

National Transportation Center

Project ID: NTC2014-SU-R-04

DESIGN AND IMPLEMENTATION OF A DETECTION, CONTROL, AND WARNING SYSTEM (DCWS) FOR DILEMMA ZONE APPLICATIONS

Final Report

by

Gang-Len Chang University of Maryland College Park Sung Yoon Park University of Maryland College Park Chien-Lun Lan University of Maryland College Park

for

National Transportation Center at Maryland (NTC@Maryland) 1124 Glenn Martin Hall University of Maryland College Park, MD 20742

November 2014

ACKNOWLEDGEMENTS

This project was funded by the National Transportation Center (NTC) @ Maryland.

DISCLAIMER

The contents of this report reflect the views of the authors, who are solely responsible for the facts and the accuracy of the material and information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation University Transportation Centers Program and Maryland State Highway Administration in the interest of information exchange. The U.S. Government and Maryland State Highway Administration assume no liability for the contents or use thereof. The contents do not necessarily reflect the official views of the U.S. Government Maryland State Highway Administration. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

EXCU	JTIVE SUMMARY	7
1.0 1.1	INTRODUCTION AND LITERATURE REVIEW RESEARCH BACKGROUND	
1.2 1.3	LITERATURE REVIEW RESEARCH OBJECTIVES	
2.0	DESIGN OF THE DILEMMA ZONE PROTECTION STSTEMS	11
2.1	ADVANCED WARNING SIGN	11
2.2	ALL-RED EXTENSION	12
2.3	ADVANCED WARNING SIGN AND ALL-RED EXTENSION	12
3.0	DATA COLLECTION AND DESIGN OF EXPERIMENTS	14
3.1	CALIBRATION OF THE DRIVER RESPONSE MODEL	14
3.2	OVERVIEW OF THE TARGET INTERSECTION	15
3.3	SIMULATION DEVELOPMENTS	16
4.0	RESULT AND SENSITIVITY ANALYSIS	18
4.1	SELECTED MOES	18
4.2	RESULT ANALYSIS	18
4.3	SENSITIVITY ANALYSIS	19
4.	.3.1 Locations of AWS on Drivers' Responses to the Yellow Phase	19
4.	.3.2 The Impact of Traffic Volume on Driver Behavior	19
5.0	CONCLUSION	21
6.0	REFERENCE	22

LIST OF TABLES

Table 1: Locations of AWS and Leading Flash Duration for Different Speed Limits	12
Table 2: Estimated Results for Binary Logistic Model for Selected Variables	14
Table 3: The Percentage of Drivers Taking the "Pass" Decision During a Yellow Phase Betw	veen
Field Data and Simulated Results by VISSIM Given the Distance and Speed	15
Table 4: Data Collected from Simulation and Field for 200 Feet and 800 Feet from the Stop I	Line
	17
Table 5: MOEs under Four Dilemma Zone Protection Systems	18
Table 6: Impact of AWS locations to red-light runners.	19
Table 7: The Impact from Different Volume Levels to the Number of Red-Light Running	
Vehicles and Average Remaing All-Red Time	20

LIST OF FIGURES

Figure 1: Proposed AWS with speed limit control	11	
Figure 2: Design of proposed dilemma zone protection system with operational relations	13	;

Figure 3: Intersection layout and locations of the detectors at the intersection of US 40 and R	ed
Toad Road	16
Figure 4: Turning Movements	16
Figure 5: Speed distributions from field and simulation for 200 feet and 800 feet from the stop	ρ
line	17

EXCUTIVE SUMMARY

This paper presents the evaluation results for an intelligent dilemma zone protection system that integrates advanced warning signs with all-red extension strategies to reduce the number of red-light running vehicles and also to provide extra time to clear the intersection. To realistically reflect the drivers' response to the yellow phase, a behavioral model has been developed and calibrated with field data from six intersections. The calibrated behavioral model has been incorporated in VISSIM to generate the simulation platform for experimental analysis. Based on the well-calibrated simulation network, the study has conducted extensive simulation experiments and compared the proposed system's performance with other two designs based on the number of red-light runners and remaining all-red time for those running on red. The results indicate that the proposed system offers the best protection on safety measures. Sensitivity analyses have also been conducted to assess the impact on the number of red-light running vehicles if different locations are selected for the advanced warning sign and under the different traffic volumes.

