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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

DESIGN AND EVALUATION OF A DYNAMIC DILEMMA ZONE SYSTEM FOR A HIGH SPEED RURAL INTERSECTION

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16. Abstract

The goal of this research was to develop a system that utilizes the dynamic detection technology and to evaluate the performance of this system. The first step of this study was to select an intersection experiencing a high frequency of crashes that could be remedied by a dilemma-zone protection system. Next, a dynamic dilemma-zone protection system was designed using three microwave sensors to track vehicles approaching the intersection on the major approach. The data collected by these sensors were then used in real-time to control the signal logic, providing green extensions and all-red extensions when pre-defined parameters of detected vehicles are met. To evaluate the performance of the system design and the appropriateness of the associated parameters, a field test was conducted. The data analysis included the identification of false called all-red extensions (related to efficiency) and missed all-red extensions (related to safety) to assess the overall performance of the newly installed dynamic dilemma zone protection system.

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Chapter 1: Introduction

1.1 Research background

Improving traffic safety is a priority transportation issue. A tremendous amount of resources has been invested on improving safety and efficiency at signalized intersections. Although programs such as driver education, red-light camera deployment, and operational improvements to roadway geometry have all contributed to a safer driving environment, significantly reducing traffic signal-related crashes remains a challenging task.

For example, with the rapid urban-rural migration process, many signals have been installed at high-speed and high-growth rural intersections due to their increasing traffic volumes. Most of those intersections have posted speed limits over 50 mph, which can pose a hazardous situation for motorists when approaching a signal during its yellow phase. Drivers in such situations are caught in a so-called dilemma zone: They can neither pass through the intersection before the light turns red, nor can they slowdown comfortably at the stop line. Insufficient protection of motorists within the dilemma zone often leads to red-light running and results in severe accidents due to the high speeds.

In a review of the literature, it is evident that the first intersection dilemma-zone model, also termed "Type-I Dilemma," was developed by Gazis, Herman, and Maraduin (1960) in their landmark paper, called the GHM Model. The paper defines the dilemma zone as a range in which a vehicle approaching the intersection during the yellow phase can neither safely clear the intersection nor stop comfortably at the stop-line (see Figure 1-1). The existing practice for computing the dilemma zone is based on the following kinematics equation:

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

where:

$x_c =$ the critical distance for a smooth "stop" under the maximum deceleration rate;

$x_0 =$ the critical distance for "pass" under the maximum acceleration rate;

$\tau =$ duration of the yellow phase (*sec*);

$\delta_1 =$ reaction time-lag of the driver-vehicle complex (*sec*);

δ_2 = decision-making time of a driver (*sec*);

v_0 = approaching speed of vehicles (*ft/sec*);

a_1 = average vehicle acceleration rate (ft/s^2);

a_1^* = maximum acceleration rate of the approaching vehicles (ft/s^2);

a_2 = average vehicle deceleration rate (ft/s^2);

a_2^* = maximum deceleration rate of the approaching vehicles (ft/s^2);

w = intersection width (*ft*); and

L = average vehicle length (*ft*).

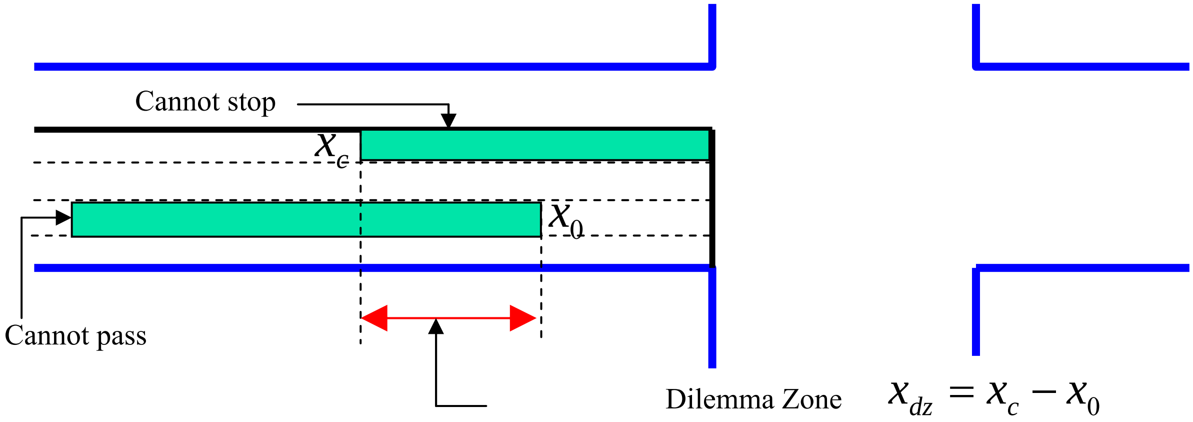

Figure 1-1: A graphical illustration of the dilemma zone at signalized intersections

The other dilemma, termed "Type-II Dilemma," was proposed to accommodate the problem of indecision when both stopping and passing maneuvers can be executed. The term defines the dilemma zone as the range in which 10 to 90 percent of drivers decide to stop (ITE, 1974). Zeeger et al. (1978) also proposed a measuring method termed as "option zone" in which 90 percent of vehicles will stop and 10 percent will choose to go through the intersection under the condition of stochastic traffic distribution.

It is noticeable from Equation 1-1 that both the length and the location of a dilemma zone may vary with the approaching vehicle speeds, driver reaction times, and vehicle acceleration/deceleration rates. A high-speed intersection is likely to contain several different dilemma zones for different groups of the driving population (e.g., conservative or aggressive). Thus, intersection dilemma zones are more likely to be spatially distributed over a wide range, rather than a constant as computed in existing practices. As such, design of effective counter measures to eliminate the dynamic dilemma zone at high-speed intersections has emerged as an imperative but difficult research issue in the traffic safety community.

A high frequency of crashes may be related to dilemma zone scenarios in Maryland, so the Maryland State Highway Administration (SHA) installed a state-of-the-art dilemma zone protection system at the intersection of US 40 (Pulaski Highway) and Red Toad Road in North East, MD. This intersection experienced a total of 89 crashes from 2000-2010, 40 of which could have been avoided by implementing sufficient dilemma-zone protection (MAARS, 2011). The newly installed system uses microwave traffic detectors to provide real-time vehicle tracking on the major approach.

1.2 Project objective and scope

The objective of this research was to develop an effective system to protect drivers trapped in the intersection dynamic dilemma zone. The study included the following three principal tasks:

- Understanding critical factors contributing to a driver's decision during a signal yellow phase and their relations to the distribution of intersection dilemma zones;
- Designing a dynamic dilemma-zone protection system to reduce the potential for accidents at high-speed intersections; and
- Implementing the designed protection system at the intersection of US 40 and Red Toad Road and evaluating its effectiveness with field data.

1.3 Report organization

Based on the above project scope, the research findings and recommendations are organized into five chapters. A brief description of research activities reported in each chapter is presented below.

Chapter 2 summarizes the research findings from extensive field observations of driver responses during the yellow phase, including the design of field surveys, data acquisition and filtering, and statistical tests to identify critical factors affecting driver behavior. This chapter also presents the methodology to classify driving populations into conservative, normal, and aggressive groups based on their reactions to the signal yellow phase under various traffic and environmental conditions. The empirical analysis results reported in this chapter lead to the findings that the intersection dilemma zone is dynamic in nature and varies with the behavior of each driving group.

Chapter 3 presents the design of an intelligent protection system for eliminating the dynamic intersection zone, based on the empirical research findings reported in Chapter 2. The core logic of the designed system and the procedures to compute key parameters from field observations of traffic flow speeds are the focus of this chapter. A detailed description of such a system customized for the intersection of US 40 and Red Toad Road in Cecil County, Maryland, also constitutes a major portion of this chapter.

Chapter 4 reports the field implementation of the designed system for dilemma-zone protection, including sensor deployment, detection logic, and system interactions with the intersection signal controller. The core of this chapter is a detailed description of the system evaluation results with respect to detection accuracy and potential false alarms, based on extensive field observations. Potential system operational issues and future functional enhancement are also discussed in this chapter.

Chapter 5 discusses the research findings along with the lessons obtained from the system's field implementation. Recommendations for effectively contending with dilemma zone-related accidents and for enhancement of overall intersection traffic safety are also presented.

Chapter 2: Field Observations from Phase II and Modeling of Dynamic Dilemma Zones[1]

2.1 Introduction

This chapter presents the analysis results of driver responses during a yellow phase, based on field observations of 1,123 drivers collected with a specially-designed system from six signalized intersections of high crash frequency in Maryland. By classifying drivers into aggressive, conservative, and normal groups based on their responses (i.e., stop or pass) and the distances to the stop line when the signal turns yellow, the statistical tests with the ordered-probit model clearly indicate some critical variables and their impacts on a driver's decision at intersections. Such variables include average traffic flow speed, traffic volume, the green split, the number of through and crossing lanes in the target approach, signal coordination, the difference between a vehicle's approaching speed and the average traffic flow speed, a driver's gender, age, talking over cell phone or not, a vehicle's type and model, etc.

This chapter is organized as follows: Section 2-2 provides a brief review of recent literature on the dynamic dilemma zone and highlights the objectives of the empirical study. Section 2-3 illustrates the data collection plan and the research methodology, including an ordered-probit model and a multi-step statistical test. Section 2-4 summarizes the key research findings and the information essential for the design of a dilemma zone protection system. A conclusion and recommendations constitute the last section.

2.2 Literature review and research objectives

Driver responses at signalized intersections and the dilemma zone have been investigated since the initial study by Gazis et al. (1960). They discovered that incompatibility frequently exists between a driver's desire to comply with the yellow-phase indication and the encountered constraints. Olson and Rothery (1961) conducted field observations at five intersections and found that drivers tend to take advantage of a long yellow phase and view it as an extension of

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[1] Note that the research findings presented in this chapter were obtained from the research team's previous technical report sponsored by SHA on this subject (Chang, 2006) but with an emphasis on empirical observations and model developments. Since those findings serve as the basis for design of a dilemma-zone protection system illustrated in the next chapter, this chapter hereafter briefly summarizes the investigation process and primary results.

the green phase. Their research concluded that driver behavior does not seem to be affected by the yellow-light phase duration, especially since most motorists do not even know the typical phase duration. Another type of dilemma associated with a driver's decision making, the Type-II Dilemma, was proposed to accommodate the problem of indecision when both stopping and passing maneuvers can be executed. Zeeger et al. (1978) proposed the option zone, where 90 percent of the vehicles stop and 10 percent go under various traffic conditions. Liu et al. (2007) presented the results of an empirical study on dilemma zones for different driver groups at signalized intersections using a specially designed video-based system. Their empirical results revealed that the dynamic nature of the dilemma zone often varies with the behavior of the driving population. Furthermore, they concluded that the common practice of extending the yellow phase duration may not be effective.

Van der Horst and Wilmink (1986) found that drivers' responses to the yellow-light phase is governed by a multitude of factors, including driver attitude and emotional states, the crossing ability before the red phase, the consequence of stopping and passing, interactions with other drivers, and the vehicle's approaching speed. They used extensive numerical analyses to illustrate the complex decision-making process and its relations to associated factors. Their employed parameters were also adopted in later studies by Milazzo et al. (2002), Shultz et al. (1998), and the Green Book (AASHTO, 2001).

In classifying driver responses during the yellow phase and identifying potential affecting factors, Shinar and Compton (2004) observed more than 2,000 drivers at six intersections during a 72 hour study period. They concluded that male drivers are more likely than female drivers to take aggressive actions; senior drivers, in comparison with young drivers, are less likely to manifest aggressive driving patterns during a yellow-light phase; the presence of passengers was associated with lower rates of aggressive driving; and the likelihood of taking aggressive actions increases with how much drivers valued their time.

It has also been recognized in the literature that a driver's response to a yellow phase varies with other factors, such as talking on the phone. For instance, Patten et al. (2004) investigated the effects of mobile-phone use on drivers' cognitive workload and attention resource allocation. They reported that the reaction time of most drivers increases significantly during the use of cellular phones. Caird et al. (2005) used a driving simulator to measure the performance of 77 participants (older and younger drivers) while approaching signalized intersections during a yellow phase. Xiang et al. (2005) performed an extensive investigation of driver responses using participants from different populations and using a variety of vehicle characteristics. Based on the survey results, they classified driver behaviors into several distinct patterns and found that a driver's stopping/passing behavior was affected by multiple factors, such as gender, age, and cellular phone use. El-Shawarby et al. (2007) characterized driver behavior at the onset of a yellow-phase transition on high-speed intersection approaches using field data from 60 participants. Their study examined the effects of age and gender on driver behavior and, consequently, on the distribution of dilemma zones. Gates et al. (2010) investigated the influence of vehicle type on various aspects of driver behavior in a dilemma zone, including brake response time, deceleration rate, and red-light-running occurrence. A very recent study by Amer et al. (2010) introduced a state-of-the-art behavioral model (BM) that offers a tool to simulate the driving behavior after the onset of a yellow indication.

Despite the promising accomplishments reported in the literature, much remains to be addressed on this subject, especially on the following critical issues:

- The effects of other factors unrelated to individual characteristics on driver behavior (such as signal control features, vehicle mechanical dynamics, intersection geometric features, and average traffic flow characteristics) have not been adequately analyzed. The complex interactions between those factors and their collective impacts on drivers have not been addressed either.
- In most studies, data were collected with drivers in a driving simulator or strictly controlled field experiments. Driver behavior extracted from such environments could be biased due to the lack of consideration of its interaction with surrounding traffic environments.
- Due to the constraints of the sample size and the measurement method, key factors affecting the behavior of different driving populations remain unclear.

The research results presented in this chapter attempt to address the above issues from the following aspects:

- Collecting detailed information on the characteristics of drivers, roadway geometric features, traffic flow rates, average traffic flow speeds, vehicle dynamics, and vehicle types and performances through a specially designed video-based system with properly synchronized far-side and near-side cameras.

- Classifying drivers into three groups: aggressive, conservative, and normal, based on the critical distance to the stop line and their stop/go decisions at the onset of yellow-phase transition.
- Employing a multi-step, discrete statistical test to explore the complex interrelations between a driver's response (i.e., discrete in nature) to an intersection yellow phase, characteristics associated with individual driver and vehicle performance, traffic environments, and key intersection geometric features.
- Serving as the basis for traffic safety professionals to design more effective safety improvement strategies, based on a better understanding of various factors that may affect a driver's decision during a yellow phase.

2.3 Data collection plan and research methodology

With assistance from the SHA's Office of Traffic and Safety, this study selected six intersections of high crash frequency (Maryland 193 at Maryland 201-WB, Maryland 650 at Metzerott Road-NB, Randolph Road at Glenallan Road-WB, Maryland410 at Belcrest Road-WB, Maryland410 at Adelphi Road-WB, and Maryland193 at Mission Drive-WB) for field data collection. Those selected sites are located in both urban and rural areas and are not close to any special facilities (e.g., schools, bars, or military bases).

One of the most critical issues for investigating driver behavior is to design a reliable system for acquiring field data. This is because all data related to driver behavior (e.g., speed and acceleration rates) needs to be sufficiently accurate. Failure to do so may render either misleading or inconclusive results even with a large sample of observations. In conducting this study, the research team has designed a cost-effective tool to reliably observe the complex interaction process between a driver's response during a yellow phase and a variety of contributing factors. The core logic of the developed system is to superimpose reference lines over the video image, allowing measurement of a vehicle's travel times between these lines to obtain the vehicular speed change profile during the yellow phase and other behavioral related data.

