ITS APPLICATION: DESIGN AND EVALUATION OF AN INTELLIGENT DILEMMA ZONE PROTECTION SYSTEM FOR A HIGH SPEED RURAL INTERSECTION

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ABSTRACT

This paper presents the design and evaluation of a dilemma zone protection system that utilizes the dynamic detection technology to track individual vehicles as they approach an intersection of interest. A high-speed rural intersection in Maryland experiencing a high frequency of crashes was selected for system installation and evaluation. Data collected from 3 sensors, designed specifically for tracking individual vehicles, were deployed along the target approach were used in real time to control the signal logic, providing green or all-red extensions when the pre-defined parameters of detected vehicles are met. To evaluate the performance of the system design and the effectiveness of the associated parameters, a field test was further conducted. The data analysis included the identification of falsely-called red extensions (related to efficiency) and missed red extensions (related to safety) to assess the overall performance of the newly installed system. The field observation results indicate that the newly designed dynamic dilemma zone protection system using an all-red extension offers distinct advantages over traditional systems by providing additional protection to high-speed vehicles even when they are in the “cannot go zone” and make an incorrect decision to go.

1. INTRODUCTION

Improving traffic safety has increasingly been regarded as a priority transportation issue in most states. 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.

In 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 *(1)* 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 interval can neither safely clear the intersection nor stop comfortably at the stop-line (Figure 1). The existing practice for computing the dilemma zone is based on the following kinematics equation:

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

where:

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

x_0 = the critical distance for "intersection clearance" under the maximum acceleration rate;

τ = duration of the yellow interval (*sec*);

δ_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*).

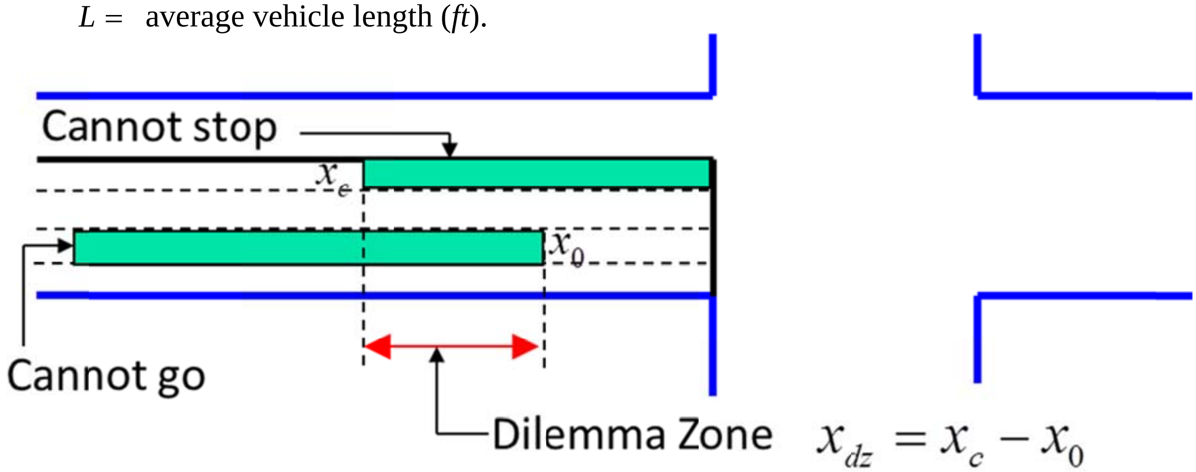

FIGURE 1 Graphical illustration of the dilemma zone at signalized intersections

The other dilemma, termed "Type-II Dilemma," was proposed to accommodate the problem of indecision when both stopping and intersection clearance maneuvers can be executed. The term defines the dilemma zone as the range in which 10 to 90 percent drivers decide to stop *(2)*. Zeeger et al. *(3)* 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 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.

In Maryland, due to a high frequency of crashes that may be related to dilemma zone scenarios, the Maryland State Highway Administration (MDSHA) 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 has experienced a total of 89 crashes from 2000-2010, 40 of which were right-angle crashed that *may* be corrected by sufficient dilemma zone protection *(4)*. The installed system used specially designed traffic detectors to provide real-time vehicle tracking as vehicles approached the intersection on the major approach. The data was then used in signal timing decisions, including dilemma zone protection.

