Evaluating the Potential of Advanced Vehicle Detection Systems in Mitigating Dilemma Zone Safety Conflicts

The dilemma zone described throughout the literature refers to the area where drivers experience difficulty with stop/go decision making when presented a circular yellow indication and incorrect decisions lead to increased rear-end crashes and more serious angle crashes. Results showed that the application of space sensors reduced dilemma zone incursions by presenting the yellow indication to drivers downstream of the dilemma zone where the stop/go decision is more easily made by drivers.

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Introduction

Among the most critical elements of safe and efficient operation at signalized intersections are the approach roadway alignment, phasing and timing of the traffic signals, and the equipment used to detect the presence of vehicles. Some challenges associated with signalized intersections are believed to be impacted by the fact that traditional vehicle detection systems utilize point sensors, which are limited in the amount of information that can be collected (typically only presence). Recent research has suggested that consistently monitoring vehicles' speed and position as they approached the stop line at a signalized intersection could provide safer intersection control.[1] The National Highway Traffic Safety Administration (NHTSA) reported in 2005 that approximately 9,200 people died and almost one million were injured in intersection-related crashes. NHTSA estimates that 805 of the fatalities were the result of red light running (RLR).[2] This paper explains the results of a field experiment that modeled and evaluated the impacts associated with both point (fixed) and space (continuous) advanced detection systems in an effort to mitigate some of the challenges described above.

Background

The dilemma zone is a complex issue associated with traffic engineering and safety and has been the focus of numerous published studies. Although the term "dilemma zone" has been part of the traffic engineering lexicon for some time, ambiguity exists regarding its meaning. To ensure the development of successful solutions, it is important that a consistent definition be adopted. This document, building upon previously established terminology,[3,4] describes two general classes of dilemma zone conflicts: Type I and Type II.

The Type I dilemma zone, first referenced by Gazis et al. in 1960, describes the inability, due to the physical parameters of the situation, to safely proceed through the intersection or stop in advance of the stop line at the onset of a yellow indication while approaching a signalized intersection.[5] The Type II dilemma zone, not formally identified until 1974 by Parsonson, accounts for drivers' difficulty in making the appropriate decision at the onset of the yellow indication.[6] Figure 1 presents both Type I and Type II dilemma zones.

Given the unique nature of the Type II dilemma zone, several attempts have been made to define its precise location. In 1978, Zegeer and Deen defined the boundaries of the Type II dilemma zone in relation to driver decisions, identifying the beginning of the zone as the position where 90 percent of drivers stopped, and the end of the zone where only 10 percent of drivers stopped.[7] This definition was supported by the works of May and Herman et al.[8,9] In 1985, Chang et al. defined the boundaries in terms of travel time to the stop line. They found that 85 percent of drivers stopped if they were 3 seconds or more from the stop line, and nearly all drivers continued through the intersection if they were 2 seconds or less from the stop line.[10] Supporting examples of defining the Type II dilemma zone in relation to the time to stop line can be seen in the works of Webster et al. and Bonneson et al.[11,12] From several of the previously mentioned studies it has been concluded that the Type II dilemma zone exists in the area between 5.5 seconds and 2.5 seconds from the stop line. Combining the various definitions with consideration of safe operation, studies such as that by Zimmerman and Bonneson[13] have supported the notion of measuring intersection safety by the number of vehicles caught within the Type II dilemma zone.

The crash scenarios most often associated with dilemma zones include abrupt stops leading to rear-end crashes, and failures to stop leading to right-angle crashes. Since right-angle crashes tend to result in serious injuries, added emphasis is placed on their prevention. Angle crash severity increases as intersection approach speed increases, placing added emphasis on dilemma zone challenges at high-speed signalized intersections.

