Addressing Dilemma Zone Issues With Control Solutions

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16. Abstract:

Rural, high-speed signalized intersections are associated with vehicle crashes attributable to problems in dilemma zones (DZs). DZs are areas where at the onset of yellow, some drivers may decide to proceed and some may decide to stop. This disagreement among drivers can lead to rear-end crashes and/or right-angle crashes.

The purpose of this study was to evaluate different DZ protection methods and provide general guidelines with regard to the strengths and weaknesses of each method. Researchers developed general guidelines to assist engineers at the Virginia Department of Transportation in selecting the best DZ-protection method, based on a comparison of the estimates of predicted safety benefits for the different methods for a given set of traffic conditions.

The results of this study indicate that green hold/termination systems and radar-based protection systems are superior to the multi-loop system, with the radar-based system providing the most protection. This is attributed to the capability of the radar-based system to monitor vehicle speeds continuously and act accordingly, whereas the green hold/termination system assumes constant vehicle speeds. The results also indicate that the prevailing multi-detector loop setups perform differently depending on traffic volume.

The study recommends that the software developed in this study (DZ-Pro) be used to optimize the configuration of the detectors for the existing traffic volume. A before-and-after comparison of the frequency of red-light running indicated a significant reduction in red-light running (up to 80% reduction) when the radar-based DZ protection system was activated.

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FINAL REPORT

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INTRODUCTION

Past research shows that approximately 45% of all crashes in the United States occur at intersections (Bonneson et al., 2002a; Zimmerman, 2007; Zimmerman and Bonneson, 2005). A major proportion of these crashes occur because of red-light runners (RLRs), who either misjudge the required time to clear the intersection or do not pay attention to the signal display (Bonneson et al., 2002). Dilemma zones (DZ) are areas where, at the onset of yellow, some drivers may decide to proceed, and some may decide to stop. Driver-decisions in dilemma zones (DZs) during a traffic signal change interval play a significant role in affecting the road safety at signalized intersections. Hence, minimizing the number of vehicles caught in DZ at the onset of yellow (i.e., providing DZ protection) becomes necessary to prevent improper decisions to brake hard in response to a yellow signal indication (leading to rear-end crashes) or to proceed into the intersection without being able to clear it before the beginning of red (leading to red-light running incidents and possibly right-angle crashes).

The need for DZ protection is more pronounced at high-speed isolated rural or suburban intersections, or intersections with reduced sight distance. Other factors such as the diversity of traffic composition (i.e., cars and trucks) and the grade of the roadway near the intersection make it especially important to address DZ safety issues with smart control solutions. There are, however, many potential solutions that vary in technology, infrastructure, and methodology/algorithms. There are currently no available tools or guidelines that can assist engineers in identifying and selecting the best control method for DZ protection under different traffic conditions.

The key objective of this study was to evaluate different DZ protection methods, and provide general guidelines on the strengths and weaknesses of each method. The research aimed to produce guidelines that can assist engineers at the Virginia Department of Transportation (VDOT) in selecting the proper DZ protection method, based on an estimate of the methods' predicted safety benefits, for a given set of traffic conditions. To achieve this objective, it was necessary to model vehicle trajectories at signalized intersections during different signal phases, model the operation of traffic signals with and without advanced traffic operation features activated, and develop high-fidelity fast simulation optimization tools that can aid in the development of the guidelines.

PURPOSE AND SCOPE

The purpose of this study was to provide general guidelines for using advanced control features to address DZ issues at high speed signalized intersections. Solutions that use point detection, space detection, and speed traps are compared based on their effectiveness. The guidelines are provided at the following levels:

1. Provide guidelines for optimal design of existing actuated controller systems including the following:
    - determination of optimal detector locations
    - determination of optimal vehicle extension parameters.
2. Evaluate and provide guidelines for the use of green hold and termination systems logic, including the following:
    - evaluation of the green hold/termination systems
    - identification of shortcomings of existing systems and determination of optimal alternate operation mechanisms to address their limitations.
3. Provide a comparison of each DZ protection method (e.g., actuated controller, green hold/termination) to help VDOT make decisions about which system to use at a particular intersection, considering other related factors and preferences.

4. Provide guidelines on the integrated use of controller-actuated beacons (CABs) and develop operational guidelines for VDOT on their use with DZ protection systems, taking into account the anticipated driver response to the CAB (anticipated shift in DZ).

METHODS

To achieve the study objectives, eight tasks were conducted:

1. Conduct a literature review and review VDOT's experience with DZ protection systems.
2. Select two sites for data collection.
3. Develop a field data collection system.
4. Instrument field sites and collect before and after data.
5. Conduct data analysis.
6. Develop a simulation optimization platform for DZ protection systems.
7. Compare the performance of different DZ protection systems.
8. Develop general guidelines for selecting DZ protection systems.

Literature Review and VDOT's Experience

A literature review was conducted on (1) safety and efficiency issues, development efforts, and past research on DZ and control solutions (e.g., green extension systems, green termination systems, etc.); (2) queue estimation at signalized intersections; and (3) simulation optimization techniques and new advanced control features. Meetings were conducted with VDOT engineers to discuss and identify issues related to DZ control solutions. In addition, several meetings and phone interviews were conducted with DZ control solution vendors to discuss their algorithms, technological capabilities and limitations, and potential implementation issues.

Site Selection

The research team met with the VDOT technical review panel, discussed findings from the literature review, and identified a list of criteria for site selection. Issues identified for site selection fell into two categories: traffic criteria and hardware criteria. The traffic criteria were as follows:

1. high DZ-related (i.e., rear-end / right-angle) crash frequency and/or high red-light-running frequency

2. high-speed rural/suburban isolated intersection (45 mph or above)

3. light-to-medium traffic volumes (i.e., no more than 1400 vph on a typical two-lane approach to focus on DZ issues and not congestion-related issues)

4. two or more through lanes on major approaches

5. relatively flat grade and good visibility of the signal from all approaches

6. left turn lane(s) on major approaches.

The hardware criteria were as follows:

1. NEMA TS2 traffic cabinet

2. preferably having video detection equipment installed, otherwise willingness of the VDOT district to install video detection for the purpose of the study

3. preferably with Ethernet connection to the cabinet.

Two sites were sought. Proximity to Virginia Tech was also listed as a factor for easier equipment installation, monitoring, and troubleshooting.

Developing Field Data Collection System

The Virginia Tech Signal Control & Operations Research and Education System (VT-SCORES) lab has, over the past few years, been developing several systems and algorithms applicable to this research. The team developed an enhanced (second-generation) intersection safety data collection and evaluation system to read and store radar-based (Wavetronix) data and integrate it with the signal phase, detector, and video data in a synchronized database. Advanced Bus Interface Units (BIUs) with serial ports were used to read the data stream exchanged between the controller and other cabinet components. Signal phase indications are read from the first Terminal and Facility (TF1) BIU. Detector change information is read from the first detector BIU (Det1BIU), which provides detector on-and-off status for the first 16 detectors in the cabinet. Two Wavetronix radar units (called click 304 units) are connected to the PC, with each click 304 unit providing the radar data for one approach. Up to four cameras and their video streams are also connected to the computer. Finally, a Sierra wireless modem is used to transfer the data remotely to the lab. It should be noted that during the course of the project, a third generation (Windows-based) data collection system was developed and used to collect detector information. The Windows-system is more user friendly than the previous version and is easier to maintain and upgrade. The technology integration in this system is shown in Figure 1.

