at the onset of a yellow phase (Chang et al., 1985; and Gates and Noyce, 2007). Yosef and Mahmassani (1981) developed a model using a discrete probit modeling method, based on each individual's time and distance to the intersection.

2.4 **Green Light Optimized Speed Advisory**

The Green Light Optimized Speed Advisory (GLOSA) is a system developed to provide advisory speeds for approaching vehicles so that they can arrive at the intersection during a green phase. The GLOSA can convey the message to approaching vehicles by either on-board connected vehicle (CV) technologies or roadside variable message signs (VMS).

The U.S. Department of Transportation initiated several CV applications, including the Real-Time Information Synthesis program. One such application is to advise an optimized speed to those equipped vehicles (AERIS, 2015). The eCoMove project in the European Union also

intends to achieve similar mobility goals by using CV communications (eCoMove, 2015). Each vehicle receives signal timing information from the roadside infrastructure and selects its own speed profile (Barth et al., 2011; Xia et al., 2013). The GLOSA system resulted in a reduction of 7 to 13 percent in fuel consumption (Katsaros et al., 2011; Xia et al., 2012). Xia et al. (2013) further proposed an advisory speed system with the downstream traffic information gathered by the preceding connected vehicles.

Roadside variable message signs (VMS) broadcast advisory speeds to incoming vehicles. The Optimized Dynamic Speed Advice (ODYSA) system facilitates progression by providing advisory speeds for a green wave for downstream intersections (Katwijk et al., 2013). With loop detectors, such a system detects a vehicle's approaching speed and provides an individual advisory speed to the target vehicle via a message on VMS.

Despite the continued efforts by researchers over the past decades, design of an effective DZPS remains a challenging task. For example, although the use of AWS produced positive effects on reducing the number of vehicles trapped in the dilemma zone, it did not provide information about the potential downstream hazardous traffic conditions (e.g., a long queue with insufficient sight distance). Existing GLOSA systems do not consider the downstream traffic condition when they compute the optimized advisory speed, and thus they may have a reduced level of effectiveness.

2.5 Conclusion

Taking into consideration the stochastic nature of driver responses to a yellow phase and the resulting dilemma zones, researchers conducted various studies to reduce accident frequencies at intersections. 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 minimize both rear-end collisions and side-angle crashes from both preventive and reactive perspectives; (2) how to balance intersection safety and operational efficiency; and (3) how to best use hardware and software in DZPS to improve signal delay and progression.

CHAPTER 3: A Dynamic Dilemma Zone Protection System

3.1 Introduction

This chapter presents a dilemma zone protection system (DZPS) providing all-red extensions and advanced warnings on VMS. The developed DZPS consists of three principal modules: VMS for advanced warning or speed display, wide-range sensors to track individual vehicle speeds and locations in the dilemma zone, and a decision module to execute the all-red extension (Figure 3-1). The system first uses a VMS to inform approaching drivers of a yellow or red phase ahead and advises them to prepare to stop; or the VMS displays the average speed of the discharging traffic at the stop line during a green phase. Such information helps compliant drivers adjust their speeds in a timely manner to avoid possible rear-end collisions. In instances involving aggressive/non-compliant drivers, the system's wide-range sensors function to track the evolution of their speeds and locations within the dilemma zone (i.e., every 0.1 seconds), and they system determines whether or not an all-red extension call should be granted to prevent side-angle crashes.

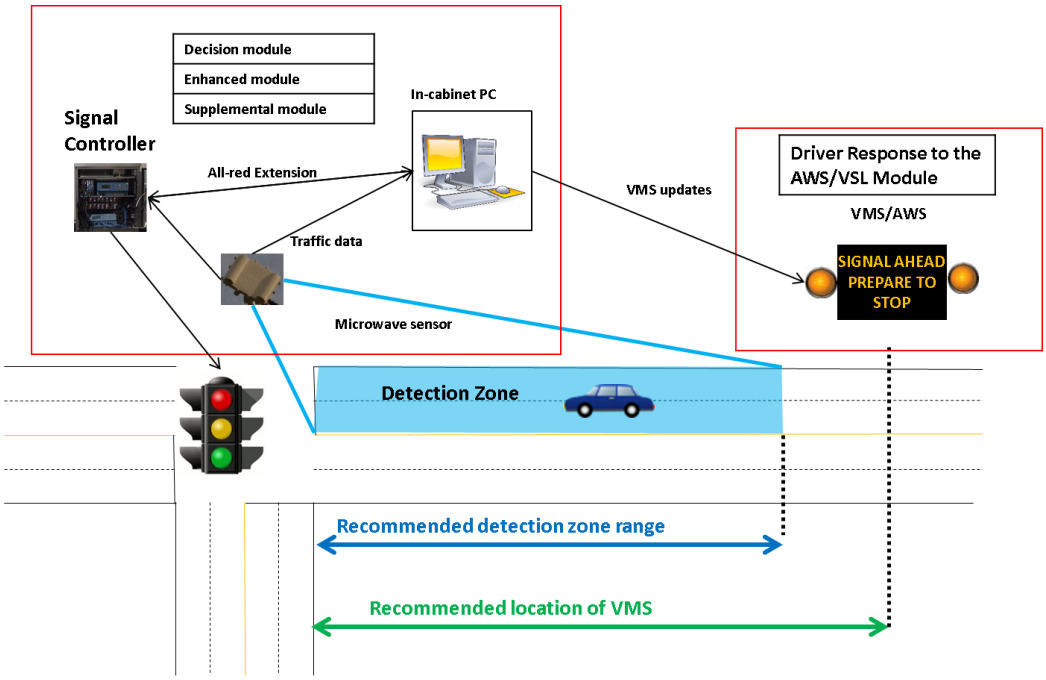


Figure 3-1 Graphical Illustration of the DZPS

Hardware Components

- Long-Range Microwave Detectors: cover the roadway segment from the stop line to the upper boundary of the pre-determined range of dilemma zones, to track individual vehicle speeds and locations. Real-time traffic information from such sensors offers the basis for the DZPS to make control decisions.
- In-Cabinet Computer: receives traffic data from the detectors and Signal Phase and Timing (SPaT) information from the signal controller. The DZPS will activate VMS and identify the locations and speeds of vehicles trapped in the dilemma zone before executing the all-red extension with its embedded computing module.

- Signal Controller: extends the all-red phase at the request of the in-cabinet computer, and provides SPaT information to the in-cabinet computer.
- VMS: receives information from the in-cabinet computer and displays the advisory messages for the incoming vehicles.

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

The VMS displays the message of **"***Signal Ahead Prepare to Stop"* during the yellow or red phase, and advises drivers to adjust their speeds in time to ensure a safe stop. If the signal is green, the VMS displays the average speed of vehicles within the monitoring zone. Both types of information help drivers to make proper speed adjustments and 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 extension duration. Equation 3-1, a function for estimating a detected vehicle's response during the yellow phase, can be calibrated with field observation data. The procedures for parameter estimation and calibration will be described in Chapter 4.

$$P_{stop} = \frac{1}{1+e^{-\alpha-\beta_1 v-\beta_2 d}} \quad (3\text{-}1)$$

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

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, to minimize the false alarm rate and improve operational efficiency.

3.2 **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 3-2 shows the operational flowchart of Algorithm-1, and its step-by-step description is following:

Step 1 – Identify vehicles trapped in their respective dilemma zones based on speeds and locations detected by the wide-range sensors
Step 2 – Calculate the required clearance times for vehicles identified in Step 1 to pass the intersection
Step 3 – Use Equation 4-1 to estimate their passing probabilities
Step 4 – Identify all vehicles with passing probabilities greater than a preset threshold (e.g. > 0.5)
Step 5 – Find the maximum required clearance time among vehicles identified in Step 4
Step 6 – Set the all-red extension based on the maximum clearance time calculated in Step 5
Step 7 – At the onset of the red phase, identify vehicles that cannot stop safely, and evaluate the all-red extension and update it if necessary

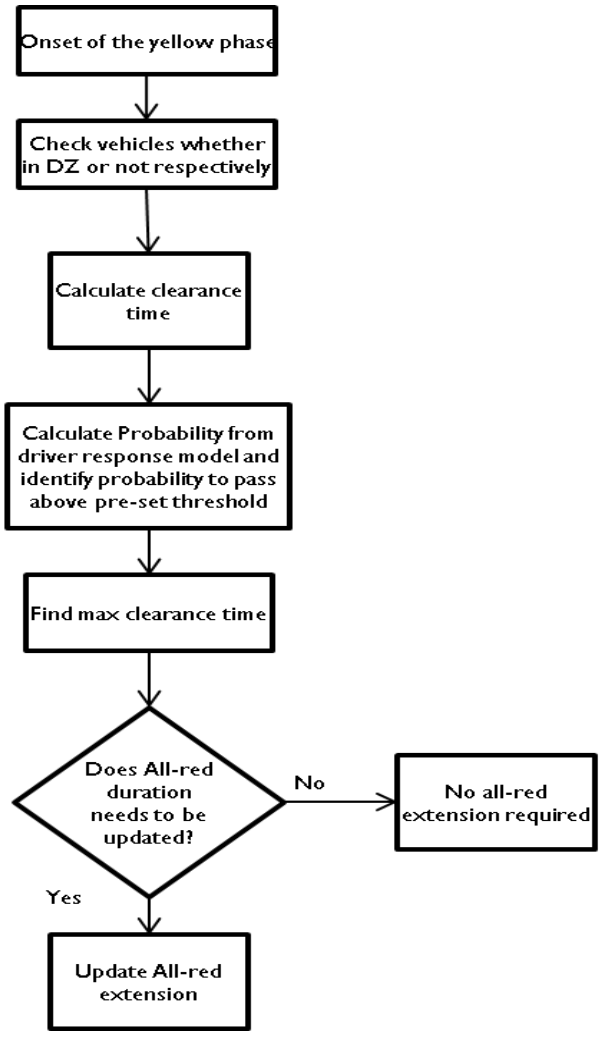


Figure 3-2 Operational flow chart for Algorithm-1

The Algorithm-1 can result in a *missed call* (vehicles should have been protected, but the system did not call an all-red extension) or a *false alarm* (vehicles could have cleared the intersection without an all-red extension but the system called one). Some drivers may also change their decision after initial responses. A supplemental module is developed to ensure that all such drivers will be protected by the deployed system.

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

As shown in Figure 3-3, the monitoring zone under Algorithm-2 is divided into four sub-zones, and the decision module treats the entire monitoring zone as a series of spatially connected sub-zones. Whether or not a decision is made to grant the all-red extension will depend on the average speed of these vehicles in the sub-zones. More specifically, it is assumed that the following vehicle's decision is affected by its leading vehicle within the same sub-zone. 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
the vehicles traveling on the leading zone(s) occupy both lanes
Then,
The following vehicles are predicted to select the "stop" decision.

During a yellow phase, the DZPS collects each vehicle's speed and location and then computes the average zone speed and the total number of vehicles in each zone. If the average speed of a zone is below a preset threshold and is 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 the total number of vehicles in the stopping zone is more than a pre-calibrated value
AND
the total length required for those vehicle is greater than the length of the zone
Then,
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.

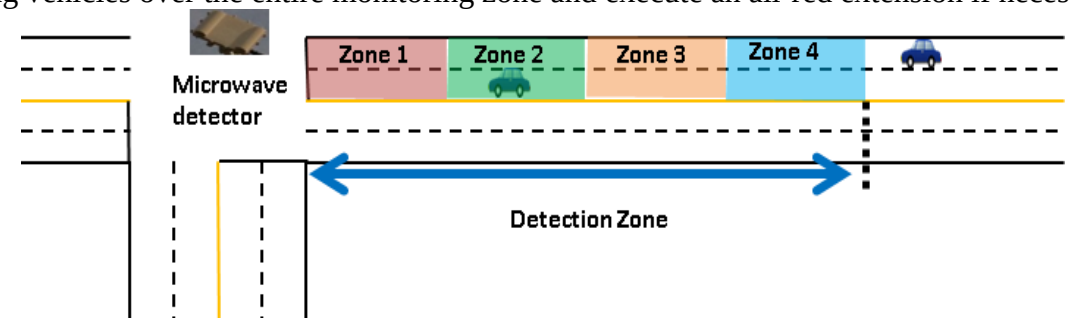


Figure 3-3 Zone based all-red extension (Algorithm-2)

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 number of potential false alarms. A step-by-step description of Algorithm-2 for the all-red extension is following:

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 zone

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. Identify whether any sub-zone should be classified as a "Stopping Zone"

Step 2-a: Check 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" and Go to Step 3.

Else

Go to Step 2-b.

Step 2-b: Check the evolution of the 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" and Go to Step 3.

Else

Go to Step 4.

Step 3. Identify "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" and Go to Step 5.

Else

Go to Step 4.

Step 4. Proceed to do the same blocking-zone identification for all sub-zones

If all zones have been checked, then Go to Step 5.

Else

Go to Step 2 for an upstream zone z +1

Step 5. Identify passing vehicles

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

If there exists any "Blocking zone," then

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

Else

Identify all passing vehicles in the entire monitoring zone

Step 6. Calculate the clearance time for vehicles identified in step 5 and convert it 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

3.4 Pre-Deployment Process and Assessment

This section is focused on illustrating the pre-deployment process and the essential assessments using Intersection-2 as an example. The pre-deployment process includes the following steps:

- Developing the simulation platform 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 3-1), the simulator for experimental analysis is capable of replicating both the DZPS and traffic characteristics, including driver responses during a yellow phase and the arriving traffic patterns (see Chapter 4 for more details). The main functions in this simulation platform to be customized 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 the computing algorithm;
- The real-time communicating relationships between the sensors, the advanced warning messages, the all-red computing algorithm, and the signal controller; and
- The signal phase and timing plan.

Table 3-1 shows the signal phase plan at Intersection-2. 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 period is 40 hours, with different random speeds for each hour.

Table 3-1 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 were built for experiments to compare the effectiveness of the DZPS. The base scenario represents the current condition, and serves as the baseline 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, and the second zone is from 500 feet to the end of the detection zone. If a speed of greater than 27 mph is detected in the first zone, or if a speed of greater than 56 mph is detected in the second zone during an all-red phase, the signal controller will extend the all-red phase. The third scenario is based on Algorithm-1 that uses the decision and the supplemental modules. The last scenario is based on Algorithm-2, which uses the zone-based all-red extension as well as the decision and supplemental modules.

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 measures:

- 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 3-2 MOEs under different all-red extension algorithms and impacts from the VMS

MOE	No Control	Default [1]	Algorithm-1	Algorithm-2
Red-light-running rate[2] (RLR/cycle)	8.9%	8.9%	9.5%	9.1%
Extension call rate[3] (extension call/ cycle)	-	52%	30%	25%
Detection rate[4] (protected RLR)	-	56%	100%	100%
False alarm rate (false alarms/cycles)	-	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 protect red-light-running vehicles, this study tuned the DZPS system to offer 100 percent detection and protection, which results in a relatively high false-alarm rate. As shown in Table 3-2, Algorithm-1 produces a 21 percent false-alarm rate and Algorithm-2 slightly outperforms Algorithm-1 with a false-alarm rate of 16 percent. Further performance enhancements can be achieved if trade-offs between intersection safety and operational efficiency are considered early in the design process.

Step 3 -Sensitivity analysis

Figure 3-4 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 3-4, 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 like to 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 at high-speed and generally low-volume intersections, any such systems should aim for a 100 percent detection rate as the foremost function.

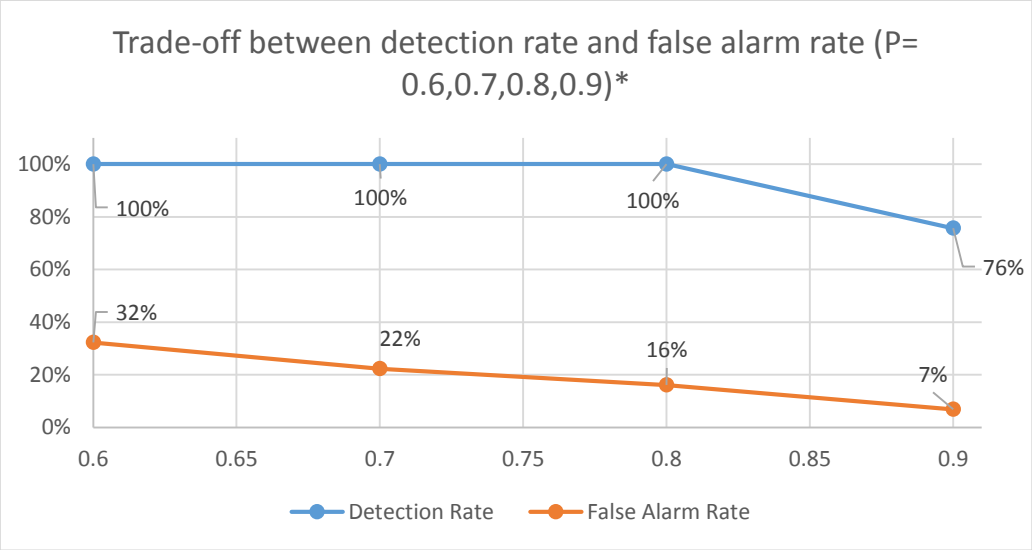


Figure 3-4 Trade-off between capturing rate and false alarm rate using different thresholds of probability (* P is the probability threshold to determine if the detected drivers will take the "Pass" action during the yellow phase)

Table 3-3 demonstrates the red-light-running rate and the 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 a more pronounced reduction in the speed of approaching vehicles. For example, the resulting RLR rate will drop from 7.4%to 2.3% if the actual impact of the VMS on the prevailing speed is increased from 5 mph to 15 mph.

Table 3-3 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
Average speed at 1000 feet from the stop line	59.3(7.1) [1]	60.3(6.9)	58.4(7.9)	57.8(9.4)
Average speed at 400 feet from the stop line	54.4(7.6)	48.6(10.1)	42.3(12.1)	36.7(14.7)
Red-light-running rate (RLR / cycle)	8.9%	7.4%	4.2%	2.3%
1 The number in the parenthesis shows the standard deviation.				