2. LITERATURE REVIEW

Driver responses at signalized intersections have been investigated along with the dilemma zone issue in the literature since its initial study by Gazis et al. *(1)*. They indicated that incompatibility frequently exists between a driver's desire to comply with the yellow-interval indication and the encountered constraints. Olson and Rothery *(5)* conducted field observations at five intersections and found that drivers tend to take advantage of a long yellow interval and view it as an extension of the green interval. Their research concluded that driver behavior does not seem to be affected by the yellow-interval duration, especially since most motorists do not even know the typical phase duration. Another type of dilemma associated with a driver's decision making, termed as "Type-II Dilemma," was proposed to accommodate the problem of indecision when both stopping and intersection clearance maneuvers can be executed. Zeeger et al. *(3)* also proposed a method, termed "option zone," where 90 percent of the vehicles stop and 10 percent go under various traffic conditions. Liu et al. *(6, 19-20)* 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; they also concluded that the commonly used practice of extending the yellow phase duration may not be effective.

In studying a driver's response to the yellow-light phase, Van der Horst and Wilmink *(7)* indicated that such a process is governed by a multitude of factors, including driver attitude and emotional states, the crossing ability before the red phase, the consequence of the decisions to stop or go, 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 with associated factors. Their employed parameters were also adopted in later studies by Milazzo et al. *(8)*, Koppa *(9)*, BMI *(10)*, Shultz et al. *(11)*, and the Green Book *(12)*.

In classifying driver responses during the yellow interval and identifying potential affecting factors, Shinar and Compton *(13)* observed more than 2000 drivers over a total of 72 hours at six intersections. 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 interval; the presence of passengers was associated with lower rates of aggressive driving; and the likelihood of taking aggressive actions increases with a driver's value of time.

More recent studies *(14-16)* have explored the use of wide area detectors to provide real-time information for signal control, including dilemma zone protection. Each of these studies showed the potential for using dynamic dilemma zone protection to improve the safety and efficiency of a target intersection.

3. DESIGN OF DILEMMA ZONE PROTECTION SYSTEM

Despite the impressive contributions reported in the literature, many critical research issues remain in the design and evaluation of a dynamic dilemma zone protection system. The goal of this research was two-fold; the first task is to design a dynamic actuated signal control system that provides dilemma zone protection with an all-red extension based on the target vehicle's real-time speeds and distances to the stop-bar. Next, the study evaluated the system design using independently collected field data. The details of the study are discussed in the following sections.

The Study Site

Serving as a primary arterial in Cecil County, Maryland, US 40 is a four-lane, median-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.

The traffic signal at the US 40 and Red Toad Road intersection is controlled by a semi-actuated two-phase system with no pedestrian accommodation. The green interval 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 sensors. The yellow interval for US 40 is 5.5 seconds and a fixed all red interval of 3 seconds is incorporated. Dilemma zone protection is provided by extending the all-red interval by up to an additional 2.5 seconds for vehicles meeting predefined thresholds during the default all-red interval for US 40. These thresholds are based on the detected vehicles' speeds and distances to the intersection stop line (details in system design subsection), this all-red extension may be called even if the green duration has not been extended to its maximum.

Pre-Design Survey and Analysis

To understand the flow characteristics of the target intersection, a pre-design survey was conducted using video recording devices. The survey covered both the eastbound and westbound approaches of US 40 and collected space mean speed, vehicle classification and individual vehicle response (stop or go) to the yellow interval. Table 1 summarizes the key findings from this pre-design survey.

TABLE 1 Summary of pre-design survey findings

Parameter	Westbound	Eastbound
Mean Speed (mph)	49.2	49.6
Median Speed (mph)	49.9	50.4
Std. Deviation (mph)	12.3	11.7
Minimum Speed (mph)	19.6	21.6
Maximum Speed (mph)	86.7	79.3
85 Percentile Speed (mph)	62.4	62.0