As shown in Figure 2-1, the entire system for field data collection includes the following components:

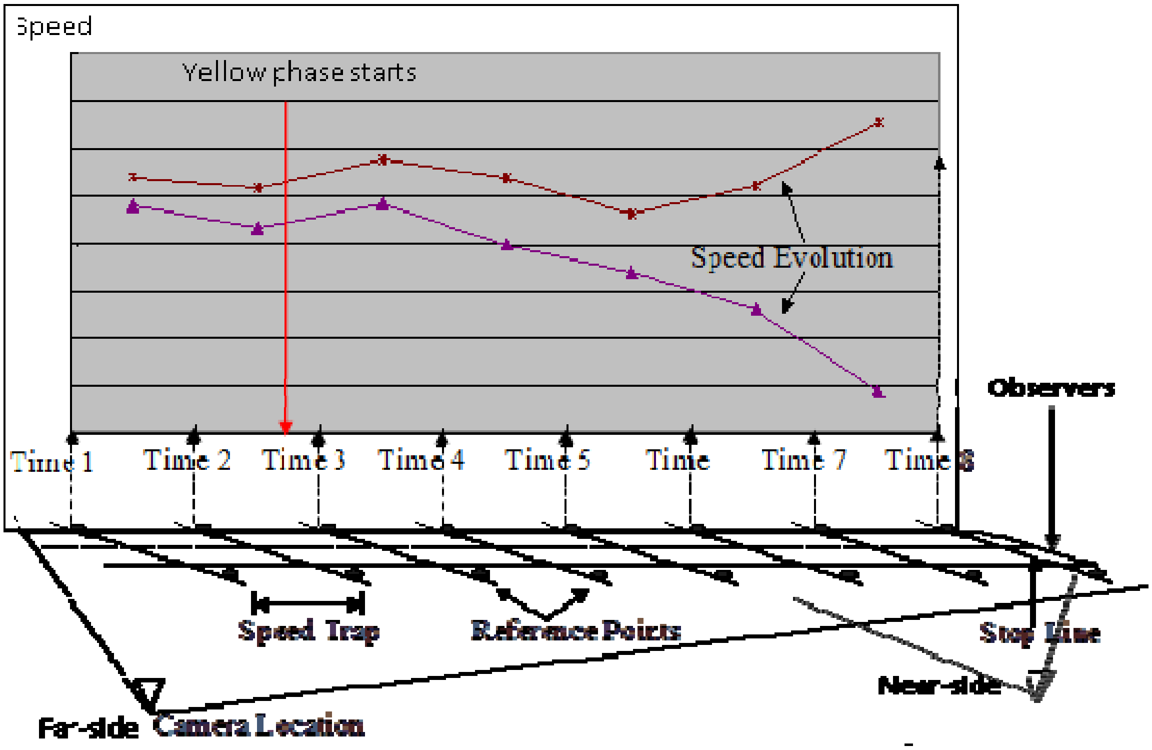


Figure 2-1: A graphic illustration of the video-based data collection system – design and components

- Two DVD video cameras (with variable time-elapse rates of up to 30 frames per second) were placed at the locations with precisely measured distances from the intersection; one camera was placed at the far side along the roadway segment to monitor the speed change of each approaching vehicle trapped in a yellow phase, while the other was placed near the stop line for collecting individual vehicle-related information and intersection control features;
- Two or three observers stationed at the stop line, responsible for recording individual driver characteristics and activities such as a driver's gender, approximate age, number of passengers in vehicle, cell phone use, vehicle type and vehicle model;
- Several rewritable DVD to facilitate computer operations and to save the video tape conversion time;
- An adjustable tripod to allow a flexible setup of the camera orientation;

- Orange cones, placed at an identical spacing along the roadway before the survey period as the “reference points” for camera calibration and video benchmarking that offer the information for computing the change of vehicle speeds. The procedures to optimize the distance between reference points and validation of the measurement accuracy can be found in Liu et al. (2006);
- A frame-by-frame video editing computer program (see Fig. 2-2), that is able to:
  - -Read the video file directly from the video disk without any converting or capturing job;
  - -Superimpose reference lines onto the video image to form a speed trap for measurement;
  - -Slice the video footage into a small set of segments (i.e., frame-by-frame) to facilitate future analysis;
  - -Record timestamps; and
  - -Synchronize the far-side and near-side videos to match the speed change profile of each target vehicle with associated traffic condition factors, intersection geometry factors, control features, vehicle performances, and individual driver-related characteristics (Liu et al., 2006).

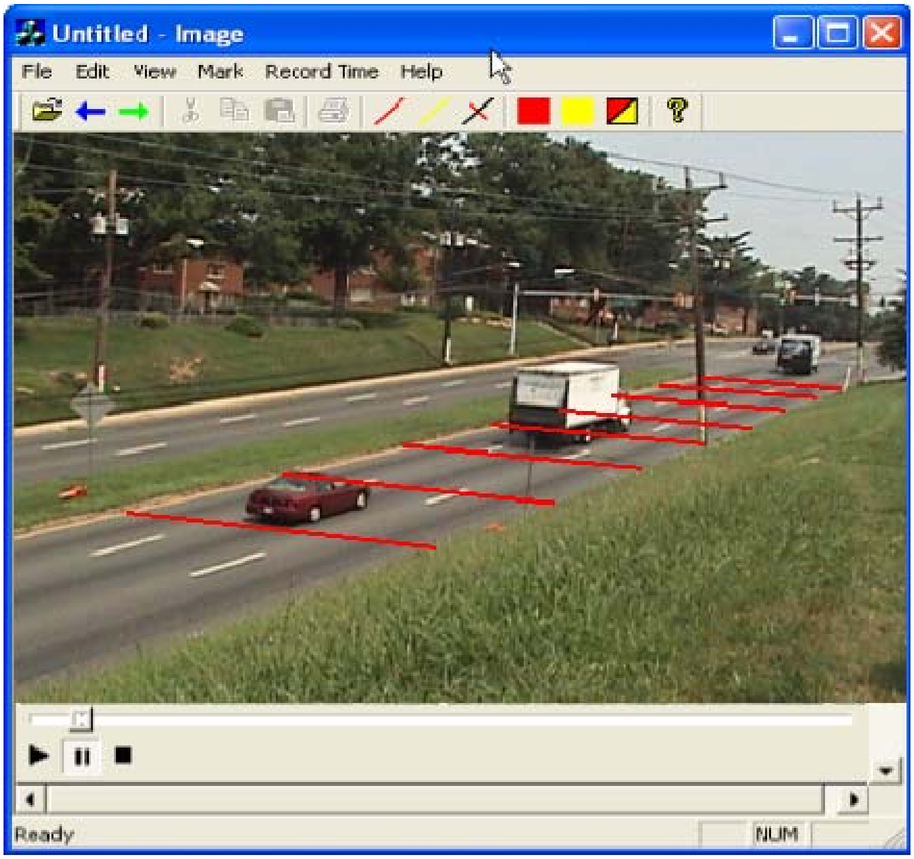


Figure 2-2: The developed frame-by-frame video editing computer program

Using a specially designed video-based system, the research team collected a total of 56 near-side and far-side videos for 30 morning peak hours (7:00-8:00 a.m.) and 26 evening peak hours (3:30-4:30 p.m.) during the period from May 15th to July 31st, 2005. All videos were taken during weekdays under good weather conditions and visibility. More than 3,000 samples were extracted from the collected videos. To ensure the data reliability, the research team compared each sample from the stop-line observers, near-side videos, and far-side videos. Only after the three sources were matched did the research team include the sample in the analysis dataset. Also, for some ambiguous characteristics such as driver age, the driving population was first classified into several age groups in the laboratory experiments and field observers were trained to make consistent classifications of various sample individuals. This pre-training process enabled all field observers to produce consistent results. Upon completing the aforementioned procedure, 1,123 individual driver responses collected during the yellow-light phase were deemed acceptable for use in the analysis. The key information associated with each intersection is shown in Table 2-1, and all collected variables are organized into the following groups for further analysis:

- Traffic environment-related variables: average speed per cycle, average flow rate per lane per cycle, vehicles in platoon or not, green split of the target approach (the ratio of green time to the cycle length), and lane position of the vehicle.
- Intersection-related variables: yellow phase duration, cycle length, number of through lanes in the target approach, number of cross lanes by the target approach, speed limit of the target approach, signal coordination or not with the next intersection, and visibility of the next intersection's signal.
- Individual vehicle dynamics variables: distance-to-stop-line, expected time-to-stop-line, and the approaching speed when drivers perceive the commencement of a yellow phase, speed change before and after the yellow phase, average acceleration/deceleration rates during the yellow phase, and average perception-reaction time of the driving population (Liu et al., 2006).
- Individual driver-related variables: pass or stop decision, gender and age of drivers, passenger in vehicle or not, and driver talking on cell phone or not.
- Individual vehicle related variables: vehicle's type (sedan, SUV, pick-up, sports car, van, truck, or bus) and vehicle's manufacturer (U.S., Japan, Europe, or Korea).

Table 2-1: Summary of intersection characteristics

Intersections*	1	2	3	4	5	6
Cycle length (seconds)	150	150	120	150	150	150
Yellow phase duration (seconds)	4.5	5	4	4.5	5	5.5
Target approach green split	0.387	0.603	0.450	0.316	0.248	0.785
Speed limit (mph)	40	40	35	35	35	45
Number of through lanes in target approach	4	3	3	2	2	3
Number of cross lanes by the target approach	3	3	2	5	5	4
Coordination with next signal	Yes	No	Yes	Yes	No	No
Next signal visibility	Yes	No	Yes	Yes	No	No
Number of observations	292	360	77	128	150	116

*Intersection indices (1-6) refer to: Maryland 193 at Maryland 201, Maryland650 at Metzerott Road, Randolph Road at Glenallan Road, Maryland410 at Belcrest Road, Maryland410 at Adelphi Road, and Maryland193 at Mission Drive, respectively

Driver behavior and characteristics at signalized intersections were not uniformly distributed. Thus, for convenience of analysis, this study first classified the driving population into three distinct patterns based on their response during a yellow phase (the classification method follows), and then evaluated their complex interrelations with those field-observed variables.

Classification of driver's response

The classification is based on the assumption that there is a critical distance (d_c) perceived by a normal driver at each intersection when noticing the beginning of a yellow phase. A normal driver, (i.e., neither aggressive nor conservative), is most likely to take the stop action if the current location to the stop line (x_d) is longer than the perceived critical distance (d_c). By the same token, a driver may choose to pass the intersection during the yellow phase if the perceived d_c is longer than x_d. The critical distance, d_c, is not directly observable from the field data and it may vary with individual driver characteristics and surrounding conditions, such as intersection geometric features and traffic volume. Hence, this study employed a discrete choice model for estimating the average d_c for driving populations at each intersection (see Appendix A for details). A summary of the definition for each driving group is listed below, and the resulting critical distances as well as the distribution of driving populations at each intersection are shown in Tables 2-2 and 2-3.

- Conservative drivers are those drivers who took the stop action even though they could have proceeded through the intersection during the yellow phase (i.e., the driver makes a stop even the distance to the stop line x_d is less than the critical distance, d_c);
- Normal drivers are those drivers who took the stop action when $x_d > d_c$ or the pass action when $x_d < d_c$;
- Aggressive drivers are those drivers who passed the intersection during the yellow phase even though they were quite far away from the stop line ($x_d > d_c$).

Table 2-2: The estimated average critical distance, d_c, for the driving populations

Surveyed Intersections	Yellow Duration(sec)	Cycle Length (sec)	Critical distance, d_c (ft)
193 at 201	4.5	150	234ft
650 at Metzerott	5	150	205ft
Randolph at Glenallan	4	120	269ft
410 at Belcrest	4.5	150	200ft
410 at Adelphi	5	150	177ft
193 at Mission	5.5	150	278ft

Table 2-3: Distribution of driving populations at each intersection

Surveyed Intersections	Total Samples	Aggressive Pass	Normal	Conservative Stop
193 at 201	292	4% (13)	89%(260)	7% (19)
650 at Metzerott	360	8% (28)	81%(292)	11% (40)
Randolph at Glenallan	77	8% (6)	84%(65)	6% (6)
410 at Belcrest	128	5% (6)	90%(115)	5% (7)
410 at Adelphi	150	7% (10)	83%(125)	10% (15)
193 at Mission	116	8% (9)	84%(97)	8% (10)
Summary	1123	6% (72)	85%(954)	9% (97)

Based on the above classification results, this study further analyzed the speed differences among driving groups at each intersection. As shown in Table 2-4, at all observed intersections, the aggressive driver group usually executed an approaching speed approximately 10-20 percent faster than the average traffic flow speed, while the conservative driver group on the average exhibited an approaching speed approximately 10-15 percent slower than the average traffic flow speed, confirming the assumption of characteristic discrepancies among different driving groups.

Table 2-4: Speed difference analyses among driving groups

Surveyed Intersections	Group	Average Speed/Std. (mph)	Percentage Above Average Traffic	Paired-t Ratio
193 at 201	A-Pass*	41.05/5.03	+16.0%	6.314
	Normal	35.39/5.13	0%	0.108
	C-Stop*	32.35/3.37	-8.6%	-6.290
650 at Metzrott	A-Pass	38.74/7.36	+13.5%	5.540
	Normal	34.13/6.92	0%	-0.564
	C-Stop	30.00/5.29	-12.1%	-7.644
Randolph at Glenallan	A-Pass	52.25/7.43	+13.8%	8.126
	Normal	45.91/4.59	0%	-0.728
	C-Stop	40.81/6.30	-11.1%	-8.903
410 at Belcrest	A-Pass	38.09/8.44	+15.3%	9.353
	Normal	31.19/7.16	-5.6%	-3.668
	C-Stop	29.55/7.08	-10.6%	-13.679
410 at Adelphi	A-Pass	38.70/6.48	+21.5%	6.014
	Normal	30.49/5.13	-4.3%	-2.990
	C-Stop	27.21/4.94	-14.6%	-8.769
193 at Mission	A-Pass	54.40/6.70	+12.0%	11.396
	Normal	44.15/6.36	-9.1%	-7.402
	C-Stop	41.00/5.57	-15.6%	-7.886

[*] A-Pass means aggressive pass group, and C-Stop means conservative stop group.

To facilitate the statistical analysis, Table 2-5 presents the notations for all field observed variables, which will be used in the hereafter presentation.

Table 2-5: Notation for factors observed during field experiments

Traffic environment related variables	
Cycle-based average traffic flow speed	AVGSPEED (mph)
Cycle-based lane flow rate	VOLUME (veh/hr/lane)
Vehicle in platoon or not	PLATOON (1 – Yes, 0 – No)
Green split	SPLIT
Lane position of the vehicle	MIDL (1 – inner lane, 0 – not inner lane)
Intersection related variables	
Yellow phase duration	YD (seconds)
Cycle length	CYCLE (seconds)
Number of through lanes	THRUL
Number of cross lanes	CROSSL
Speed limit sign posted or not	POST (1 – Yes, 0 – No)
Speed limit value	SPL (mph)
Signal coordinated or not	COOR (1 – Yes, 0 – No)
Individual vehicle dynamics variables	
Approaching speed when the yellow phase starts	I_SPEED (mph)
Percentage of vehicles above the average traffic flow speed	PER_ABOVE
Individual driver related variables	
Driver's gender	MALE (1 – Yes, 0 – No)
Driver's age (< 26 years old – Young, > 46 years old - SENIOR)	YOUNG (1 – Yes, 0 – No) SENIOR (1 – Yes, 0 – No)
Passenger in vehicle or not	PASSENGER (1 – Yes, 0 – No)
Driver on cell phone or not	PHONE (1 – Yes, 0 – No)
Individual vehicle related variables	
Vehicle is Sedan or not	SEDAN (1 – Yes, 0 – No)
Vehicle is SUV or not	SUV (1 – Yes, 0 – No)
Vehicle is Pick-up or not	PU (1 – Yes, 0 – No)
Vehicle is Sports car or not	SPORTCAR (1 – Yes, 0 – No)
Vehicle is Van or not	VAN (1 – Yes, 0 – No)
Vehicle is Truck or not	TRUCK (1 – Yes, 0 – No)
Vehicle is Bus or not	BUS (1 – Yes, 0 – No)
Vehicle is made in US or not	US (1 – Yes, 0 – No)
Vehicle is made in Japan or not	JAP (1 – Yes, 0 – No)
Vehicle is made in Europe or not	EUR (1 – Yes, 0 – No)
Vehicle is made in Korean or not	KOR (1 – Yes, 0 – No)
Dependent variables	
Driver's response patterns	GROUP (1 – conservative stop, 2 – normal, 3 – aggressive pass)

The dependent variable is used to characterize drivers based on their decisions during a yellow phase, into one of three groups: conservative stop, normal, or aggressive pass. Since the dependent variable is discrete and inherently ordinal in nature, this study employed the ordered-probit model to investigate the effects of various factors (e.g., gender and cellular phone use) on the resulting driver characterization.