3.5 **Conclusions**

This chapter presented the DZPS to offer 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 developed system can exercise its AWS to alert approaching drivers of their need to reduce speeds 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.

The chapter also demonstrated 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 an acceptable false alarm rate.

CHAPTER 4: Development of a Simulation Platform

4.1 A Simulation Platform for System Evaluation

This chapter presents the design and calibration of a simulation platform for evaluating 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 evaluate traffic impacts prior to the full-scaled field deployment. More specifically, the developed simulator for dilemma zone protection offers the following functions:

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

The overall design of the developed DZPS (see Figure 3-1) includes all-red extension, advisory speed, and queue prediction modules. The traffic data from wide-range sensors serve as the primary input data for the signal controller and the in-cabinet PC to take actions. 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 4-1 shows the relationships between the real-world operations of the developed DZPS and the simulation platform. Using the built-in functions from VISSIM and C# programs for COM interface, the simulation platform replicate both the traffic conditions and their interactions with the deployed DZPS after being calibrated with field data.

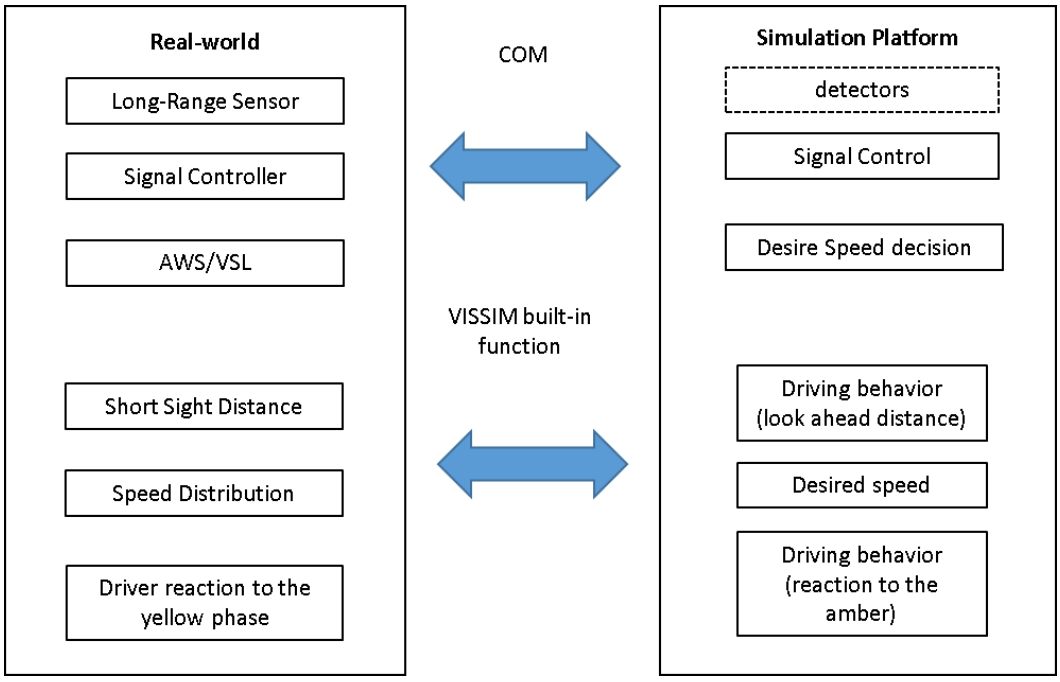


Figure 4-1 Relationship between the DZPS design and a simulation platform

All DZPS algorithms have been implemented and evaluated in a microscopic traffic simulation environment VISSIM (VISSIM, 2011). The following key functions are provided by VISSIM for developing the simulator:

- Provides the flexible driving behavior models to replicate observed behaviors;
- Allows for modification of the system's operating characteristics in real time; and
- Allows for effective interactions of the DZPS with other embedded VISSIM models, using computer languages such as C#, C++, and Visual Basic.

The listed key components of DZPS were programmed in the simulation platform by either built-in simulation functions from VISSIM or coded programs in C#. Figure 4-2 shows the structure of the simulation platform. To better replicate a driver's reaction in traffic simulation, some behavior modules were developed to replace VISSIM's internal functions using the COM interface, including modules on the driver response to variable speed messages and their perceived sight distances.

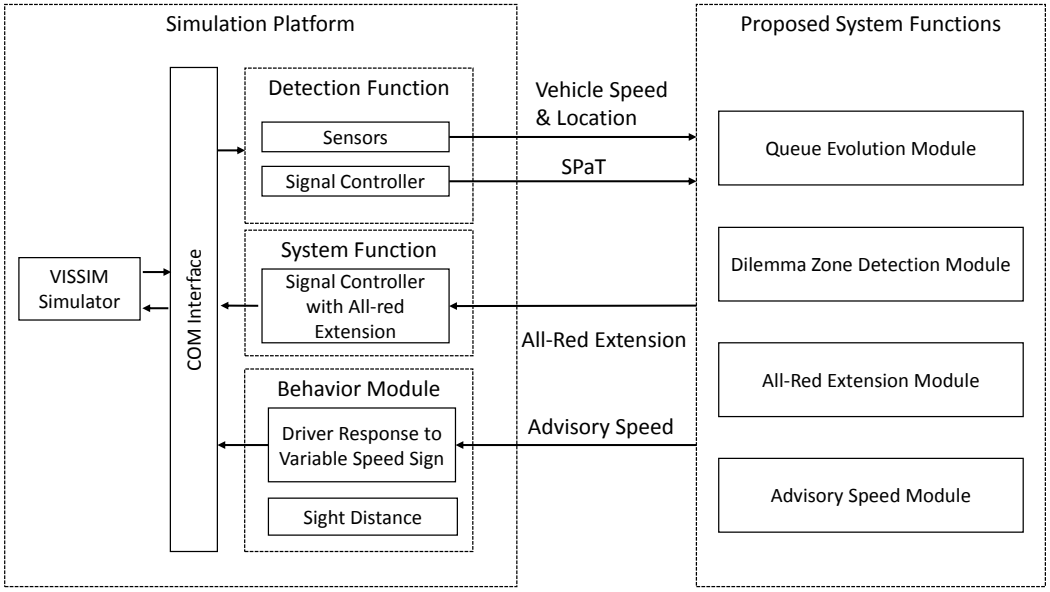


Figure 4-2 Framework of the simulation platform

The simulation platform consists of two major parts: a VISSIM simulator providing traffic data and executes simulations and a developed program that replaces the parameters in VISSIM to affect driver behaviors.

Figure 4-3 illustrates the interrelations between key components in the simulation platform, showing the data flows between the VISSIM intersection simulator and other system functions developed with the C# program. The intersection simulator, after calibration with the collected field data, is used to replicate the arriving traffic patterns, their evolutions, and the corresponding signal states. The outputs from VISSIM at each time step (e.g., location of each vehicle and its speed) is fed back to the control module via the customized interface to predict each driver's response to the yellow phase, to display the message on the VMS, and to determine if an all-red extension should be activated.

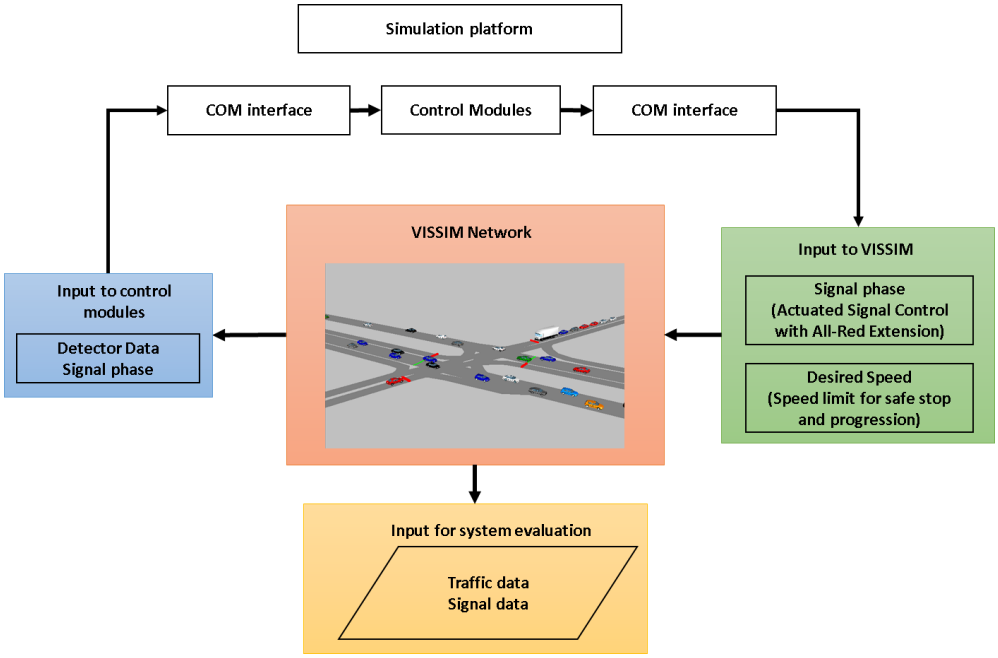


Figure 4-3 Data flows in simulation platform

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

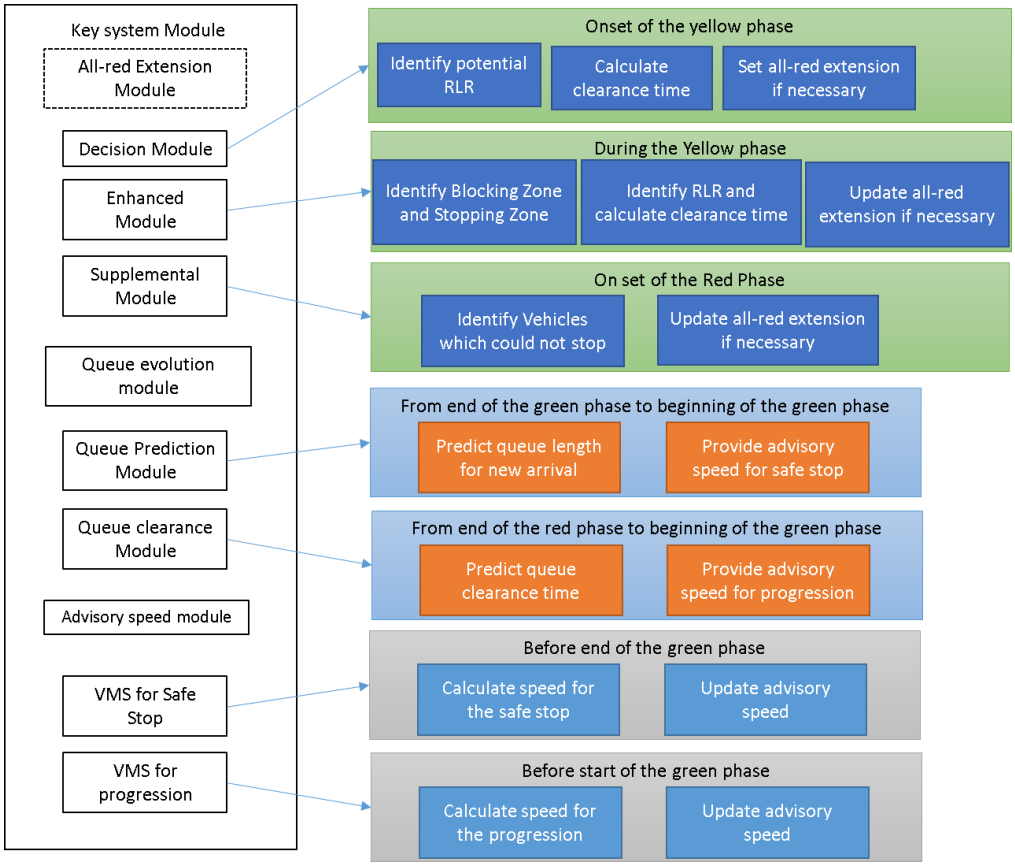


Figure 4-4 Key functions in each system module

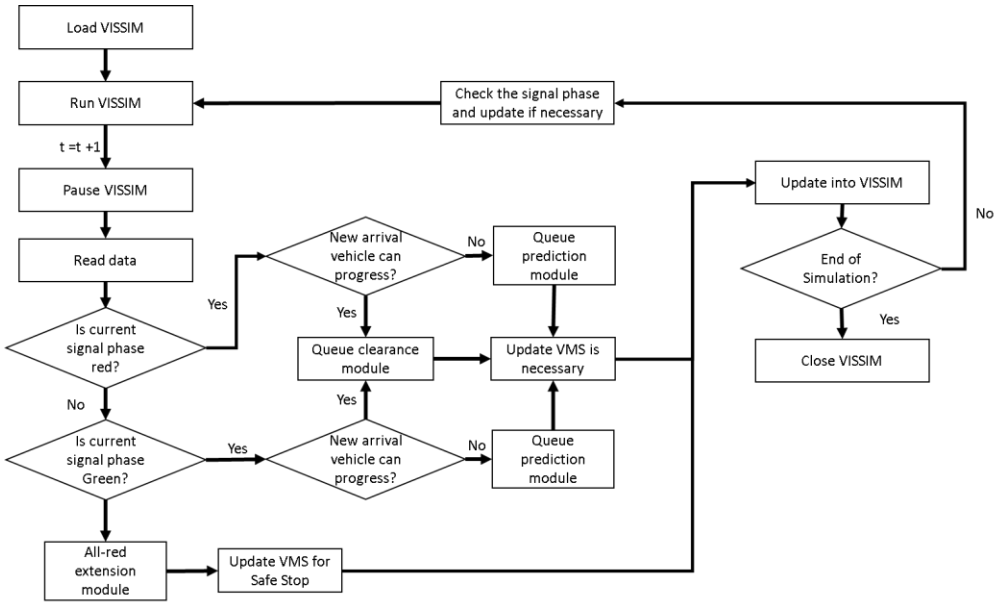


Figure 4-5 Simulation Platform and its operational flowchart

A queue evolution module and an advisory speed limit module are tied together to calculate the advisory speed, but are not necessary to activate the VMS in every cycle. Once a vehicle is detected, the simulator identifies its advisory speed based on the minimal acceptable speed and the free-flow speed. If the arrival vehicle can progress through the intersection without any speed adjustment, the advisory speed will remain in the "OFF" state, and vehicles travel at their current speeds to approach the intersection. For the developed simulator to have the fidelity of replicating the response of traffic patterns under the DZPS operations, it should 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 all-red extensions;
- Reliably simulating the arriving traffic patterns, including the distributions of flow rate, speed, acceleration/deceleration rate, and vehicle composition; and
- Reflecting the responses of drivers to the VMS message and to the yellow phase.

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

4.2 **Key Components in the Simulation Platform**

VISSIM provides several types of driving behaviors and takes programmed models from the NET framework in real time, the simulation platform was developed with the following features to evaluate the DZPS's performance prior to its field development.

- Wide-range traffic monitoring sensors
    - Provide 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 and the turning movement ratio from the field data collection
- Driving behaviors
    - Vehicle approaching speed, and acceleration and deceleration rate from the field data collection
- Reactions to the yellow phase
    - Drivers' reactions to the yellow phase from the field data
- Advanced warning sign/advisory speed (AWS/VSL)
    - Provides the information to drivers when the signal changes to yellow or red, and provides the advisory speed to vehicles to progress through the intersection
- Response to AWS/VSL
    - Drivers' reactions to AWS/VSL when they encounter an 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 in the VISSIM Simulator

As stated previously, the VISSIM simulator allows users to set up the key parameters to realistically reflect the actual field conditions. The following VISSIM built-in functions serve as the basis for simulating the traffic characteristics:

Geometry/Traffic flow

The geometric characteristics, such as the short sight distance from the major or minor streets and downgrades, are the major factors affecting the intersection safety. The geometric features of the intersection can be obtained from satellite images and site visits. In addition, the traffic flow data, obtained from field observations, includes traffic volumes, turning movement ratios, and percentages of heavy vehicles. Figure 4-6 shows the target intersection's geometric features from the satellite imagery, traffic volumes, and the VISSIM simulator for the US 301 and Croom Station Road intersection in Prince George's County, Maryland. As shown in Figure 4-6, it has a short-sight distance, a downgrade toward the intersection, and a high percentage of heavy vehicles observed during the field data collection.

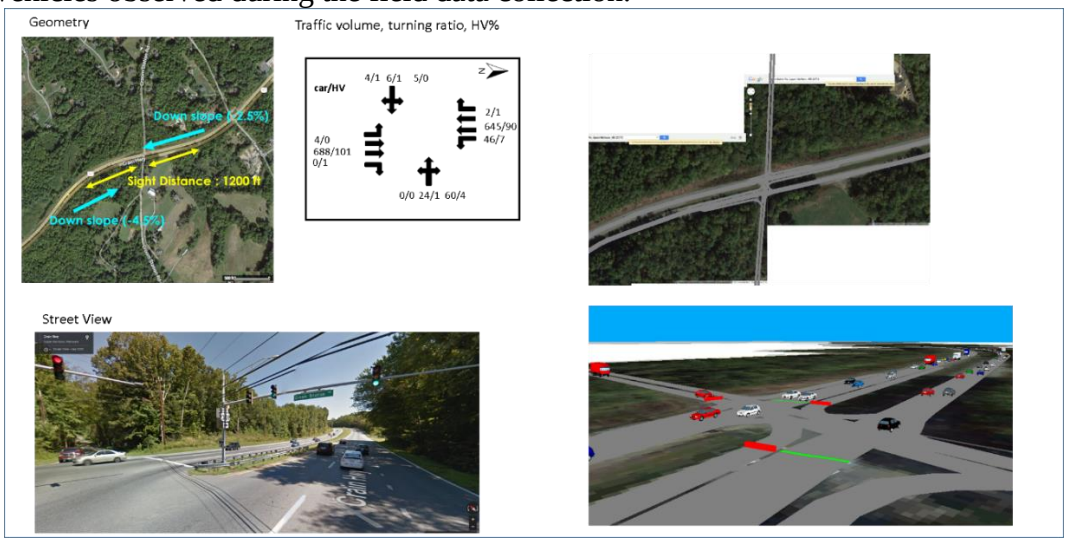


Figure 4-6 Location Overview for US 301 @ Croom Station Road and simulation network, Prince George County, MD

Driving behavior data – such as the spatial distribution of speeds, acceleration and deceleration rates during the yellow and red phases – were collected during pre-deployment field observations to calibrate the simulation platform. Four video recorders were deployed at 200, 400, 650, and 1050 feet from the stop line.