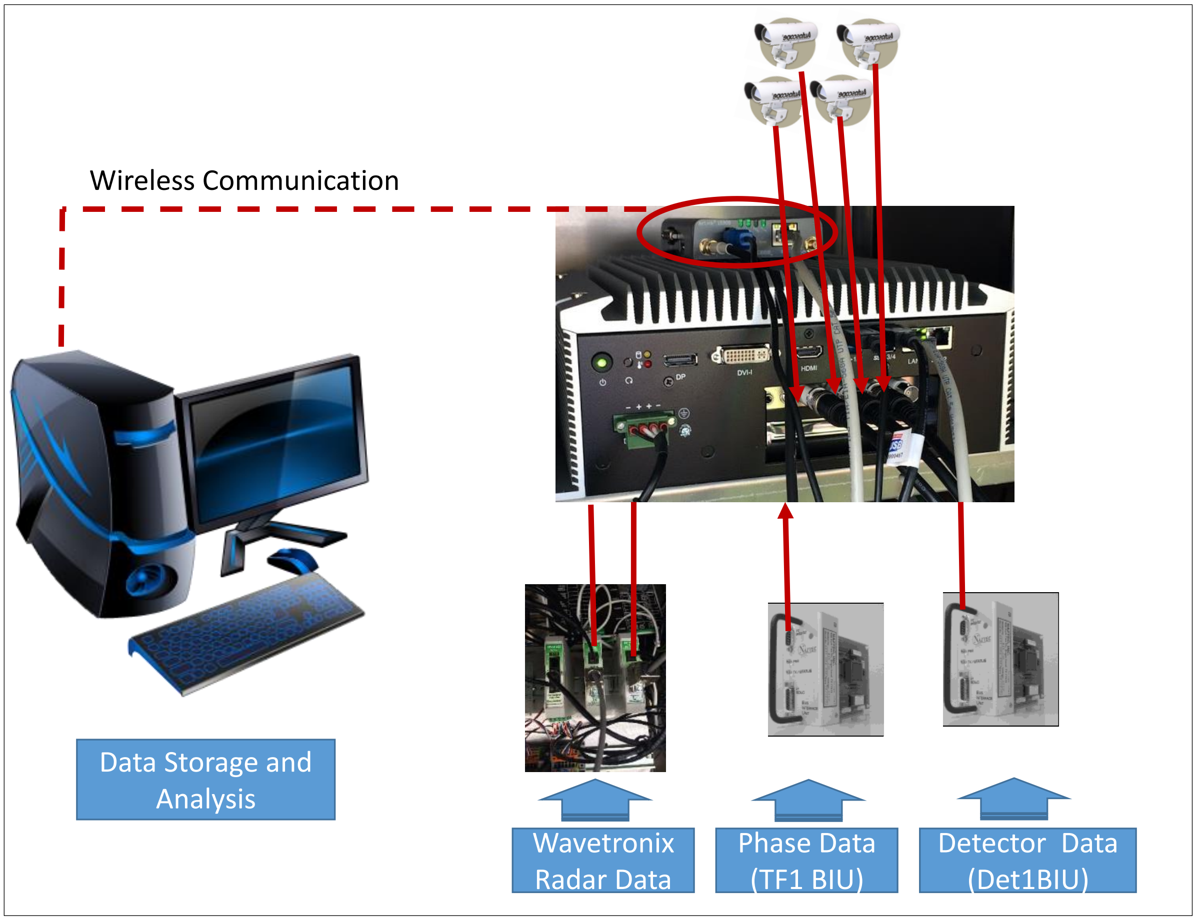


Figure 1. VT-SCORES Data Collection System

Instrumenting Field Sites and Collecting "Before" and "After" Data

Two Wavetronix systems were installed at each of the two selected sites. The data collection system was used to collect high-resolution data (i.e., time-stamped changes in phase and detector status). The use of high-resolution data is very beneficial; it can provide in-depth insight into traffic characteristics and signal operation that cannot be obtained otherwise, reducing the need for a long duration of data collection for statistical analysis purposes; and it can provide an opportunity to develop novel and advanced algorithms and performance measures. The adequacy of the duration of each data collection period was tested using statistical data analysis of the collected data.

The Wavetronix system is a DZ protection system that uses radar data to track individual vehicles and determine whether they are in their DZ. If the Wavetronix DZ protection feature is activated, the Wavetronix processor places virtual detector calls on the controller until vehicles exit their respective DZ boundaries. The purpose of using Wavetronix systems in this project was twofold: (1) to utilize the Wavetronix radar in collecting vehicle trajectory data that were ultimately used in several tasks in this project, and (2) to conduct a macroscopic-level analysis of radar-based DZ protection systems. The terms "before" and "after" refer to data collected before and after the DZ protection feature in each Wavetronix system was activated.

It should be noted that Wavetronix works by feeding its radar data to its processor, which in turn decides when to place detector calls to the controller. The Wavetronix processor therefore sits between the radar data and the controller. One limitation of this technology is that the radar data feed can be sent to either the controller or the data collection computer. This means that richer data (individual vehicle trajectories and speeds) can be obtained for the before data but not for the after data. For the after data, Wavetronix detector input can be captured from the controller side only, through the detector BIU. This technological limitation resulted in the following situations:

1. The before dataset provides more opportunities for traffic and driver behavior modeling, and can provide more information about the site characteristics. It was therefore used in the research for this purpose.

2. The detailed arrival information collected during the before period was used to conduct trace-driven simulations, where vehicles are "injected" into the simulation engine with the actual vehicles' arrival times and speeds. This approach provides an apples-to-apples comparison for different control strategies using the same traffic data.

3. Before and after comparisons cannot be made using trajectory data and were therefore made using aggregated data output from the controller side (i.e., red light runners, traffic volume, arrival patterns, etc.).

The Wavetronix radar system was used to feed the traffic data stream to the data collection computer. The video feeds from the video detection cameras at the two sites were used for two purposes: (1) a combination of an activation of virtual video detectors drawn after the stop bar and a red signal indication is used to flag RLRs, and (2) a continuous video buffer is temporarily recorded at the computer. If a red-light-running incident is flagged, the previous 10 s of video is then recorded and stored as an MPEG video file for data archiving and review.

Data Analysis

A software tool was developed to analyze vehicle trajectories. A screenshot of the integrated data plots is shown in Figure 2. The figure is an illustrative example from one of the sites. Vehicle trajectories are shown as dots on the time-space diagrams for each main approach. The dot color indicates the vehicle speed, as defined on the color map to the right of each diagram. The color of the x-axis shows the signal indication (green, yellow, or red). This tool was used to visualize vehicle trajectories and calculate the number of vehicles caught in a DZ.