The core concept of an ordered-probit model for a dependent variable of three classes can be presented with the following latent regression expression (Greene and Hensher, 2003):

$$y^* = \beta' x + \varepsilon$$

Where, y^* is unobservable, its observable outcomes are:

$$y = 1 \text{ if } y^* \leq 0$$

$$y = 2 \text{ if } 0 < y^* \leq \mu_1$$

$$y = 3 \text{ if } \mu_1 < y^*$$

The unknown parameter μ_1 represents the boundaries between ordered responses that will be estimated with β' (the vector of parameters for explanatory variables); ε is the error term assumed to be normally distributed with cumulative distribution denoted by $\Phi(\cdot)$. The following probabilities result:

$$\Pr ob(y = 1) = \Phi(0 - \beta' x) - 0$$

$$\Pr ob(y = 2) = \Phi(\mu_1 - \beta' x) - \Phi(0 - \beta' x)$$

$$\Pr ob(y = 3) = 1 - \Phi(\mu_1 - \beta' x)$$

A graphic depiction of the relationship between the probability and the observed outcomes is shown in Figure 2-3. The unobservable latent variable y^*, in the above model is the difference between the estimated distance to the stop line and the threshold value d_c. The independent variables are all observable and potentially associated variables.

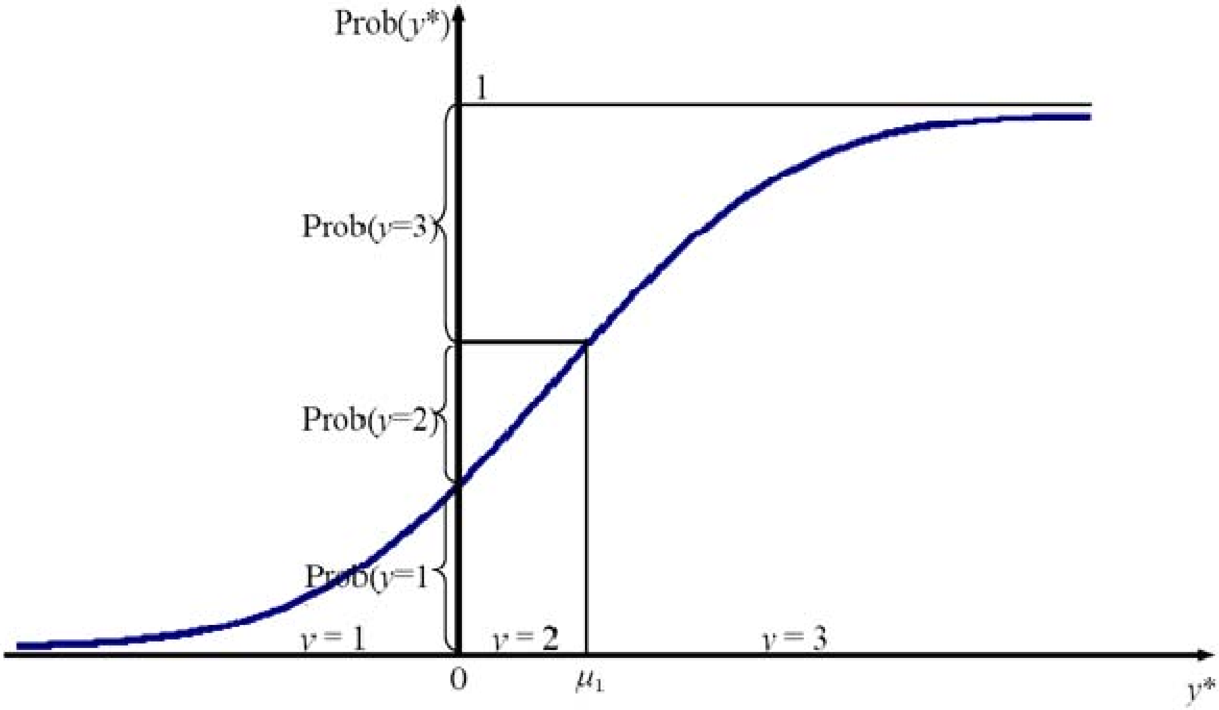


Figure 2-3: An illustration of the probability distribution in an ordered-probit model

Multi-step statistical tests

The statistical test with the ordered-probit model for all associated variables consists of three steps. The focus of Step-I analysis is to identify critical traffic environment-related variables, which serve as the set of background variables for Step-II and Step-III analyses. The list of variables for Step-I test is shown below:

- Step-I**:**
    - Dependent variable – one of the following responses: conservative stop, normal, and aggressive pass
    - Independent variable set – *AVGSPEED, VOLUME, PLATOON, SPLIT,* and *MIDL (Test-1)*

Based on the identified background variables, the analysis at Step-II is to investigate the impact of the following variables on the response of drivers during the yellow phase. All tests performed at Step-II and the included variables are also shown below:

- Step-II**:**
  - *Test-2* – significant background variables + intersection-related variables [yellow phase duration *(YD)* + cycle length *(CYCLE)* + number of through lanes *(THRUL)* + number of cross lanes *(CROSSL)* + speed limit sign being posted or not *(POST)* + speed limit value *(SPL)* + coordination with next intersection *(COOR)*]
  - *Test-3* – significant background variables + individual vehicle dynamics variables [a vehicle's approaching speed when the yellow starts *(I_SPEED)* or the difference (in percent)between each individual driver's speed and the average traffic flow speed *(PER_ABOVE)*]
  - *Test-4* – significant background variables + individual driver-related variables [gender variable *(MALE)* + young driver variable *(YOUNG)* + senior driver variable *(SENIOR)* + variable for passengers or not *(PASSENGER)* + talking-on-phone variable *(PHONE)*]
  - *Test-5* – significant background variables + individual vehicle-related variables *[SEDAN, VAN, SUV, PU, SPORTCAR, TRUCK, JAP, US, EUR]*
  - *Test-6* – global test of all significant variables identified through tests 1-5 to finalize the list of critical variables on driver's responses (conservative stop, normal, or aggressive pass)

Some variables, though shown to be statistically insignificant during individual tests in Step-II, could collectively reveal significant impacts on a driver's response. To capture those possible hidden effects, this study performed Step-III analysis to explore the compound effects of individual- and vehicle-related variables on a driver's response. To prevent multicollinearity, each multiplication of individual driver- and vehicle-related variables was tested at one time with all significant background variables, intersection-related variables, vehicle dynamics variables, and all individual driver and vehicle-related variables. All tests performed at Step-III include:

- Step-III**:**
    - *Test-7 to Test-76* – significant background variables + significant intersection related variables + significant individual vehicle dynamics variables + individual vehicle related variables + individual driver related variables + [individual driver related variables * individual vehicle related variables]

The flowchart for performing the proposed multi-step tests is illustrated in Figure 4-4.

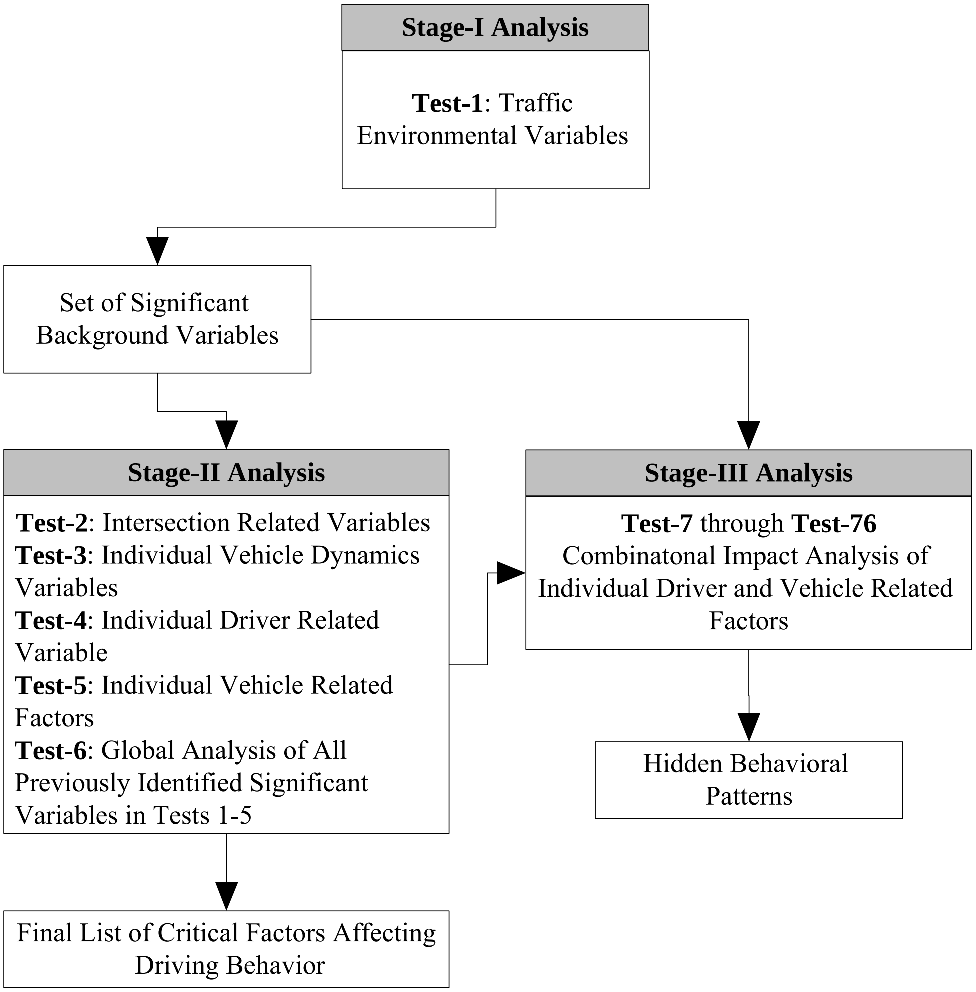


Figure 4-4: The multi-stage statistical test procedure with the ordered-probit model

2.4 Analysis of observation results

The results of Test-1 in Table 2-6 show the effects of Step-I variables on a driver’s response during the yellow phase. The positive and significant coefficient for the average traffic flow speed implies that drivers are more likely to take aggressive passing actions in response to the observed yellow phase during high-speed traffic conditions. This finding seems to justify the need to place speed enforcement at high-speed intersections to improve traffic safety. A negative coefficient for the traffic volume and green splits indicates that drivers tend to be self-restrained during conditions of high volume or a long green time and are less likely to take the aggressive-pass action during the yellow phase.

Test-2 shown in Table 2-6 presents the estimated effects of intersection-related variables on the response of drivers during the yellow phase. As expected, the number of through and crossing lanes in the target approach and signal coordination showed significant effects on driver response. A negative sign for the number of through lanes, *THRUL* (-.187), and a positive sign for the required crossing lanes, *CROSSL* (.112) imply that drivers in a major intersection approach with multiple lanes are more likely to take non-aggressive responses during a yellow phase. This may be due to the collective impacts of various variables, such as experiencing a higher volume (as reflected in the same estimation), having a longer green duration, and thus showing less desire to take an aggressive risk during the yellow phase.

In contrast, drivers in the minor approach of a major-minor intersection tend to take a more aggressive action during the yellow phase. Also revealed is the fact that good signal coordination (*COOR*: .228) between adjacent intersections tends to encourage drivers to take aggressive actions during the yellow phase. This may be due to the fact that traditional signal progression models focus only on maximizing the operational efficiency of intersections, but neglect to reduce the total number of vehicles trapped in the dilemma zones. Other variables such as the yellow phase duration, the cycle length, and the posted speed limit do not exhibit any significant impact on a driver’s decision during a yellow phase, among those available sample observations.

Table 2-6. Estimation results of Stage I and II tests

	Parameter Coefficient [P value] (Sample Size)	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Final List of Significant Variables
Background Variable Set – Traffic Environmental Factors	C	3.426 [<.001]	3.779 [<.001]	4.248 [<.001]	4.889 [<.001]	4.191 [<.001]	6.034 [<.001]	
	AVGSPEED [+]	.0382 [<.001]	.0392 [<.001]	.0401 [<.001]	.0346 [<.001]	.0440 [<.001]	.0185 [.045]	×
	VOLUME[-]	-.307E-02 [<.001]	-.307E-02 [<.001]	-.309E-02 [<.001]	-.325E-02 [<.001]	-.331E-02 [<.001]	-.992E-03 [.073]	×
	SPLIT[-]	-2.199 [<.001]	-2.261 [<.001]	-2.217 [<.001]	-1.804 [<.001]	-2.226 [<.001]	-2.627 [<.001]	×
	MIDL[-] (570)	-.247 [.213]						dropped in test 1
	PLATOON[-] (268)	-.521 [.408]						dropped in test 1
Intersection Related Variables	YD[+]		.0725 [.643]					dropped in test 2
	CYCLE[-]		-.508-02 [.422]					dropped in test 2
	THRUL[-]		-.187 [.009]				-.0898 [.034]	×
	CROSSL[+]		.112 [.003]				.0501 [.053]	×
	POST[-] (497)		-.0174 [.863]					dropped in test 2
	SPL[-]		-.0289 [.198]					dropped in test 2
	COOR[+] (497)		.228 [.019]				.367 [.038]	×
Individual Vehicle Dynamics Variables	I_SPEED[+]			.113 [<.001]			.064 [.030]	×
	PER_ABOVE[+]			4.160 [<.001]			3.432 [<.001]	×
Individual Driver Related Variables	MALE[+] (750)				.652 [.063]		.216 [.089]	×
	YOUNG[+] (591)				.925 [.004]		.647 [.054]	×
	SENIOR[-] (163)				-.977 [.083]		-.441 [.211]	dropped in test 6

	PASSENGER[-] (192)	-.609 [.378]			dropped in test 4
	PHONE[-] (118)	-1.087 [.039]		-0.816 [.050]	×
Individual Vehicle Related Variables	SEDAN[+] (540)		.0378 [.667]		dropped in test 5
	VAN[-] (150)		-.851 [.021]	-.382 [.115]	dropped in test 6
	SUV[-] (225)		-.222 [.316]		dropped in test 5
	PU[+] (94)		.609 [.221]		dropped in test 5
	SPORTCAR[+] (81)		1.263 [.009]	0.745 [.063]	×
	TRUCK[-] (26)		-.246 [.693]		dropped in test 5
	JAP[+] (445)		.666 [.021]	.331 [.011]	×
	US[-] (559)		-.252 [.541]		dropped in test 5
	EUR[-] (80)		-.725 [.354]		dropped in test 5

Note: Significance tests are performed at the 0.10 level; Cells highlighted represent the significant variables in a test.

Test-3 focuses on investigating the effect of an individual vehicle's approaching speed, while Test-4 evaluates drivers' response differences. Test-5 analyzes the effects of the presence of passengers, talking over the cell-phone, vehicle types, and vehicle model. Although the estimated relations are not consistent across all six observed intersections due to the difference in sample size, their statistical indications have revealed the following interesting relations:

- Drivers in higher-than-average flow speed are more likely to behave aggressively when encountering a yellow phase (*PER_ABOVE*: 4.160/p-value < .001, see Test-3 in Table 2-6);
- Male drivers are more likely to take aggressive actions when approaching the yellow phase (*MALE*: .652/p-value = .063, see Test-4 in Table 2-6);
- Young drivers tend to take aggressive actions when approaching the yellow phase (*YOUNG*: .925/p-value = .004, see Test-4 in Table 2-6), whereas senior drivers are more likely to be conservative (*SENIOR*: -.977/p-value = .083, see Test-4 in Table 2-6);

- Drivers talking on a phone tend to take conservative actions when approaching the yellow phase (*PHONE*: -1.087/p-value = .039, see Test-4 in Table 2-6);
- Drivers in vans tend to take conservative actions when approaching the yellow phase (*VAN*: -.851/p-value = .021, see Test-5 in Table 2-6);
- Drivers in sports cars tend to take aggressive actions when approaching the yellow phase (*SPORTCAR*: 1.263/p-value = .009, see Test-5 in Table 2-6);
- Drivers in Japan-made cars exhibited the pattern of taking aggressive decisions during the yellow phase (*JAPAN*: .666/p-value = .021, see Test-5 in Table 2-6).