1.0 INTRODUCTION AND LITERATURE REVIEW

1.1 RESEARCH BACKGROUND

According to a report from the National Highway Traffic Safety Administration, there were 756,570 intersection-related crashes in the US in 2009, which account for 36 % of total crashes. Approximately, 165,000 people were injured annually due to the neglect of red-light instruction (Choi 2010). According to the Office of Traffic Safety report, in the state of Maryland, traffic signal-related crashes constitute about 30% of the total accidents, among which 20% involved red-light running in 2002. The existence of dilemma zones at signalized intersections is one of the main contributors to the high frequency of such accidents. Over the two past decades, tremendous efforts have been made by responsible highway agencies to improve the intersection safety such as driver education, red-light camera deployments, operational improvement on geometry design, dilemma zone protection systems.

As reported in the literatures, one may define the following two types of dilemma zones. The first type was developed by Gazis, Herman, and Maraduin (Gazis et al. 1960), known as the "Type-I Dilemma". Its dilemma zone is defined as a range within which the approaching vehicles can neither make comfortable stops nor pass the intersection safely. The second type of dilemma zone (Technical Committee 18 1974) was defined to describe the problem of indecision when both stopping and passing can be done which is known as the "Type-II Dilemma". Such dilemma zone often refers to the spatial range where 10 to 90 percent of drivers decide to stop (Zegeer and Dean 1978).

Maryland State Highway Administration (MDSHA) has long concerned the need to prevent the intersection-related accidents and introduced an intelligent protection strategy at the intersection of US 40 and Red Toad Road in Cecil County (Chang et al. 2012). The target intersection experienced 89 accidents during 2000 and 2010, and about 50% of total accidents were related to right-angle crashes, which were likely due to the presence of dilemma zones. Right-angle crashes have been dramatically reduced since the deployed intelligent dilemma zone protection system. Impressed by the performance of the dilemma zone protection system, MDSHA has decided to deploy the protection system on more sites experiencing similar accident patterns. Hence, further enhancement of the implemented strategy so as to better justify its cost/benefit has motivated this study.

1.2 LITERATURE REVIEW

Notably, the effectiveness of any deployed dilemma zone protection systems depends on the following two major factors: (a) will drivers be willing to be less aggressive and slow their approaching speed; and (b) can any measure be taken to protect drivers from the side-street to crash with those aggressive drivers trapped in the dilemma zone on the primary road? The latter can certainly be addressed with the dynamic all-red extension function as reported in our

previous study (Chang et al. 2012). The former, however, primarily vary with the behavior of the driving populations, especially their reactions and decisions when encountering a yellow signal phase. Understanding of such local-specific driving behaviors will certainly contribute to the development of effective advisory strategies to drivers traveling over high-speed hazardous intersections.

Many researchers have investigated drivers' reactions to yellow and dilemma-zone protection strategies over the past decades. Liu presented the results of an empirical study on drivers' responses during the yellow phase for different driver groups at six signalized Maryland intersections (Liu et al. 2007). Discrepancies in behavior patterns were observed among different driving populations. Several contributing factors, such as age, gender, presence of passengers, and cellphone usage, were identified to have significant effects on drivers' reactions to the amber phase. They also concluded that the common practice of extending the yellow phase may not be effective. Chang evaluated the effectiveness of all-red extension which provides additional clearance time for the red-light running vehicles and reduce the likelihood of having the rightangle accidents (Chang et al. 2012). Similar efforts were found in the development of detection, control, and warning systems (DCWS) (Zimmerman et al. 2014). With the use of the vehiclespecified in-pavement system, DCWS can provide an advanced warning to drivers who were about to be trapped in dilemma zones. Instead of directly protecting those trapped in the dilemma zone, the experimental study reports that warning signs can prevent them from being trapped in the dilemma zone if more information is provided to drivers in their decision-making. On this subject, McCoy also conducted a field study on the effectiveness of advanced warning flashers and advanced detection system (McCoy and Pesti 2003). Their research showed that the advanced warning flashers could reduce the total number of vehicles in the dilemma zone and the flashers tend to encourage more drivers to stop at the intersections.