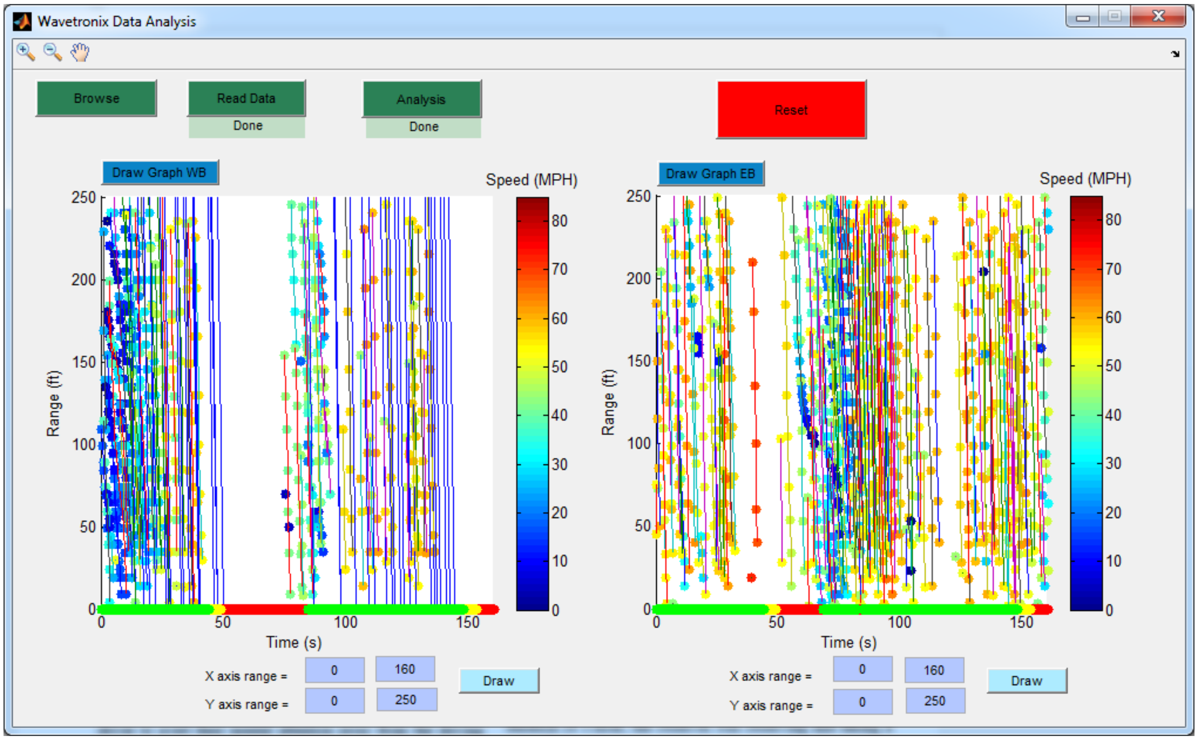


Figure 2. Data Visualization Tool

A data analysis and detector validation tool was also developed. The tool helps visualize and validate the compatibility of the phase status, time-space diagram (from the Wavetronix data), and detector status to screen out any sensor errors, and fuse data from different sources as shown in Figure 3. The status bar in Figure 3 shows the time (in 0.1 s) and location of the cursor (in feet). The figure shows that the detector "on" status (from detector input) coincides with the vehicle trajectory (from radar). It also shows that two vehicle trajectories belong to the same vehicle that happened to stop near the stop bar, resulting in a detector activation that bridges the gap between the two trajectories.

The developed tools were used to conduct a number of analyses. The first data analysis task was to evaluate data variability to determine the required sample sizes for statistical validity. Variability both within and across days was examined. A second data analysis task relating to base data validity was the comparison of red light violations as identified in the radar data versus violation data from the video detection data. This was necessary as radar data were available only in the "before" dataset. Following these baseline analyses, several evaluations were conducted to compare performance before and after implementation of the DZ protection system. These include a comparison of red-light violations and development of safety surrogate histograms.

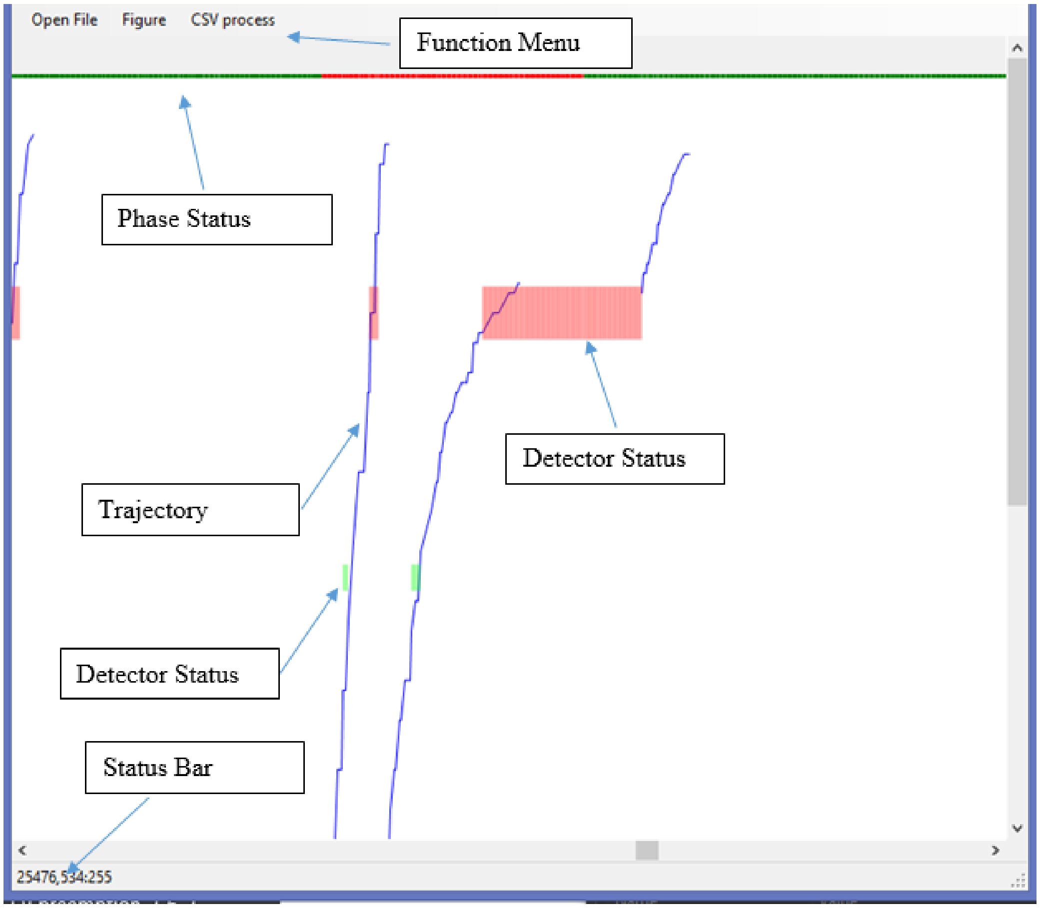


Figure 3. Data Analysis and Detector Validation Tool

Developing a Simulation Optimization Platform for Design and Evaluation of DZ Protection Systems

The design and evaluation of the merits and limitations of each DZ protection system is a complex task that cannot be adequately performed using off-the-shelf simulation software. Each one of the three DZ protection systems (multi-loop, green hold/termination, and radar-based systems) depends on and implements different concepts in its operation. The multi-loop system counts on the assumptions that vehicles travel with speeds close to the design speed with minimal variance. Designing an optimal placement of detectors and associated vehicle extension times needs to deal with the system's inherent limitations (i.e., loops cannot be customized for each vehicle's speed). In addition, the objective function used in the optimization needs to account for the realistic vehicle behavior (i.e., different speeds, varying vehicle trajectories, etc.).

The green hold/termination and the radar-based systems monitor individual vehicles and can therefore account for a larger variance in traffic speed. The green hold/termination system assumes that vehicles continue travelling with the same speeds from the time their speeds are estimated (i.e., using a far upstream detector) and until they clear the stop bar. The system therefore assumes that the effect of existing queues and backward shockwaves on approaching traffic is minimal. The radar-based system on the other hand tracks individual vehicles continuously, and can therefore account for changes in individual vehicle speeds.

Each one of the systems mentioned interacts with the actuated controller logic. The interaction between the traffic behavior, the DZ protection system, and the controller logic makes the behavior of the overall system complex. Commercial traffic simulation software provides some means for emulating the specialized logic implemented in these systems using, for example, COM programming. However, using these means results in long simulation run times, which makes the simulation of multiple runs for the purpose of conducting a simulation-optimization task infeasible.

To address these limitations, the research team used AnyLogic software (Borshchev, 2013) to develop a specialized and fast tool that can be used to conduct modeling and simulation (stochastic and trace driven) of each studied DZ protection system. A multi-paradigm simulation combining discrete-event and agent-based modeling was adopted; agent-based models were used to simulate the actuated controller operation, and discrete-event models were used to simulate traffic movements.

Comparing the Performance of Different DZ Protection Systems Using Trace-Driven Simulation

Trace-driven simulation refers to simulation runs where vehicle input is generated based on data obtained from the field (i.e., vehicles are injected into the simulation engine using the speed and generation time of actual vehicles monitored in the field). This type of simulation is used to conduct what-if scenarios. In this case, the scenarios are running the multi-detector system, the green hold/termination system, and the radar-based system. The data were all obtained from the before field data. However, the "actual" scenario of the vehicle data was extracted from the field data before the simulation was conducted. That was achieved by tracing vehicles back to before the time they encountered the shockwave that emerges from the red-duration at the signal. There are two main steps conducted in this task: (1) cleaning data and (2) tracing vehicles back to reference time.

The radar data sometimes produce multiple segments for the same vehicle as it approaches the stop bar. This usually happens when the vehicle meets a queue (the shockwave extending upstream), slows down or stops, then accelerates again when the signal turns green. The data cleaning task screens the segment trajectories and combines/eliminates multiple segments to extract the vehicle speed before it was affected by the shockwave. Once the actual vehicle's speed is obtained, it is traced back to a reference time line (1350 ft from the stop bar). This process results in all vehicles being injected at the same physical point on the network during the simulation.