Test-6 performs a global analysis of all individually significant variables identified through Tests 1-5 to finalize the list of variables that exhibit critical impacts on driving behavior. Note that the variables *SENIOR* and *VAN* were dropped from the list due to their insignificance at a 0.10 level, and all significant variables in Test-6 are listed in the last column of Table 6.

Step-III analysis results, shown in Table 2-7, reveal significant compound effects of individual- and vehicle-related variables on a driver's response during the yellow phase. For example, the number of passengers that exhibits a negative but insignificant sign when the test is based on all samples (see Test-4 in Table 2-6, but shows significant effects when the sample was divided by gender. As indicated in Table 2-7, female drivers tend to be conservative when passengers are present (*FEMALE*PASSENGER*: -1.132/p-value < .001, see Test-26), but not male drivers. Similar discrepancies also exist between young and senior drivers when passengers are present. Also, it is noticeable that the estimation results have revealed the following additional behavioral patterns:

- Young male drivers tend to be more aggressive than senior male drivers when approaching the yellow phase (see tests 7-8);
- Young female drivers tend to take aggressive actions when approaching the yellow phase, while senior female drivers tend to take conservative actions under the same situation (see tests 23-24);
- Both female and senior drivers with passengers tend to take conservative actions when approaching the yellow phase (see tests 26 and 51);
- Female drivers talking on a phone tend to take conservative actions when approaching the yellow phase whereas male drivers do not (see tests 11 and 27);

- Senior and middle-aged drivers talking on a phone tend to take conservative actions when approaching the yellow phase whereas young drivers do not (see tests 39, 52, and 65);
- Female van drivers tend to take conservative actions when encountering the yellow phase, whereas male drivers do not(see tests 13 and 29);
- Senior and middle-aged drivers in vans tend to take conservative actions when approaching the yellow phase whereas young drivers do not (see tests 41, 54, and 67);
- Male drivers in SUVs tend to take aggressive actions when encountering the yellow phase, whereas female drivers do not(see tests 14 and 30);
- Young drivers in sports cars tend to take aggressive actions when approaching the yellow phase (see test 44);
- Young drivers in Japan-made cars tend to take aggressive actions when encountering the yellow phase (see test 47);
- Senior drivers in European cars tend to take conservative actions when approaching the yellow phase (see test 62).

Table 2-7: Estimation results of the Stage III analysis (Compound Variables)

Test #	Variables	Coef.	P-Value	Test #	Parameters	Coef.	P-Value
7	MALE*YOUNG	0.787	[<.001]	42	YOUNG*SUV	0.199	[.185]
8	MALE*SENIOR	-0.433	[.005]	43	YOUNG*PU	0.916	[<.001]
9	MALE*MIDDLE	0.107	[.314]	44	YOUNG*SPORTCAR	1.551	[<.001]
10	MALE*PASSENGER	0.249	[.170]	45	YOUNG*TRUCK	0.509	[.426]
11	MALE*PHONE	0.643	[.154]	46	YOUNG*BUS	0.127	[.913]
12	MALE*SEDAN	0.028	[.774]	47	YOUNG*JAP	0.822	[<.001]
13	MALE*VAN	0.237	[.126]	48	YOUNG*US	0.361	[.001]
14	MALE*SUV	0.707	[<.001]	49	YOUNG*EUR	0.059	[.820]
15	MALE*PU	0.613	[.035]	50	YOUNG*KOR	0.046	[.904]

16	MALE*SPORTCAR	0.984	[<.001]	51	SENIOR*PASSENGER	-1.023	[<.001]
17	MALE*TRUCK	-0.246	[.393]	52	SENIOR*PHONE	-1.041	[<.001]
18	MALE*BUS	-0.104	[.876]	53	SENIOR*SEDAN	-0.424	[.018]
19	MALE*JAP	0.705	[<.001]	54	SENIOR*VAN	-1.648	[<.001]
20	MALE*US	0.166	[.074]	55	SENIOR*SUV	-1.469	[<.001]
21	MALE*EUR	0.293	[.221]	56	SENIOR*PU	0.15	[.658]
22	MALE*KOR	0.61	[.369]	57	SENIOR*SPORTCAR	0.207	[.730]
23	FEMALE*YOUNG	0.272	[.022]	58	SENIOR*TRUCK	-0.604	[.379]
24	FEMALE*SENIOR	-1.394	[<.001]	59	SENIOR*BUS	-0.105	[.928]
25	FEMALE*MIDDLE	-0.934	[<.001]	60	SENIOR*JAP	-0.329	[.153]
26	FEMALE*PASSENGER	-1.057	[<.001]	61	SENIOR*US	-0.756	[<.001]
27	FEMALE*PHONE	-1.2	[<.001]	62	SENIOR*EUR	-1.579	[<.001]
28	FEMALE*SEDAN	-0.028	[.817]	63	SENIOR*KOR	-1.638	[<.001]
29	FEMALE*VAN	-1.615	[<.001]	64	MIDDLE*PASSENGER	-0.318	[.050]
30	FEMALE*SUV	-1.419	[<.001]	65	MIDDLE*PHONE	-1.108	[<.001]
31	FEMALE*PU	0.089	[.957]	66	MIDDLE*SEDAN	-0.068	[.594]
32	FEMALE*SPORTCAR	1.343	[<.001]	67	MIDDLE*VAN	-1.097	[<.001]
33	FEMALE*BUS	-0.162	[.922]	68	MIDDLE*SUV	-1.40E-03	[.993]
34	FEMALE*JAP	-0.169	[.182]	69	MIDDLE*PU	0.129	[.676]
35	FEMALE*US	-0.837	[<.001]	70	MIDDLE*SPORTCAR	-0.128	[.744]
36	FEMALE*EUR	-0.996	[.047]	71	MIDDLE*TRUCK	-0.399	[.271]
37	FEMALE*KOR	-0.78	[.004]	72	MIDDLE*BUS	-0.244	[.795]
38	YOUNG*PASSENGER	-0.331	[.110]	73	MIDDLE*JAP	-0.18	[.203]
39	YOUNG*PHONE	0.569	[.237]	74	MIDDLE*US	-0.424	[<.001]
40	YOUNG*SEDAN	0.233	[.024]	75	MIDDLE*EUR	-0.668	[.011]
41	YOUNG*VAN	0.13	[.508]	76	MIDDLE*KOR	-0.599	[.087]

2.5 Potential applications

Note that the above relationships between driver responses during a yellow phase and related variables are based on more than 1,000 field observations at six intersections. Some of these reported relations are likely to vary at different intersections in different regions. However, the above empirical information offers some valuable information for understanding the complex interrelations between the decision of drivers and all contribution factors. The estimation results can be used in classifying the distribution of driving populations at a target intersection and in identifying some factors that may cause drivers to act aggressively in response to the yellow phase. More importantly, with some additional modeling work, traffic safety engineers can design effective strategies to counter traffic signal-related crashes, especially for those associated with dilemma zones. For instance, one can:

- Enhance traditional signal timing models for possible reduction of aggressive driving-related factors identified in this study without losing operational efficiency. Based on the significant variables identified in this paper, one can develop a series of quantitative models to predict a driver's decision (aggressive pass, normal pass, normal stop, or conservative stop) in response to the yellow phase and the number of aggressive drivers potentially trapped in the dilemma zone during each signal cycle. Such models can be incorporated into the traditional signal control framework to improve intersection safety.
- Propose driver education guidelines based on the behavioral findings in this study to depress aggressive maneuvers during the yellow phase. For example, integration of the research results with vehicle incident reports will disclose the interrelation between vehicle characteristics, aggressive driving maneuvers, and signal-related incidents. Such valuable information will be critical to the design of customized driver educational plans.
- Develop a driver response prediction model to support the dilemma-zone protection system, as shown in Figure 2-5. During a yellow phase, the system will track the target driver, and the expected model will concurrently predict the response of the target driver, based on measurable variables (e.g., traffic environment-related variables and individual vehicle dynamics). The system will activate a warning message and extend the all-red

phase to prevent any rear-end collision or side crash if the target driver is computed to be trapped in the dilemma zone and predicted to take the aggressive passing maneuver.

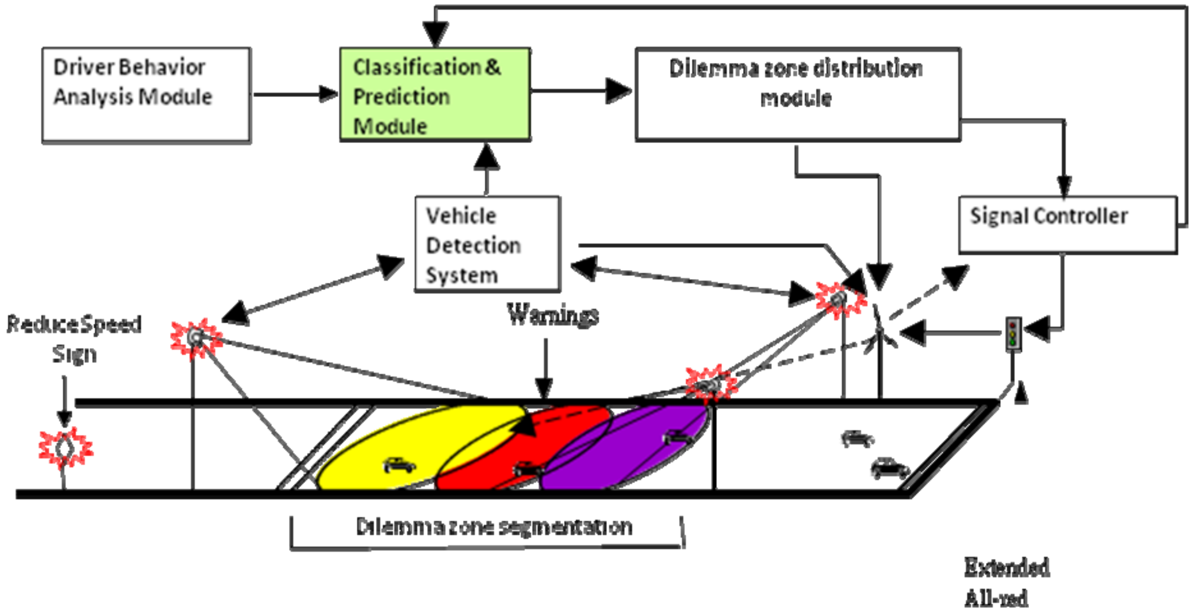


Figure 2-5: A dynamic dilemma-zone protection system

2.6 Conclusions

This study observed the behavior of 1,123 drivers in response to an encountered yellow phase and their surrounding traffic conditions at six signalized intersections. To contend with the difficulty in measuring driver responses during the relatively short yellow phase, this study developed a video-based system that enables users to track an individual driver's speed change during the yellow phase before reaching the intersection. The comprehensive field data obtained with the system provides the basis for this study to profile the behavior of drivers during the yellow phase and to identify various associated factors.

Based on the decision of each individual driver during a yellow phase and the field observations, this study further classified the driving populations into aggressive, normal, and conservative groups. Using an ordered-probit model and a multi-step statistical analysis procedure, this study has successfully identified the underlying factors that may have significant impacts on the response of drivers at signalized intersections. The compound impacts of multiple factors on the decision of drivers during a yellow phase have also been evaluated.

In summary, through extensive field observations and statistical analyses, this study has reached the following tentative conclusions:

- Driving populations at most signalized intersections, based on their responses during the yellow phase, can be classified into three distinct groups: aggressive, normal, and conservative.
- A variety of factors may affect a driver's decision on taking an aggressive or a conservative action during the yellow phase. Examples of factors include: average traffic flow speed, green splits, traffic volume, signal coordination, number of approach lanes, talking on the phone or not, vehicle type, age, and gender.
- The speed of a vehicle approaching the intersection in comparison with the average flow speed seems to be the best indicator for identifying the level of a driver's aggressive tendencies.
- The intersection's geometric features may affect a driver's response to the encountered yellow phase. For example, drivers on minor streets are more likely to take an aggressive pass decision during a yellow phase due to the short green phase.
- A coordinated signal system may encourage drivers to take an aggressive passing decision during the yellow phase.
- Some behavioral variables could have significant compound impacts on a driver's response during the yellow phase. For example, male drivers in SUVs tend to take aggressive actions when approaching the yellow phase, but not female drivers.
- Understanding the behavioral discrepancy between different driving populations and the critical contributing factors is essential for researchers and responsible agencies to design safety improvement strategies

Chapter 3: Design of a Dynamic Dilemma-zone Protection System

3.1 Research Background

This chapter presents the design of a dilemma-zone protection system for the intersection of Red Toad Road at US 40 in Cecil County, Maryland, based on the research findings reported in Chapter 2. The entire design procedure comprises three steps: location identification, traffic characteristics analysis, and system design.

Serving as a primary arterial in Cecil County, Maryland, US 40 is a four-lane divided highway with a posted speed limit of 55 mph and isolated intersection control. It has a high traffic speed and long spacing between intersections, and thus is inherently subject to dilemma zone safety concerns. The target intersection at Red Toad Road provides a left turn bay for each approach on US 40 and has a historic pattern of crashes that may be corrected by sufficient dilemma zone protection. In fact, 40 of the 89 police reported crashes from 2000-2010 at this intersection were the straight movement angle collision type (MAARS, 2011).

Figure 3-1 shows the accident records reported by the SHA’s Office of Traffic and Safety, where 13 crashes between 2004 and 2009 were related to driving behavior in the dilemma zone. Given these statistics and the increasing severity of such crashes in recent years, the US 40 at Red Toad Road intersection emerged as the prime candidate for the installation of a dynamic dilemma-zone protection system.

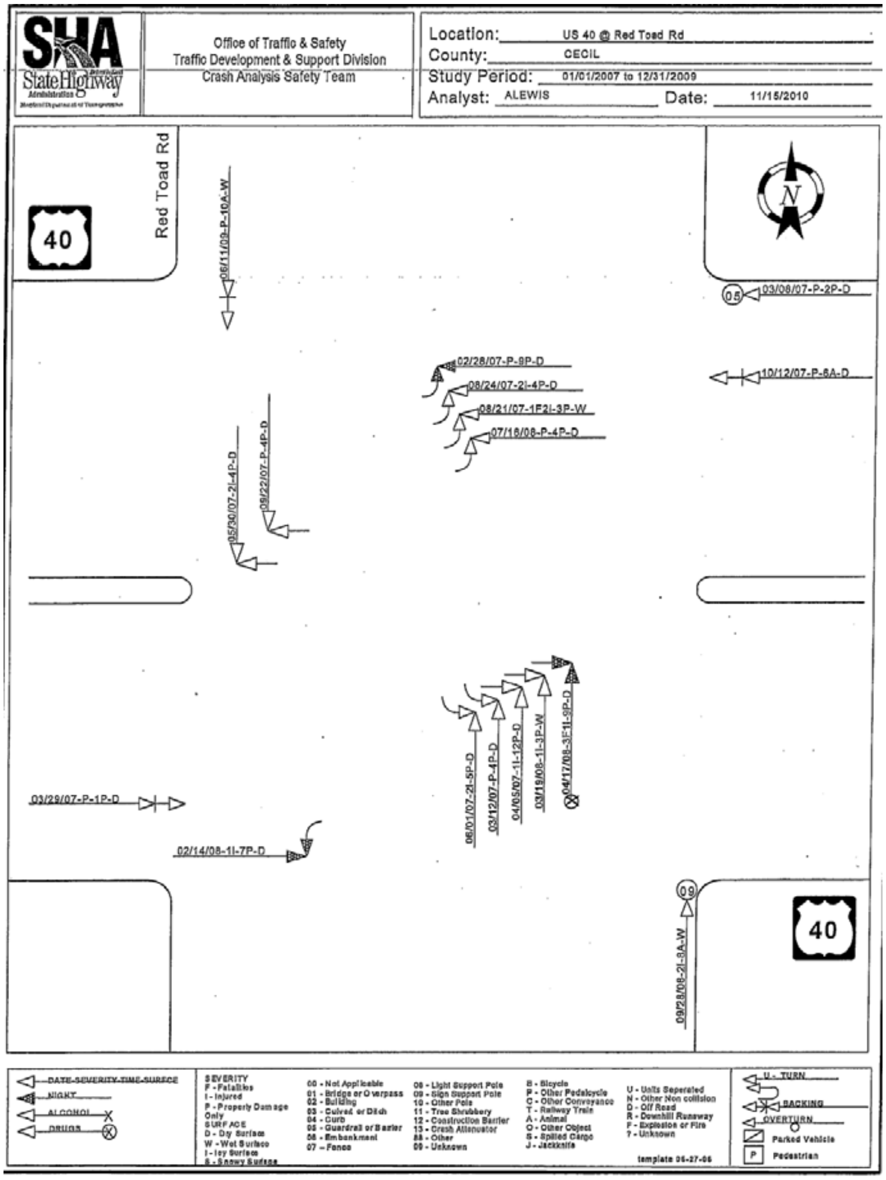


Figure 3-1: Accident records for the intersection of Red Toad Road on US 40

This chapter is organized as follows: The next section first illustrates the pre-design traffic analysis for the target site, including a concise description of the field data collection and the resulting distribution of dilemma zones that are found to be dynamic in nature. This section is followed by presentation of a preliminary system design in Section 3-3, including the required detector functions, sensor locations, and required communications with the intersection controller. The final design, considering the sensitivity of the selected traffic sensors and the constraints of signal controller, constitutes the last section.