Along the same research line, many studies showed the effectiveness of the advanced warning sign (AWS) from field observations. For example, Bowman showed 23% reduction (Bowman 1993) and Messer et al. (Messer et al. 2004) showed 40 % reduction on red-light running vehicles. Sayed et al. (Sayde et al. 1999) found with AWS that the accidents were reduced, compared to other intersections without AWS. Some studies also indicated that the most commonly used sign for AWS is "Prepare to Stop When Flashing" (Eck and Sabra 1985, Pant and Xie 1995).

For the same purpose, some researchers intended to prevent accidents due to the dilemma zone by changing the duration of green phase. By either extending or terminating the max green before max-out, it is expected that the system can keep vehicles from been trapped in the dilemma zone. Bonneson et al. (Bonneson et al. 2002) predicted the start of other phases by monitoring individual vehicles, and Tarko et al (Tarko et al. 2006) proposed a green extension strategy by using a probabilistic model which could estimate the likelihood of encountering the dilemma zone over each time step. Peterson (Peterson 2008) showed the system frame work of the LHOVRA which is used in Sweden for improving safety in dilemma zone.

1.3 RESEARCH OBJECTIVES

The objective of this research is to investigate the compound effectiveness of integrating the advanced warning sign with the all-red phase extension on minimizing the dilemma zone caused accidents. Empirical observations of driver responses during the yellow phase at six intersections are used to calibrate a driver's behavior model, which in turn use as the basis for conducting laboratory experiments and performance evaluation.

2.0 DESIGN OF THE DILEMMA ZONE PROTECTION STSTEMS

Most existing dilemma zone protection systems can mainly be categorized into two types. The first type is to reduce the speed of the approaching vehicles by AWS or an on-board warning system to prevent vehicles from trapped in a dilemma zone. The other type is to provide the protection by changing signal duration. For actuated controllers, the green time can be extended over the max-green or can be terminated earlier. Some actuated controllers can extend the all-red phase extension for red-light running vehicles. The proposed protection system for experimental analysis consists of both AWS and the all-red extension function.

2.1 ADVANCED WARNING SIGN

AWSs mainly function to advise drivers of the downstream intersection for possible phase changes. It may affect drivers' reactions to the yellow phase due to the intricacy nature of human behavior. There are several types of warning signs reported in the literature, such as "Be Prepare to Stop When Flashing", "Red Signal Ahead When Flashing". The proposed AWS is designed to couple with advisory speed controls, as shown in Figure 1. The purpose of such a design is to advise drivers to stop ahead of time at the displayed speed.



Figure 1: Proposed AWS with speed limit control

The location to install the warning device and its activation time it are the two major issues in design of the proposed system. The distance of from starting point of an identified dilemma zone, D_S , can be shown with Equation (1).

$$D_{\rm S} = T_{\rm PRT}^{*} v + \frac{v^2}{2a} \tag{1}$$

 T_{PRT} : perception-reaction time (2.5 seconds); v: speed of the detected vehicles; a: deceleration rate in ft^2 . So the location of the AWS, D_W , should be longer than D_S .

$$D_w \ge D_S$$

The T_{PRT} is the perception and reaction time to the AWS, and the interval of 2.5 seconds is recommended in the MUTCD 2011 in Table, 2C-4. The activation time can also be calculated from the GHM Model, based on the travel time to the end of the dilemma zone. Drivers passing the AWS prior to the activation will have enough time to reach the end of the dilemma zone before the signal turns to yellow. Table 1 shows the computed locations of AWSs under different speeds limits and the needed leading flash durations.