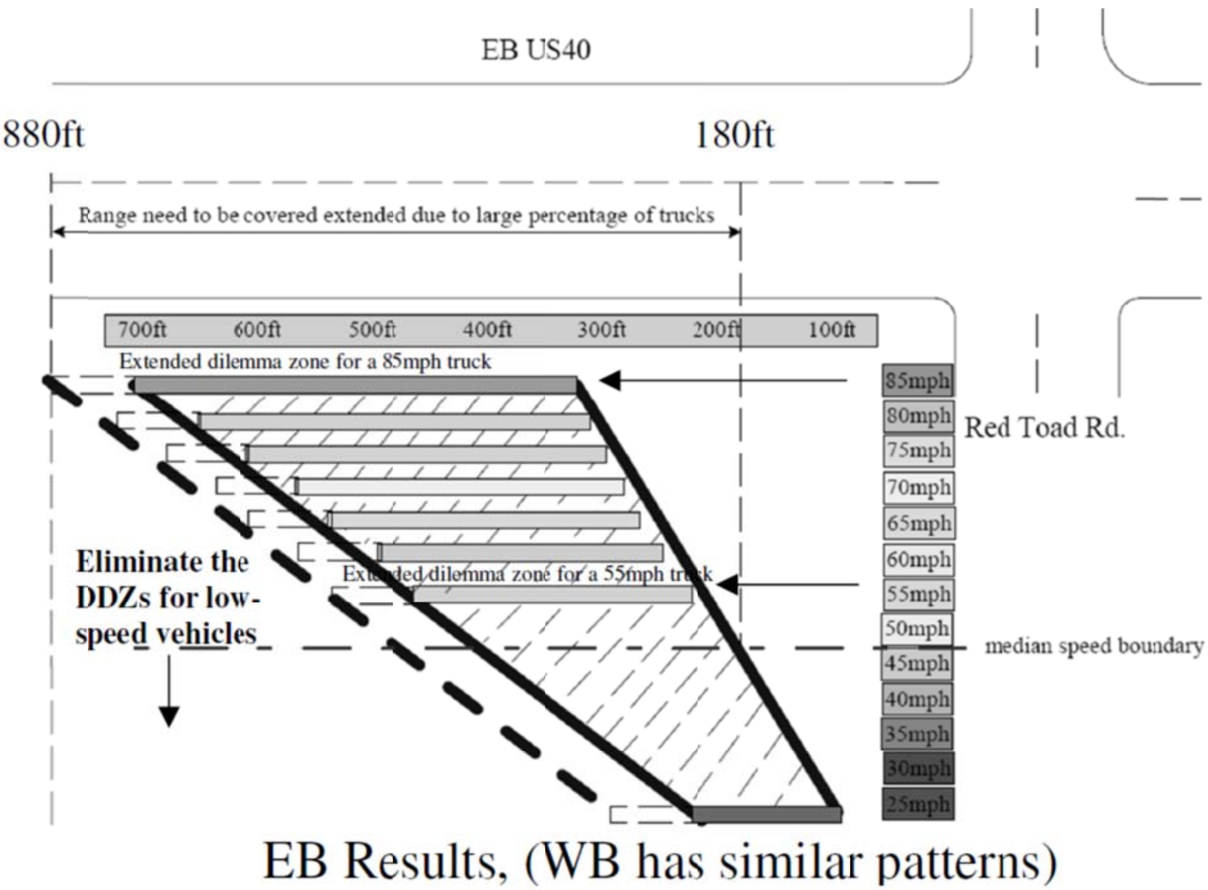

FIGURE 2 The range of the normal and extended dilemma zone due to the large percentage of trucks

System Design

Figure 2 illustrates the spatial distribution of dilemma zones for vehicle groups approaching the intersection at different speeds. Vehicles traveling below 50 mph were observed to be more likely to stop during the yellow-phase. In addition, most vehicles involved in incidents were approaching the intersection at the speeds of 55 mph or above. Thus, 55 mph was set as the threshold speed for the dilemma zone monitoring and protection system.(The key system design issue was how to monitor those vehicles trapped within the dilemma zone. To ensure each trapped vehicle can safely clear 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.

The extended all-red interval 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 clear the intersection. The methodology of "looking" for vehicles at the onset of the default all-red period allows for an all-red extension even if the maximum green time has not been achieved. Additionally, this logic will provide protection for those motorists who make the incorrect decision in attempting to clear the intersection when they are in fact in the "cannot go zone", upstream of the dilemma zone, described in Figure 1.