3.2 Traffic characteristics analysis for system design

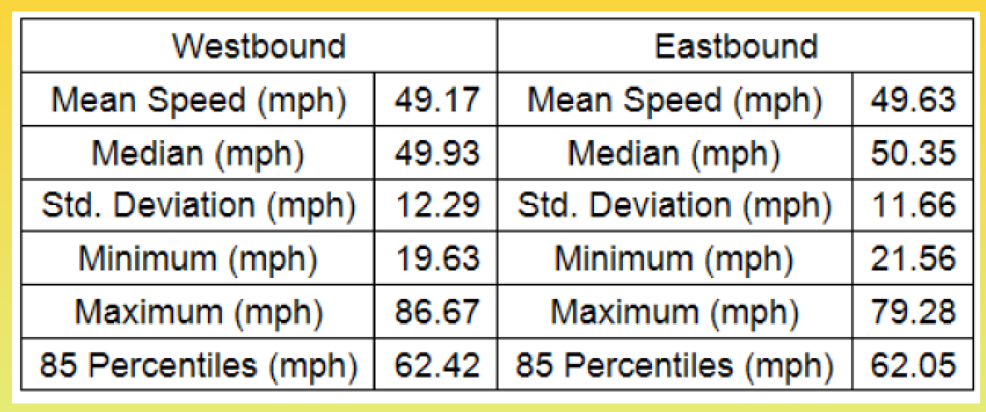
The traffic signal at the US 40 and Red Toad Road intersection is controlled by a fully actuated two-phase system with no pedestrian accommodation. The green phase for US 40 is held unless there is a call from Red Toad Road. The minimum green time for US 40 is 25 seconds after a call is received from Red Toad Road. The maximum green time for US 40 is 60 seconds (90 seconds in peak periods) with the gap-out logic controlled by microwave sensors. The yellow phase for US 40 is 5.5 seconds and a fixed all-red phase of 3 seconds is incorporated. Dilemma-zone protection is provided by extending the all-red phase upon the detection of vehicles with predefined parameters within 3 seconds of the onset of US 40 red (details in following subsection). This all-red extension may be called even if the green duration has not been extended to its maximum.

To understand the traffic flow characteristics, a pre-design survey was conducted with the same field data collection procedures described in Chapter 2, where both speed tubes and video-recording devices were placed on the roadside of both westbound and eastbound to collect the following information:

- Space mean speed of individual vehicles;
- Vehicle types and distribution over each target interval (i.e., every five minutes); and
- Individual vehicles' reaction (stop or go) during a yellow phase.

Table 3-1 summarizes the key traffic flow data essential for computing the distribution of dynamic dilemma zones at an intersection. Figure 3-2 presents the eastbound and westbound speed distributions of the observed vehicles at the US 40 and Red Toad Road intersection.

Table 3-1: Summary of traffic flow speed distribution



Westbound		Eastbound	
Mean Speed (mph)	49.17	Mean Speed (mph)	49.63
Median (mph)	49.93	Median (mph)	50.35
Std. Deviation (mph)	12.29	Std. Deviation (mph)	11.66
Minimum (mph)	19.63	Minimum (mph)	21.56
Maximum (mph)	86.67	Maximum (mph)	79.28
85 Percentiles (mph)	62.42	85 Percentiles (mph)	62.05

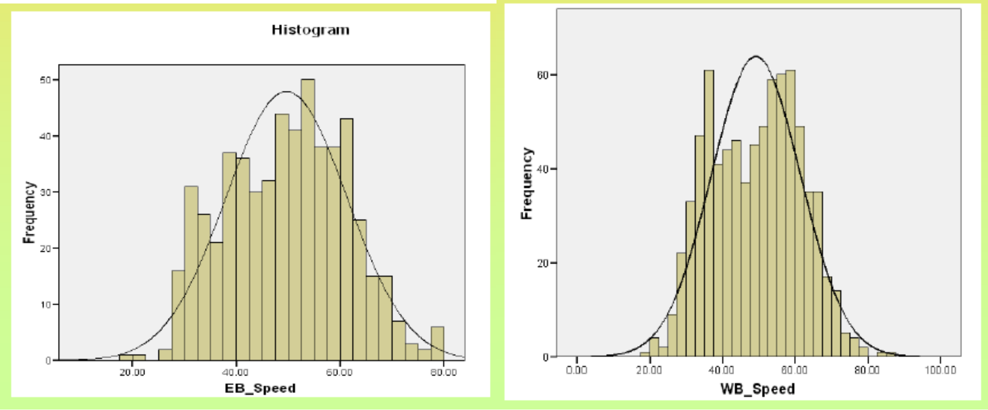


Figure 3-2: Distribution of traffic flow speeds (mph) computed from individual vehicles

The above statistics and the graphical results reveal vital information for understanding the behavioral patterns of the driving population:

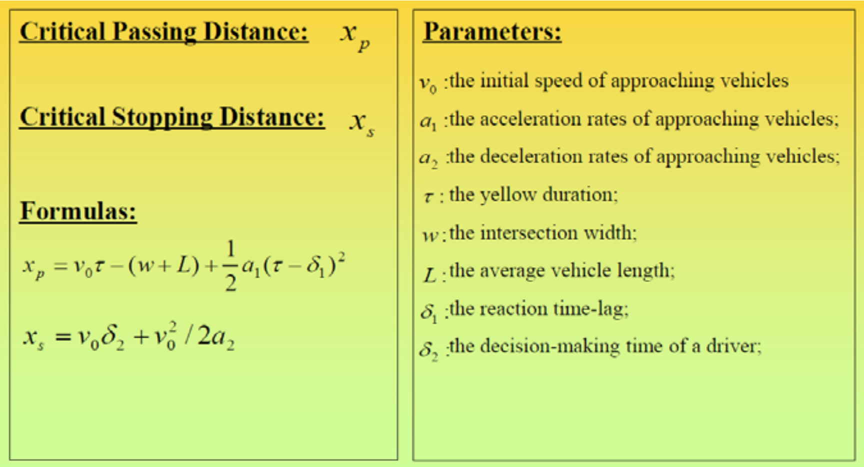
- Although the average and the median speeds are close to the posted speed limit of 50 mph, the traffic flow speeds at the target intersection indeed are distributed in a wide range, as evidenced in their speed variance (about 12mph);
- The maximum speeds of 86 mph eastbound and 79 mph westbound are far over the posted speed limit, and drivers at such high speeds are more likely to be trapped in a dilemma zone of the "cannot-stop" scenario; and
- The minimum vehicle speeds of approximately 20 mph (both eastbound and westbound) indicate the existence of some slow drivers who may be caught in a dilemma zone of the "cannot-pass scenario" when encountering a yellow phase.

The next step computed the location of dilemma zones for drivers with different approaching speeds. Table 3-2 lists the variables and equations applied to compute the critical stopping and passing distances for each speed-group of drivers. The resulting distribution of dilemma zones for each speed group is further illustrated in Figure 3-3, where drivers at the approaching speed of 85 mph may encounter a dilemma zone of 400 feet, that is, in the range of 700 feet to 300 feet from the intersection stop line. The range of such dilemma zones become shorter and closer to the intersection for the groups driving at slower approaching speeds. For example, the driving group traveling at the posted speed limit of 50 mph may experience the dilemma zone of about 230 feet (between 200 feet and 430 feet), which is much shorter than the size of dilemma zones for the aggressive drivers. Since the 85th percentile of the traffic speed distribution is about 62 mph and more than 92 percent of drivers travel at speeds greater than the posted, it is reasonable to set the posted speed limit as the lower bound for design of the dilemma-zone protection system. Hence, the initial design set the segment between 180 feet and 700 feet from the intersection stop line as the target dilemma zone that needs to be eliminated with the proposed system.

However, the field survey showed that the traffic flows at the target intersection consist of a larger percentage of trucks, most of them moving at a speed far above the posted limit. In addition, the most severe accidents at the target intersection involved trucks. Since the braking and acceleration factors of trucks differ significantly from passenger cars, the initial design was revised to accommodate the dilemma zones that are likely to be experienced by high-speed trucks.

Figure 3-4 illustrates the distribution of dilemma zones for different driving groups computed with the operational characteristics of trucks. Note that the roadway segment to be monitored by the proposed dilemma-zone protection system increases from 520 feet in the initial design (see Figure 3-3) to 700 feet (between 180 feet to 880 feet) in the revised design when considering the truck impacts. As a result, the core logic of the proposed protection system is set as follows: "*the signal controller will extend the all-red phase to ensure all vehicles detected in the dilemma zone (see Figure 3-4) can either safely pass through the intersection or comfortably decelerate to a complete stop.*"

Table 3-2: Equations for computing the dilemma zone



Critical Passing Distance: x_p

Critical Stopping Distance: x_s

Formulas:

$$x_p = v_0\tau - (w+L) + \frac{1}{2}a_1(\tau-\delta_1)^2$$

$$x_s = v_0\delta_2 + v_0^2/2a_2$$

Parameters:

v_0 :the initial speed of approaching vehicles
a_1 :the acceleration rates of approaching vehicles;
a_2 :the deceleration rates of approaching vehicles;
τ : the yellow duration;
w :the intersection width;
L :the average vehicle length;
δ_1 :the reaction time-lag;
δ_2 :the decision-making time of a driver;

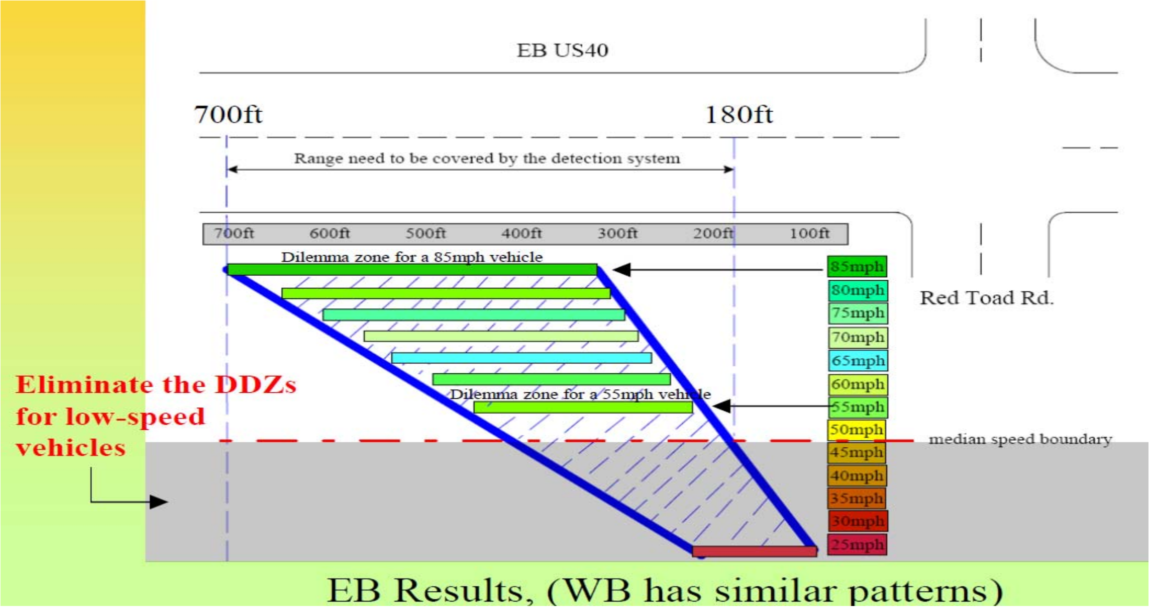


Figure 3-3: Distribution of dilemma zones for different driving groups (passenger cars)

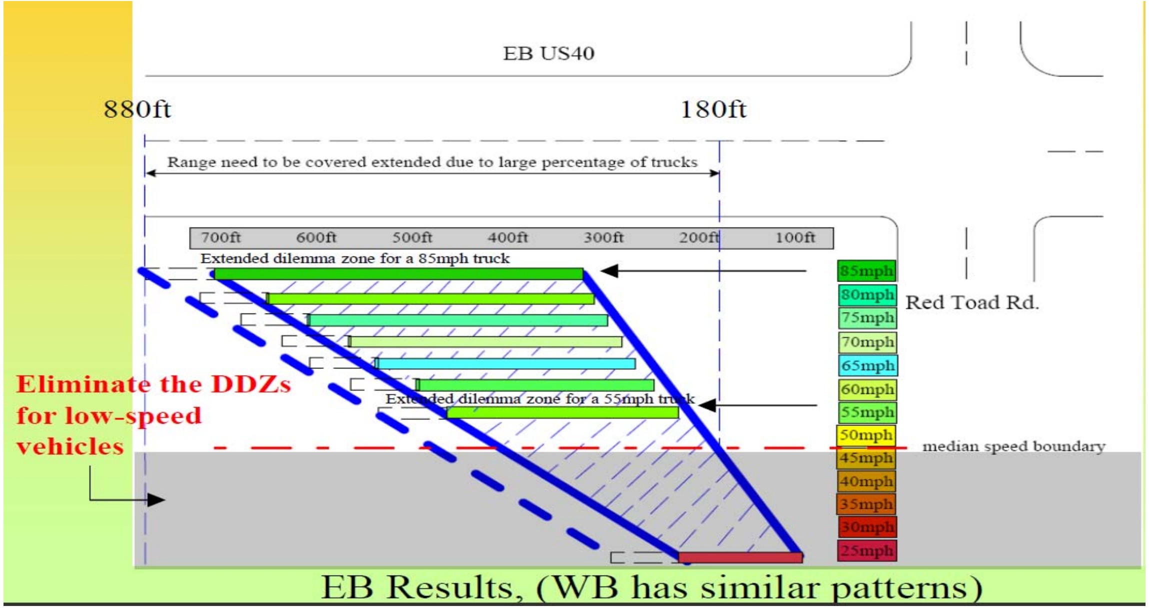


Figure 3-4: Distribution of dilemma zones for different driving groups (trucks)

3.3 System design features

Given the computed dilemma zone of 700 feet, the key system design issue is how to monitor those vehicles trapped within this range when the signal changes to the yellow phase. Figure 3-5 illustrates the roadway segment that covers the dilemma zones for 90 percent of the driving populations and for vehicle speeds ranging from the speed limit of 50 mph to the very aggressive drivers of 85 mph. To ensure each trapped vehicle can safely pass through or stop at the intersection, the proposed system should also have the capability to track each vehicle's speed and distance to the intersection stop line.