Speeds (mph)	AWS for DZ (feet)	Leading flash duration (sec)
45	350	2
50	450	3
55	500	3
60	600	4
65	650	4
70	750	5

Table 1: L	ocations of	AWS and Le	ading Flash	Duration for	Different Speed	Limits
------------	-------------	------------	-------------	---------------------	------------------------	--------

2.2 ALL-RED EXTENSION

Since some aggressive drivers often have the tendency to run over intersections regardless of the warning or advice, the all-red extension function can provide protection to those on the side street from crashing against those drivers. Such an all-red extension protection system has been deployed in MD (Chang et al. 2012). Its core logic is to estimate the target vehicles' times of arrival at every 0.1 second during the all-red interval. If the approaching vehicle's speed is above the threshold, the interval of the signal will hold the all-red phase until it passes the intersection.

2.3 ADVANCED WARNING SIGN AND ALL-RED EXTENSION

By combining these two protections, the proposed system can not only prevent vehicles from been trapped in a dilemma zone, but also provide additional clearance time for red-light running vehicles. Key components of the proposed protection system are:

- *Microwave long-Range Detector:* detect each individual vehicles' speed and location (also estimated arrival time to the intersection);
- *Advanced Signal Controller:* offer the function of all-red extension which can control the AWS; and
- *Advanced Warning Sign*: receive information from the controller and display the preset speed limit when activating with the advisory speed.

The microwave detector will provide the detected vehicle's speed, location, and estimated arrival time to the advanced signal controller. The signal controller will determine when to end the green phase and to activate the AWS. During the all-red phase, based on the detector's

information, the controller will decide whether an all-red extension is needed or not. Figure 2 shows the intersection layout and data flows for the proposed system.



Figure 2: Design of proposed dilemma zone protection system with operational relations

3.0 DATA COLLECTION AND DESIGN OF EXPERIMENTS

3.1 CALIBRATION OF THE DRIVER RESPONSE MODEL

A total of 1123 individual driver's responses over the yellow phase at six intersections have been collected and used as the basis for a model calibration (Liu et al 2007). At the onset of the yellow phase, a driver can choose from two mutually exclusive courses of action: Stop or Go; a binary logistic model is thus chosen for the model development. The following steps describe the calibration procedures for the driver response model and its application in the simulation experiments.

- Step1: Identifying Contributing Factors

The potential contributing factors to a driver's decision, based on the estimation results are shown in Table 2. Notably, the probability for a driver to stop will increase with the distance from the stop line while vehicles with higher speed are less likely to stop. Younger people tend to pass the intersection with high speed when they encounter in the dilemma zone. In the use of phones or presence of other passengers, drivers are more likely to stop.

VARIABLES	Coeff.	P-Value
Initial_Speed	0.043	0
Initial_Position	-0.271	0
Age[Middle]	1.577	0.008
Age[Senior]	4.811	0
Phone[not on $= 0$]	-2.774	0
Passenger[None = 0]	-2.152	0
Costant	-1.529	0.59

Table 2: Estimated Results for Binary Logistic Model for Selected Variables

- Step 2: Calibration of VISSIM's Embedded "Reaction to Amber" Model with Field Data

Since the information related to age group, passenger, and phone usage will not be available in VISSIM, the field data has been calibrated for the equation embedded in VISSIM with two observable variables shown in Equation (2), where v and d_x denote the speed and distance of vehicles, respectively, at the onset of the yellow phase.

$$P_{stop} = \frac{1}{1 + e^{-\alpha - \beta_1 v - \beta_2 d_x}} \tag{2}$$

The initially estimated values of those key parameters are: $\alpha = 0.798$, $\beta_1 = -0.288$, $\beta_2 = 0.043$ from field data. This model with its initial set of parameters is then used to perform the simulation experiments.