A tool was developed in the C# programming language to conduct the procedures. Each vehicle is saved as a record in a csv file. The record includes the time and speed when the vehicle is at the reference timeline. When the simulation engine reads the files, it stores each column in a collection (time, range, speed). An event timer then injects vehicles into the simulation engine using the information in the collections.

Developing General Guidelines for Selecting a DZ Protection System

One of the objectives of this research was to develop general guidelines for selecting an appropriate DZ protection system for a given set of conditions. Two of the major characteristics that determine which system is recommended are the traffic volume and timing plan at a given site. The higher the traffic volume, the greater is the effect of queues on individual vehicle speeds. As such, there are conditions where the benefits of using green hold/termination systems and a radar-based system become more pronounced. Existing literature does not specify these conditions. Providing general guidance about when to use the multi-detector system, the green hold/termination system, or the radar-based system was therefore needed. The research team simulated each of the three major systems with different traffic volumes, ranging from light to heavy, and used the number of vehicles caught in DZ as a performance measure to compare the three systems. All the runs were conducted using our developed simulation-optimization platform as will be shown in the results section.

If the multi-detector system were to be used, then guidance is also needed to determine the optimal placement and extension setting for each detector. The researchers used their simulation-optimization platform to conduct this optimization (with the objective of minimizing the number of vehicles caught in DZ) and compared the optimized scenario to prevailing guidelines. Existing literature suggests that there are three commonly used multi-detector configurations for DZ protection: Bonneson's configuration (Bonneson et al., 2002; Bonneson et al., 1994); Sackman's configuration (Sackman et al., 1977); and Southern Section Institute of Transportation Engineers (SSITE) configuration (Parsonson et al., 1974; SSITE, 1976). SSITE's configuration uses only two detectors, and the other two configurations use three detectors under a 45 mph design speed condition. The configurations of these three designs at a 45 mph design speed are presented in Figure 4. In this figure, the vertical line indicates the intersection; the horizontal lines indicate the road segments before the intersection; the marked distances indicate the detectors' distances to the intersection in feet; and the amounts of time above the horizontal lines indicate the overall green extension time for each detector in seconds.

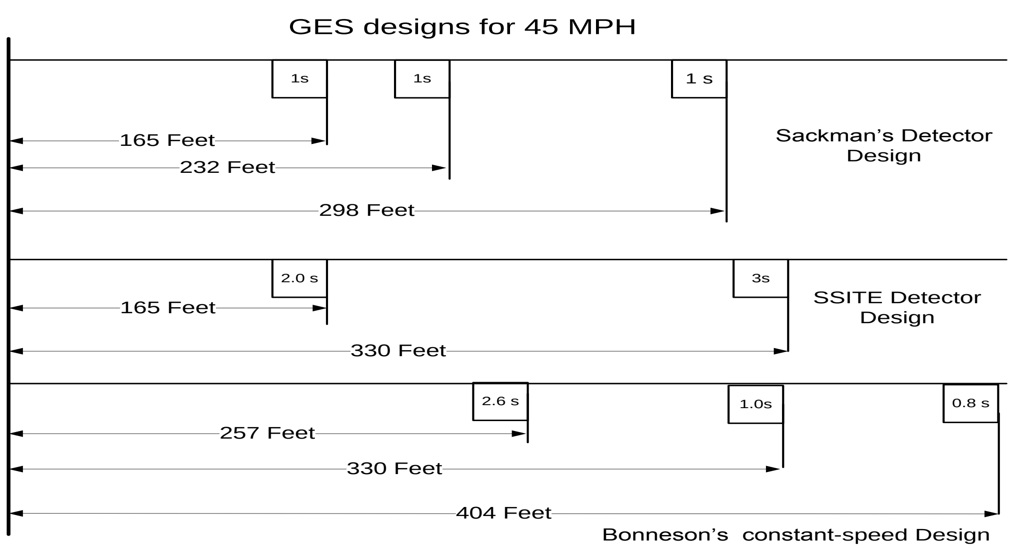


Figure 4. Different Green Extension System Designs in the 45 mph Design Speed

Finally, and since each site would have different traffic volumes throughout the day, as well as different timing plans, there was a need to develop software to (1) compare the performance of each DZ-protection system at individual sites, and (2) optimize the location and vehicle extension setting of each detector in a multi-detector system. The research team developed the DZ-Pro system as a Java-based web-hosted program to assist VDOT engineers in comparing and selecting a DZ-protection system for any given site.

Developing General Guidelines for Integrated Use of CABs

There are two issues concerning the integrated use of CABs and DZ protection systems. These issues are (1) the effect of CAB on driver behavior near the DZ and (2) possible changes in DZ boundaries because of the presence of the CAB system. Each of these two issues was addressed using the following methods.

Effect of CAB on Driver Behavior Near the DZ

Drivers approaching the intersection while the CABs are flashing tend either to accelerate or decelerate depending on their speed or distance from the stop bar. In this part of the study, the research team focused on identifying and quantifying the key variables that can result in a change in vehicle trajectory as it approaches the intersection and developing a model that relates the changes to variables that were found significant.

A dataset of detailed vehicle trajectories obtained from the field sites was used in this analysis. Variables included in this analysis were vehicle speed, range, detection timestamp as obtained from the radar data, and signal phase indications that were obtained from the traffic cabinet. The following steps were followed to perform the analysis.

1. For every cycle, all vehicle trajectories with time stamps spanning the onset of yellow time were extracted. These were vehicles that were approaching the intersection while the yellow was about to start.

2. The acceleration values of vehicles were obtained. This was done by calculating the speed difference between successive time steps and dividing this difference by the time between the two readings. Negative values indicated decelerations.

3. The change in acceleration (named as ‘Delta acceleration’ in this study) was calculated as the difference in acceleration between the current time stamp and the previous time stamp. This is intended to examine the effect of decision commitments and distinguish cases where drivers have already started accelerating or decelerating in previous time steps.

4. From the calculated values of acceleration, the value with highest magnitude of acceleration was identified. This would correspond to the time when the driver made a decision to either reduce the speed or increase the speed while approaching the intersection. This is one of the key variables identified for the analysis.

5. Further, the speed, range and timestamp of the vehicle for this corresponding instance where maximum magnitude of acceleration was observed were identified.

6. The identified timestamp is then subtracted from the timestamp for the onset of yellow timing and was recorded as time (T).

7. Based on the trajectories of the vehicles, the position and speed of the vehicle at the onset of the yellow were identified and these were used to estimate the time to intersection (TTI). This was done by initially subtracting the distance between the stop bar and the Wavetronix from the identified range of vehicle and dividing this by the corresponding vehicle speed at that instance.

Finally, the obtained data for the selected cases included time (T), time to intersection (TTI), speed of the vehicle, the corresponding range, acceleration, Delta acceleration and the hour of the day during which this case was identified. These data were further used to test the statistical significance of each variable with respect to acceleration for developing a relationship among the variables. The response surface analysis was conducted to develop a model between the max acceleration and all independent variables and their interactions.

DZ Boundaries With CAB Operation

The literature generally provides two main definitions of DZ. Type I DZ definition is geared towards vehicle characteristics as will be explained in the next section. Type II DZ definition, on the other hand, focuses on driver perception, with its beginning and ending boundaries identified as TTI values where 90% and 10% of vehicles stop at the onset of yellow, respectively. To study the effect of CAB operation on type II DZ, vehicles' trajectory data at the two instrumented sites were captured at the onset of yellow. Next, the dataset was divided into stopping and non-stopping vehicles. Examining video recordings showed that some vehicles do not necessarily stop before the stop bar; rather, they pass the stop bar with a low cruising speed and stop before the intersection. Hence, a discriminant analysis was conducted to determine the speed at which vehicles are stopping to separate the stopping vehicles from the passing ones. Then, TTI is calculated for each vehicle based on its distance to the stop bar and its speed at the onset of yellow.