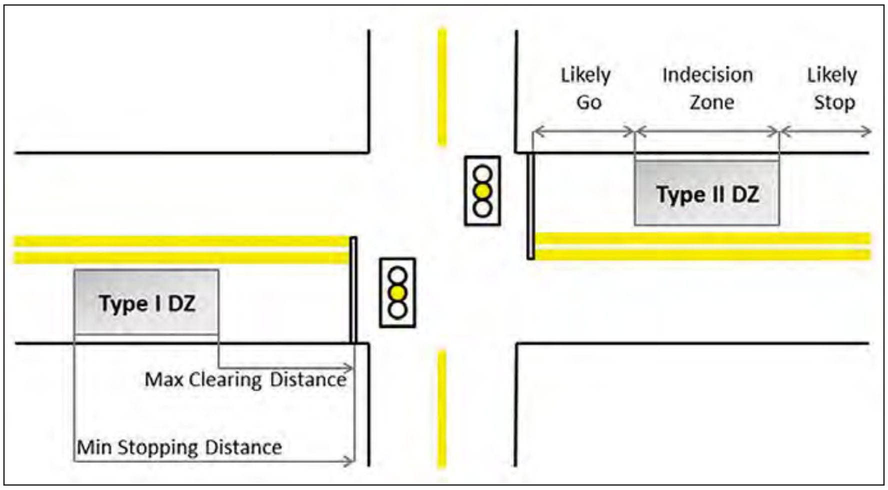

Figure 1. Type I and Type II dilemma zone diagram.

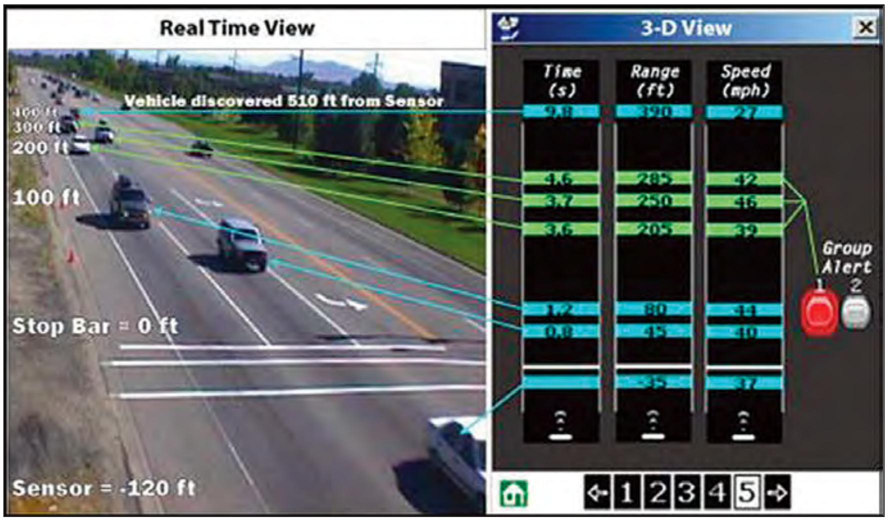

Figure 2. Image of SmartSensor vehicle detection.

Methodology

A field experiment was conducted to meet the research objective of evaluating the impacts of using a space sensor to provide advanced vehicle detection and mitigation for Type II dilemma zone incursions at high-speed signalized intersections. The following section describes the experimental methodology implemented within the research.

A high-speed signalized intersection operating predominantly in free-flow conditions was identified in Clarendon, Vermont, as having both the requisite safety-related issues, and infrastructure to allow for the successful implementation of the sensor. Dilemma zone incursions were observed during the use of advanced detection via point sensors and with the space sensor. Eight hours of video were collected under each condition, and a direct comparison was made between the types and frequency of dilemma zone incursions during both conditions.

The Vermont Agency of Transportation (VTrans) currently implements several design and operational strategies to promote the safe and efficient operation of state-owned high-speed signalized intersections. The signal timings used at these intersections include change and clearance intervals. The interval lengths are applied constantly across intersections of similar functional classification in close proximity to one another. In addition to change and clearance intervals, VTrans commonly uses advanced vehicle detection.

VTrans uses in-pavement inductive magnetic loop detectors at the stop line and approximately 400 ft. in advance of the stop line. These point sensors allow for vehicles to be detected in advance of the signal and allow for extensions of 2 seconds to be added to the mainline green time until the maximum green time has been reached, to allow for vehicles to safely continue through the intersection prior to conflicting movements being released into the intersection.

Identification of an adequate experimental site was crucially important. Highway Tech, a regional provider of traffic signal technology, assisted in the selection of a suitable test site based upon their knowledge of the operational requirements of a space sensor. This evaluation involved a single intersection approach (the northbound approach of Route 7 at Route 103). The major road (Route 7) oriented in the north/south direction intersects the minor road (Route 103) oriented in the east/west direction to form a four-way fully actuated signalized intersection. Route 7 is a median-divided roadway. Its northbound approach includes an exclusive left turn lane, two through lanes, and an exclusive right turn lane. Each lane is 12 ft. wide. The left and right shoulders are 2 ft. and 11 ft. wide, respectively. The exceptionally large mast arm supporting the signal heads provided a location for the sensor to be mounted such that it was in the center of the approaching through lanes. The northbound approach has limited horizontal curvature with no obstructions, which allowed for the sensor to work effectively and the approach to be observed via video.