• Step 3: Comparison of Simulated Drivers' Responses in VISSIM with the Field Data

Due to other embedded behavior mechanisms in VISSIM, its simulation results using the field calibrated behavioral model may not yield the same driver response pattern as shown in the field data. Hence, additional step of parameter update has been taken to ensure that the behavioral response model, incorporated to VISSIM, can reproduce the same response patterns as observed in the field data.

Table 3 shows the results of VISSIM and field observed drivers who took the "Pass" action during the yellow phase. Notably, the calibrated results do not offer a perfect fit of the field data. The results in Table 3, especially with the initial calibrated parameters ($\alpha = 0.798$, $\beta_1 = -0.288$, $\beta_2 = 0.043$) seem do not offer the promise for laboratory experiments. After adjusting parameters, $\alpha = 0.798$, $\beta_1 = -0.35$, $\beta_2 = 0.455$ were chosen for the minimized total difference as shown in Table 3.

 Table 3: The Percentage of Drivers Taking the "Pass" Decision During a Yellow Phase Between

 Field Data and Simulated Results by VISSIM Given the Distance and Speed

Speed of	Locatio	on of vehi	cle from	stop line	onset of y	vellow									
on set of	0 - 100	ft		100 - 2	00 ft		200 - 3	00 ft		300 - 4	00 ft		400 - 5	500 ft	
yellow	Field	Initial	Final	Field	Initial	Final	Field	Initial	Final	Field	Initial	Final	Field	Initial	Final
30 - 40	100%	100%	100%	86%	100%	59%	21%	100%	48%	2%	89%	18%	0%	18%	0%
mph															
40 - 50	100%	100%	100%	100%	100%	100%	74%	100%	56%	50%	100%	64%	20%	100%	8%
mph															
50 - 60	100%	100%	100%	100%	100%	100%	88%	100%	80%	50%	100%	71%	0%	100%	0%
mph															
E: 11			1	4 - 1	- 41 49	D?	1	<u> </u>	C	1.1 . 1					

Field: percentage of drivers taking the "Pass" decision from field observations Initial: percentage of drivers taking the "Pass" decision fromVISSIM with initial coefficients Final: percentage of drivers taking the "Pass" decision from VISSIM after re-calibration.

3.2 OVERVIEW OF THE TARGET INTERSECTION

US 40 at Red Toad Road in MD is an intersection deployed with the dilemma zone protection system with all-red extension capability. The intersection is an isolated four-lane, median-divided highway with its posted speed limit of 55 mph. The traffic signal at the US 40 and Red Toad road intersection is an actuated control with two phases and without pedestrian phase. The minimum and maximum green times are 25 seconds and 60 seconds (90 seconds for peak hours) for US 40, respectively. The yellow and all-red durations are 5.5 seconds and 3.0 seconds, respectively. The all-red phase can be extended up to 5.5 seconds. The detection range is up to 875 feet with Smart Sensors Advanced installed on both the east and west approaches. The Smart Sensor Advanced is capable of providing location and speed of vehicles in 0.1 seconds interval with estimated time of arrival. Figure 3 show the locations for each detector.



Figure 3: Intersection layout and locations of the detectors at the intersection of US 40 and Red Toad Road



Figure 4: Turning Movements

Volumes and turning fractions are collected from the MDSHA Internet Traffic Monitoring System as shown in the Figure 4, and the speed profiles and percentages of heavy vehicle data are collected from the target site.

3.3 SIMULATION DEVELOPMENTS

The VISSIM network has been developed for the intersection of US 40 and Red Toad Road, and calibrated with the field data with respect to the time-varying flow rates and drivers' responses at the onset of yellow. Series of detectors have been placed in the network to simulate the function of the long range microwave detector by Wavetronix. In each approach lane, a total of 20 detectors with the length of 25 feet were placed for replacing one long range detector. The detector information is retrieved at every 0.1 seconds. Two desired speed decision points are placed for each major approach. The first is placed at the AWS location and the second is located after the stop line to increase the speed back to the prevailing speed.