Conceivably, 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 880ft. 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 must rely on either a series of point sensors or a wide-beam radar or microwave sensor.

A review of the available traffic sensors in the market for this study showed that Wavetronix® has developed a microwave detector (the SmartSensor Advance) to address the limitations of traditional dilemma zone protection with loop detectors *(18).* Such a specially designed sensor functions like a series of loop detectors and can dynamically track vehicles as they approach the intersection. In fact, vehicle speeds and distances are updated every 0.1 seconds. The implemented sensor has a detection range of 500ft within which the sensor can continuously measure vehicle speeds and distance from the intersection stop bar. The computing module within the sensor continuously updates the estimated time-varying arrival times of each detected vehicle and informs the signal controller to take proper action. Using a time-based rather than a distance-based tracking method, the dilemma zone protection system can ensure a safe intersection clearance or stop of each vehicle based on its speed evolution within the detection zone.

The detection range of a sensor is only 500ft, which is shorter than the EB protection zone of 880ft at the US 40 and Red Toad Road intersection. The proposed system design uses a seamless combination of two such sensors to provide ample dilemma zone protection for the EB approaching vehicles (Figure 3). The first sensor was placed on the signal mast and the second signal was placed in 375 ft from the stop bar, covering upto 875 ft. This design decision is based on severity of the crash history for the EB direction. Because the intersection is operated under an actuated control, one identical sensor was also deployed in the WB (covering out to 500 ft from the WB stop-bar) to ensure the proper function of the controller when called by the sensors to take preset strategies.

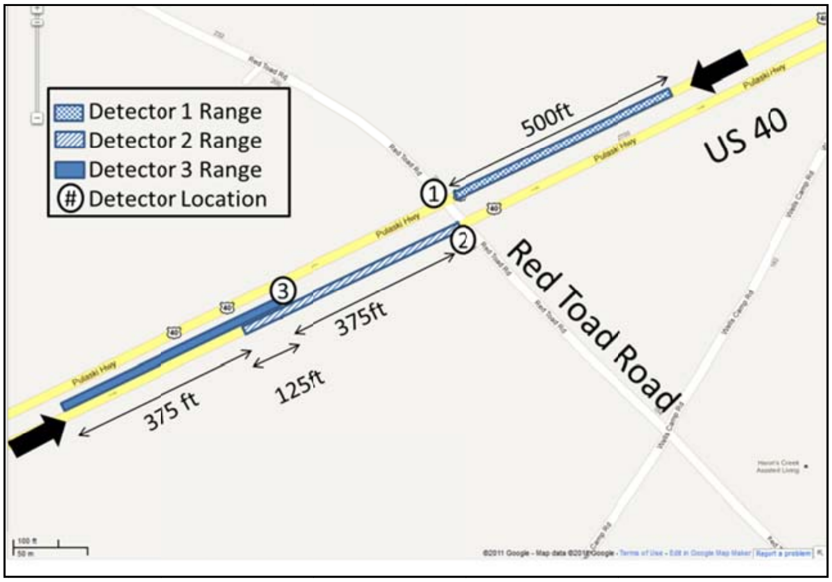

FIGURE 3 Sensor locations and detection range for the final design *(17)*

System Logic

The logic for the system to decide to extend the all-red interval was based on estimated time of clearance of the intersection. The time of clearance was determined by speed and distance of vehicles detected within 3 seconds of the onset of the US 40 red interval. The time of clearance is updated every 0.1 seconds until the end of the default all-red interval. At this point, the final decision on all-red extension is determined. In the proposed design, the time of clearance was used to control the signal logic.

Specifically, the system determines the time for a target vehicle to clear the intersection at the onset of the US 40 red interval, updating that decision every 0.1 seconds. If the time of intersection clearance is less than the remaining default all-red interval, then no all-red extension is called. On the other hand, if the time of intersection clearance is greater than the remaining default all-red interval but less than or equal to the remaining default all-red interval plus 2.5 seconds (the maximum all-red extension), an all red-extension is called. The length of the all red-extension is a function of the detected speed and distance at the end of the default all-red interval. In the instance when the time of intersection clearance is greater than the remaining default all-red interval plus 2.5 seconds (the maximum all-red extension), the system assumes the vehicle will stop and no all-red extension is provided.