Table 4-1 shows a comparison of the field observations and simulation results. 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 phase

To simulate the responses of the driving population encountering a yellow phase, the study took the following steps:

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

A total of 1,123 individual drivers' responses to a yellow phase at six intersections were used as the basis for model calibration (Liu et al., 2007). The function, "Reaction to amber" in the VISSIM, has two parameters – the vehicle's location and its speed at the onset of the yellow phase. The field data have 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.

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

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. By comparing the distribution of driver responses under the simulated environment with the field-observed results, one can further adjust model parameters until the simulator realistically replicates the observed distribution of driver responses. Equation 4-2 shows the model developed by Liu et al. (2007), and Equation 4-3 presents the updated model calibrated with field data from the target intersection.

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

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

The model calibration objective is to minimize the total differences between the field and the simulation on the percentage of drivers passing the intersection, as shown in Equation 4-4.

$$\text{Minimize } \sum \left| P_{stop\ in\ simulation} - P_{stop\ in\ filed\ data} \right| \quad (4\text{-}4)$$

Table 4-2 summarizes the percentage of passing drivers from the field data collection and the simulated output (using the embedded VISSIM function) 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 field observations, offering a reasonably reliable basis for experimental analysis in the simulator.

Table 4-2: Percentage of drivers making the "Pass" decision during the yellow phase between the field data and simulated results

Speed of vehicle at onset 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

The wide-range traffic monitoring sensor is one of the major key components in the developed DZPS and 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 all-red extension and the queue evolution modules. The data from such sensors are also used to determine whether arriving vehicles require advisory speeds for progression through the intersection.

Figure 4-7 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.

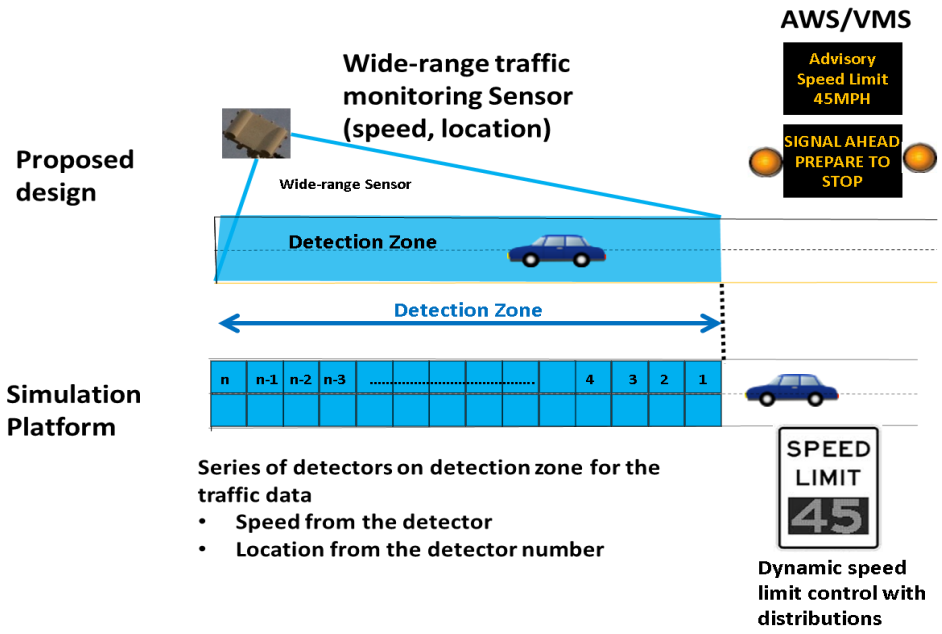
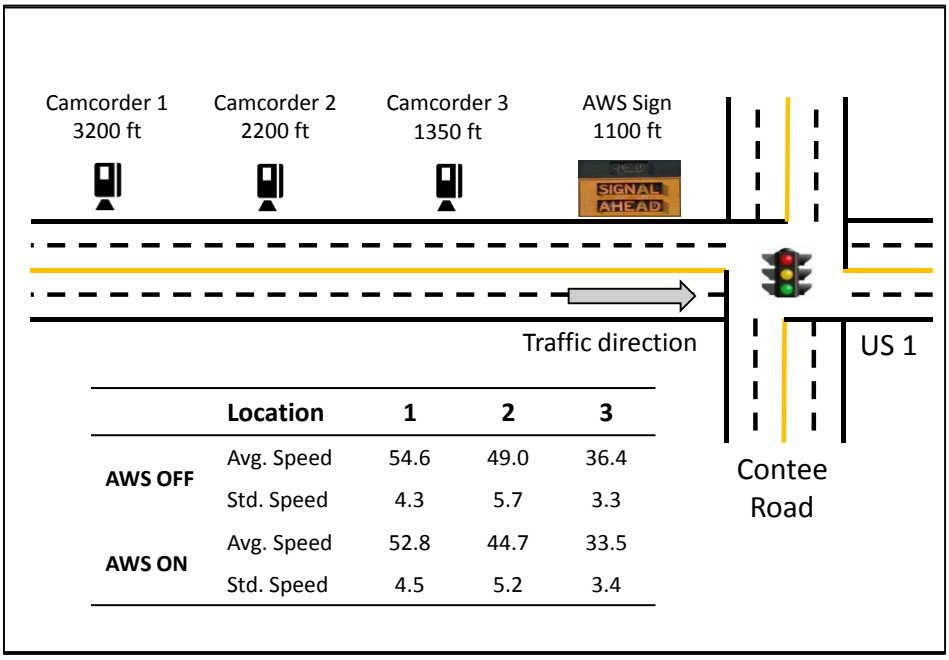


Figure 4-7 Wide-range traffic monitoring system and Advisory speed limit in the simulation platform

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

Once the drivers of approaching vehicles notice the advisory speed limit or the advanced warning sign, they react to the sign by either changing their speeds to conform with the advisory speed or to slow down as a response to 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.



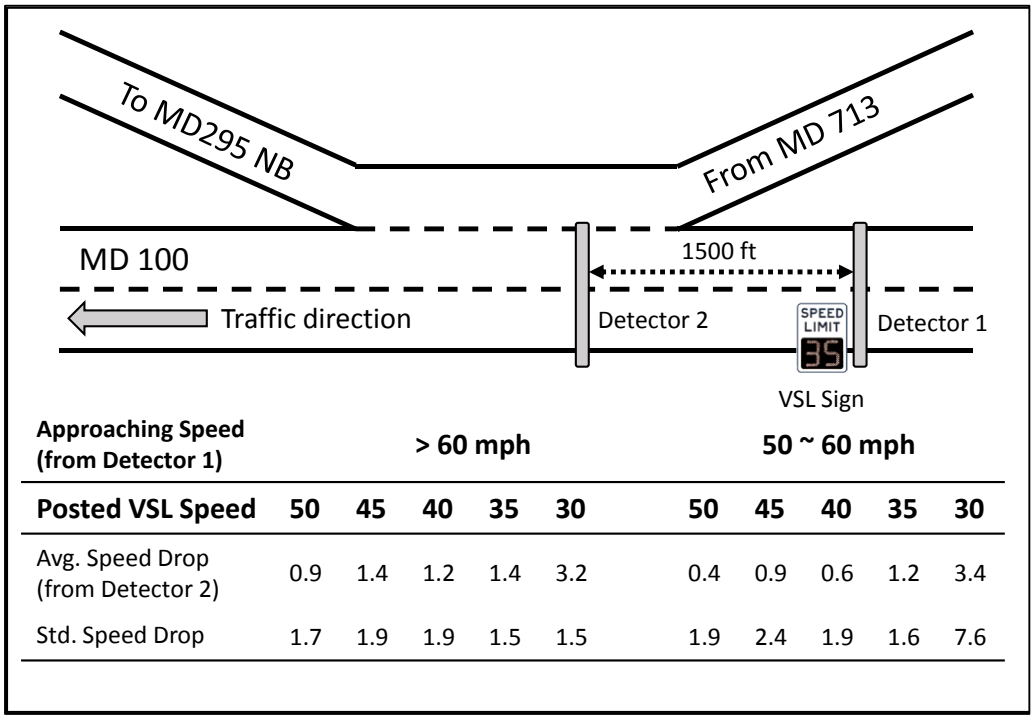
	Location	1	2	3
AWS OFF	Avg. Speed	54.6	49.0	36.4
	Std. Speed	4.3	5.7	3.3
AWS ON	Avg. Speed	52.8	44.7	33.5
	Std. Speed	4.5	5.2	3.4

Figure 4-8 Impacts of Impacts of the AWS from field studies

Figure 4-8 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 4-8 (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 4-9).



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 4-9 Impacts of the VSL control from field studies

As demonstrated in Figure 4-9, 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 4-10.

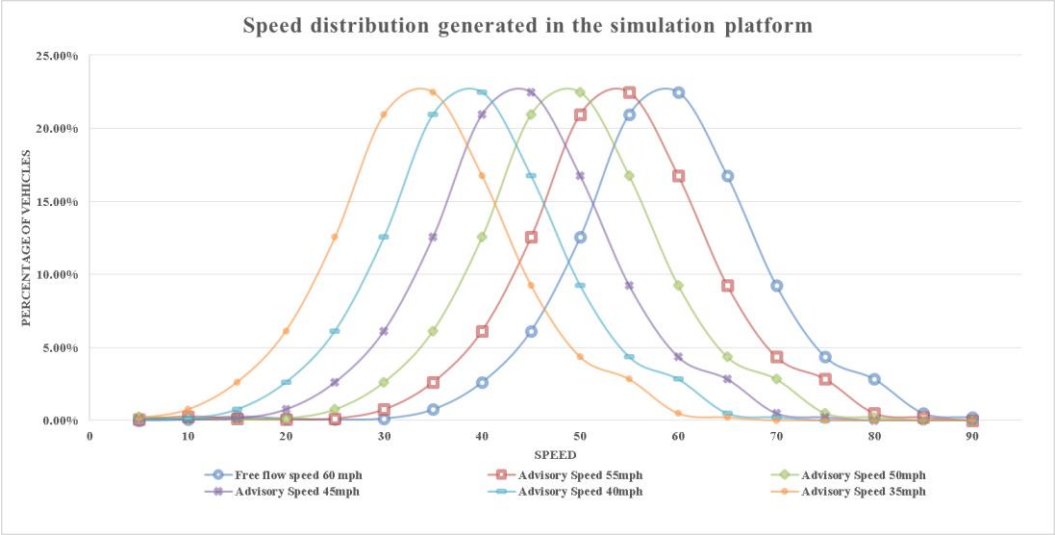


Figure 4-10 Speed distribution generated for drivers' response to the AWS/VSL

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 was programmed in the simulation platform. Figure 4-11 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 checks the current signal status and calls for executing the 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.

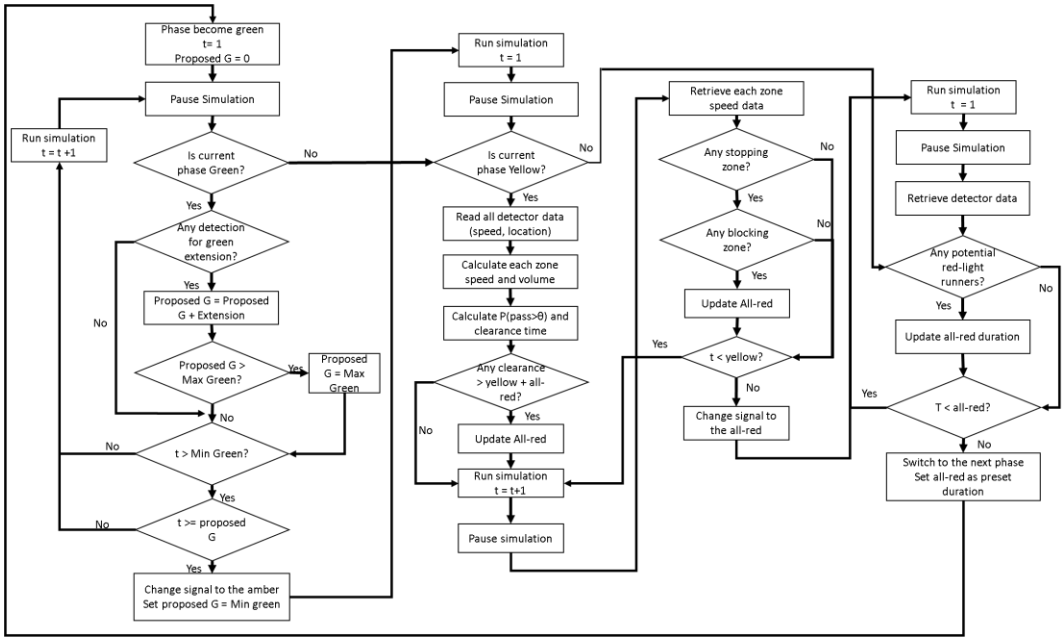


Figure 4-11 Flowchart for signal controller

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: Results of Performance Evaluation

5.1 Introduction

This chapter presents the performance evaluation results of the DZPS deployed at two high-speed intersections: US 40 @ Western Maryland Parkway (Intersection-1) and MD 213 @ Williams/Locust Point Road (Intersection-2). Field evaluations of the deployed DZPS were conducted one month after their activation dates. Figure 5-1 show the key geometric features of these two intersections and the detection sensor locations.

Figure 5-1 Intersection of US 40 and MD 910C and Intersection of MD 213 and Locust Point Rd

5.2 Location Overview of the Deployed DZPS

The Intersection-1, US 40 and Western Maryland Parkway in Washington County, Maryland, is a three-leg intersection where Western Maryland Parkway (three approaching lanes, two for left-turn and one for right-turn vehicles) ends at US 40, a four-lane divided highway with a posted speed limit of 55 mph. The neighboring intersections are about 1,400 feet and 4,500 feet away on either side along US 40 and the target approach has an on-ramp to I-81 700 feet upstream. There were 15 crashes recorded at this intersection between 2010 and 2012, and 12 of them were potentially related to the responses of drivers in the dilemma zone. This intersection's DZPS, activated in October 2016, includes one web-based monitoring module, two sensors on the eastbound US 40 for vehicle detection and all-red activation, and one sensor on westbound US 40 for green extension under actuated control (see Figure 5-1 for exact sensor locations). Its spatial distribution of dilemma zones for vehicles with different approaching speeds prior to the system deployment is shown in Figure 5-2.

The Intersection-2, MD 213 at Williams Street/Locust Point Road in Cecil County, Maryland, is a four-leg intersection. MD 213 is a two-lane undivided highway a posted speed limit of 50 mph and Williams Street/Locust Point Road is a two-lane undivided highway a posted speed limit of 30 to 35 mph. There were six crashes recorded at this intersection between 2010 and 2013, and four of them were side-angle crashes potentially related to the responses of drivers in the dilemma zone. This intersection's DZPS, activated in early 2017, includes one web-based monitoring module, two sensors each on the northbound and southbound approaches of MD 213 for vehicle detection and all-red activation (see Figure 5-1 for exact sensor locations).

Its spatial distribution of dilemma zones for vehicles with different approaching speeds prior to the system deployment is shown in Figure 5-3.