Once the sensor was installed on the mast arm and the cable was run into the traffic signal cabinet, its operational configuration had to be established. This was

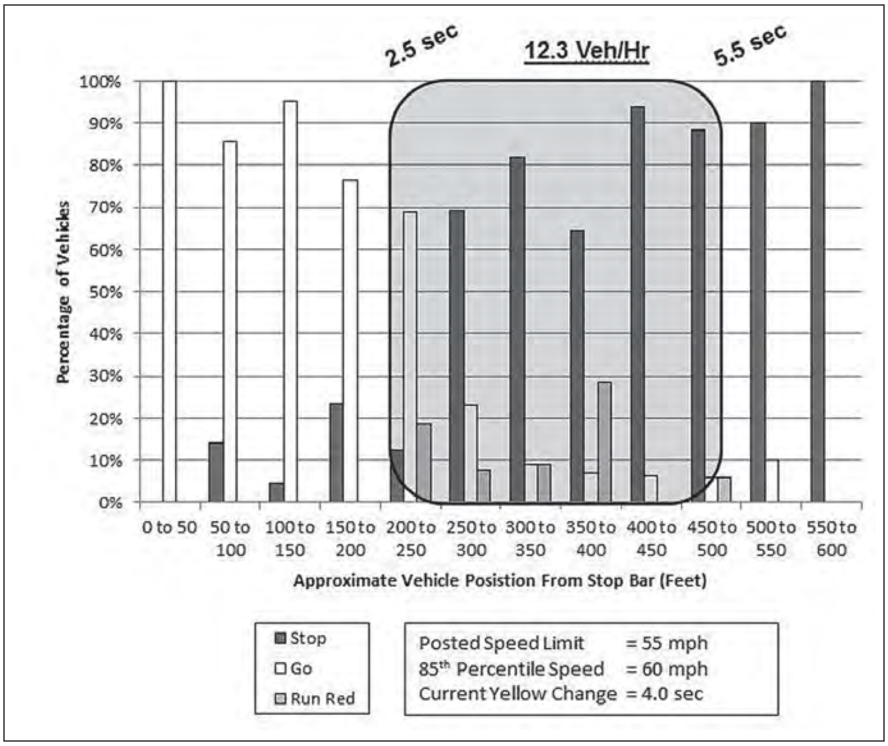

Figure 3. Driver behavior observed under in-pavementinductive loop dilemma zone protection.

achieved by connecting the space sensor hardware in the traffic signal cabinet to a laptop-based software program.

The space sensor uses digital wave radar technology to provide continuous detection up to 500 ft. from the sensor head, resulting in about 400 ft. of continuous detection back from the stop line. Figure 2 depicts the threshold for vehicle detection and the type of information recorded for each vehicle observation. The real-time view depicts that the sensor is detecting vehicles approximately 500 ft. out (400 ft. from the stop line). Figure 2 shows that the distance from the stop line as well as the current speed of all approaching vehicles is being detected, and the time to stop line is subsequently derived from these values.

The sensor was configured for the purpose of monitoring stop line arrival time. This allows for time, speed, and distance to be observed on a per vehicle basis every 5 milliseconds. The sensor system extends the green time to any vehicle that is predicted to be caught in a Type II dilemma zone based on their position and speed at the time the yellow indication would be activated. The operating rules for green extensions and the maximum green time were held consistent while the signal functioned under both the loop and space sensor vehicle detection systems.

The space sensor uses a time to stop line definition for the dilemma zone. The boundaries can be manually defined for the beginning and end of the dilemma zone as well as identifying minimum and maximum allowable speeds for an individual vehicle to be considered as encountering a dilemma zone.

Observations of intersection operations and driver behavior were conducted through the collection of video data. Cameras were unobtrusively mounted (15 to 20 ft. off the ground) on fixed structures along the roadside with an approach setback of 500 to 600 ft. from the stop line. The cameras were oriented to face toward the signal heads on each major intersection approach. This system allowed for the clear identification of vehicle position and signal indication from a single location.