All records were then categorized based on 0.1-second increments in TTI, and the percentage of stopping vehicles for each TTI was calculated. These percentages were plotted based on the corresponding TTI. A regression model was fitted for the data. Finally, based on the fitted model, corresponding TTIs for 90% and 10% of stopping vehicles were calculated.

The procedure was conducted separately for each site, to observe the changes (if any) in the values of dilemma zone boundaries between different directions and different sites.

RESULTS AND DISCUSSION

Literature Review and VDOT's Experience

Dilemma Zone Definitions

The literature generally provides two main definitions of DZ, with one definition geared towards vehicle characteristics and the other geared towards driver characteristics. The definition geared towards vehicle characteristics focuses on the physical ability of a vehicle to stop or go at the onset of yellow. Gazis et al. (1950) defined the DZ as the area bounded by (1) the distance from the stop line to the farthest vehicle that can completely stop (x_c) and (2) the distance from the stop line to the farthest vehicle that can cross the intersection at the onset of yellow (x_0). Their definition is illustrated in Figure 5 and is often referred to as the GHM model. These two critical distances are calculated in accordance with Equations 1 and 2:

$$x_c = v_0\delta + \frac{v_0^2}{2a_2} \qquad \text{[Eq. 1]}$$

and

$$x_0 = v_0\tau_0 + \frac{1}{2}a_1(\tau_0 - \delta)^2 - L - w \qquad \text{[Eq. 2]}$$

where

v_0: Initial vehicle speed at the onset of yellow
a_1: Maximum acceleration
a_2: Maximum deceleration
δ : Perception-Reaction time
L: Vehicle length
w: Width of intersection
τ_0 : Inter-green duration.

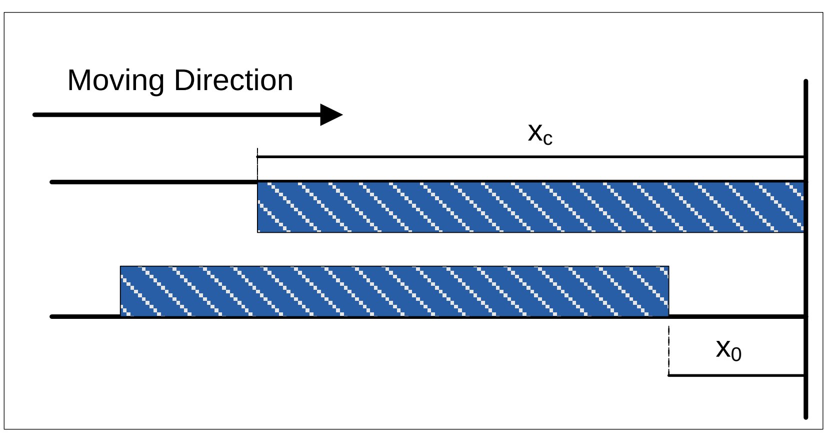


Figure 5. Type I DZ Parameters

When x_c is greater than x_0, the Type I DZ exists with a length of x_c-x_0. This type of DZ can be removed by adjusting the inter-green duration to make (x_c-x_0) zero as in Equation 3 (by setting the vehicle's acceleration to zero):

$$\tau_0 = \delta + \frac{v_0}{2a_2^*} + \frac{L+w}{v_0} \qquad \text{[Eq. 3]}$$

Practitioners now divide the inter-green duration (τ_0), originally defined in the GHM model, into:

permissive yellow interval

$$y = \delta + \frac{v_0}{2a_2^*}$$

and all-red clearance

$$r = \frac{L+w}{v_0}$$

The GHM model and its extensions (Institute of Transportation Engineers, 1985; Liu and Herman, 1996) are essentially kinematic models that assume that all vehicles will stop, if they can, at the yellow onset. However, Olson and Rothery (1961) observed that some vehicles used the yellow interval as the green extension. May (1968) concluded that some vehicles accelerated and/or decelerated heavily to escape the DZ, and Liu et al. (2007) observed that driver behaviors were considerably different from the theoretical assumptions.

These findings caused researchers to create a second definition of DZ (sometimes referred to as the indecision or option zone). Parsonson et al. (1974) defined a Type II DZ as beginning where 90% of vehicles would stop at the onset of yellow, and ending where only 10% of vehicles would stop at the onset of yellow. Many researchers attempted to identify Type II DZ area under different conditions. Some reported values include 2.5 s to 5 s (Zegeer, 1977); 2.0 s to 4.5 s (Chang et al., 1985); 3.0 s to 5.0/6.0 s (Bonneson et al., 1994); and 1.7 s to 4.7 s (Papaioannou, 2007) based on different local observations. This DZ definition takes into account different driver characteristics and hence is more realistic.

Actuated Controller Operation and Dilemma Zone Protection

Actuated controllers provide a limited traditional DZ protection system. The rationale behind its operation is the use of advance detectors to receive vehicles' calls and extend the current green phase until either no vehicle calls are received during a pre-specified period or the maximum green time is reached. Fully actuated controllers are typically connected to stop bar detectors and two to three advance detectors. An optimally configured actuated controller will use stop bar detectors to clear the waiting queues, and then revert to advance detectors to continue extending the green to provide DZ protection. When the current green duration is between the minimum green and the maximum green, a vehicle passing an advance detector will extend the green time for a "vehicle-extension" period. If the subject vehicle reaches the next detector before the extension expires, the extending timer will be reset at the new point of activation, and the green will be extended by another "vehicle extension" period. In a field setting with, for example, two detectors on each lane, two lanes per approach, and two major approaches (with the simultaneous gap-out feature activated, meaning that both major approaches will have to detect gaps in traffic in order for both phases to end), any vehicle that activates any of the eight detectors will reset the vehicle extension timer as illustrated in Figure 6. If the vehicle extension timer expires at any particular point in time, the controller will end the green phase with a "gap-out." If vehicles keep extending the green duration until the green phase reaches its maximum green, the controller will end the phase with a "max-out."

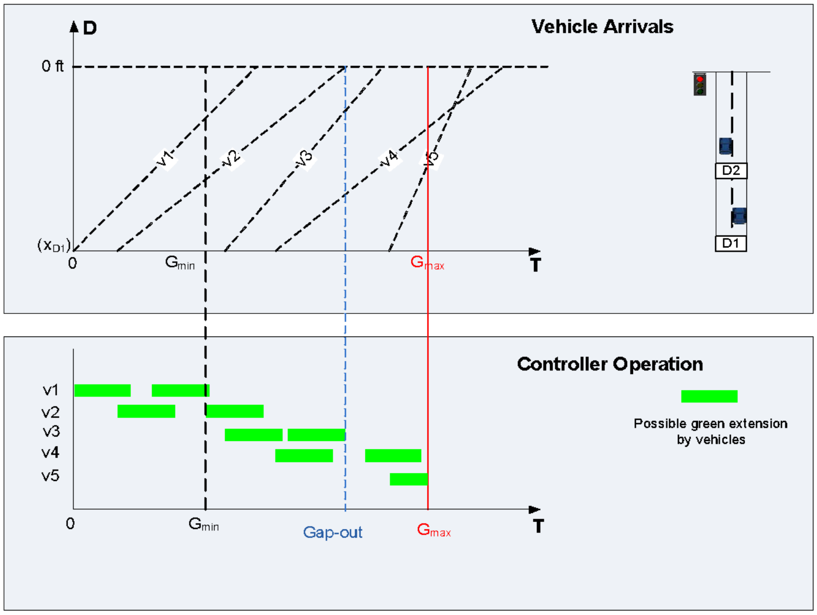


Figure 6. Operation of Actuated Controller With Advance Detectors

When a gap-out occurs, the controller provides some sort of DZ protection (assuming that vehicles are all travelling at the design speed limit and enough detectors are placed at optimal locations with optimal vehicle extension time) whereas when a max-out occurs, the controller provides no protection for trapped vehicles. Contingent on local traffic volume and controller/detector settings, an actuated controller will end up with different percentages of cycles with the green ending by a max-out (called max-out ratios) (Bonneson, 1996; Bonneson et al., 1994). The core concept of traditional actuated controller design is how to design advance detectors so that the controller can maintain an acceptable max-out ratio. State of the practice varies from using only one advance detector placed at the far end of the DZ to the use of multiple detectors placed at strategic locations. Bonneson et al. (1994) illustrated different designs with different protection percentage goals. However, all these available system designs make big assumptions about the controller operation (ignoring the simultaneous gap-out controller feature, dealing with one vehicle at a time, and assuming constant vehicle speed). In addition, the use of a max-out timer as a performance measure is a surrogate measure that can be used if vehicle information is not known. In the work of the researchers, a direct performance measure is used: the number of vehicles caught in DZ.