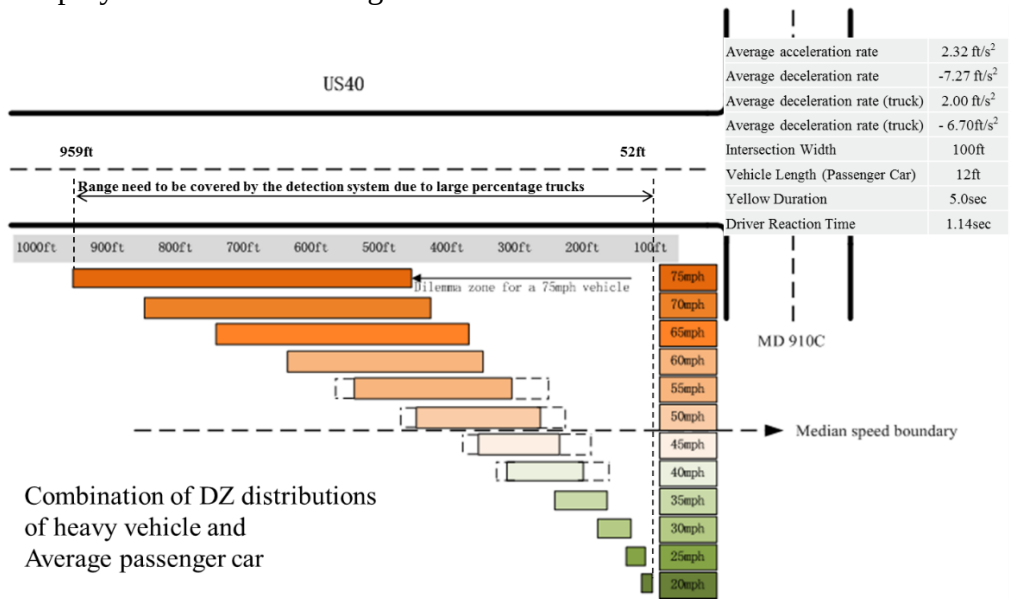


Figure 5-2 Spatial Distribution of the dilemma zones at intersection of US 40 and MD 910C prior to the system deployment

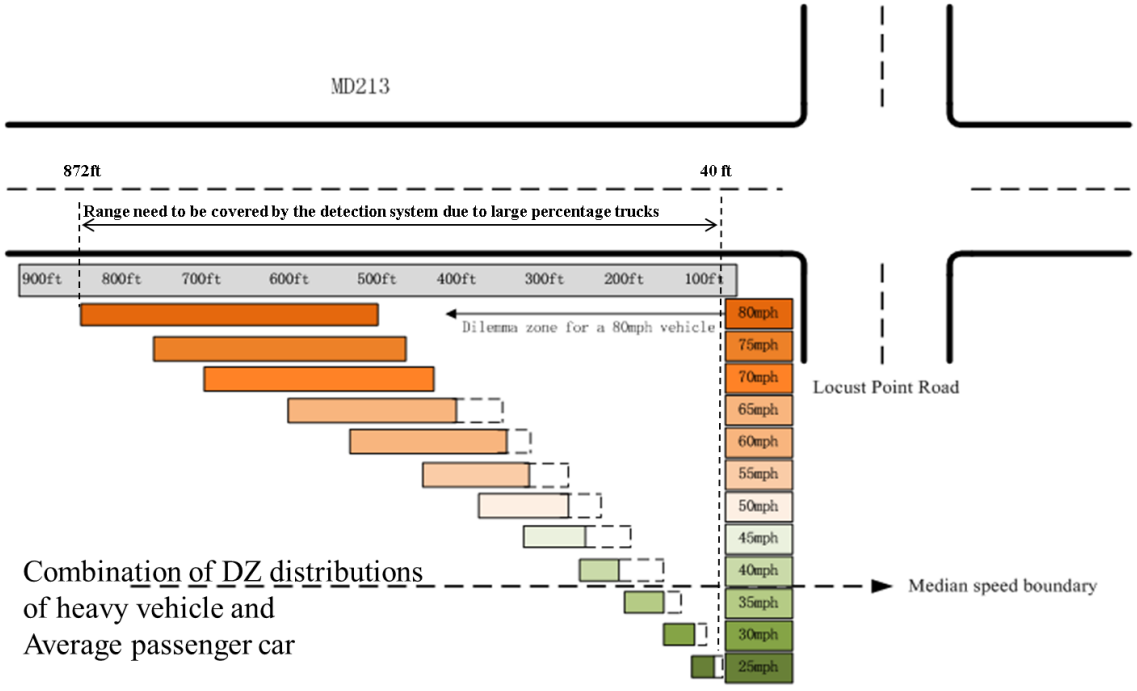


Figure 5-3 Spatial Distribution of the dilemma zones at intersection of MD 213 and Locust Point Road prior to the system deployment

5.3 **Data collection procedures**

The field data during the "before" period were collected with five camcorders at 200, 300, 500, 700, and 900 feet from the stop line to measure the speed of each approaching vehicle, and one camcorder was used concurrently to record the signal timings. After the DZPS deployments, all essential data for "before-and-after" impact comparison were collected from both the deployed wide-range sensors and the roadside camcorders.

Table 5-1 shows one vehicle's trajectory data detected by the wide-range sensors, including signal status and the distance to the stop line. Figure 5-4 shows the vehicle running the red light: entering the intersection 1.7 seconds after the start of the all-red phase. It was traveling at a speed of 49 mph at 455 feet from the stop line at the onset of the yellow phase, and 46 mph at the distance of 115 feet from the stop line at the onset of the red phase. After that, it did not reduce its speed and went through the intersection during the all-red phase.

Figure 5-4 Screen capture on a red light running vehicle from the camcorder

Table 5-1 Sample data of a vehicle's trajectory from the wide-range monitoring sensors

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

The collected before-and-after data were used for investigating its impacts on the following traffic flow characteristics and driver behaviors:

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

In addition, changes in the total dilemma zone length, the total number of red-light running incidents, and the false alarm rate were also evaluated. More specifically, the performance evaluation employed the following measures of effectiveness (MOE):

- MOE-1: *Distribution of the dilemma zones*, varying with each individual vehicle's approaching speed and accelerate/deceleration rate.
- MOE-2: *Drivers' responses to the yellow phase* at different approaching speeds and distances from the stop line.
- MOE-3: *Traffic flow characteristics*, including the approaching speed distributions, and average acceleration/deceleration rates.
- MOE-4: *The detection rate* of the DZPS with respect to red-light running incidents and all-red extensions.

5.4 **Impacts on the traffic flow characteristics**

Figure 5-5 and Table 5-2 show the spatial distribution of the observed speeds. The maximum speed detected at different locations does not seem to be impacted by the deployed DZPS. However, the average traffic speeds after the deployment were detected to decrease significantly. For example, the average speed was reduced 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 for Intersection-1. Similar decreasing patterns were also observed at Intersection-2, where the average flow speed was reduced from 46.1 mph to 45.7 mph at the distance of 900 ft from the stop line, 42.8 mph to 37.9 mph at 500 ft, and 33.6 mph to 34.3 mph at 200 ft. One can conclude that the deployment of DZPS sensors indeed impacted driver behaviors, and most of drivers reduced speed except for aggressive drivers – those approaching at speeds far exceeding the posted speed limit.

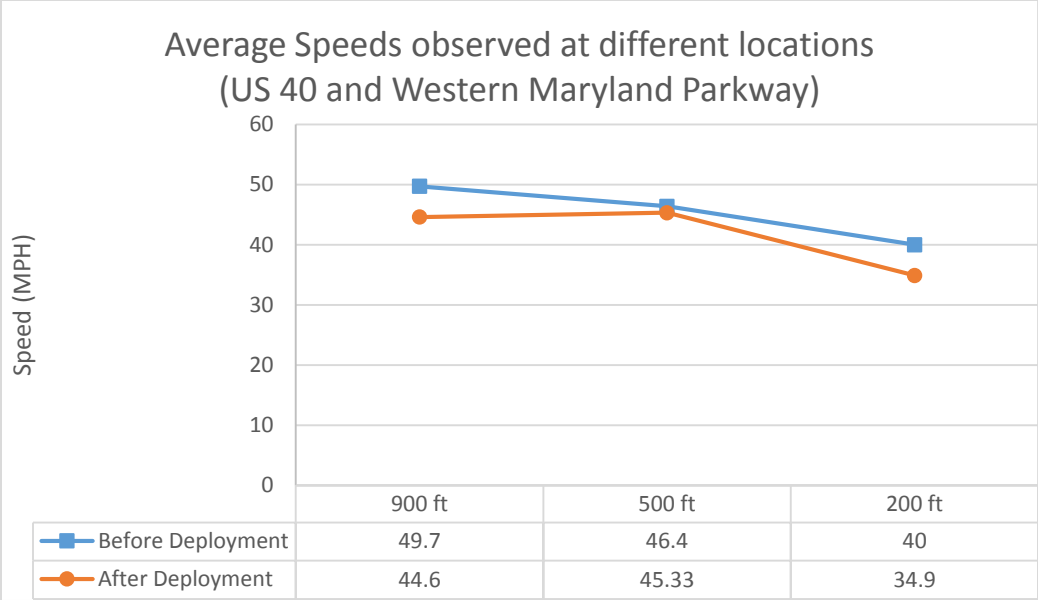


Figure 5-5(a) US 40 and Western Maryland Parkway

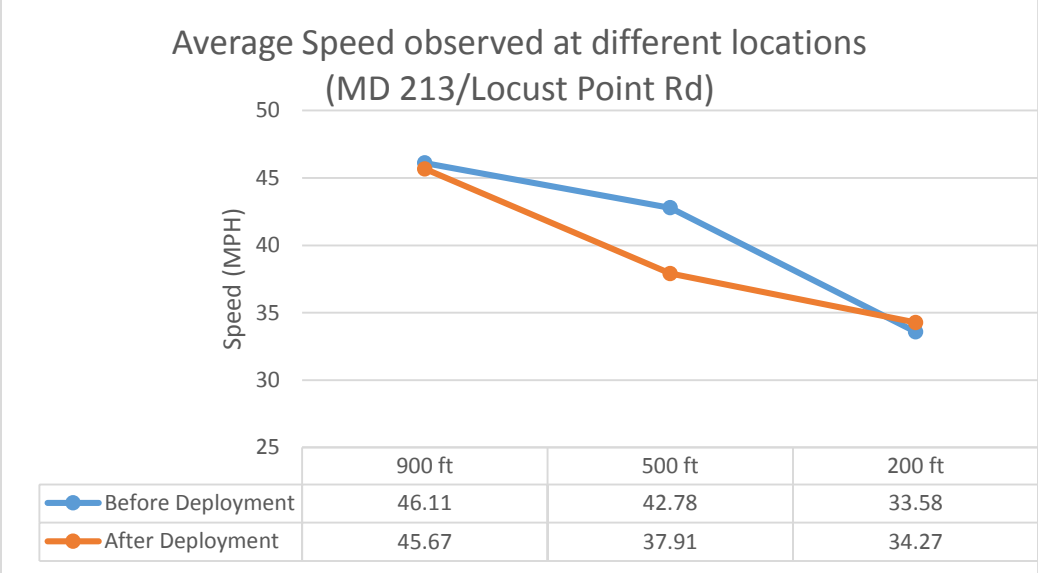


Figure 5-5(b) MD 213 and Locust Point Road

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

Table 5-2 Distribution of the speeds before-and-after the DZPS deployment at Intersection-1

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 5-6 shows the cumulative speed distribution before and after deployment at Intersection-1, and Table 5-3 summarizes the percentage of vehicles within each speed bin. Note that the speed limit at the location for the DZPS deployment is 55 mph. As shown in Table 5-3, the percentage of high-speed vehicles has been reduced from 29% to 16%, a reduction of 13 percent. The deployed roadside sensor had some impacts on drivers, as reflected in their reduced speeds when approaching the intersection. 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 increased the percentage of drivers approaching at the speeds below or around the speed limit.

However, for aggressive drivers (i.e., over 55 mph) observed at the distance of 500 feet from the stop line, the deployed system did not seem to impact their approaching speeds (Figure 5-6). This actually justifies the need to implement control strategies (e.g., the all-red extension) to prevent those drivers from causing crashes with side-street entering vehicles. Figure 5-7 and Table 5-4 shows the similar speed reduction pattern at Intersection-2.

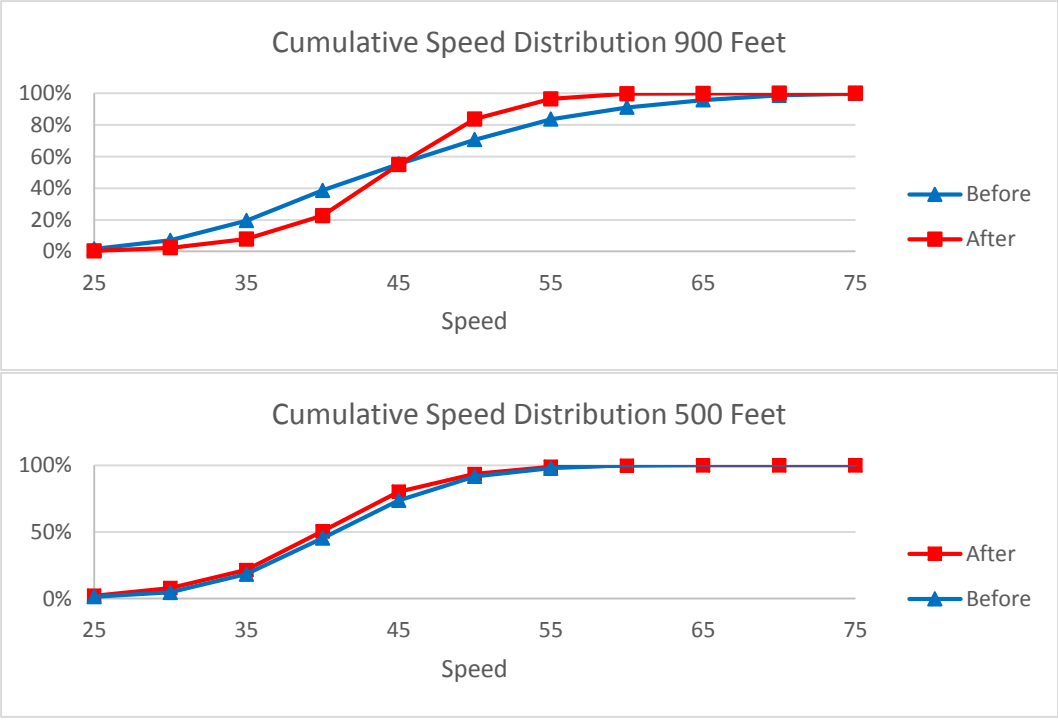


Figure 5-6 Cumulative distribution of the approaching speeds at Intersection-1

Table 5-3 Frequency distributions by speed bin at Intersection-1

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				

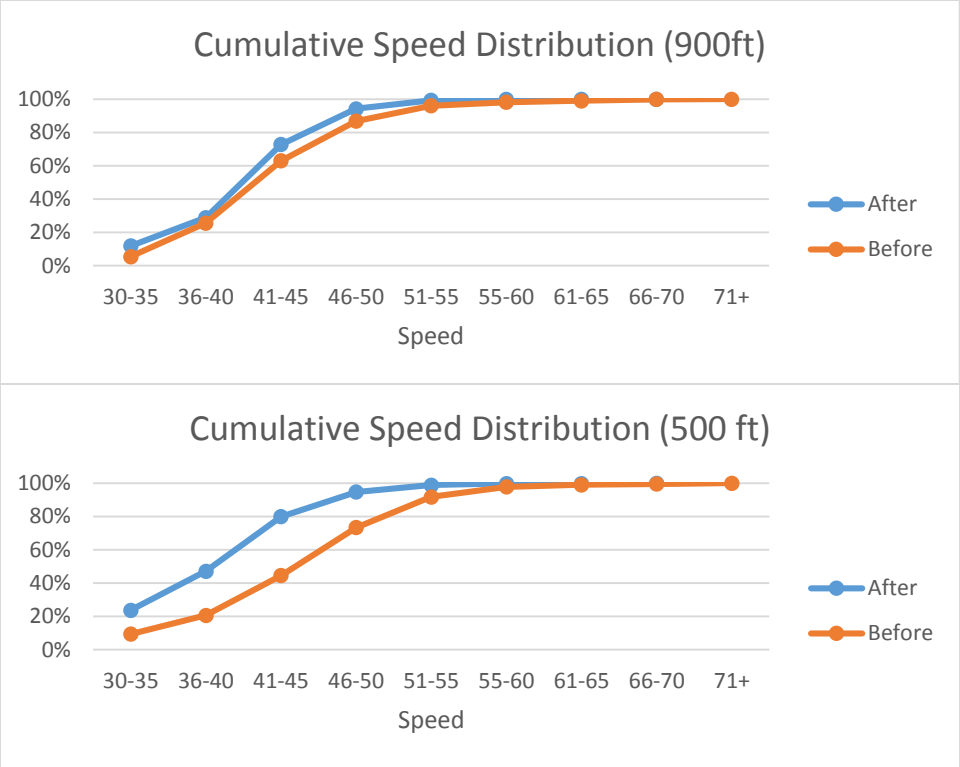


Figure 5-7 Cumulative distribution of the approaching speeds at Intersection-2

Table 5-4 Frequency distributions by speed bin at Intersection-2

Speed	Before		After	
	Frequency	Percentage	Frequency	Percentage
70-75	3	0%	0	0%
65-70	3	0%	2	0%
60-65	8	1%	0	0%
55-60*	37	6%	7	1%
50-55	113	18%	32	5%
45-50	177	29%	115	17%
40-45	147	24%	254	38%
35-40	69	11%	182	27%
~35	58	9%	77	12%
Over the Speed Limit (total)	51(615)	8%	9(669)	1%
* Speed limit: 55 MPH				

5.5 **Impacts on the deceleration rate and the distribution of dilemma zones**

The average acceleration/deceleration rate of approaching vehicles during the all-red phase was calculated from the extracted video data and the sensor log files. The average deceleration rate was changed from -7.28 $^{ft}/_{S^2}$ to -11.27 $^{ft}/_{S^2}$ after the deployment at Intersection-1, and -9.79 $^{ft}/_{S^2}$ to -10.69 $^{ft}/_{S^2}$ at Intersection-2. An increase in the average deceleration rate implies that drivers were likely to "Stop" at the onset of the yellow phase after noticing the deployed DZPS.

Based on the new calculated acceleration/deceleration rate, one can then compute the distribution of dilemma zones after the system deployment. Figure 5-8 (a) shows the distribution of dilemma zones before and after the deployment at Intersection-1. 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. The length of the dilemma zone for each speed bin was reduced. Figure 5-8 (b) shows the distribution of dilemma zones before and after the deployment at Intersection-2.