The following operational features for the final design of the dilemma zone protection system were based on conservative pre-design survey observations:

- Call a green extension after reaching the minimum green time if a vehicle was detected within 500ft of either intersection stop bar with a minimum speed of 27 mph;
- Call an all-red extension if a vehicle is detected within 500ft of either US 40 approach at a minimum speed of 56 mph at the onset of the US 40 red interval. The length of the extended all-red interval 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. The section of EB US 40 covered uniquely by the second EB sensor (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 67 mph for an all red extension to be called.

Thus, vehicles detected under these threshold speeds are assumed to stop, which was consistent with field observations after system deployment. In contrast, those vehicles detected at or above the threshold speed will activate the all-red extension function. The length of the all red extension is based on time of intersection clearance, a function of detected distance and speed at the end of the end of the US 40 default all-red interval. Note that those control parameters are subjected to change if periodical field observations have detected significant changes in driving responses to the target signal with the deployed sensor system.

4. SYSTEM EVALUATION

System Evaluation Methodology

To evaluate the performance of the installed system, several candidate data collection plans were considered. While 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 infeasible. Additionally, the specific nature of the parameters needed to call the all-red extension requires high accuracy measurement 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 at only the eastbound approach of US 40, using both perpendicular videos and tube detectors.

The data collection plan used five video recording cameras and four tube detectors. Four of the video cameras were used to track vehicle speeds at predefined distances from the EB 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 100ft, starting at 200ft from the EB US 40 intersection stop bar. Since a microwave sensor only reaches to 875ft from the intersection, the final tube detector was placed at this location rather than at 900ft from the stop bar. The remaining video camera was used to capture the EB US 40 signal phases and timings. Figure 4 provides a summary of the equipment and deployed locations on EB 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 MDSHA signal shop that includes all red-extension events recorded by the intersection's actuated controller.

FIGURE 4 Data Collection Equipment Locations

Data Reduction

With data coming from multiple sources with independent internal clocks, the data from each data source was synchronized using handheld GPS units to ensure consistency between all devices. Before starting the data collection, a GPS unit was placed next to each of the tube detectors and the signal clock to estimate the time offset of each data source. 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.

Using the video data from high-precision camcorders, the research team members were 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 EB 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 play back 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 5.

FIGURE 5 Snapshot of video reduction software and vehicle identification that activated the all-red extension

The tube detector data was extracted from the devices using the associated “out-of-the-box” software. 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.

Evaluation 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 interval 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 threshold speed for vehicles within 500ft from the intersection stop bar was 56 mph; for those from 500ft to 875ft the speed was set to be 65 mph. The goal of this analysis was to evaluate the system performance by identifying any incorrect signal calls, including false negatives (at the cost of safety) and false positives (at the cost of efficiency). The analysis procedure to evaluate the system’s detection accuracy consists of the following steps for each vehicle data source (4 tube sources, 4 video sources):

Step 1: Identify the signal status when there are vehicles detected in the protection zone, using an algorithm developed in this study that can match the time stamps for each detected vehicle to a signal phase.

Step 2: For vehicles detected in a red interval, subtract the starting time of the associated red interval 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 had the potential to call the all-red extension.

Step-3: Determine if the extended all-red interval should be activated by comparing the speeds of the vehicles detected within three seconds of red with the threshold speeds mentioned above, based on the distance from the stop bar in which the detection took place. For those events that warranted the all red extension, verify that the extension was indeed called using the signal log file.

Step-4:For all red extensions called, verify that there was at least one vehicle with the detection range meeting the threshold criteria for an all red extension.

During the four-hour observation period, a total of 164 red intervals was observed at US 40 with 521 vehicles detected within three seconds of the onset of a red interval, within which 495 (95 percent) were passenger vehicles, and just 26 (5 percent) were commercial trucks. Only one all-red extension was called by the EB 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 single red interval 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 interval were analyzed from all vehicle data sources. Comparing the detected vehicle's speed with the threshold speed at the target distance confirmed that the call was indeed validated where a van traveling at 57.5 mph was observed at the distance of 400ft from the stop bar. This detection called for extending the all-red interval for an additional 1.1 seconds.