The COM interface from VISSIM 5.20 using C# program is used to program the function of allred extension in an actuated signal control, and all other key behavior variables. The simulation model, prior to conducting experimental analyses, have also been calibrated with field-collected data during PM peak hours (from 4:30 to 5:30), as shown in Table 4.

	200 feet		800 feet	
	Field data	Simulation	Field data	Simulation
Average Speed (mph)	37.52	42.75	48.17	42.75
Min speed (mph)	1.86	0	20.4	24.5
Max speed (mph)	75.2	78.1	83.6	87.3
Volume (veh)	824	848	911	932

Table 4: Data Collected from Simulation and Field for 200 Feet and 800 Feet from the Stop Line

The figure 5 compares speeds from the field and VISSIM simulation at the locations of 200 feet and 800 feet from the stop line.



Figure 5: Speed distributions from field and simulation for 200 feet and 800 feet from the stop line

4.0 RESULT AND SENSITIVITY ANALYSIS

4.1 SELECTED MOES

The MOE for an all-red extension system can be the average of the remaining all-red time since it shows additional clearance time for red-light running vehicles. From the all-red extension, the remaining all-red time is expected to be increased. The MOE for an AWS system is measured by the total number of red-light running vehicles. By providing a warning sign in advance, the total numbers are expected to be reduced.

4.2 **RESULT ANALYSIS**

Table 5 shows the results of 10-hours simulation under the following four types of protection systems.

Base Scenario: actuated control without any protection.

Scenario 1: actuated control with all-red extension only.

Scenario 2: actuated control with advanced warning sign only.

Scenario 3: actuated control with all-red extension and advanced warning sign.

A total of 175 red-light runners were observed from the base scenario which does not provide any protection, and the average remaining all-red phase for those who run on red is 1.47 seconds. With both the AWS and all-red extension deployed, the total number of red-light runners has been reduced by 20%, and those also received additional 0.6 seconds to clear the intersection. The average number of vehicles run on red has reduced from 10.8 to 8.5 vehicles per 1000 vehicles in scenario 3 as highlighted in the Table 5. As expected, scenario 3, using the combination of two protection systems, shows the compounding benefits for both safety measures.

	Base Scenario	Scenario 1	Scenario 2	Scenario
Total number of vehicles run on red	175	141	151	138
Vehicle running on red rate (per 1000 veh)	10.8	8.7	9.3	8.5
Average remaining all-red time (sec)	1.47	2.08	1.4	2.13
Total number of vehicles	16206	16206	16206	16206
Simulation durations (hr)	10	10	10	10
% of changes in number of vehicles running on red (%) from Base line Scenario*	-	-19%	-14%	-21%
Additional remaining all-red time in Base line Scenario (sec) **	-	0.61	-0.07	0.66

Table 5: MOES under Four Dilemma Zone Protection Systems	Table 5	: MOEs un	der Four D	Dilemma Zone	Protection	Systems
--	---------	-----------	------------	---------------------	------------	---------

* (total number of vehicles run on red from scenario each - total number of vehicles run base scenario)/total number of vehicles run in the base scenario

** average remaining all-red time from in the base scenario - average remaining all-red in each scenario

Further statistical tests have also been conducted and concluded that the differences between with and without the all-red extension systems are significant at the statistically 95% confidence level.

4.3 SENSITIVITY ANALYSIS

4.3.1 Locations of AWS on Drivers' Responses to the Yellow Phase

To evaluate the sensitivity of the simulation results with respect to the AWS location, the speed limit is set to be 55 mph and only the location and the leading flash time have been changed accordingly. The simulation results are shown in Table 6. Note that in the range between 300 to 500ft, the total number of red-light running vehicles decrease with an increase in the AWS's distance, but reach an approximately stable level if AWS is placed over 500 feet. The average remaining all-red interval decreases as the distance increases. This indicates that if the location of the warning sign is too close to the intersection, drivers will not have enough time to reduce their speeds which may require activating the all-red extension.