Eight-millimeter videotapes were digitized and measurement points were transposed onto the digital files to accurately identify the position of the vehicle at the onset of the circular yellow indication. The digital video file was overlaid with 50-ft. intervals extending back from the stop line for several hundred feet.

Results and Analysis

The before (point sensor) and after (space sensor) field data captured along the northbound approach of Route 7 to Route 103 were analyzed with consideration given to several different performance measures. The measures described in the sections below were selected as they related to improved operation, safety, or both. The data reduction effort included each lead vehicle within 600 ft. of the intersection at the onset of the yellow indication, and recorded the vehicle position at the onset of the yellow and resulting driver behavior (i.e., stop, go, or run red).

Figures 3 and 4 present the observed field data for both the point sensor and space sensor scenarios, respectively. The results are consistent with expectations as the drivers closer to the signal tended to proceed through intersection and drivers further away tended to stop in advance of the intersection. Based on the measured 85th percentile speed of 60 mph and the 2.5- to 5.5-second definition, the predicted dilemma zone region is located between 220 ft. and 484 ft. and is depicted within the shaded region of the figures.

The frequency of vehicles captured in the dilemma zone was 12.3 vehicles per hour (vph) under the point sensor condition (Figure 3) and 9.8 vph using the space sensor (Figure 4). All observed RLR originated within the dilemma zone region for both sensor types, further highlighting the critical importance of identifying the true dilemma zone boundary in preventing RLR. It is important to note that the current change interval is set at 4.0 seconds, yet employment of the Institute of Transportation Engineers (ITE) equation results in a recommended yellow time of approximately 5.0 seconds.

Comparative Analysis

The initial comparison between sensors examined vehicle position at the onset of the yellow indication. This comparison is based on the notion that the space sensor system is designed to identify a vehicle that would likely have trouble responding to an impending yellow indication, so that the green may be extended appropriately. Comparing the distribution of vehicle positions at the onset of the yellow indication, the space sensor sys-

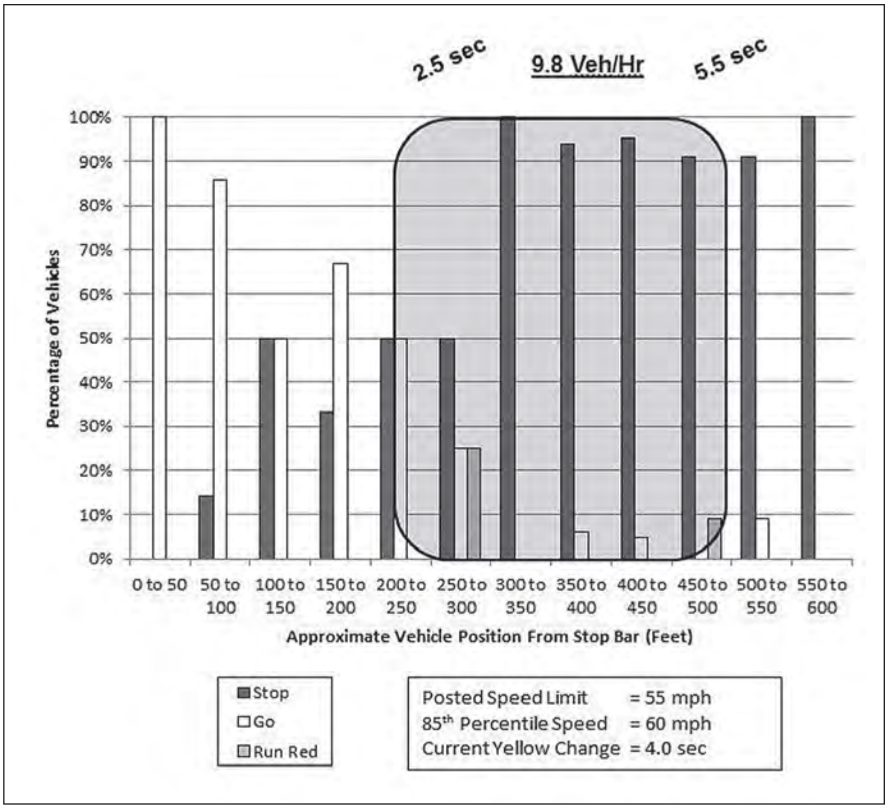

Figure 4. Driver behavior observed under radar-based space sensor dilemma zone protection.

tem shifted vehicles toward a position downstream of the dilemma zone. The total distribution of vehicles aggregated into 50-ft. intervals under each sensor was analyzed using a Chi-square test, resulting in a statistically significant difference ($p < 0.05$). This distribution shift, which resulted in an approximate 20 percent reduction in the frequency of vehicles exposed to the circular yellow indication from within the dilemma zone under the space sensor condition (12.3 vs. 9.8 vph), was also statistically significant.