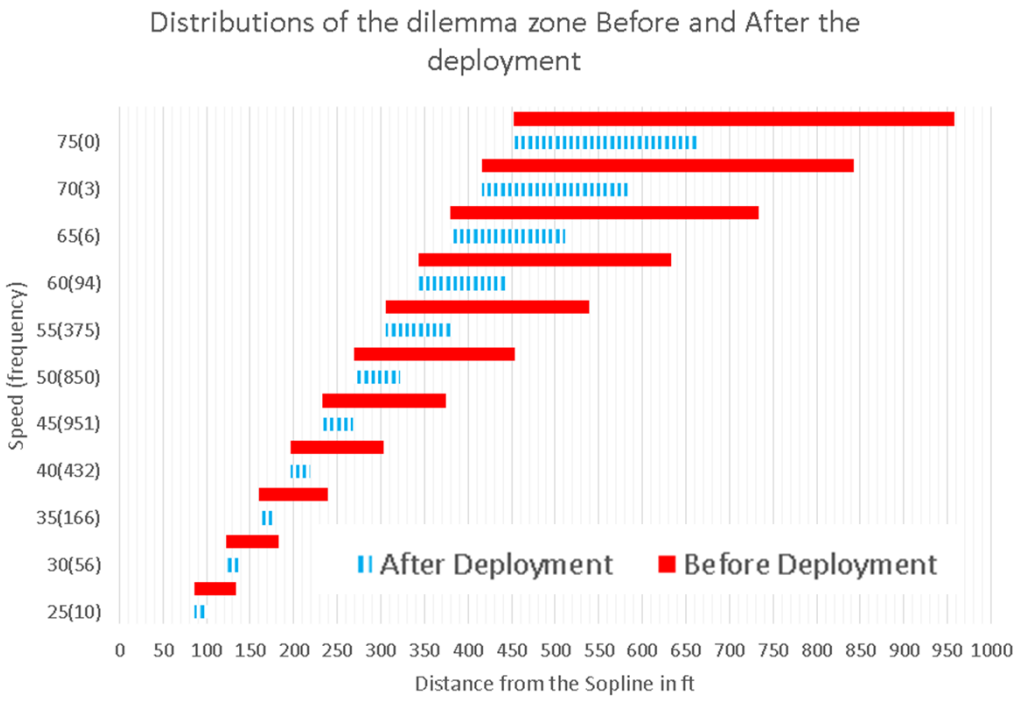


Figure 5-8(a) US 40 and Western Maryland Parkway

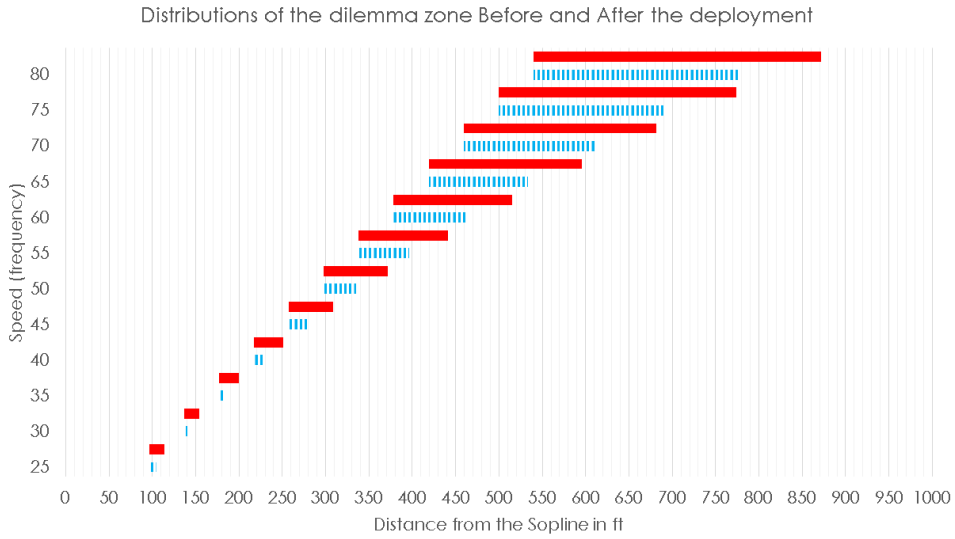


Figure 5-8(b) MD 213 and Locust Point Road

Figure 5-8 Before-and-after distributions of dilemma zones

5.6 **Impacts on driving populations and intersection safety**

Table 5-5 summarizes the decisions of drivers during the yellow phase at Intersection-1. The percentage of drivers taking the "Pass" action at the onset of the yellow phase decreased for those approaching at a moderate speed (i.e., 45-55 mph for the speed limit of 55 mph). For example, 50% of the vehicles traveling at 45-55 mph at the 300-400 feet from the stop line chose to pass the intersection in the before-deployment period, and only 43% did so in the after-deployment period. Such a reduction varied between 6% and 15% depending on the distance to the stop line. For drivers approaching the intersection at the speed above the speed limit, the presence of DZPS did not seem to have any impact on their decisions. The percentage of high-speed vehicles making the "passing" decision during the yellow phase remains relatively stable from the before- to the after- deployment period (Figure 5-9).

Similarly, at Intersection-2 50% of the vehicles traveling below the speed limit at around 300-400 feet took the "pass" action in the before-deployment period (Table 5-5 (b)), and only 18% did so in the "after-deployment" period. Overall, the total number of vehicles traveling over the speed limit was reduced at both intersections (Table 5-3 and Table 5-4), due likely to the presence of the roadside sensors.

Table 5-5 Before-and-after comparison of drivers taking the "pass" decision at the intersection

Table 5-5 (a) US 40 and Western Maryland Parkway

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)

Table 5-5 (b) MD 213 and Locust Point Road

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% (13)	100% (100)	100% (6)	74% (73)	43% (21)	50% (24)	18% (28)	20% (5)	3% (61)
55+ mph	100% (9)	100% (2)	100% (20)	100% (5)	88% (47)	100% (6)	50% (16)	44% (21)	10% (20)	19% (31)
Percentage of drivers taking the "Pass" decision from the field observations The number in parenthesis denotes the sample size.										

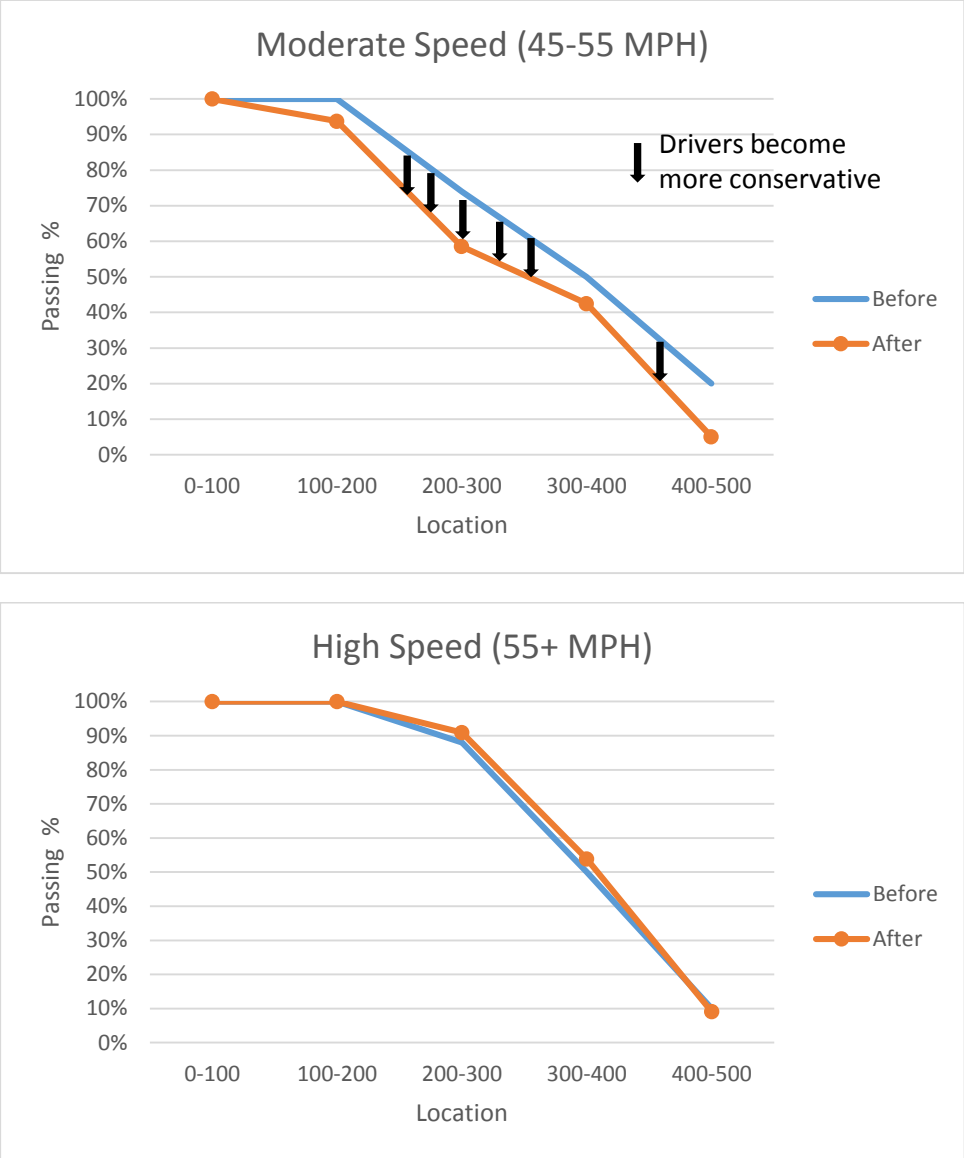


Figure 5-9(a) US 40 and Western Maryland Parkway

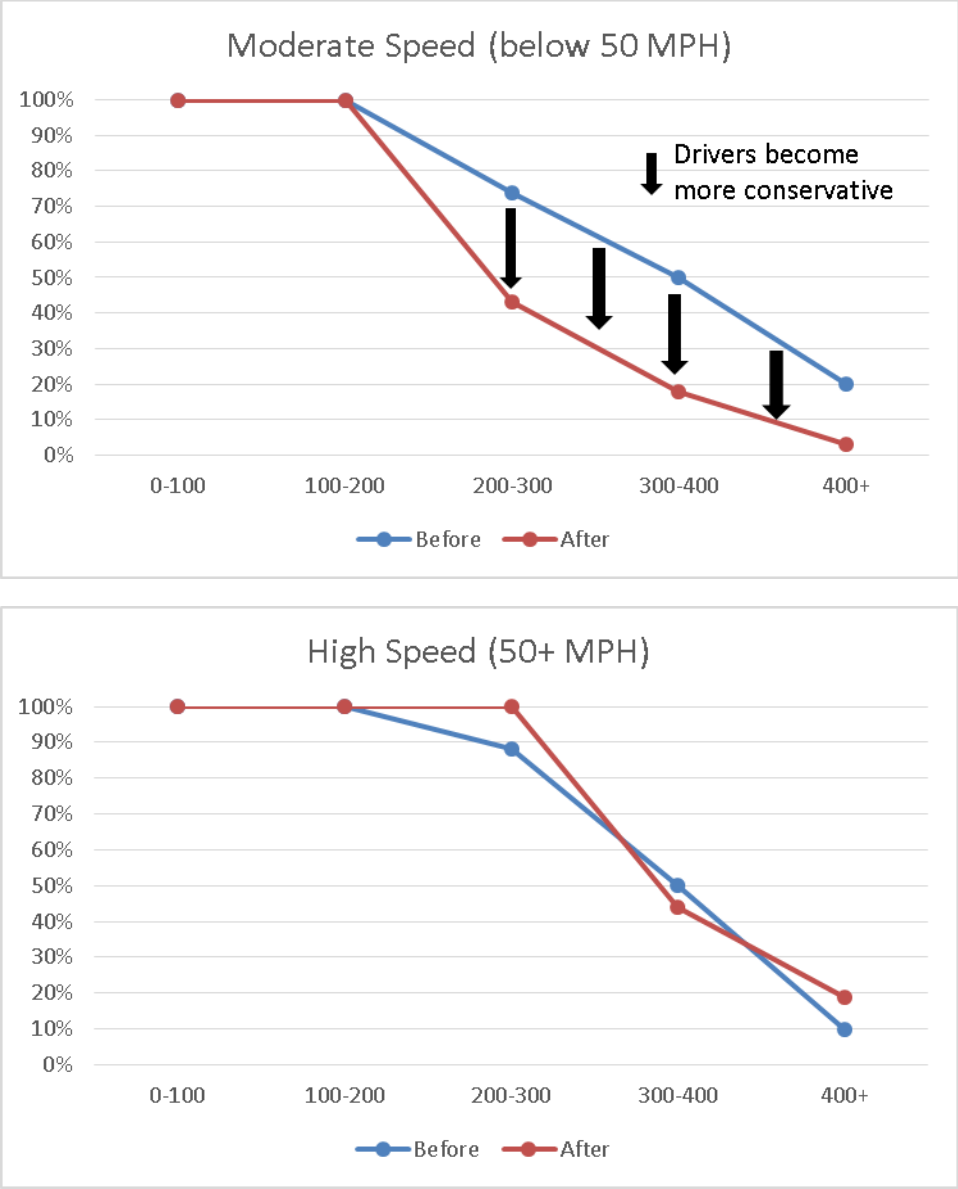


Figure 5-9(b) MD213 and Locust Point Road

Figure 5-9 Before-and-after comparison of drivers taking the "pass" action during the yellow phase under different approaching speeds at the intersection

5.7 **Safety evaluation indicator**

It often takes several years of sufficient field data to directly evaluate any traffic safety impacts. A surrogate MOE, the total length of dilemma zones, was used for the short-term evaluation of the safety improvement at these two intersections.

Figure 5-10 shows the dilemma zone length by approaching speed before and after the deployment. As shown with Equation 5-1, the length of the dilemma zone exhibits a polynomial relation with a vehicle's approaching speed.

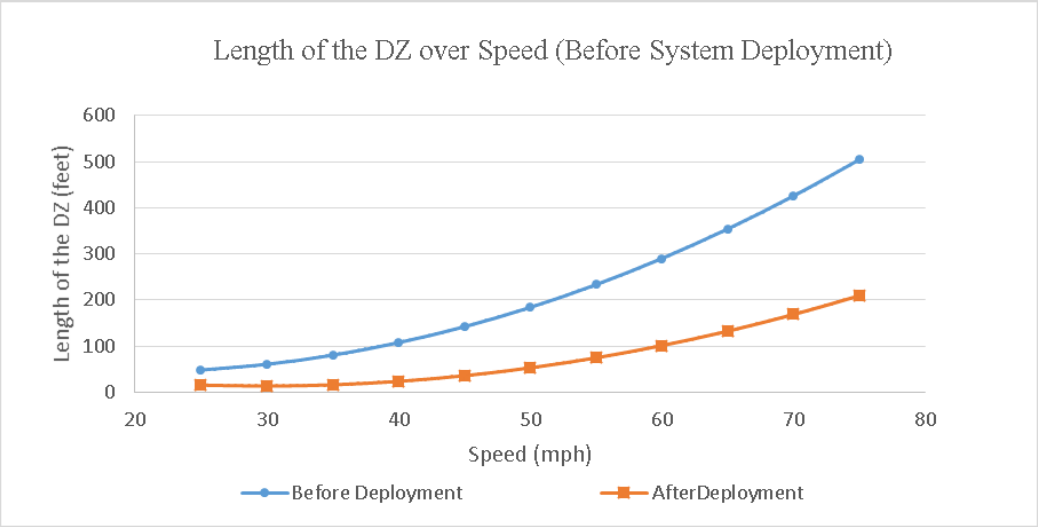


Figure 5-10 Length of the dilemma zone over different speeds (before-and-after the deployment)

$$L_{DZi} = \alpha * v_i^2 + b * v_i + c \quad (5\text{-}1)$$

Once the estimated lengths of dilemma zones were obtained, a safety surrogate, the weighted total length of the dilemma zones, was constructed as follows:

$$DZ_L = \sum L_i * \frac{Vol_i}{Vol_{Total}} \quad (5\text{-}2)$$

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 value of the weighted total dilemma zone length is 73 feet and 44 feet, respectively, for before- and after- deployment period. The ratio between these two dilemma zone lengths is 0.60, implying that the likelihood of a vehicle trapped in dilemma zones has been reduced by 40% after deploying the DZPS.

5.8 **Detection accuracy**

The performance of DZPS with respect to the detection of red-light running vehicles and timely execution of all-red extensions was evaluated in the following steps:

- Synchronize the times of the video files and sensor log data;
- Identify red light running vehicles from the video files;
- Identify all-red intervals from the video files;
- Determine whether the all-red intervals were extended for red light running vehicles; and
- Calculate the detection rate, the extension rate, and the false alarm rate.

The definitions of the selected MOEs are: (1) the extension rate is the number of all-red extensions over the total number of cycles; (2) the detection rate is the number of detected red light running vehicles from the system over the total number of red light running vehicles; and (3) the false alarm rate is the number of all-red extensions without red-light-running vehicles over the total number of cycles.

Table 5-6 shows that the deployed system successfully detected all red-light running vehicles and executed all-red extensions in time for those aggressive drivers. However, the 100 percent detection rate is accomplished at the cost of 30% and 16% false alarm rates at these two intersections. Theoretically, one can investigate an optimal tradeoff between the detection rate and the false alarm rate.

Table 5-6 Evaluation of the DZPS's detection performance

MOE	Simulation	Field Operation* (US 40)	Field Operation** (MD 213)
Red-light-running rate (RLR) (RLR / cycle)	9.5%	1.6%	1.6%
Extension call rate (extension call / cycle)	30.0%	31.7%	17.6%
Detection rate (protected RLR)	100.0%	100.0%	100.0%
False alarm rate (false alarm / cycle)	21.0%	30.0%	16.0%
* Five red light running vehicles during the data collection (312 cycles). * Seven red light running vehicles during the data collection (441 cycles).			

5.9 **Closures**

A field evaluation of the deployed DZPS was conducted at each deployed intersection about one month after the system activation date. The performance evaluation results were presented in this chapter. More drivers were observed to take a conservative action of "stop" during the yellow phase in the after deployment period. The deployment of the DZPS did not impact aggressive drivers traveling at a speed over the posted speed limit. It justifies the need to deploy a system that can prevent vehicles from the side street to crash with aggressive red-light runner vehicles.

CHAPTER 6: Research Summary and Conclusions

6.1 Summary of accomplished tasks

The research team designed, deployed, and evaluated a dynamic dilemma zone protection system (DZPS). It features two mutually supplemented functions - offering both proactive and reactive protections to drivers approaching a signalized intersection during a yellow phase.

The design for proactive protection is to use an advanced warning sign/variable message sign to actively convey the messages to the approaching drivers regarding what actions are to be taken during the yellow phase. For those failing to complying with the advice and thus trapped in a dilemma zone, the DZPS's reactive protection function can instruct the signal controller to extend the all-red extension time to prevent potential angle-crash accidents.