Locations of AWS(ft)	Total number of red-light runners	Average remaining All-red time (sec)			
300	167	2.5			
400	157	2.3			
500 *	138	2.1			
600	139	1.8			
700	134	1.8			
* Proposed location of AWS for 55 mph					

Table 6: Impact of AWS locations to red-light runners

4.3.2 The Impact of Traffic Volume on Driver Behavior

Three different volume levels have been generated for sensitivity analysis, which are 500 veh/hr/ln as low volume, 750 veh/hr/ln as medium volume, and 1000 veh/hr/ln as high volume, while all other control logic and parameters remain unchanged. As the results are shown in Table 7, the number of red-light running vehicles increases with the volume. However, the rate of red-light running vehicles remains around ten vehicles per 1000 vehicles, indicating that volume is not a major contributing factor for red-light running vehicles. However, the average remaining all-red time decreases slightly with traffic volume. This is likely due to the fact that the relatively slow speed under a congested state cannot justify the call of an all-red extension, based on the current control logic.

 Table 7: The Impact from Different Volume Levels to the Number of Red-Light Running

 Vehicles and Average Remaing All-Red Time

Volume level	Total number of red-light running vehicle	Average remaining All-red interval for red-light running vehicles (sec)	Average number of run on red vehicles per 1000 vehicles
Low (500 veh/hr/ln)	138	2.3	10.35
Medium (750 veh/hr/ln)	202	1.9	10.05
High (1000 veh/hr/ln)	263	1.7	9.75

5.0 CONCLUSION

This study has employed simulation experiments to evaluate a proposed dilemma zone protection system that uses advanced warning to advise drivers and exerts the all-red extension to prevent those non-compliance drivers from causing accidents. To reflect the actual drivers' responses to the yellow phase, the simulation system developed with VISSIM has been incorporated with a driver behavior model which is calibrated with the field data of 1123 drivers from six locations.

Prior to conducting simulation analyses, the responses of drivers to the yellow phase under VISSIM have also been compared with the field observation for the target site to ensure the fidelity of the simulated system. The simulation has been conducted for different protection strategies which are AWS only, all-red extension only, and AWS and all-red extension. The results of simulated experiments confirm an expectation that the integration of advance warning system with all-red extension can better protect drivers and improve traffic safety. Based on the simulation results, the research team will conduct further field deployment of the system to evaluate the performance of the protection system.

One potential extension of the proposed dilemma protection system is to integrate it with the popular variable speed control system. With such an additional function, one can offer advices to drivers approaching the intersection to slow down during the off-peak period during which drivers are more likely to be over the speed limit and be trapped in his/her dilemma zone. However, during the peak congested period, one may extend the function of variable speed control to advise drivers with a proper speed so as to ensure that they can traverse over the intersection without blocking by the signal or vehicles in the queue.