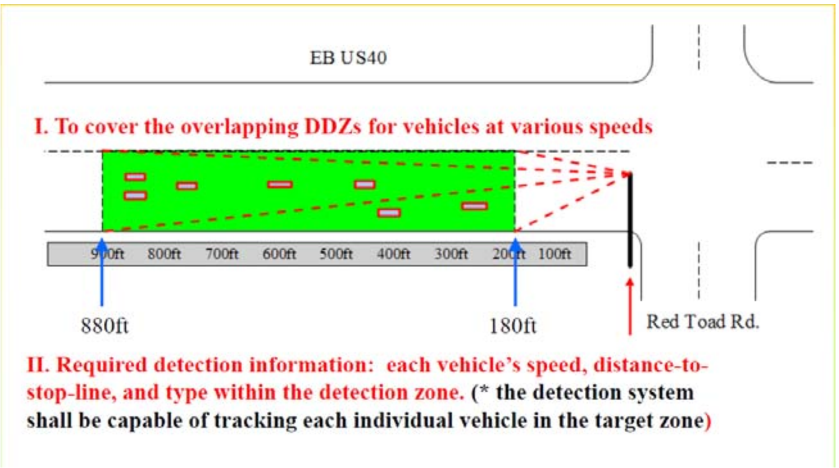


Figure 3-5: Roadway segment under the dilemma zone protection

With respect to the operations, the proposed dilemma-zone protection system should also be able to work with the signal controller (an actuated control) at the target intersection to perform the following operations:

Case-I: A high-speed vehicle is within the dilemma zone and the actuated controller is ready to gap-out:

> **Required action**: Inform the controller to extend the green time if it has not reached the maximum duration (see Figure 3-6).

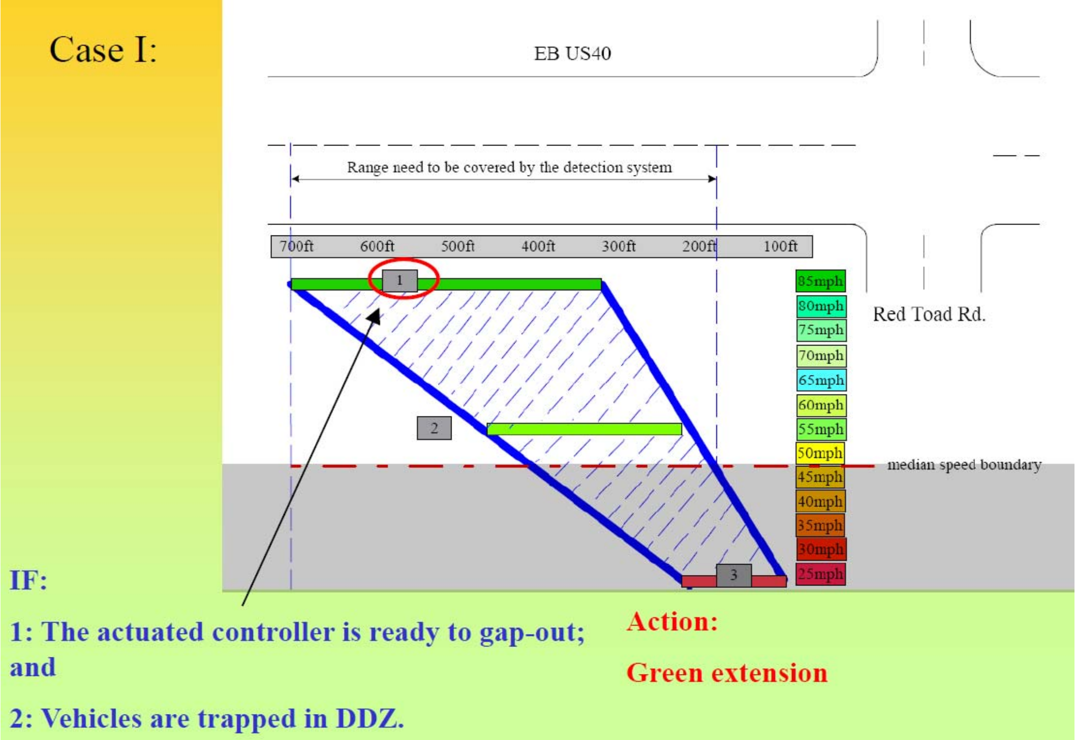
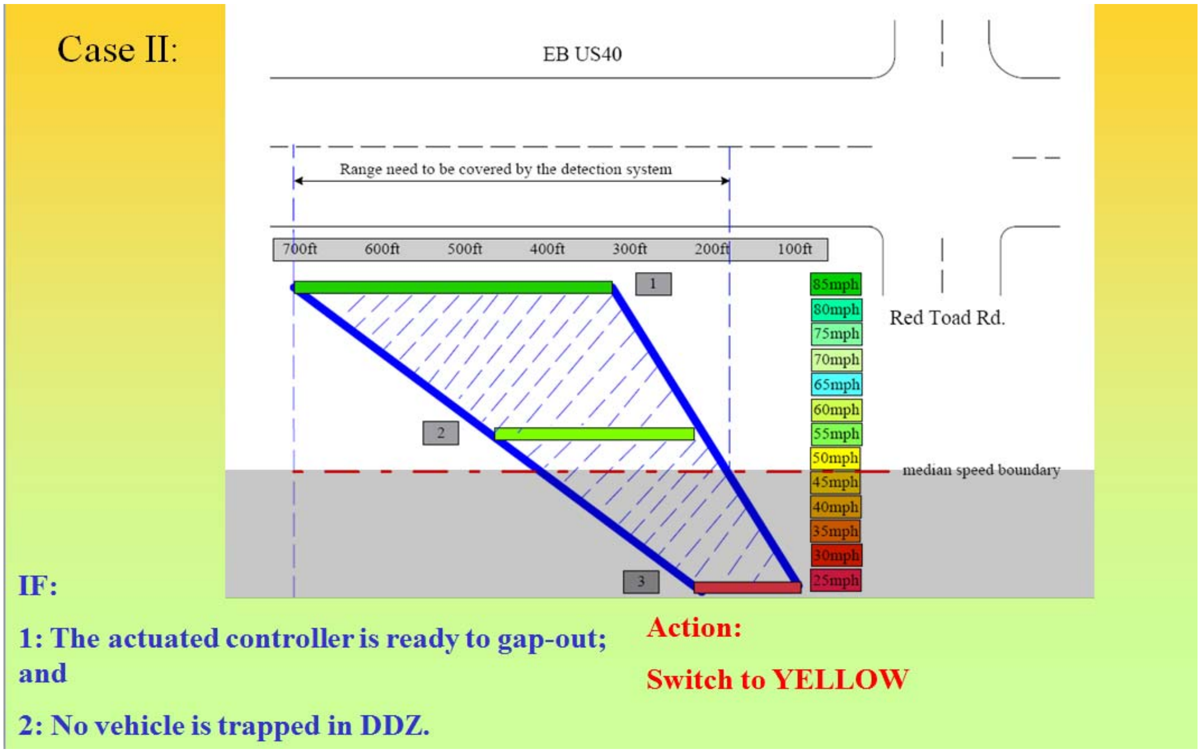


Figure 3-6: Graphical illustration of the system operations for Case I

Case-II: No vehicle is within the dilemma zone and the actuated controller is ready to gap-out:

Required action: Inform the controller to switch to the yellow phase (see Figure 3-7).



Case II:

IF:

1: The actuated controller is ready to gap-out; and

2: No vehicle is trapped in DDZ.

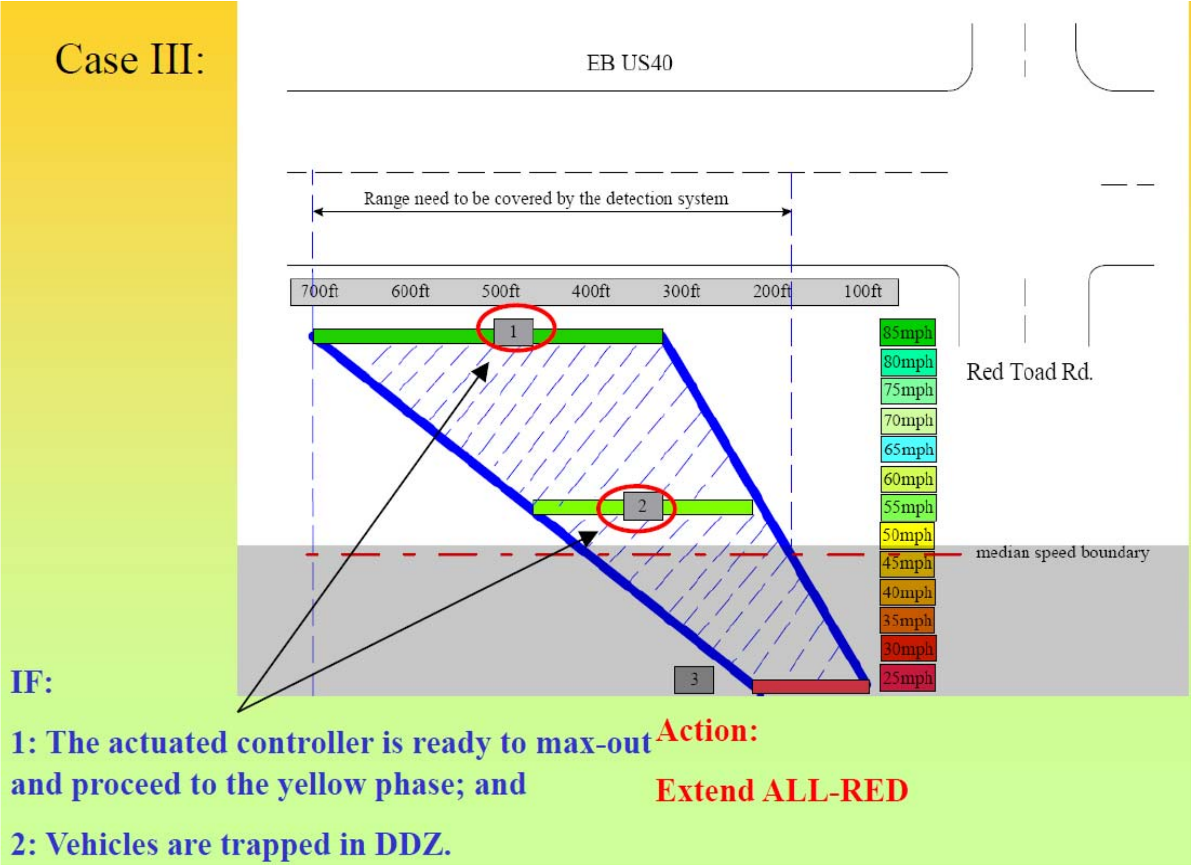
Action:

Switch to YELLOW

Figure 3-7: Graphical illustration of the system operations for Case II

Case-III: A high-speed vehicle is within the dilemma zone and the actuated controller is ready to gap-out:

Required action: Inform the controller to switch to the yellow phase and execute the extended all-red to clear the traffic (see Figure 3-6).



Case III:

IF:

1: The actuated controller is ready to max-out and proceed to the yellow phase; and

2: Vehicles are trapped in DDZ.

Action:

Extend ALL-RED

Figure 3-8: Graphical illustration of the system operations for Case III

Note that Case-III is the most critical scenario in which the proposed dilemma zone system is expected to demonstrate its effectiveness. The extended all-red phase is designed to provide extra time for those vehicles trapped in the dilemma zone (especially for high-speeding vehicles in the far end of the protection zone) to safely pass through the intersection.

The key to the success of such a system is to identify an effective traffic sensor system that can reliably monitor the speed and location of each vehicle within the target zone of 700 feet. Since most traffic sensors for urban traffic control are designed for point measurement (i.e., either loop-based or narrow-beam radar detectors), the proposed protection system will have to rely on either a series of point sensors, a wide-beam radar, or microwave sensor.

A review of the available traffic sensors in the market for this study showed that Wavetronix® developed the SmartSensor Advanced, a microwave detector. to address the limitations of traditional dilemma zone protection provided by loop detectors (Wavetronix, 2012). The sensor functions like a series of loop detectors and can dynamically track vehicles as they approach an intersection. The SmartSensor Advanced has a detection range of 500 feet, within which the sensor can continuously measure vehicle speeds and distance from the intersection stop bar. Figure 3-9 illustrates the difference in detection range between the SmartSensor Advanced and a conventional loop detector.

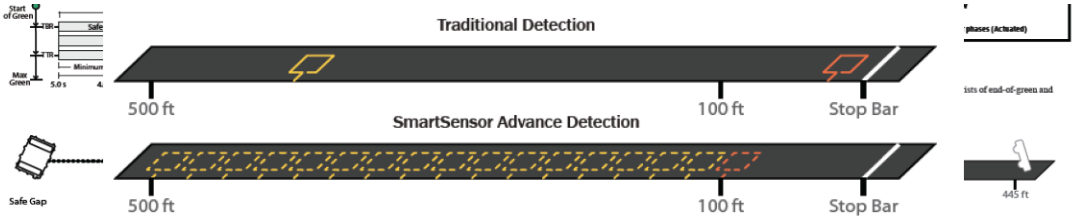


Figure 3-9: Comparison of the detection function between Smartsensor Advanced and conventional loops.

Figure 3-10 shows that a deployed SmartSensor Advanced that can be installed either at the roadside or attached to the bar for a signal head.

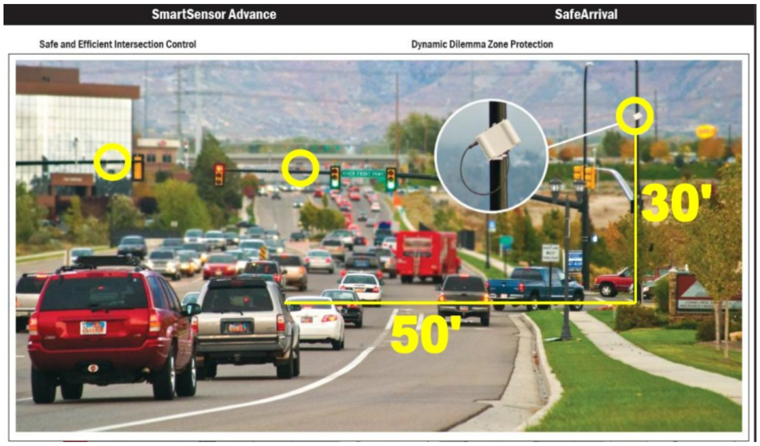
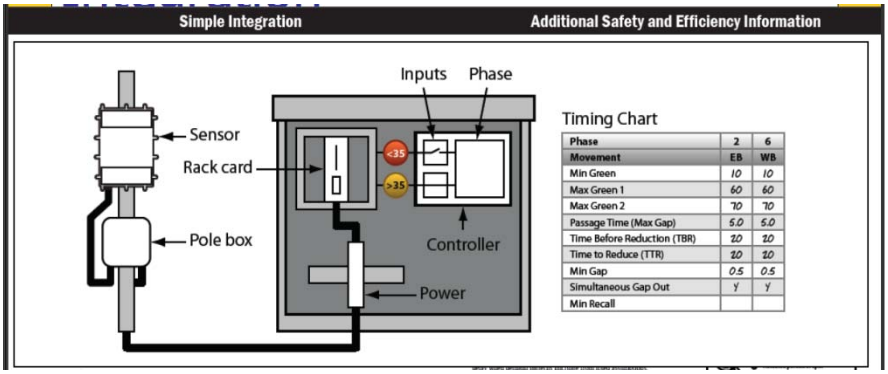


Figure 3-10: Roadside operations of Smartsensor Advanced

Figure 3-11 highlights the operational flows between the sensor and the interaction controller, where the computing module in the SmartSensor Advanced will continuously update the estimated arrival time of each detected vehicle and inform the signal controller to take appropriate actions. By using a time-based rather than a distance-based tracking method, the dilemma-zone protection system can ensure a safe pass or stop of each vehicle based on its speed evolution within the detection zone. At the same distance from the stop bar, faster-moving vehicles, for example, may be given extra time to allow for safe clearance of the intersection, whereas slower-moving vehicles may only encounter a green gap-out scenario under the actuated control.



Timing Chart

Phase	2	6
Movement	EB	WB
Min Green	10	10
Max Green 1	60	60
Max Green 2	70	70
Passage Time (Max Gap)	5.0	5.0
Time Before Reduction (TBR)	20	20
Time to Reduce (TTR)	20	20
Min Gap	0.5	0.5
Simultaneous Gap Out	Y	Y
Min Recall		

Figure 3-11: Operational flows between the SmartSensor Advanced and signal controller

Final proposed design

The detection range of a SmartSensor Advanced is 500 feet – shorter than the eastbound protection zone of 700 feet at the US 40 and Red Toad Road intersection. The proposed system design uses two SmartSensor Advanced to provide ample dilemma zone detection for the eastbound vehicles. Because the intersection is operated under an actuated control, another sensor was deployed in the westbound direction to ensure the dilemma zone protection and proper function of the signal controller. Figure 3-12 shows the sensor locations at the target intersection.