Green Hold and Termination Systems

In order to address the issue of using unrealistic assumptions for the traditional DZ protection measures used in actuated controllers, several efforts were made to address type II DZs on a vehicle-by-vehicle basis, including the green extension systems (GES) (Zegeer, 1977), LHOVRA (Peterson et al., 1986), the green termination system (Kronborg, 1997), the detection-control system (D-CS) (Bonneson et al., 2002), and the Platoon Identification and Accommodation System (PIA) (Chaudhary et al., 2006). Systems evolving from these efforts utilize speed estimation and prediction technology to predict the number of vehicles in the DZ on a rolling horizon basis, and enslave the controller by issuing phase holds and force-off commands. These commands hold the green phase as long as there is a vehicle in the DZ, and force the green phase to end when the DZ is clear (with some variations among these different systems on objectives and constraints). The green hold/termination systems embrace the type II DZ definition by predicting when a vehicle will arrive at the stop bar, and then back-calculate the beginning and end of the DZ by typically subtracting 5.5 s and 2.0 s, respectively (these values are usually input by users).

Calculation of the beginning and end of DZ for two different vehicles is illustrated in Figure 7, where points B and F are the estimated arrival times of each vehicle to the stop bar, points C and G define the beginning of each vehicle's DZ and points D and H define the end of each vehicle's DZ. The DZ for each individual vehicle is shown in thick lines in each vehicle trajectory. In this illustrative example, the two vehicle trajectories are obtained during the green time. The decision of when to end the green (the onset of yellow) is continuously evaluated by the green hold/termination algorithm. If the yellow is to be presented as shown in the figure, vehicle 1 would be about 1 s away from the stop bar, which means that vehicle 1 would have exited its DZ and the driver will have no hesitation in continuing to cross the stop bar. Vehicle 2 would be about 3 s away from the stop bar, which means that vehicle 2 would be in its DZ. Looking at the figure, one can immediately tell whether a vehicle is caught in its DZ (if the onset of yellow line passes through the thick DZ line), will continue (if the thick DZ line is to the left of the onset of yellow line), or will stop (if the thick DZ line is to the right of the onset of yellow line, meaning that the vehicle has not *entered* its DZ yet, and would therefore be more likely to stop).

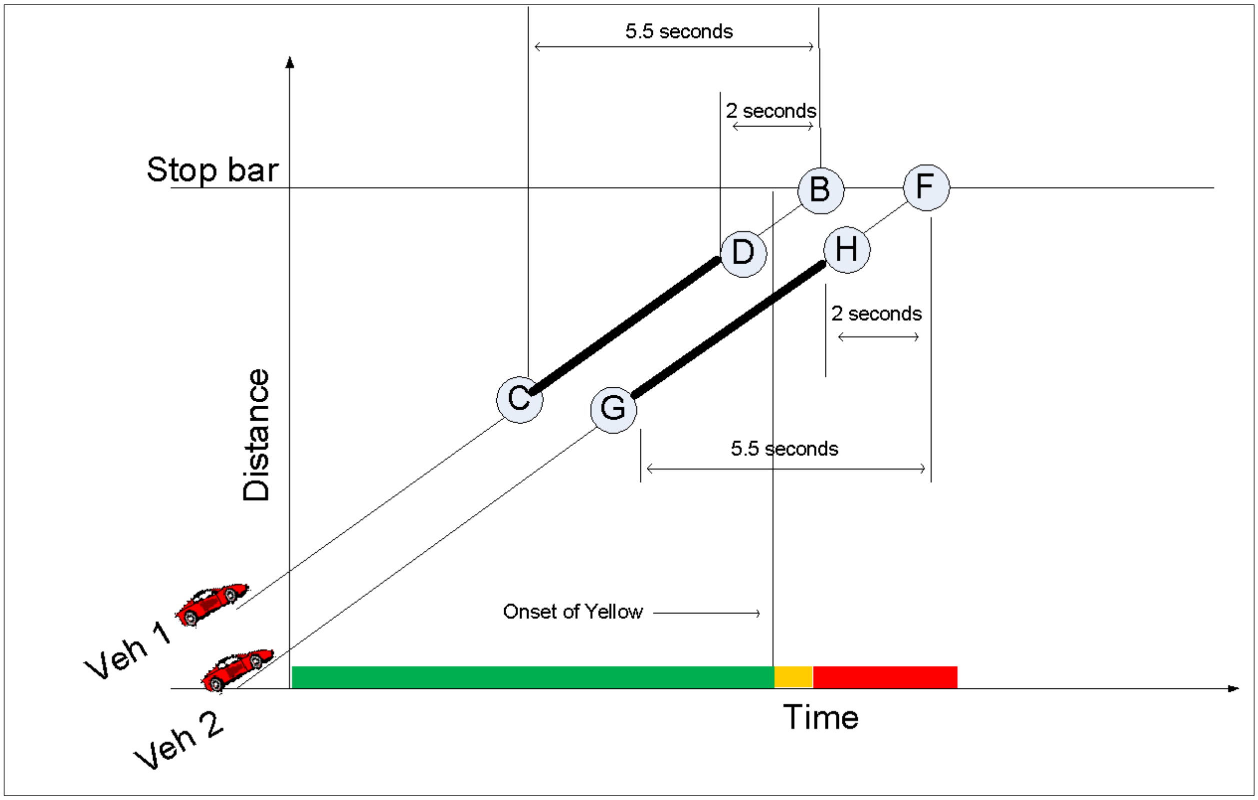


Figure 7. Illustration of the Dynamic Beginning and End of DZ for Individual Vehicles

These vehicle-based green extension systems are very promising, with some of them recently implemented in some National Electrical Manufacturers Association (NEMA) traffic controllers (e.g., D-CS is implemented in Naztec controllers). However, they assume simplified vehicle trajectories (no car-following models or interaction with signal shockwave), and their benefits are lower with certain traffic patterns.

Integrated DZ Protection and Controller Activated Beacons

Even with green hold and termination systems, phase max-outs might occur if the system was not optimally configured or a persistent stream of traffic existed on one of the two major approaches. In these cases, driver warning via dynamic advance warning flashers (AWF) or controller activated beacons (CAB) might be warranted. Most of these CAB systems start flashing as soon as the green phase ends and continue flashing until the phase turns green again. If the CAB were desired to start flashing few seconds before the green ends (i.e., for DZ related applications), a fixed length (typically 6 to 8 seconds) trailing overlap green is placed at the end of the actual green phase. The CAB would start flashing at the end of the actual green phase, but the signal indication would still show green because of the overlap interval. Drivers would see the CAB start flashing before the green ends, unaware (and unaffected) that the green indication shown after the CAB starts flashing is actually an overlap.

Effectiveness of CABs

Several research studies have been conducted on the effectiveness of CABs. Accident studies were conducted on isolated high-speed signalized intersections in California (Klugman et al., 1992) and Ohio (Pant and Xie, 1995); the results indicated that CABs were effective in reducing accidents. A safety study in British Columbia (Sayed et al., 1999) showed a reduction in the total number of accidents, but the reduction was statistically insignificant.