Note that the image data at 400ft from the stop bar was captured by the camcorder video. Thus, the vehicle that activated the all-red extension was able to be positively identified (see Figure 5). Using the video to capture the signal phases, it was possible to observe the event in which vehicle ran over the extended red interval just before the side street (Red Toad Road) traffic was released. Screenshots of this event at the end of the three seconds of the default all-red and at the end of the all-red extension are shown in Figures 7 and 8, respectively.

(A) (B)

FIGURE 6

(A)Vehdilce position after 3 seconds of all–red. (B)Vehicle position at end of all-red extension.

As shown in Figure 6A, three seconds after the start of the default all-red interval, the vehicle that triggered the all-red extension was approximately 150ft from the EB US 40 intersection stop bar. Figure 6B depicts the vehicle's position at the end of the all-red extension, barely clearing the intersection just before the conflicting traffic from Red Toad Road was released.

The analysis used the same procedure to investigate false negative calls that come at the cost of safety. Each red-interval in which the all-red extension was not called provided an opportunity to evaluate the possibility of false negatives. Again, the speeds of all vehicles detected within three seconds of the onset of a red interval were compared with the threshold speed at each respective distance for detection. Of the remaining 520 vehicles detected within three seconds of the onset of a red interval in US 40, none met the criteria that required the system to call the all-red extension nor did any of these vehicles run the red signal.

In addition to validating the single all red extension, the analysis also checked to see if any vehicles are trapped in the traditional dilemma zone (our systems look for vehicles at the onset of red, rather than at the onset of yellow). Using Equation-1, the size and location of a dilemma zone was calculated with the following parameter values: τ=5.5 sec, W= 70 ft, L= 12 ft δ_1= 1.14 sec, δ_2= 1.14 sec, a_1^*= 11.2 ft/s^2, and a_2^*= = 16.2 ft/s^2.

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 interval. Interestingly, only a single vehicle exceeding the threshold speed of 76 mph was detected during the yellow interval. This vehicle was detected with a speed of 77 mph which corresponds to 9 foot dilemma zone existing from 692-701 ft from the stop bar. However, the vehicle traveling at 77 mph was detected at a distance of 875ft from the stop bar; well within the “cannot go zone”. Thus, the yellow interval of 5.5 seconds effectively prevented any vehicles from being trapped in a dilemma zone during this study.

It is also important to realize that the vehicle that called the all red extension would have not been protected using a traditional dilemma zone protection system which 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 as such a system would assume this vehicle would comfortably stop before the end of the all-red interval. Thus, a green extension or all red extension (if max green had been achieved) would not have been called. In doing so, the vehicle would have entered the intersection near the termination of the default all red interval of 3 seconds (Figure 6B), potentially resulting in 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 interval. Such an instance was clearly captured and indicated in the video during this study.

5. CONCLUSIONS AND RECOMMENDATIONS

The goal of this research was to design and evaluate a dynamic dilemma zone protection system at a high-speed rural intersection of US 40 and Red Toad Road, in Northeast Maryland. The designed system took advantage of state-of-the-art vehicle detection technology to control the traffic signal logic. In doing so, the system was able to effectively prevent a potential incident during the brief evaluation period. Perhaps more importantly, the system had no false-negative calls in which a vehicle traveling above the threshold speed at a given distance from the stop-bar was not given an all-red extension to clear the intersection.

Based on the research findings, a dynamic dilemma zone protection using an all-red extension offers some distinct advantages over more traditional dilemma zone protection systems. First, the dynamic dilemma zone protection system provides protection based on an estimated time of arrival at the intersection. Traditional loop detectors provide protection only for those vehicles traveling at the design speed and at the location of the detector. Next, the use of the all-red extension allows the system to provide additional protection to high speed vehicles even if the maximum green time has not been achieved. Therefore, if a driver makes the incorrect decision in trying to clear the intersection when in the “cannot go zone”, the system can still provide additional time for clearance.

Despite the promising results of this study, more research needs to be conducted to develop a robust dynamic dilemma zone protection system. Such a system should be able to track and predict possible responses to the yellow signal. Based on those responses, the detection system can appropriately control the traffic signal to provide sufficient dilemma zone protection when needed. Future research may combine an automated enforcement system that provides the all-red extension but also tickets the drivers who enter the intersection during the all red-interval.

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