Prior to field development of the DZPS, the research team developed a customized simulator for such a system and conducted extensive experimental analyses to identify potential operational issues and assess the resulting impacts on approaching drivers and traffic patterns. The statistical results from rigorous field observations confirmed the effectiveness of the deployment. The DZPS achieved a detection rate of 100 percent on red-light running vehicles and activated all-red extensions in time to prevent side-angle crashes. Primary research results and deployment findings from this project are summarized below:

- *Identifying critical issues* from an in-depth review of existing studies, including the design of dilemma zone protection systems (e.g., advanced warning signs), driving behavior during the yellow phase, and signal control strategies (e.g., green early terminations or green extensions).
- *Developing critical functions,* including estimating the spatial distribution of dynamic dilemma zones, predicting a driver's decision in their dilemma zone as to "stop" or "pass" during a yellow phase, and computing the all-red extension duration needed to prevent crashes.
- *Constructing a customized simulation platform* to identify critical deployment issues and assess the impacts of DZPS on the behavior of driving populations prior to the actual field deployment.
- *Designing a dynamic all-red extension algorithm* to ensure safety but not at the cost of excessive delay. The all-red extension algorithm consists of three major components: a decision module, an enhanced module, and a supplemental module.

Field evaluation results after deployment showed that the deployed DZPS's roadside sensors had a significant impact on driving behaviors, such as the distribution of traffic flow speeds, deceleration/acceleration rates, and the decision during the yellow phase. The deployed systems achieved a detection rate of 100 percent and execute an all-red extension in time to protect the red-light running vehicles.

6.2 Further Research Tasks

Much remains to be studied to better ensure intersection traffic safety, especially in view of the complexity of driving behaviors and the diversity of driving populations. Some future research tasks are listed below:

- *Impacts of VMS and AWS on the intersection traffic patterns***:** Although both designs have long been used by the traffic community to improve intersection safety, rigorous field studies on their impacts on the driving populations under different traffic conditions are quite limited. Such information, however, is essential to the design of any system or strategy to improve intersection safety. Hence, more field studies on this subject are needed.

- *Integration of the DZPS with connected vehicles***:** The emerge of connected vehicles in the traffic community can offer some unique real-time information for the responsible traffic agency to reliably detect traffic flow information, the spatial and temporal distributions of approaching vehicles, and the vehicle composition in the intersection detection zone. Hence, integration of the DZPS with connected vehicles under various penetration rates in the traffic flows can certainly enhance the system's reliability and reduce its dependence on the costly wide-range sensors.

- *Development of an evaluation function for intersection safety***:** To further confirm the benefits of the developed DZPS, more field data from other locations should be analyzed and compared. Key model parameters in the DZPS such as speed, volume, acceleration, deceleration, percentages of trucks, and the distribution of dilemma zones under various traffic conditions should be recalibrated and structured in a convenient form for field applications. Furthermore, additional field performance data can be used to develop an evaluation tool for the responsible agency to assess the benefits of a proposed DZPS prior to its field deployment.

- *Long-term impacts of the DZPS on traffic safety and driving populations:* Since the deployment of DZPS is relatively new to the traffic community and its initial field performance results are quite promising, more research should focus its long-term impacts on drivers' response after they have developed more knowledge about the all-red protection function. For example, drivers may evolve to be more aggressive under the DZPS, and the compliance rate with the VMS may diminish over years without effective enforcement. Such critical issues certainly deserve further investigation and more definitive answers will be needed prior to the full-scale promotion of the DZPS.

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APPENDIX

Operational Manual

Design, Deployment and Evaluation of the

Dilemma Zone Protection System

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Operational Manual

- Design, Deployment, and Evaluation of the Dilemma Zone Protection System -

A-1. Introduction

This operational manual is intended to serve as the guideline for traffic engineers to design, deploy, and evaluate a dilemma zone protection system (DZPS) at intersections plagued by rear-end collisions and angled crashes. The entire manual consists of the following three parts: (1) pre-deployment site selection and analysis; (2) design and field deployment of a DZPS, and (3) field evaluation of the deployed system's impacts on the driving population and safety improvement. Key operational steps to be taken in each part along with illustrative examples are presented in the following sections.

A-2. Part-1: Pre-deployment analysis and candidate site selection

All steps proposed in Part-I are for traffic engineers to evaluate the applicability of the DPZS to all candidate sites and analyze the potential benefits after deployment. Only those intersections experiencing a high frequency of side-angled crashes and/or rear-end collisions are likely to benefit from the DPZS deployment. Analysis of driving behaviors with respect to response discrepancies during the signal yellow phase should also be conducted to confirm that those accidents are mostly due to the presence of dilemma zones. A brief description of activities to be done at each step is presented below:

Step1: Screen candidate intersections with a crash history diagram (at least 3 years)

As shown in Figure A1, the crash diagram for US 40 and MD 910C, the intersection experienced a total of seven side-angled crashes (accidents in blue square), an average of 2 per

year. Figure A2 shows the crash diagram for MD 213 and Locust Point Road/William Street that experienced one fatality in year 2011 from a side-angled crash. Note that the criteria for screening those candidate sites for deploying any dilemma zone protection systems have not been established consistently by either federal or state agencies. The following criteria, preliminary in nature, are set based on the accident data at those DPZS deployments in Maryland:

- *Experience two or more side-angle accidents per year; OR*
- *Record one fatality per year due to side-angled crashes.*

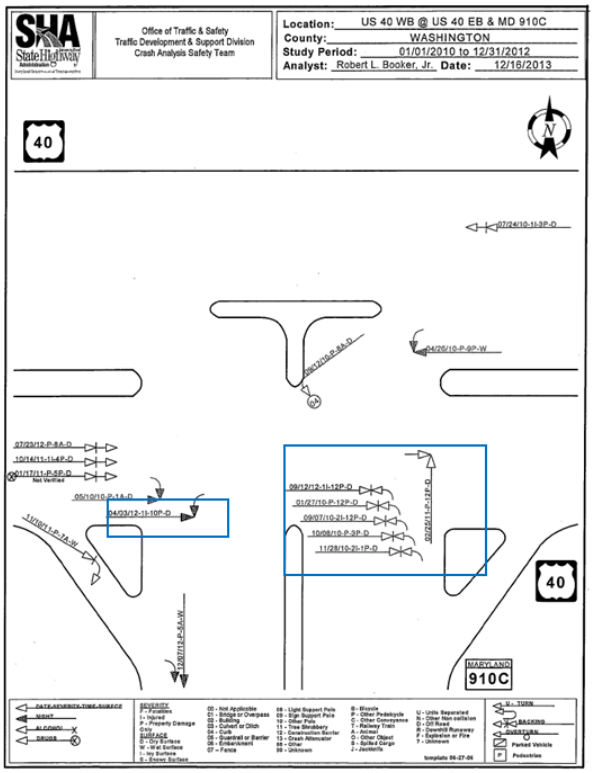


Figure A11 Accident history diagram at US 40 and Western Maryland Parkway in Washington County Maryland

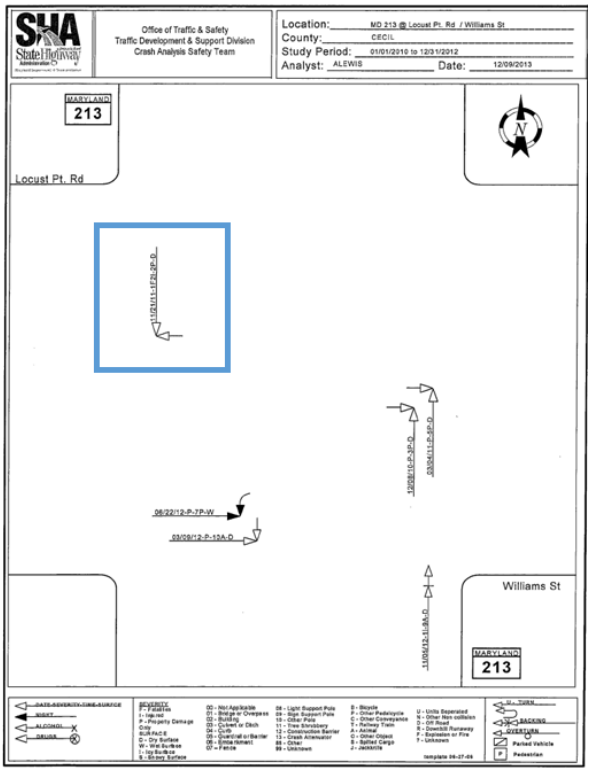


Figure A12 Accident history diagram on MD 213 and Locust Point Road in Cecil County

Step2: Identifying key factors contributing to intersection accidents from field data

For those DZPS candidate sites identified with the screening criteria, responsible traffic engineers should further collect the following data from each site and identify key factors that may contribute to intersection accidents:

- The percentage of aggressive drivers (e.g., hard braking during the yellow phase) and high-speed vehicles (20 mph over the posted speed limit)
- Geometric features of the candidate intersection (e.g., grade, sight distance, sight blockage with a minor street)
- The spatial-speed distribution of vehicles approaching the candidate intersection (i.e., 200ft, 500 ft, and 900 ft)
- The average acceleration/deceleration rate of vehicles approaching the candidate intersection.

- The percentage of drivers making the "stop" decision during the yellow phase under different average approaching traffic flow speeds.
- Signal timings (durations of the yellow and the red phase)

Table A1 shows the data collected from the intersection of US 40 and Western Maryland Parkway at three different locations to compute deceleration rates and acceleration rates. Table A2 shows the frequency distribution of the approaching speeds to the intersection, where about 30% of total drivers exceed the speed limit.

Table A7 Distribution of the speeds prior to the DZPS deployment at US 40 and Western Maryland Parkway

Location	**900 feet**	**500 feet**	**200 feet**
Data Collection Period	Before	Before	Before
Average speed (mph)	49.7	46.4	40
Standard Deviation	10.6	6.7	9.07
Minimum speed (mph)	18.9	10.9	4.58
Maximum speed (mph)	72.1	69.4	61.2
Sample Size	1233	1371	1343

Table A8 Distributions by speed bin for approaching vehicles prior to the deployment (900ft)

At the intersection of US 40 and Western Maryland Parkway

Speed	**Before**	
	Frequency	**Percentage**
75+	**14**	**1%**
70-75	**36**	**3%**
65-70	**58**	**5%**
60-65	**92**	**7%**
55-60*	**160**	**13%**
50-55	189	15%
45-50	206	17%
40-45	236	19%
35-40	153	12%
30-35	68	6%
25-30	19	2%
Over the Speed Limit (total)	**360** (1231)	**29%**
* Speed limit: 55 MPH		

The intersection of US 40 and Western Maryland Parkway is a proper candidate location for a DZPS deployment because it has experienced more than two side-angle crashes per year, and drivers are relatively aggressive (30% of drivers exceed the speed limit).

A-3. Part-II: Design of the dilemma zone protection system

Based on the collected field data and the decision to deploy the DPZS, responsible engineers should take the following actions in the design phase:

Step1: Calculate the upper limit of the dilemma zones and their spatial distribution

The upper limit of the dilemma zones is critical to the selection of each candidate intersection's monitoring zone. One can apply the following equation to compute such a limit, and then determine the number of sensors to be deployed.

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

Where:

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

x_0: Critical distance to clear the intersection under the maximum acceleration rate;

τ: Duration of yellow interval (s);

δ_1: Reaction-time lag of the driving populations (s);

δ_2: Average decision-making time of the driving populations (s);

v_0: Approaching speed of individual 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).

Figure A3 shows the spatial distribution of the dilemma zones at the intersection of US 40 and Western Maryland Parkway. The upper limit of the dilemma zone is 960 feet from the stop line for vehicles approaching the intersection at a speed of 75 mph. Since each DMZS

sensor can cover up to 600 feet, two wide-range sensors, one should deploy two such sensors to cover the entire dilemma zones of 960 ft.

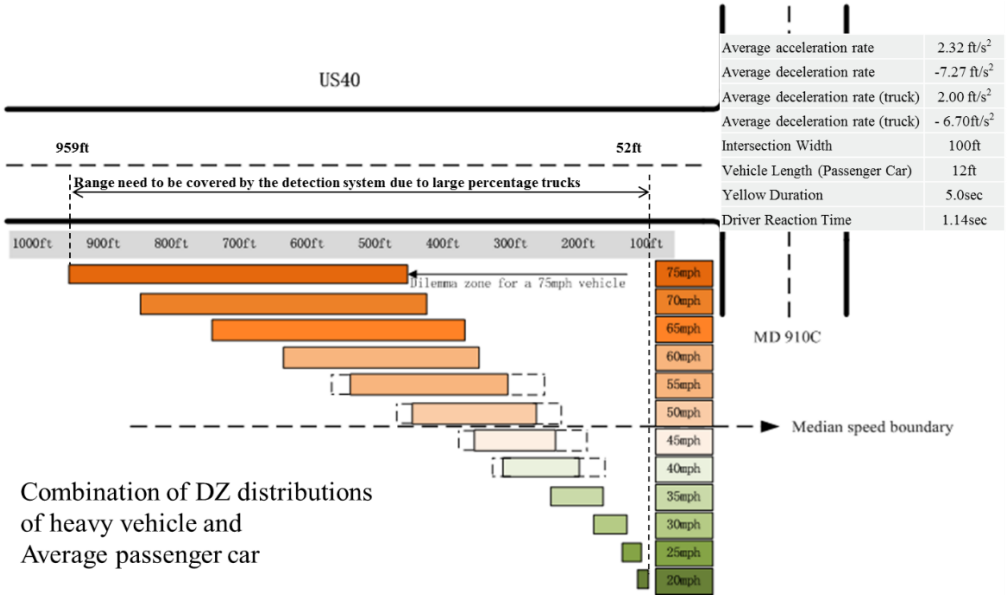


Figure A13 Spatial Distribution of the dilemma zones at the intersection of US 40 and MD 910C

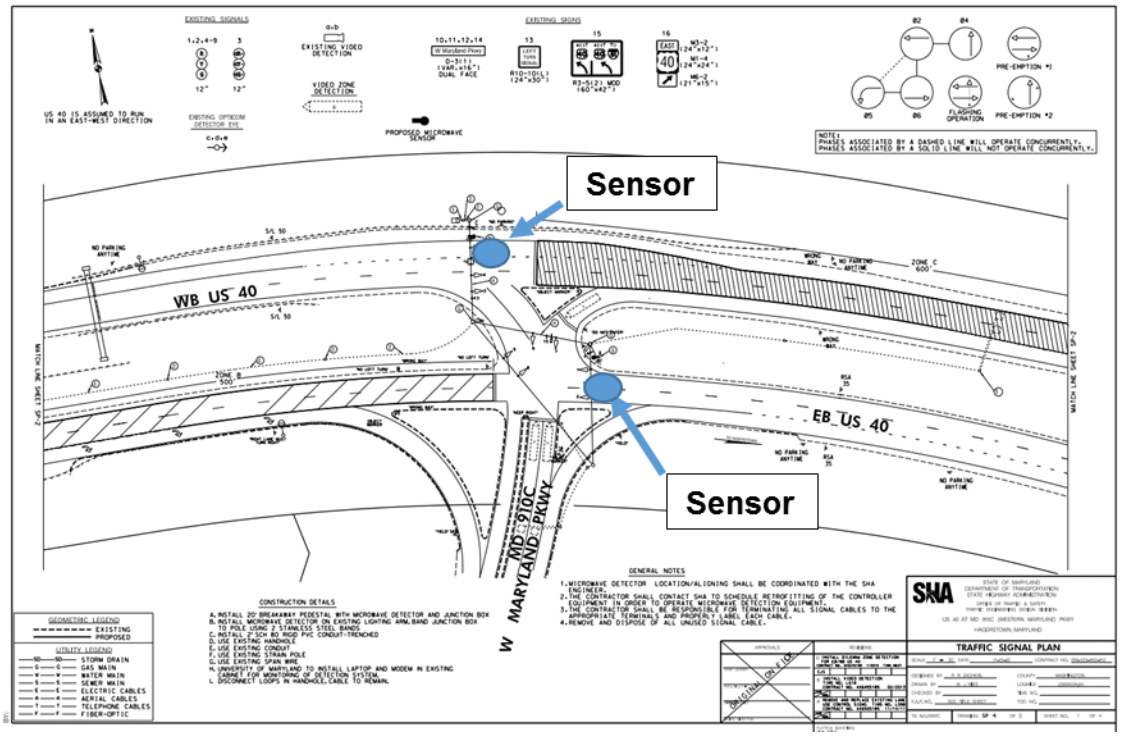
Step 2: Deployment of the DZPS's sensors

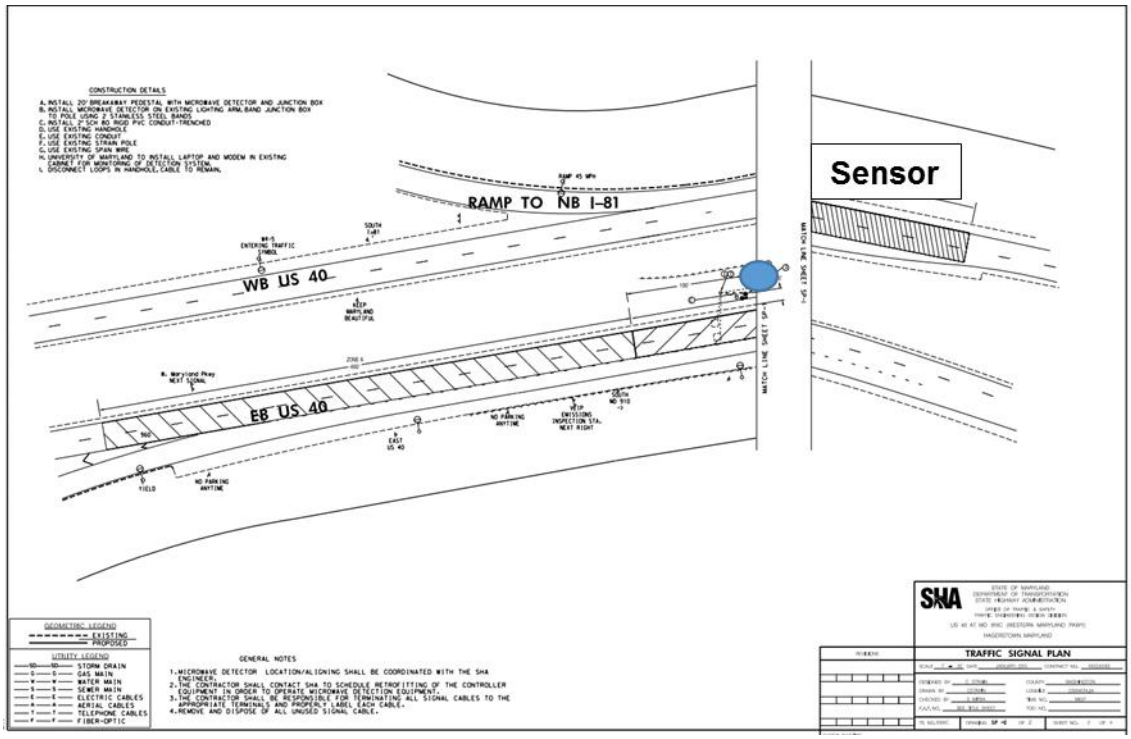
After identifying the upper limit of the dilemma zones and the number of sensors to be deployed, the next step is to identify the physical location of the sensors for the DZPS. To optimize the system's detection rate, one should address the following issues in the design:

- Make sure to cover all dilemma zones in the sensors' monitoring range;
- Make sure that all sensors are not blocked by trees or other objects;
- The height of deployed sensors should be between 20 and 40 feet;

Figure A4 shows the design plan of the DZPS at the intersection of US 40 and MD 910C and its system configuration. Since the upper limit of the eastbound traffic is up to 960 feet from the stop line, two sensors have been deployed for the eastbound approach. The first sensor was

located at the signal pole at the intersection; and the second sensor was placed 500 feet from the stop line with a new pole.