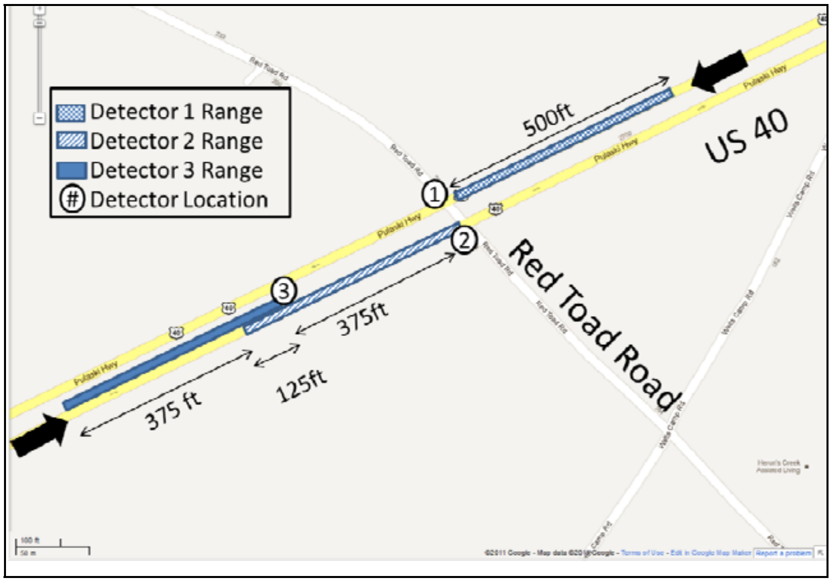


Figure 3-12: Sensor locations and detection range for the final design

Based on extensive field tests of the deployed sensors' sensitivity and its interaction effectiveness with the intersection controller, the final design of the dilemma-zone protection system for the US 40-Red Toad Road intersection was given the following operational features:

- Call a green extension after reaching the minimum green time if a vehicle was detected within 500ft of either intersection stop bar (Sensor 1 and 2 detection range) with a minimum speed of 30 mph;
- Call an all-red extension if a vehicle is detected within 500ft of either US 40 approach with a minimum speed of 56 mph within the first three seconds of the all-red phase. The length of the extended all-red phase is determined by the vehicle's speed and its distance from the stop bar with a maximum extension of 2.5 seconds.
- Additional dilemma zone protection for EB US 40 was provided by sensor 3 (Figure 3-12). The section of EB US 40 covered solely by sensor 3 (from 500ft to 875ft relative to the EB stop bar) was used only for all red extension. Within this range, a vehicle must be detected with a minimum speed of 65 mph for an all red extension to be called.

Chapter 4: Field Evaluation

4.1 Introduction

This chapter describes the procedures and data used to evaluate the effectiveness of the system designed to protect vehicles in the dilemma zones. The evidence supporting effectiveness evaluations was computed from the field measurement of driving populations. Evaluation of the system's performance was focused on its detection accuracy and false alarm. Detection accuracy determines whether the system can accurately detect vehicles trapped in the dilemma zone and activate the call for all-red extension. The latter issue, false alarms, concerns the performance reliability that is measured by the number of all-red extensions called by the designed system when the detected vehicles are not in their dilemma zones.

To rigorously perform such an evaluation, the research team first conducted the field traffic observations to obtain the following data at a high level of accuracy:

- Speed evolution of every vehicle in the target zone during the yellow and all-red phases;
- Vehicle type and the evolution of its acceleration and deceleration rates in the detection zone during the yellow and all-red phases; and
- The time and duration of each activated all-red extension.

With the above information, it is possible to compute whether or not any vehicle was trapped in the dilemma zone and if the designed protection system was activated in a timely manner to eliminate potential accidents.

This chapter is organized as follows: Section 4-2 details the field data collection procedures, including locations and equipment used to monitor traffic conditions. Section 4-3 reports the observed traffic conditions and evaluation results, highlighting the designed system's effectiveness in preventing accidents. Section 4-4 concludes with research findings and suggestions.

4.2 Field Data Collection

To evaluate the performance of the dynamic dilemma-zone protection system, several data collection plans were considered. Although a bird's-eye video is a convenient method for mimicking the continuous microwave detection system, this site was on a level grade, making this method unfeasible. Additionally, the specific nature of the parameters needed to call the all-red extension requires high accuracy measures of speeds at given distances. Thus, non-perpendicular views of approaching vehicles may introduce parallax-related errors. With these considerations in mind, the research team decided to conduct an in-depth data collection of only the eastbound approach of US 40, using both perpendicular video and tube detectors.

The data collection plan used five video recording cameras and four tube detectors. Four video cameras were used to track vehicle speeds at predefined distances from the eastbound intersection stop bar by measuring the time to traverse a known perpendicular distance in each video frame.

To measure vehicle speeds at each preset distance within the system's detection range, video cameras and tube detectors were alternated every 100 feet, starting at 200 feet from the eastbound US 40 intersection stop bar. Since a microwave sensor reaches 875 feet from the intersection, the final tube detector was placed at this location rather than at 900 feet from the stop bar. The remaining video camera was used to capture the eastbound US 40 signal phases and timings. Table 4-1 provides a summary of the equipment and deployed locations on eastbound US 40. To determine when an all-red extension was called and from which approach, the research team used the signal log files provided by the SHA signal shop that includes all red-extension events recorded by the intersection's actuated controller.

Table 4-1: Data Collection Equipment Locations

Distance From Stop Bar	Equipment Used	Data Type
200ft	Video Camera	Speed, Class, Lane
275ft	Video Camera	Signal
300ft	Tube Detector	Speed, Class, Lane
400ft	Video Camera	Speed, Class, Lane
500ft	Tube Detector	Speed, Class, Lane
600ft	Video Camera	Speed, Class, Lane
700ft	Tube Detector	Speed, Class, Lane
800ft	Video Camera	Speed, Class, Lane
875ft	Tube Detector	Speed, Class, Lane

To ensure the consistency between all field information collection devices, the data from each data source were synchronized using handheld GPS units. Before starting the data collection, the GPS unit was placed next to each of the tube detectors and the signal clock to estimate the time offset of each data source (Figure 4-1). The offset between each data source's internal clock and the GPS clock was calculated and applied to the respective data files. Similarly, each video began by recording the GPS unit to establish a universal time for all video sources. The GPS time was input into each video using video reduction software.

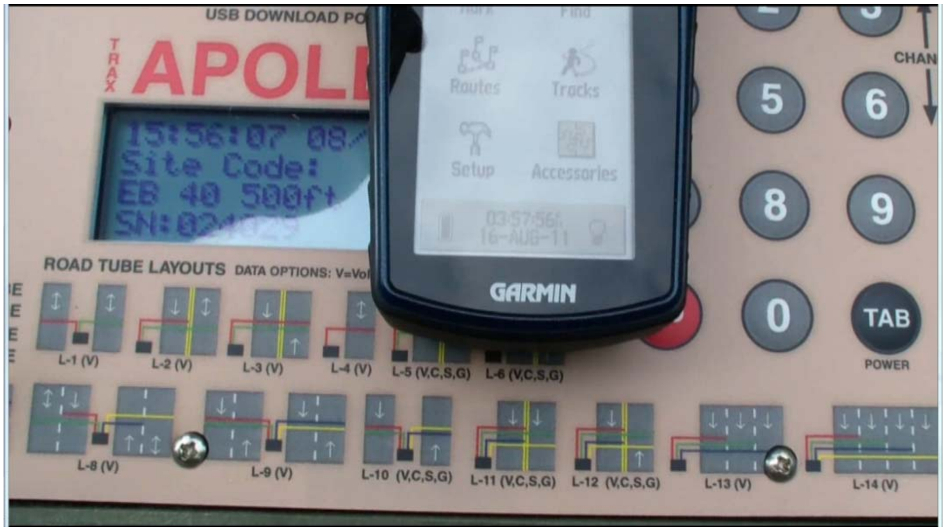


Figure 4-1: Synchronization of data sources with GPS clock

Data Reduction

Using the video data from high-precision camcorders, the research team was able to compute vehicle speeds by measuring their times to traverse a marked distance in each video frame. The distance was marked using construction cones placed on both sides of eastbound US 40. The time to traverse each marked distance was determined by creating time stamps for each vehicle as it entered and exited the measurement zone. To improve the accuracy of the manual video reduction, this study also produced a specially designed computer program to clearly mark the entrance and exit of the measurement zone as well to slow the video down to 1/128 playback speed. This software was used to create timestamps for each EB US 40 phase change during the analysis period and also to synchronize the time stamp clock to the recorded GPS clock. A snapshot of this software is provided in Figure 4-2.

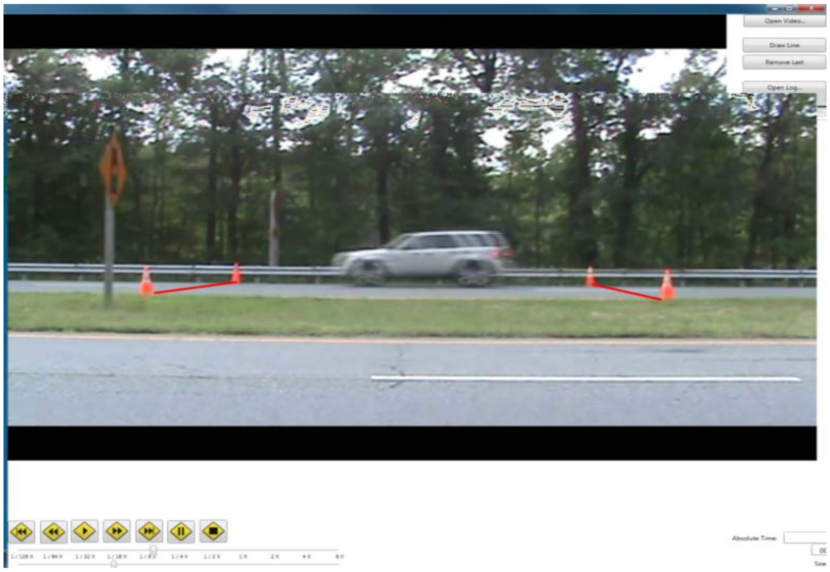


Figure 4-2: Snapshot of the video reduction software

The tube detector data was extracted from the devices using the software that came with the devices. Each tube detector has its own internal clock to create the time stamps for vehicle detections. Thus, each tube detector had a unique offset relative to the GPS clock. The time offset for each tube detector was computed and applied to each respective data file. Similarly, the time offset for the signal controller was incorporated into the all-red extension log file.

Before conducting data analysis, the research team recognized that the video camera downtime needed to be considered when comparing the results with those collected via tubes. The concern was that some video cameras recorded to DVDs, and the recording time was limited to one-hour segments. Therefore, the DVDs in these devices required changing after one hour of recording. However, during this period the tube detectors were still collecting data. Thus, the detections captured by the tube detectors during these periods were removed from the analysis.

4.3 Analysis results

To evaluate the performance of the dilemma-zone protection system, the analysis focused on vehicles detected within the first three seconds of the red phase for EB US 40. During this period, the system looked for vehicles at or above the pre-defined threshold speeds based on their distances from the stop bar. The analysis procedure to evaluate the system's detection accuracy consists of three steps:

First, it was necessary to identify the signal phase when there are vehicles detected in the protection zone. This detection was done with an algorithm that can match the time stamps for each detected vehicle to a signal phase; the algorithm was designed for this study.

Second, for vehicles detected in a red phase, the starting time of the associated red phase was subtracted from each vehicle's detection time. If the difference between the start of the red time stamp and the detection time of the target vehicle was less than three seconds, this observation was determined to have the potential to call the all-red extension.

Finally, it was determined whether the extended all-red phase should be activated by comparing the speeds of the vehicles detected within three seconds of red with the threshold speeds; this calculation was based on the distance from the stop bar in which the detection took place. The threshold speed for vehicles within 500 feet from the intersection stop bar was 55 mph; for those from 500 feet to 875 feet the speed was 65 mph.

During the four-hour observation period, 164 US 40 red phases was observed, and 521 vehicles detected within three seconds of the onset of a red phase. Of these 521 vehicles, 495 (95 percent) were passenger vehicles, while 26 vehicles (5 percent) were commercial trucks. Only one all-red extension was called by the eastbound approach of US 40 during the observation period. This single event provided the only opportunity to check for detection accuracy.

Using the time stamp for the red extension from the signal log file, the red phase containing the all-red extension was identified. To check the validity of the call, vehicles detected within three seconds of the onset of the target red phase were analyzed. Comparing the detected vehicle's speed with the threshold speed at the target distance confirmed that the call was validated where a van traveling at 57.5 mph was observed at the distance of 400 feet from the stop bar. This detection called for extending the all-red phase for an additional 1.1 seconds.

The image data 400 feet from the stop bar was captured by the camcorder video. Thus, the vehicle that activated the all-red extension was able to be identified (Figure 4-3). Using the video to capture the signal phases, it was possible to observe that the vehicle ran over the extended red light just before the side street (Red Toad Road) traffic was released. (The detection and activation of the all-red phase extension prevented one side-collision accident.)

Lanes: 2

Absolute Time: 2011-08-16T12:11:06

00:04:18.717

Speed Ratio: 1 / 16 X

Figure 4-3: Vehicle detection that triggered an all-red phase extension

In Figure 4-4, three seconds after starting the default all-red phase, the vehicle that triggered the all-red extension was approximately 150 feet from the eastbound US 40 intersection stop bar. This vehicle had a speed of 55.3 mph at the location of 200 feet from the intersection, just around the threshold speed of 55 mph.

Figure 4-4: Vehicle position after 3 seconds elapsed from the default all-red phase

Figure 4-5 depicts the vehicle's location at the end of the all-red extension, barely clearing the intersection just before the Red Toad Road traffic was released.

Figure 4-5: Vehicle position at the termination of the all-red extension

Analyzing false negative calls used the same procedure as the analysis of detection accuracy. Each red phase in which the all-red extension was not called provided an opportunity to evaluate false negatives. As in the first analysis, the speeds of all vehicles detected within three seconds of the onset of a red phase were compared with the threshold speed at each respective distance for detection. Of the 520 vehicles detected within three seconds of the onset of a red phase in US 40, none met the criteria that required the system to call the all-red extension.

In addition to validating the single all-red extension, the analysis also determined whether any vehicles are trapped in the traditional dilemma zone (this system looks for vehicles at the onset of red, rather than at the onset of yellow). Using equation 1-1, and the following parameter values, the size and location of a dilemma zone was calculated.

Table 4-2: Dilemma Zone Parameter Values

Parameter	Value
□□(sec)	5.5
□□1 (sec)	1.14
□□2 (sec)	1.14
*a1 (ft/s^2)	16
*a2 (ft/s^2)	11.2
W (ft)	70
L (ft)	12

*Data from: Institute of Traffic Engineers: *Transportation and Traffic Engineering Handbook*,Prentice Hall, 1985.

Upon testing for the existence of a traditional dilemma zone at 1 mph increments, the analysis discovered that a dilemma zone did not exist unless an approaching vehicle exceeded 76 mph beyond the onset of the yellow phase. Only one vehicle exceeded the 76 mile-per-hour threshold during the yellow phase. That vehicle's speed was 77 mph, which corresponded to a 9-foot dilemma zone 692-701 feet from the stop bar. However, the vehicle traveling at 77 mph was detected at a distance of 875 feet from the stop bar; well within the cannot-pass zone. Thus, the yellow phase of 5.5 seconds effectively prevented vehicles from being trapped in a dilemma zone during this study. It is crucial to note that the vehicle that called the all-red extension would have not have been protected using the traditional dilemma-zone protections system that looks for vehicles at the onset of yellow. Assuming the vehicle that called the all-red extension approached the intersection at the same speed (57.5 mph) in which it was detected at 400 ft, the vehicle would have been located at approximately 932.4 ft at the onset of yellow. This distance would not likely be covered by a traditional dilemma-zone protection system because such a system would assume this vehicle would comfortably stop before the end of the all red phase. Thus, a green extension or an all-red extension (if max green were achieved) would not have been called. In doing so, the vehicle would have entered the intersection near the termination of the default all-red phase of 3 seconds (Figure 4-5), which creates the potential for a conflict with vehicles entering from the minor road (Red Toad Road). This observation emphasizes a distinct advantage of looking for vehicles at the onset of red rather than at the onset of yellow. A driver who cannot clear the intersection but makes the incorrect decision and attempts to do so can still be protected by extending the all red phase. In fact such an instance was captured on video during this study.