McCoy and Pesti (2003) evaluated the combination of advance detection (AD) and AWF in providing DZ protection. They reported that a combination of AD and AWF lowered the percentage of vehicles in DZs at the onset of the yellow. Pant and Xie (1995) also compared the way drivers respond to various types of warning signals in Ohio. The study was based on a speed and intersection conflict analysis. They studied the effects of "Continuously Flashing Symbolic Signal Ahead," "Prepare to Stop When Flashing" sign, "Flashing Symbolic Signal Ahead" and the passive symbolic "Signal Ahead" sign on the approach speeds of vehicles. They found that the passive sign and those with continuous flashers had similar results with reductions in approach speeds. The warning flashers tied to the signal status resulted in increased speeds as drivers attempted to beat the light. The study recommended installation of continuously flashing symbolic signal ahead signs before considering those that are tied to the signal status (prepare to stop when flashing). These studies did not consider strategic timing of the CAB advance flashing timer that would take driver responses into account.

A human factors study by Smith et al. (2001) in Minnesota used simulation studies to study the speed, braking, and acceleration patterns in simulated situations with and without advance warning systems. The results indicated that, at lower speed limits, more drivers stopped when there were no advance warning beacons, but, at higher speed limits, fewer stopped. They concluded that the advance warning flashers assisted decision making at intersections and promoted safer driving. The Blank Out Dynamic Advance Warning System (Schultz and Jansen, 2009) in Utah; the Advance Warning for the End of Green Signal (Messer et al., 2004) in Texas; and the Integrated Platoon Priority System (Liu and Bhimireddy, 2009) in Minnesota use advance detectors along with DZ detectors to provide the advance warning. The controller attempts to find a gap in traffic (an empty DZ) as soon as possible to end the green before another vehicle enters the DZ. Having a fixed green hold at the end of the phase commits the controller to continue the green for an additional x number of seconds. Meanwhile, some vehicles might enter the DZ during these x numbers of seconds and get caught in the DZ.

Conceptual Optimal Integration of Control Algorithms and Driver Warning Systems

Figure 8 shows a conceptual illustration of the CAB working mechanism. Point C depicts the trajectory point of vehicle 1 that passed the CAB sign location right before it was activated. Point B depicts the trajectory point when the same vehicle reached the stop bar of the approach; this is the point that can be used to determine the start (point C) and end (point D) of the DZ as previously illustrated in Figure 7. As discussed earlier, the DZ for this particular vehicle is shown with the thick portion of the vehicle trajectory in each of the two figures. VDOT guidelines (TE348) (VDOT, 2007) indicate the following:

1. A motorist maintaining the posted speed shall not receive a red indication at the traffic signal, if the CAB is powered but not flashing as the motorist passes it.

2. A motorist maintaining the posted speed shall not receive a yellow indication at the traffic signal, if the CAB is powered but not flashing as the motorist passes it, except when the motorist has also passed the end point of the dilemma zone (the point at which most motorists will not consider stopping for a yellow light).

3. A motorist who is not exceeding the posted speed and has not entered the dilemma zone when passing a CAB that is flashing shall receive a yellow or a red indication at the traffic signal.

Point 1 in TE348 guidelines indicates that the onset of red should only be shown from point B forward. Point 2 in TE348 indicates that the onset of yellow should only be shown from point D forward (end of DZ, indicating that the vehicle will continue without hesitation). Point 3 in TE348 guidelines indicates that vehicle 2 shown in the figure (that is not yet in its DZ when the CAB starts flashing) should receive the yellow or red indications.

Several details should be noted in this regard:

1. To guarantee that vehicle 2 receives the yellow or red indications, the yellow should be presented no later than point B plus the time headway between the two vehicles. If the approach has more than one lane, then the headway could be virtually zero (vehicle 2 can be on the second lane). In that case, the yellow must be presented no later than point B.

2. TE348 considers vehicles that maintain the posted speed. The figure, therefore, shows both vehicles driving at the same speed. Vehicles in the field might be driving at different speeds and can therefore have different DZ boundaries.

3. Point I in the figure is the point at which vehicle 2 (which is not in its DZ yet) is exposed to the start of the CAB flashing (assuming no sight distance limitations). At that time, vehicle 2 starts decelerating. If vehicle 2 accelerates instead, its DZ will start sooner (since it will arrive at the stop bar sooner). Point J depicts the time when vehicle 2 crosses the stop bar if it slows down. The thick line in the I-J trajectory corresponds to the resulting DZ in the new scenario.

4. The time between the CAB activation and the actual onset of yellow depends on the overlap setting. The overlap setting should be calculated as the time it takes a vehicle traveling with the posted speed limit to traverse the distance between the CAB location and the stop bar. This time can then be reduced by up to 2 seconds (time to the end of DZ).

These scenarios illustrate the benefits of integrating the CAB operation with the control decision of when to end the green phase. If the CAB was not present, vehicle 2 would have been caught in its DZ. However, integrated use of the CAB would result in a shift in vehicle 2’s DZ so that it would not be caught in the DZ at the onset of yellow, assuming vehicle 2 decelerates. If vehicles actually accelerate when the CAB is activated at certain sites, the beginnings and ends of their DZs (as technically defined by subtracting 5.5 and 2 seconds, respectively, from their arrival times at the stop bar) will be shifted in the opposite direction, which should be taken into account when configuring the CAB operation parameters. Data analysis was needed to clarify and quantify the actual driver behavior in the study sites.

Data analysis was conducted in this research to answer the following questions:

1. Do drivers accelerate or decelerate at the onset of the CAB activation? Does that decision vary based on other variables (e.g., time to intersection, vehicle speed, etc.)?