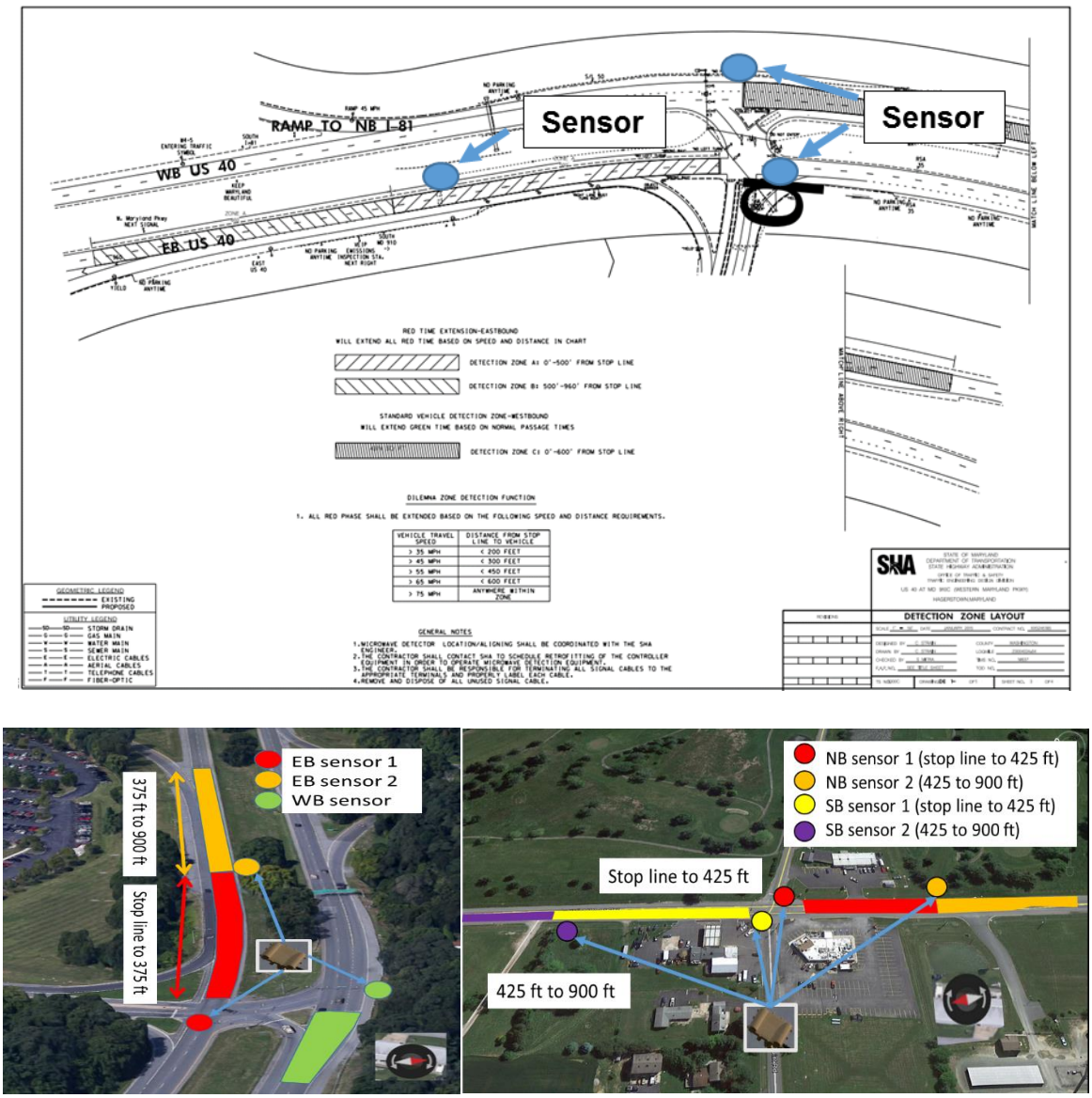


Figure A14 Design of the DZPS at the intersection of US 40 and Western Maryland Parkway

Step 3: Deployment of the DZPS

In deploying the sensors and connecting them with the signal controller, it is vital to ensure that all of the following tasks are conducted properly:

Sensor alignment, including:

- Attaching the viewfinder to the sensor (see Figures A5, and A6);
- Centering the middle of the roadway to the center of the viewfinder (see A7); and

- Rotating the sensors to line up with the center of the travel lanes.

Figure A15 Viewfinder

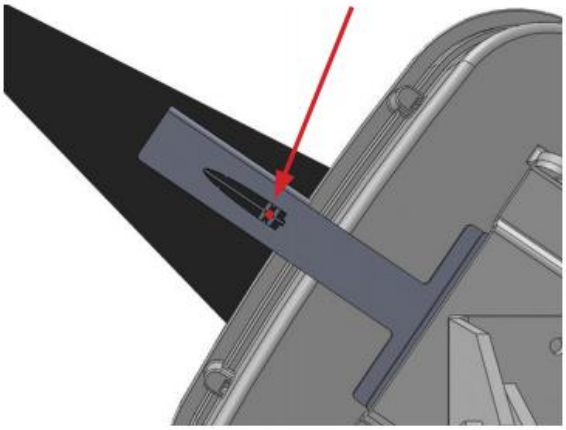


Figure A16 Attaching the view finder to the sensor and centering it in the middle of the roadway

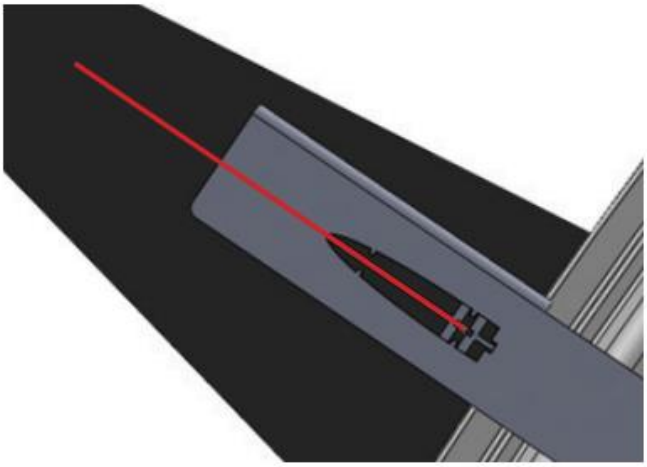


Figure A17 Aligning the center of the view finder with the center of the roadway

Hardware connections (see Figure A8), *including:*

- *Wide-range sensor* (Wavetronix Smartsensor Advanced) to provide the speed and location of all vehicles within the sensor's monitoring zone, and update the data in real time over an interval of 0.1 seconds.
- *Connection module* (Click 600) to serve as the connector between the laptop and the sensors for system setup, calibration, and power surge protection.
- *Contact closure* (Click 114) for sending the signal to the signal controller, based on the sensor setting.
- *Signal controller* (Econolite ASC/3) to have the function of an all-red extension.
- *Laptop* for use in the system setup and calibration of the sensors through the connection module

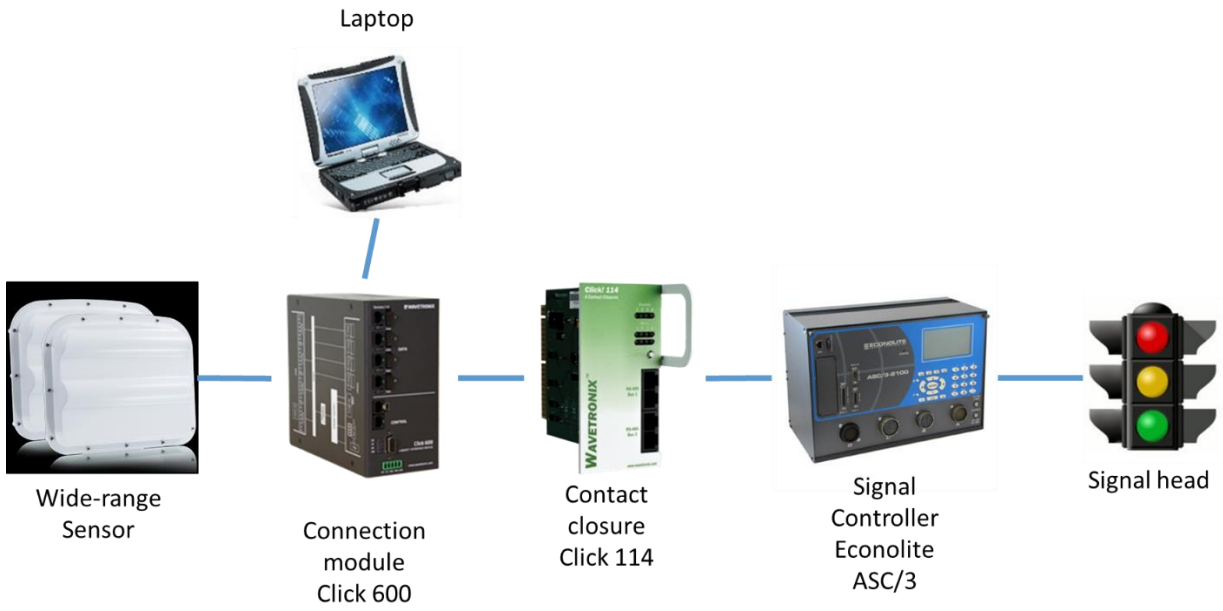


Figure A18 Hardware Connection between devices

Wiring include (see Figure A9):

- *Connection module* (Click 600 or click 222) to connect the sensors and the contact closure,
- *6-conductor cable* for the connection between the sensors and the connection module,
- RJ-11 cable for the connection between the connection module and a contact closure

Note that it is critical that all wires are properly and firmly connected before setting up the sensors.

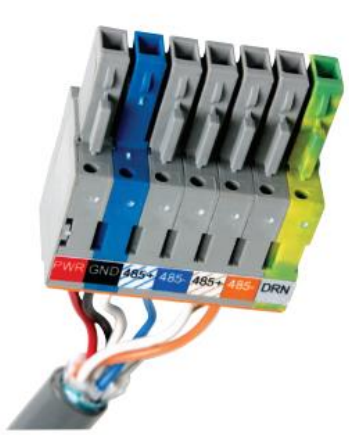
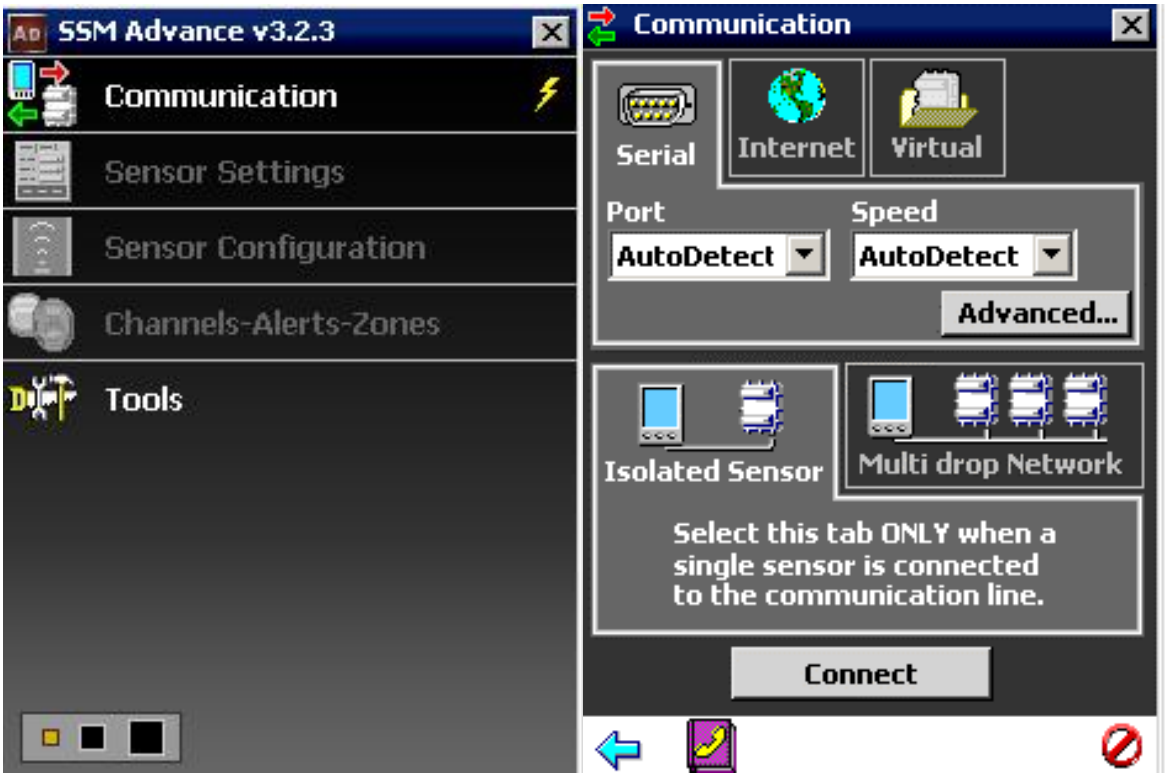


Figure A19 Connection module, Click 600, and Click 114

Sensors set-up and programming

The setup procedures include the following steps:

- Download software from https://www.wavetronix.com/en/support/products/121-smartsensor-advance-extended-range and install the software;
- Use a serial connection (RS-485) cable to connect the laptop with a connection module (Click 600);
- Launch the "SSMA" (Smart Sensor Manage Advance) program;
- Click "Communications" button in the main menu, tab to serial, and click "sensor configuration" and "installation details" (Figure A10)



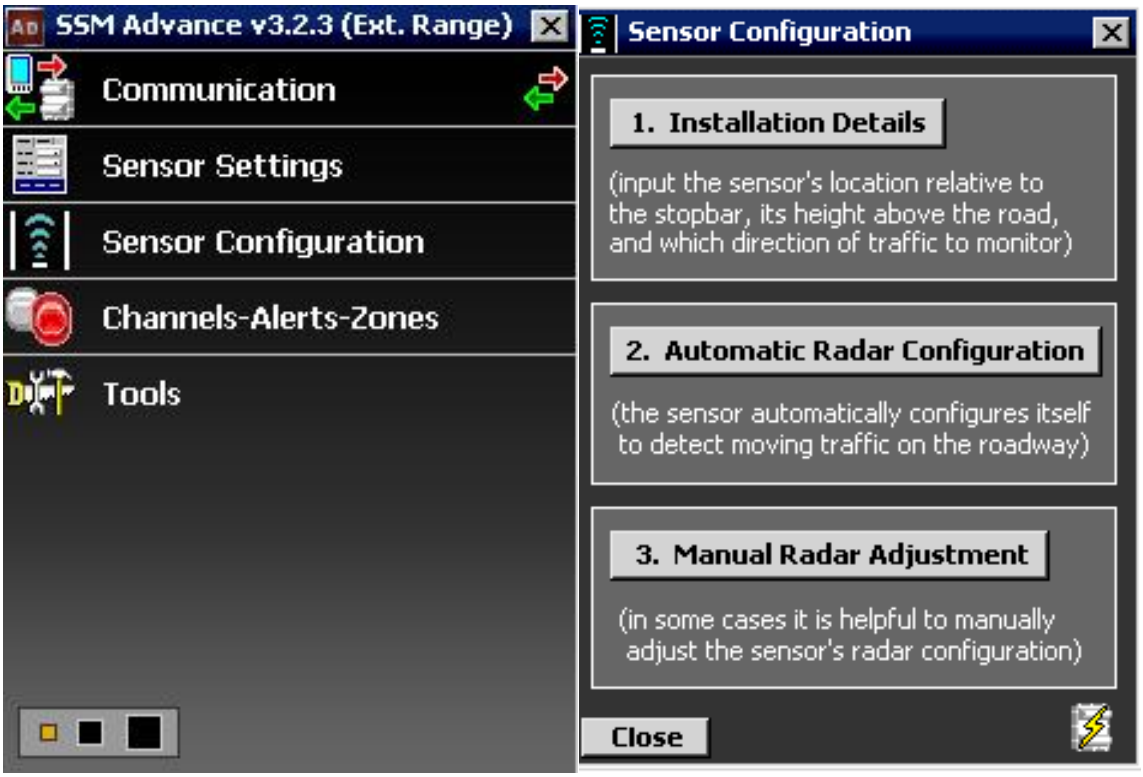


Figure A20 Sensor configuration

- Set up the geometric information such as direction, stop bar location, location of the sensor, height of the sensor. (see Figure A11)