6.0 **REFERENCE**

- Choi, E. (2010) Crash Factors in Intersection-Related Crashes: An One Scene Perspective. National Highway Safety Traffic Safety Administration Technical Report DOT HS 811 366, Washington D.C.
- Office of Traffic Safety. (2014) Maryland Traffic Safety Facts 2003. Maryland Department of Transportation. Maryland State Highway Administration. http://msa.maryland.gov/megafile/msa/speccol/sc5300/sc5339/000113/002000/002552/unrestricted/ 20065541e.pdf . Accessed May. 5, 2014
- Gazis, D., R. Herman, and A. Maradudin.(1960) The problem of the amber signal light in traffic flow. *Operations Research*, Vol. 8, No. 1, pp.112-132.
- Technical Committee 18, ITE Southern Section. (1974) Small-Area Detection at Intersection Approaches. *Traffic Engineering*, pp. 8-17.
- Zegeer, C.V., and R.C. Dean. (1978) Green-extension systems at high-speed intersections. *ITE Journal*. Vol. 48, pp. 19-24.
- Chang, G. L., M. L. Franz, Y. Liu, Y. C. Lu, and R. Tao. (2012) Design and Evaluation of a dynamic dilemma zone system for a high speed rural intersection. Report No. SP708B4J. Maryland Department of Transportation.
- Liu, Y., G. L. Chang, R. Tao, T. Hicks, and E Tabacek. (2007) Empirical observations of dynamic dilemma zones at signalized intersections. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2035, Transportation Research Board of the National Academies, Washington, D.C., pp. 122-133.
- Zimmerman, K., D. Tolani, R. Xu, T. Qian, and, P. Huang. (2014) Detection, control, and warning system for mitigating dilemma zone problem. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2298, Transportation Research Board of the National Academies, Washington, D.C., pp. 30-37.
- McCoy P. T., and G. Pesti. (2003)Dilemma Zone Protection on High-Speed Signalized Intersection Approaches: Advance Detection Versus Advance Warning Flashers and Advance Detection, In Transportation Research Board 83th Annual conference CD-ROM. Washington D.C.
- Bowman, B. L. (1993) Supplemental Advance Warning Devices, A Synthesis of Highway Practice. NCHRP Synthesis 186, Transportation Research Board, National Cooperative Highway Research Program, Washington, D.C.
- Messer, C. J., S. R. Sunkari, H. A. Charara, and R. T. Parker. (2004) Development of Advance Warning Systems for End-of-Green Phase at High Speed Traffic Signals. FHWA/TX-04/0-4260-4.Texas Transportation Institute, Texas A & M University System.
- Sayed, T., H. Vahidi, and F. Rodriguez. (1999) Advance Warning Flashers: Do They Improve Safety? In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1692, Transportation Research Board of the National Academies, Washington, D.C., pp. 30-38.
- Eck, R. W., and Z. A. Sabra. (1985) Active Advance Warning Signs at High-Speed Signalized Intersections: A Survey of Practice (Abridgement). In *Transportation Research Record*, No. 1010, Transportation Research Board of the National Research Council, Washington, D.C., pp. 62-64.
- Pant, P. D., and Y. Xie. (1995) Comparative Study of Advance Warning Signs at High-Speed Signalized Intersections. In *Transportation Research Record*, No. 1495, Transportation Research Board of the National Research Council, Washington, D.C., pp. 28-35.
- Bonneson, J. A., D. Middleton, K. Zimmerman, H. Charara, and M. Abbas. (2002) Intelligent Detection-Control System for Rural Signalized Intersections (No. FHWA/TX-03/4022-2,). Texas Transportation Institute.
- Tarko, A., W. Li, and L. Laracuente. (2006)Probabilistic Approach to Controlling Dilemma Occurrence at Signalized Intersections. In *Transportation Research Record: Journal of the Transportation*

Research Board, No. 1973, Transportation Research Board of the National Academies, Washington D.C. pp. 55-63.

- Maryland Manual on Uniform Traffic Control Devices for streets and highways 2011 Edition. (2011) Maryland State Highway Administration, Baltimore, Maryland.
- VISSIM 5.20 User Manual. (2009) PTV, PTV Planung Transport Verkehr AG, Karlsruhe, Germany.
- VISSIM 5.20-10 COM Interface Manual. (2010)PTV, PTV Planung Transport Verkehr AG, Karlsruhe, Germany.
- Traffic data of US 40 and Red Toad Road. Internet Traffic Monitoring System (I-TMS), Maryland State Highway Administration. http://shagbhisdadt.mdot.state.md.us/itms_Public/default.aspx. Accessed March 15, 2014.
- Peterson, A. (2008) Safer Signalization Using LHOVRA. Institute of Transportation Engineers 2003 Annual Meeting and Exhibit (held in conjunction with ITE District 6 Annual Meeting) CD-ROM. Seattle, Washington.