Statistical tests were conducted to further explain the differences in vehicle distributions observed under the alternate cases of advanced vehicle detection. The vehicle distributions were aggregated into three categories (downstream of the dilemma zone, in it, or upstream of it) to further describe shifts in distribution. It was determined that no difference could be identified between the two conditions for the aggregated case ($p = 0.22$). Table 1 displays the data and Chi-square result addressing this issue. This test was conducted as a way to verify that vehicles were shifted forward under the space sensor vehicle detection.

A secondary measure considered was the corresponding driver behavior for drivers captured within the dilemma zone. Specifically, an analysis was completed to identify statistically significant differences in the frequency of stop/go/run red occurrences in both sensor scenarios. A Chi-square test was again used to examine potential differences, and the results were again significant ($p < 0.05$) implying that drivers experienced less difficulty deciding to stop or proceed under the space sensor control.

The most critical driver behavior failure when interacting with a dilemma zone is associated with RLR, which was examined as yet another metric for comparing the two sensor systems. During the point sensor observation period, 5.7 percent of the 193 vehicle encounters with the yellow indication resulted in instances of RLR, whereas only 1.4 percent of the 140 vehicle encounters under the space sensor resulted in RLR. The installation of a space sensor for advanced detection resulted in an approximately 4 percent drop in RLR occurrences. A Chi-square statistical test was conducted to determine if the rate of RLR was statistically different between the two conditions (advanced detection with inductive loops or space sensor), and no statistically significant difference was found ($p = 0.063$). This means that the difference in the rates of RLR observed when the space sensor was used in place of inductive loops was approaching a statistically significant reduction.

Conclusions

In reviewing published literature regarding the dilemma zone issue and the influence of advanced vehicle detection, the potential for a radar-based space sensor to mitigate dilemma zone conflicts became apparent. In cooperation with Wavetronix, HighwayTech, and VTrans, a unit was installed at a high-speed signalized intersection approach and evaluated in comparison with a typical signal timing plan and advance vehicle detection provided by an in-pavement inductive loop.

Among the noteworthy findings and resulting conclusions are the following:

- The distribution of approaching vehicles exposed to the yellow indication proved statistically different under each sensor type ($p < 0.05$). Although it seems that the shift in vehicle distribution moved vehicles downstream of the dilemma zone under the space sensor scenario, it was not of statistical significance when aggregating (upstream, within, downstream of the dilemma

Table 1. Vehicle Distribution and Driver Behavior for Different Detection Strategies.

Advanced Sensor	Downstream	In Dilemma Zone	Upstream	Chi-square *p*-value	Stop	Go	Run Red	Chi-square *p* -value
Inductive Loop	76	98	19	0.22	68	19	11	< 0.05
Space Sensor	59	60	21		55	4	2	

zone) the observations ($p = 0.22$). The rate of drivers exposed to the yellow indication within the dilemma zone was reduced by 20 percent.
- Additionally, the distribution of driver behavior within the dilemma zone was statistically different ($p < 0.05$), with far fewer drivers passing through the intersection on yellow or running the red light. In fact red light running rates were reduced by approximately 70 percent.

Overall the results provide preliminary evidence that radar-based space sensors have the potential to improve dilemma zone safety at high-speed signalized intersections. Nevertheless, several important questions remain, and it is important that these sensor systems continue to be examined with increased scrutiny. Specific questions include the following:

- Could additional observations of space sensors, if completed at a wide variety of intersection types, result in the development of guidelines for the installation of this technology at a proposed location?
- Will longitudinal studies showcase a reduction in crashes or certain crash types at individual locations?
- What is the potential impact on the operational efficiency of side streets if the right-of-way is consistently extended on the mainline to prevent dilemma zone incursions?
- It seems that RLR could be reduced by the introduction of space sensors at high-speed signalized intersections. With this in mind, would space sensors implemented in conjunction with RLR photo enforcement result in an increased performance in mitigating RLR vehicles? ■

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