4.4 Driver Behavior & Response to Signal Change

Figure 4-6 shows the vehicle approach speeds at the onset of the yellow phase, aggregated by distance from the stop bar and time after the onset of yellow.

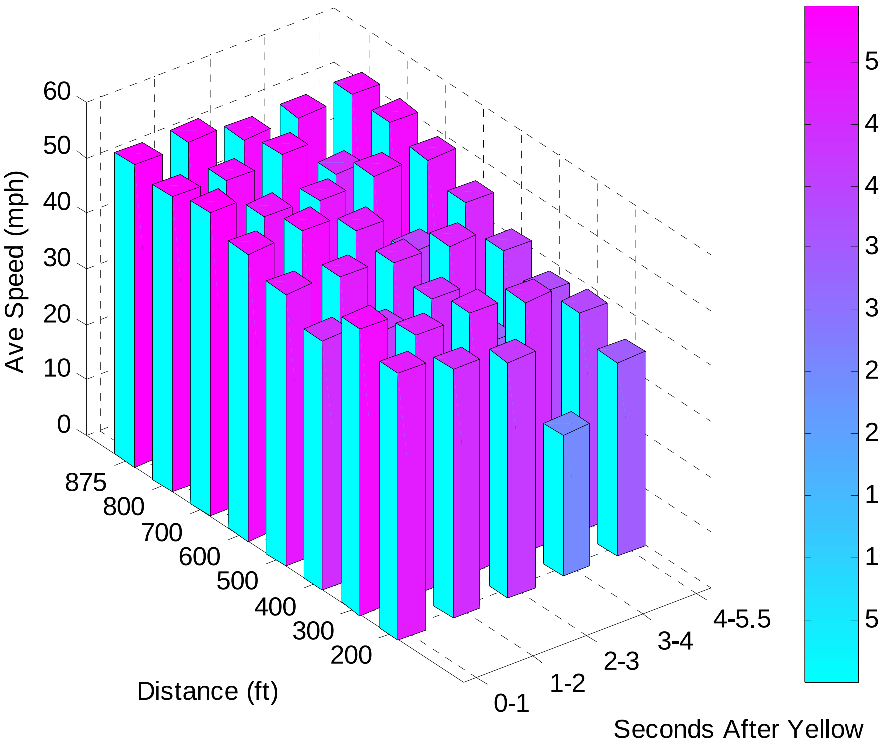


Figure 4-6: Approach Speeds During the Yellow Phase

As expected, vehicle speeds are generally lower near the intersection. One exception occurs at 300 feet from the stop bar, where speeds tend to increase regardless of how much time has passed after the onset of yellow. This observation may be explained by driver's deciding to pass the intersection, rather than continue to decelerate as they approach the intersection. Thus, it appears that at this particular intersection, some drivers decide to accelerate between the distances of 400 and 300 feet from the intersection within the yellow phase. Furthermore, for distances greater than 200 feet from the stop bar, the approach speed is fairly constant regardless of the time after the onset of yellow. As expected, at 200 feet, speeds tend to decrease as the yellow phase approaches termination as most vehicles at this location decide to stop, especially after 3 seconds of yellow.

Figure 4-7 presents vehicle speed patterns during the red phase. Here, speed patterns are consistent across the entire red phase with vehicle speed decreasing while approaching the intersection. In comparing vehicle speeds during the red and yellow phases, the research team note that at speeds are generally the same as those in yellow phase beyond 500 ft. Inside of 500 ft, the speeds during the red phase tend to be lower than those in the yellow phase as this is where most vehicles continue to decelerate to rest.

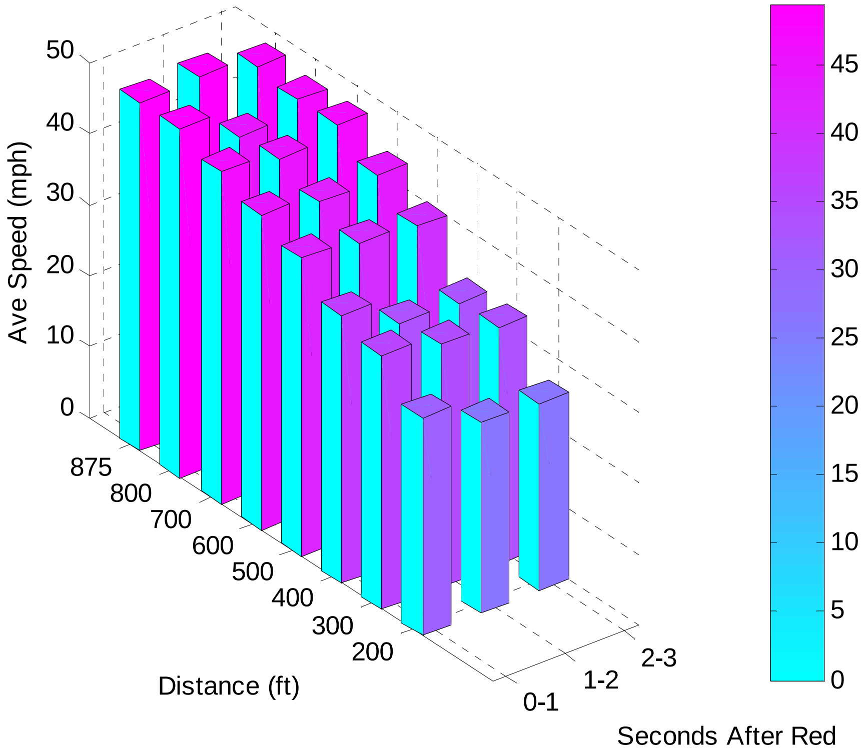


Figure 4-7: Approach speeds during the red phase

4.5 Conclusions

The detection system uses a non-traditional dilemma zone protection logic to look for vehicles at the onset of a red phase rather than at the onset of yellow. This methodology provides the opportunity to extend the all-red phase even if the maximum green time has not been achieved. Table 4-3 summarizes the classification of the detected vehicles and their average speeds and maximum speeds at each data collection location. As expected, the number of vehicles detected in the yellow phase is greater than the number detected in the first three seconds of the red phase. Also, the speeds during the yellow phase were higher than those in the red.

Table 4-3: Vehicle Detection Summary in the Yellow and All Red Phase

	Yellow Phase					***Red Phase**				
Distance	**Cars**	**#Trucks**	**Total Vehicles**	**Ave Speed (mph)**	**Max Speed (mph)**	**Cars**	**#Trucks**	**Total Vehicles**	**Ave Speed (mph)**	**Max Speed (mph)**
200	8	3	51	37.9	71.3	3	1	54	27.7	55.3
300	8	3	61	48.7	61	3	4	57	34.5	54
400	01	4	105	41.6	63.8	5	4	59	34.4	**57.5
500	07	13	120	45.9	65	3	5	68	41	56
600	18	6	124	48.5	66.3	1	2	73	43.5	55.2
700	14	13	127	50.3	69	2	2	64	46.3	58
800	18	6	124	51.9	74.1	5	2	67	46.8	62.3
875	53	16	169	53.7	77	3	6	79	50	64
TOTAL	**17**	**64**	**881**			**95**	**26**	**521**		
% of Total	**3%**	**7%**				**5%**	**5%**			

* Detected within 3 seconds of the onset of red

** All red extension was called

Chapter 5: Conclusions

5.1 Conclusions

This study reports research on understanding driver behavior during a signal yellow phase and the resulting distribution of dynamic dilemma zones. The study consisted of two parts. Using extensive field observations, Part I focused on identifying critical factors affecting a driver's decision when encountering a yellow signal phase. Part II centered on developing a dynamic dilemma-zone protection system, based on the response patterns of different populations at high-speed intersections as observed in the Part I study. The developed system has been deployed by SHA at the intersection of US 40 and Red Toad Road and evaluated by the research team to confirm its effectiveness in preventing accidents caused by dilemma zones. Primary research findings from this study are summarized below:

- Based on their responses during the yellow phase, drivers at most signalized intersections can be classified into three distinct groups: aggressive, normal, and conservative.
- A variety of factors may affect a driver's decision to take an aggressive or a conservative action during the yellow phase. Factors include: average traffic flow speed, green splits, traffic volume, signal coordination, the number of approach lanes, talking on the phone or not, vehicle type, driver age, and sex. Additionally:
    - The speed of a vehicle approaching the intersection (when compared with the average traffic flow speed) seems to be the best indicator for identifying the aggressive level of a driver.
    - Intersection geometric features may affect a driver's response to the encountered yellow phase. For example, drivers on the minor street are more likely to make an aggressive pass decision during a yellow phase due to the allocated short green phase.
    - A coordinated signal system may encourage drivers to make an aggressive passing decision during the yellow phase.
    - Some behavioral variables could have significant compound impacts on a driver's response during the yellow phase. For example, male drivers in

    SUVs tend to take aggressive actions when approaching the yellow phase, whereas female drivers do not.
  - Understanding the behavioral discrepancy between different driving populations and the critical contributing factors is essential for researchers and responsible agencies to design safety improvement strategies.
- The dilemma zone is dynamic in nature, varying with the driving population. Thus, the dilemma zone computed with the conventional method reflects only a sub-segment of the spatial distribution of dilemma zones.
- The spatial distribution of dilemma zones at a high-speed intersection varies with the speed distribution of its approaching vehicles, whose drivers can be generally classified as aggressive, normal, and conservative. The length that covers the dilemma zones of all driving groups increases with the variance of the speed distribution among the driving populations.
- The designed system for dynamic dilemma zone protection seemed to function effectively during the field evaluation period. The field image data actually evidenced its effectiveness in preventing a potential side-collision accident.
- The implemented protection system had no false negative detections during the evaluation period; that is, no vehicle meeting the criteria to call the all-red extension was missed by the dynamic detection system.
- A hazardous intersection, such as US 40 and Red Toad Road, can be monitored effectively with the relatively simple system developed in this study to improve its traffic safety.

5.2 Recommendations

Based on the above research findings, SHA should consider taking the following actions to improve traffic safety at all hazardous intersections:

- Enhance traditional signal timing models for possible reduction of aggressive driving-related factors identified in this study while maintaining operational efficiency. Based on the significant variables identified in this study, SHA can work with universities to develop a series of quantitative models to predict a driver's decision (aggressive pass, normal pass, normal stop, or conservative stop) in response to the yellow phase at hazardous intersections and the number of aggressive drivers potentially trapped in the dilemma zone during each signal cycle. Such models can be incorporated into the traditional signal control framework to improve the intersection safety.

- Maryland should consider developing driver education guidelines based on the behavioral findings in this study to discourage aggressive maneuvers during the yellow phase. For example, integration of the research results with vehicle incident reports will disclose the interrelations between vehicle characteristics, aggressive driving maneuvers, and signal related incidents. Such valuable information will be critical to the design of customized driver educational plans.
- SHA should develop a driver response prediction model to support the dilemma-zone protection system developed in this study. During a yellow phase, the system should be able to track the target drivers and concurrently predict their possible responses based on measurable variables (e.g., traffic environment-related variables and individual vehicle dynamics). The system should activate the warning message and extend the all-red phase to prevent any rear-end collision or side-crash if the target driver is computed to be trapped in the dilemma zone and predicted to take an aggressive passing maneuver.
- Proper maintenance will be needed to keep the dilemma-zone protection system deployed at the intersection of US 40 and Red Toad Road to sustain its effectiveness.
- More field evaluation should be conducted for the deployed system and the application should be expanded to different hazardous intersections if the evaluation results continue to show the expected effectiveness.
- More field studies on driving speed distributions as conducted in this project should be done for those hazardous intersections managed by SHA to accurately identify the location and length of their dilemma zones.

REFERENCES

Bonneson, J.A., and P.T. McCoy. Manual of Traffic Detector Design. 1st Edition, Institute of Transportation Engineers, Washington, D.C., June 1994, pp.42-47.

Bonneson, J.A., D. Middleton, K. Zimmerman, H. Charara, and M. Abbas. Intelligent Detection-Control System for Rural Signalized Intersections. Report No. FHWA/TX-02/4022-2. Texas Department of Transportation, Austin, Texas, August 2002.

Chang, G. L. and Y. Liu, *Interrelations between Accident Rates, Signal Yellow Times, and Vehicle Performance Characteristics*. Project Report Phase-II, pp. 46-49, MDSHA, 2006.

Determining Vehicle Change Intervals: A Proposed Recommended Practice. ITE Journal. Vol. 55, No. 5, 1985, pp. 61-64.

Gazis, D., Herman, R., and Maradudin, A., 1960. “The problem of the amber signal light in traffic flow,” Operations Research, Vol. 8, No. 1, 112-132.

Glauber, C.M. “Evaluation of a Dynamic Dilemma Zone Protection System at a Signalized Intersection.” Master’s Thesis. Bradely University. U.S. 2008.

Knodler, M., and Hurwitz, D. “Final Report: An Evaluation of Dilemma Zone Protection Practices for Signalized Intersection Control.” Vermont Agency of Transportation. Montpelier, VT. 2009

Liu, Y., Chang, G. L., Tao, R., Hicks, T., and Tabacek, E., "Empirical Observations of Dynamic Dilemma Zones at Signalized Intersections," *Transportation Research Record*, 2035, 122-133. 2007.

Maryland Accident Analysis Reporting System (MAARS). Crash History for the US 40 at Red Toad Road Intersection from 2000-2010. Access Nov. 11, 2011. Retrieved from:https://maars.cattlab.umd.edu/#

Middleton, D., D. Jasek, H. Charara, and D. Morris. Evaluation of Innovative Methods to Reduce Stops to Trucks at Isolated Signalized Intersections. Report No. TX-97/2972-S. Texas Department of Transportation, Austin, September 1997.

Pant, P.D., and X.H. Huang. Active Advance Warning Signs at High-Speed Signalized Intersections: Results of a Study in Ohio. Transportation Research Record 1368, Transportation Research Board, National Research Council, Washington, D.C., 1992, pp 18-26.

Retting, R. A., A. F. Williams and M. A. Greene. Red-Light-Running and Sensible Countermeasures - Summary of Research Findings. Transportation Research Record 1640, Transportation Research Board, National Research Council, Washington, D.C., 1998a, pp. 23-26.

Retting, R.A., A.F. Williams, C.M. Farmer, and A.F. Feldman. Evaluation of Red Light Camera Enforcement in Oxnard, CA. Accident Analysis and Prevention, Exeter, UK, 1998b.

Sayed, T., H. Vahidi, and F. Rodriguez. Advance Warning Flashers, Do They Improve Safety? Transportation Research Record 1692, Transportation Research Board, National Research Council, Washington, D.C., 1999, pp. 30-38.

Sharma, A. "Integrated Behavioral and Economic Framework for Improving Dilemma Zone Protection Systems." Ph.D. Dissertation. Purdue University. U.S. 2008.

Sharma, A., Bullock, D., Velipasalar, S., Casares, M., Schmitz, J., and Burnett, N. "Improving Safety and Mobility at High Speed Intersections with Innovations in Sensor Technology." 90th Transportation Research Board Annual Meeting, Transportation Research Board, Washington, DC, January 2011.

Stein, H.S. Traffic Signal Change Intervals: Policies, Practices, and Safety. Transportation Quarterly, Vol. 40, No. 3, 1986, pp. 433-445.

Technical Committee 18, ITE Southern Section. "Small-Area Detection at Intersection Approaches." Traffic Engineering, Feb 1974, pp. 8-17.

Wu, C-S., C. Lee, R. Machemehl, and J Williams. Effects of Multiple-Point Detectors on Delay and Accidents. Transportation Research Record 881, Transportation Research Board, National Research Council, Washington, D.C., 1982, pp. 1-9.

Zegeer, C.V., and R.C. Dean, "Green-extension systems at high-speed intersections." ITE Journal. 48, pp. 19-24.