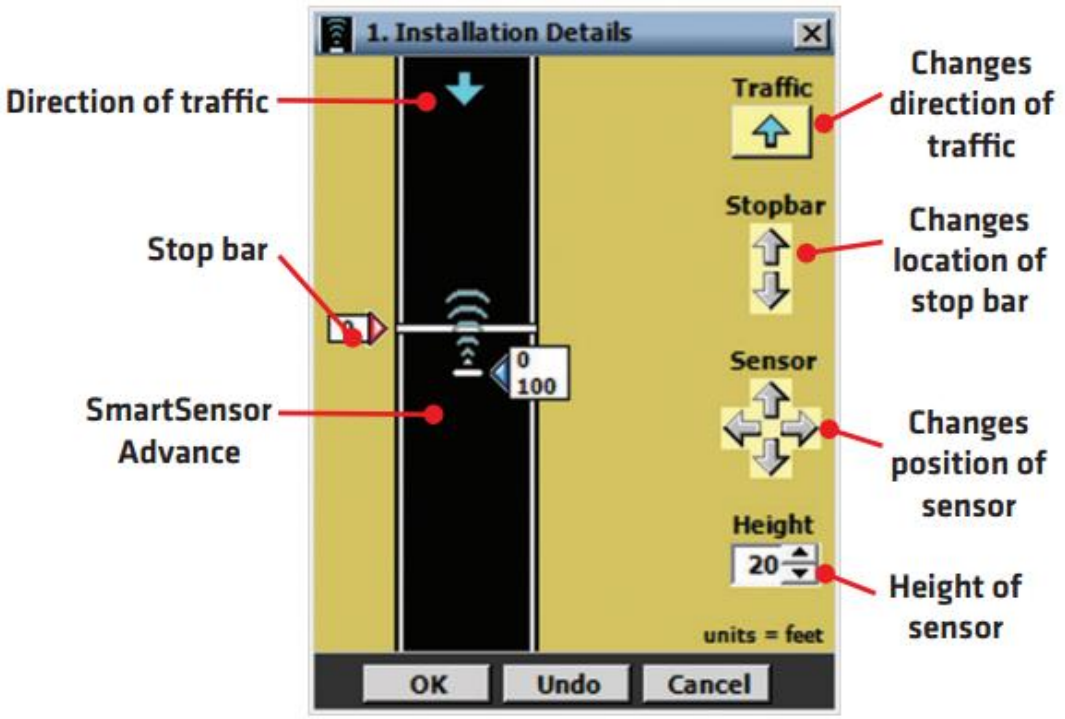


Figure A21 Sensor installation details

- Click “OK” after input and Click  to save the geometry input;
- Go to “Sensor configuration”, and “automatic radar configuration ” to automatically configure the sensors (Usually takes 2-5 minutes) (Figure A12)

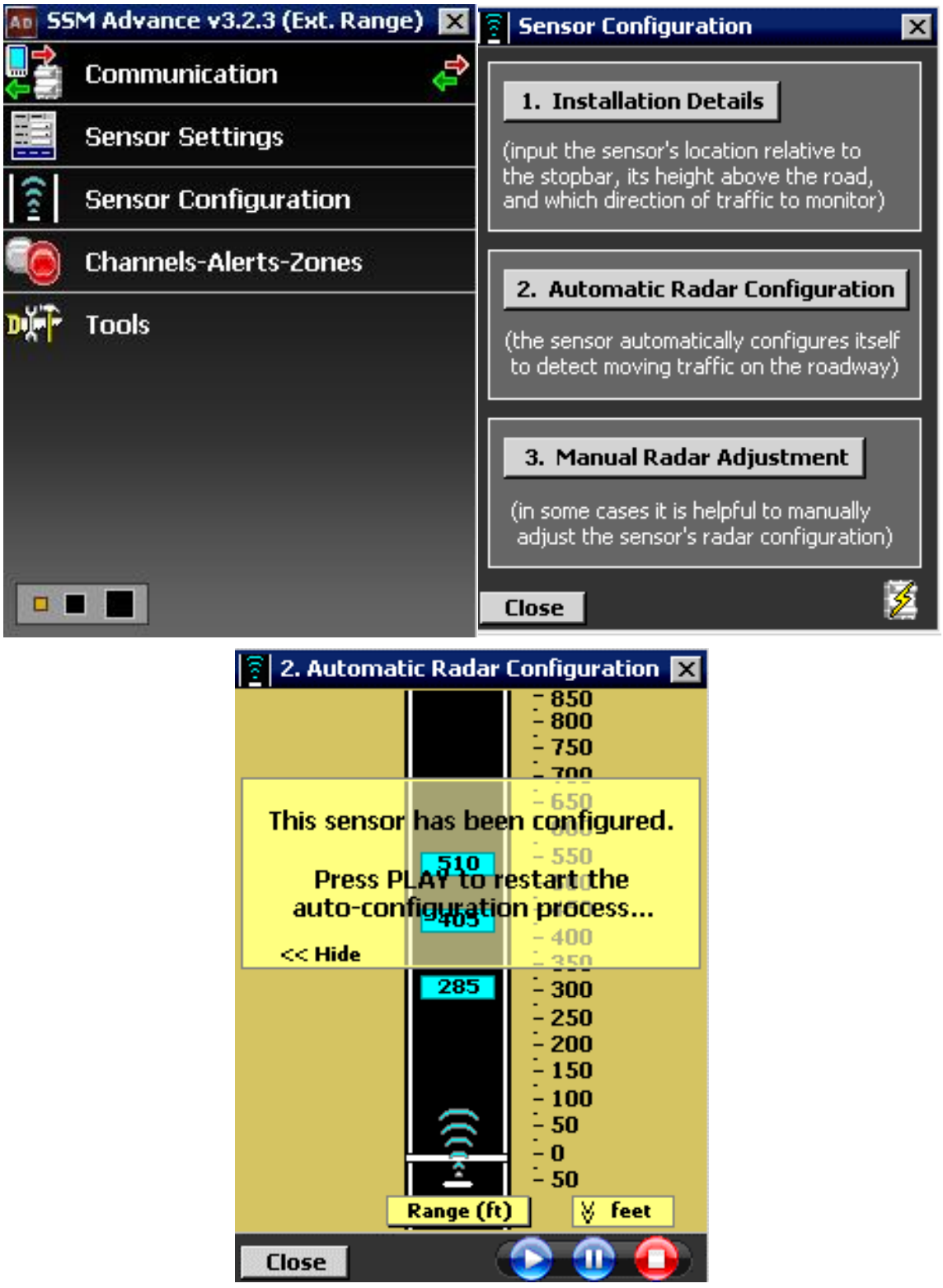


Figure A22 Automatic sensor configuration

- Go to “channel-alert-zones” and “setup channels-alerts-zones” to set up the green extension and the all-red extension criteria (Figure A13).

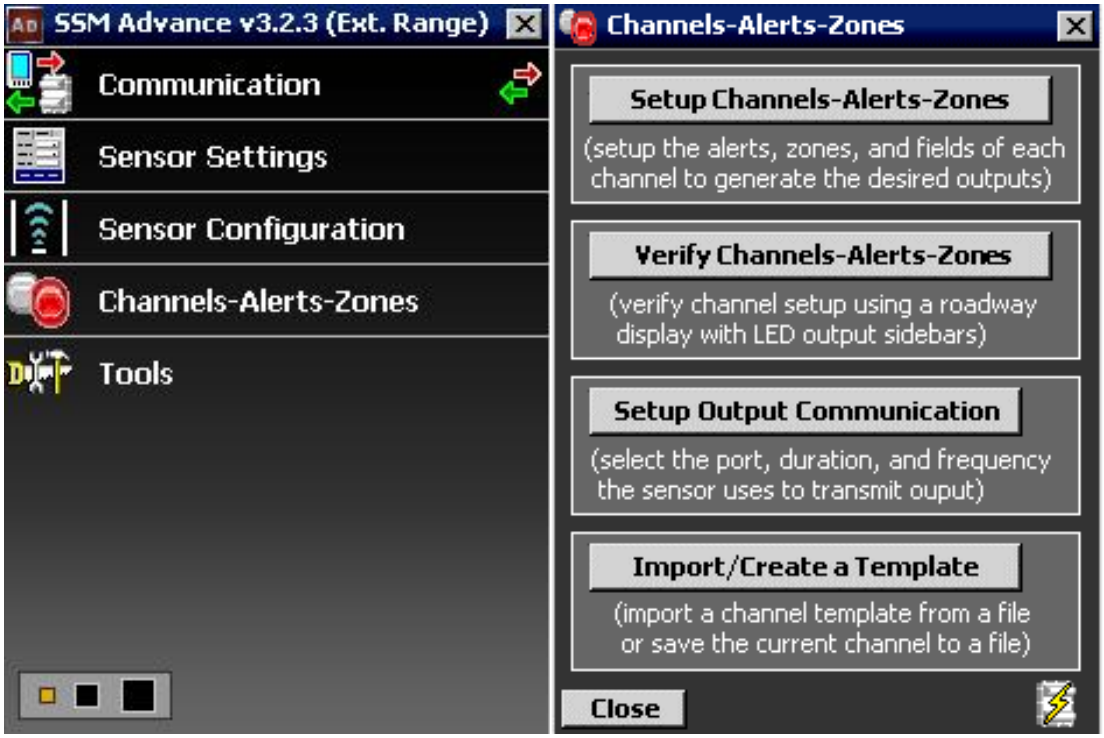


Figure A23 Programming channels

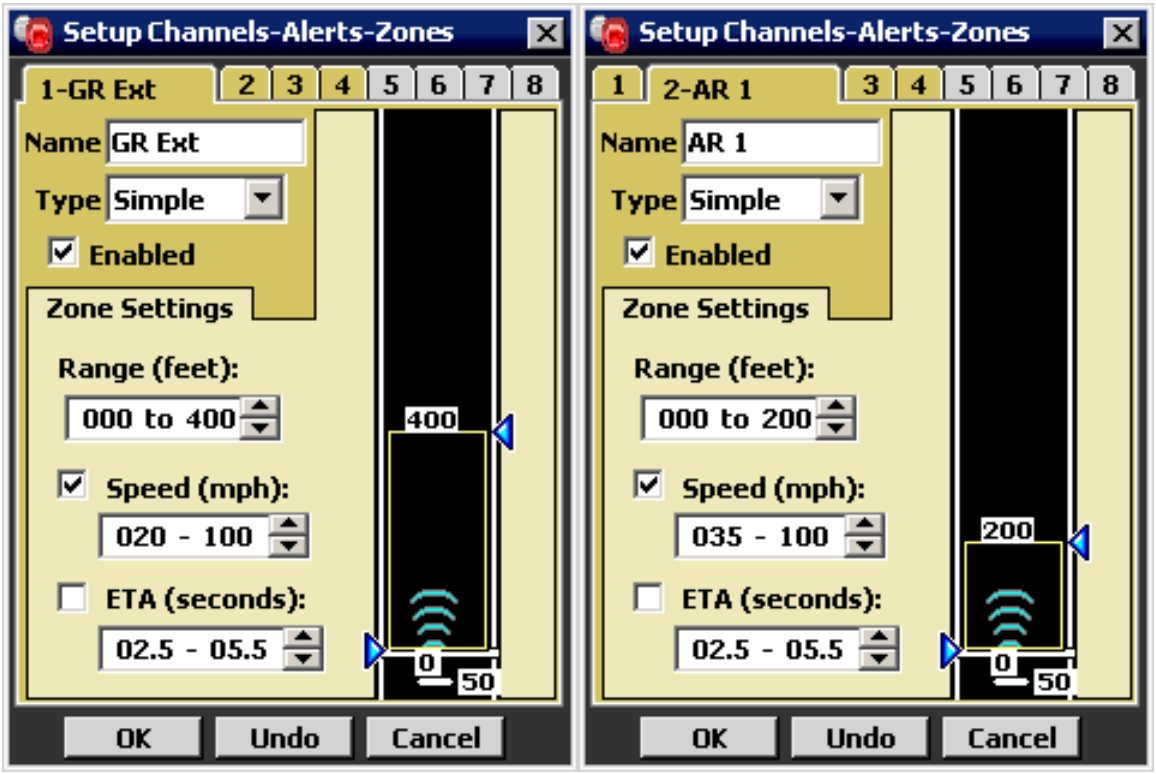
- Make sure **"enable"** is checked, and use the speed as criteria (Figure A14)
- For the example of the intersection at US 40 and MD910C, the channels are set as follows:

Channel 1 (Green Extension): range→ 0 ~ 400 ft, speed → 5 ~ 100 mph

Channel 2 (All-red extension1): range→ 0 ~ 200 ft, speed → 35 ~ 100 mph

Channel 3 (All-red extension2): range→ 200 ~ 300 ft, speed → 45 ~ 100 mph

Channel 4 (All-red extension3): range→ 300 ~ 450 ft, speed → 55 ~ 100 mph



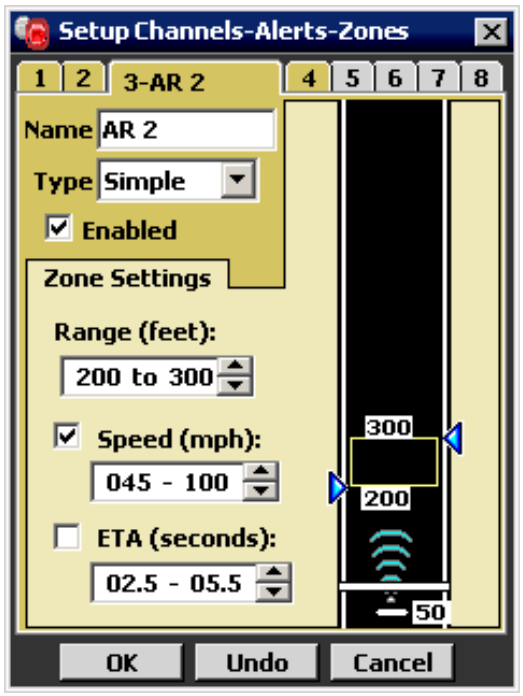


Figure A24 Set up alert zone

- Click "OK" and go to "verify channels-alert-zones" to verify vehicle detections, speed, locations, and channel calls (Figure A15).

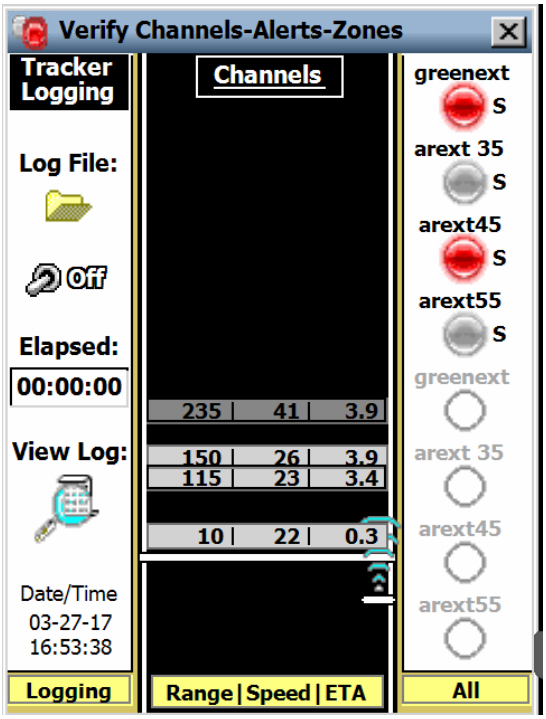


Figure A25 Verification of the sensors and channels

A-4. Post Deployment of DZPS

Validation of the sensor's functions

After the deployment is completed, it is important to ensure that all system functions can work properly. For example, field tests will be needed to check whether or not the controller can activate the all-red extension as requested, and all channels in the controller cabinet work as assigned. The procedures to evaluate the system's functions include the following:

1. Check the sensor's functions via the remote monitoring function (using the software)
2. Compare the speeds of approaching vehicles with the sensor data (using the software and a speed gun)
3. Compare the locations of target vehicles with those from the sensor data (using the software and field observations)
4. Check whether or not the sensor can send proper calls via each channel (using the software, the contact closure, and the signal controller)

Post-deployment evaluation

After completing the DZPS deployment, the following steps should be taken to ensure that the system can provide full protection for all red-light running vehicles:

1. Use camcorders to record signal timings (Figure 13A); or save the signal log file to the signal controller so one can retrieve such information and conduct analyses.
2. Identify whether any all-red extension call has been activated from the recorded video or the signal log file;
3. Identify any red-light running vehicles from the recorded data; and
4. Compare all-red extensions and red-light running vehicles to assess the rates of missed calls, false alarms, and correct calls (Table A3)

Figure A26 Screen capture of a red light running vehicles from the camcorder

Table A9 Evaluation of the DZPS's detection performance

MOE	Simulation	Field Operation* (US 40)	Field Operation** (MD 213)
Red-light-running rate (RLR) (RLR / cycle)	9.5%	1.6%	1.6%
Extension call rate (extension call / cycle)	30.0%	31.7%	17.6%
Detection rate (protected RLR)	100.0%	100.0%	100.0%
False alarm rate (false alarm / cycle)	21.0%	30.0%	16.0%
* Five red light running vehicles during the data collection (312 cycles). * Seven red light running vehicles during the data collection (441 cycles).			

Please note that there is a tradeoff between the detection rate and the false alarm rate. Since the main objective of the DZPS is to ensure safety, one should set the detection rate of red-light running vehicles at the level of 100%.