2. Does the presence of CAB result in a change in DZ boundaries and if so, by how much?

3. How does the presence of CAB affect the DZ protection systems and guidelines?

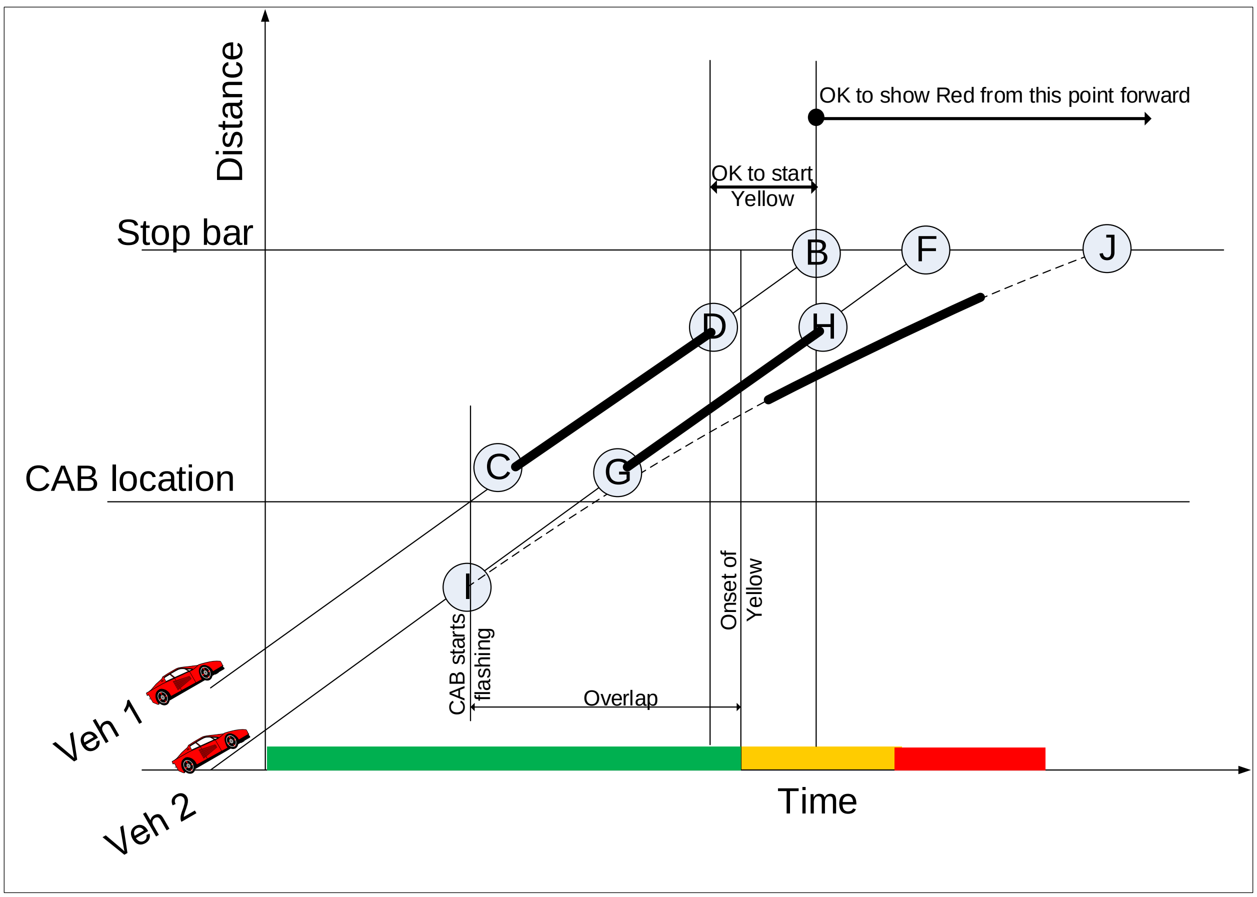


Figure 8. Conceptual Illustration of DZ Shift Attributable to CAB

Site Selection

Two T-intersections were selected for data collection. The first intersection, the US460 site, shown in Figure 9a, is located at US460 and Southgate Drive in Montgomery County. A Peek video detection system was used at this site. The second site, the US220 site, shown in Figure 9b, was located at US 220 and Route 87 in Henry County. An Autoscope video detection system was used at this site. The AADT for the US460 site is 32,000, and that at the US220 site is 16,000. The speed limit for the US460 site is 55 mph, but most traffic travels at 65 mph, and the speed limit for the US220 site is 45 mph, and most traffic travels at or near the speed limit. Data were collected eastbound and westbound for the US460 site and southbound and northbound for the US220 site.

(a) US460 Site **(b) US220 Site**

Figure 9. Study Sites: (a) US460 Site; (b) US220 Site

Developing Field Data Collection System

This task resulted in multiple system developments, including software-in-the-loop simulations (SILS) and hardware-in-the-loop systems (HILS) for testing in the lab before field installation. During the "after" data collection period, the team migrated to the third generation data collection system to collect higher resolution detector information from the traffic cabinet. The third generation system was developed in a Windows 7 environment. The new system is more flexible than the previous version and can be interfaced to other technologies in future projects as well (e.g., connected vehicles technology, eco drive, etc.).

Instrumenting Field Sites and Collecting "Before" and "After" Data

The Wavetronix System was installed at the two field sites in 2014. The installation process involved mounting the radar units, wiring the cabinet, and installing the data collection system (Figure 10). Figure 11 shows a schematic of the individual field components of the data collection system.

Figure 10. Field Installation of Data Collection System

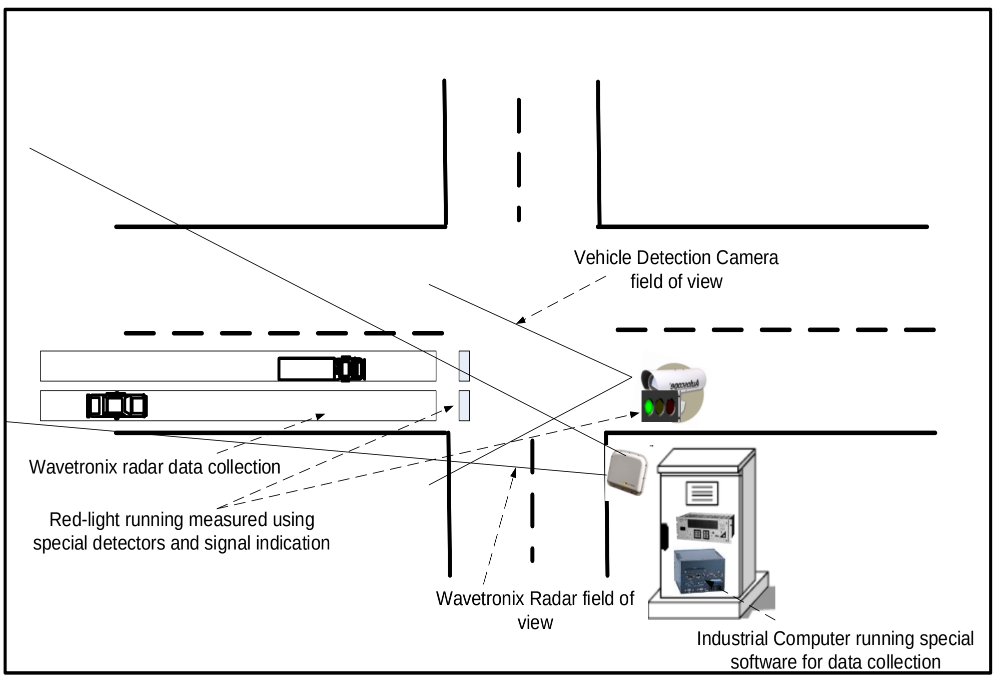


Figure 11. Intersection Instrumentation

Figure 12 shows a screen capture of the video detection setup at one of the selected sites. Video detectors were set up before the stop bar and used for normal intersection operation, while video detectors set up after the stop bar were used for RLR data collection. The total number of vehicles crossing the stop bar was logged to determine the traffic volume. This information was used to correlate the DZ protection system performance, in terms of the number of RLRs and other performance measures, with traffic volume. This information was also used to (1) compare the arrival patterns before and after the installation of the protection system to judge whether or not the system affects driver behavior, and (2) count the number of RLRs before and after the Wavetronix DZ-protection feature was activated.

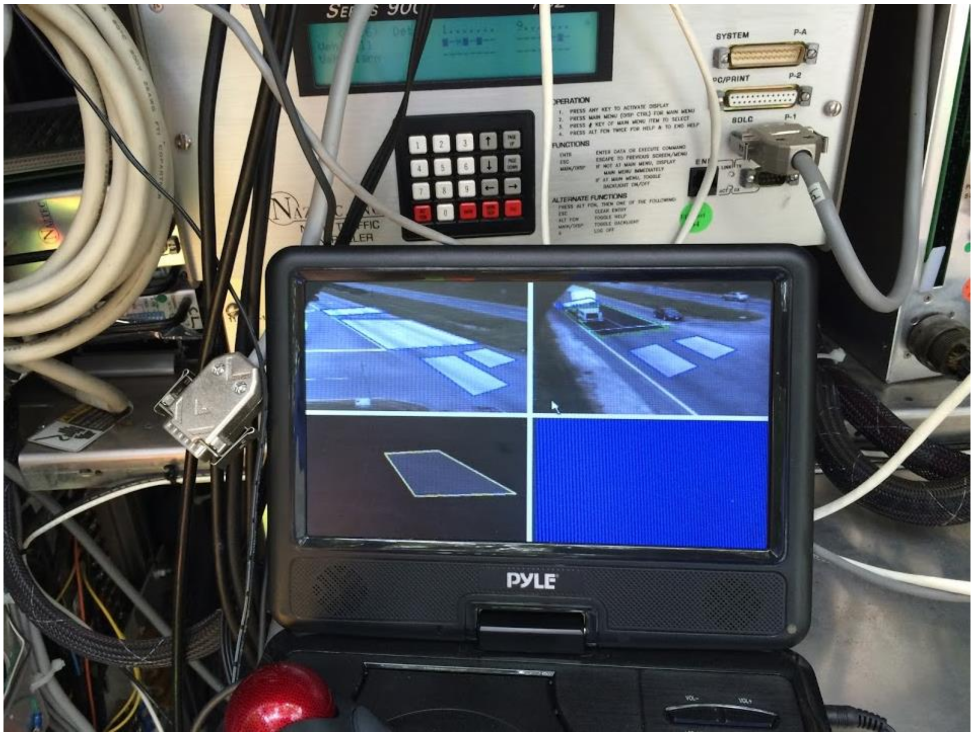


Figure 12. Video Detection Setup at the US460/Southgate Intersection

Data Analysis

A cursory analysis was conducted first to verify site measurements and traffic characteristics. The Wavetronix equipment was installed at the far side of the intersection to monitor vehicle trajectories and driver behavior as vehicles approach and pass the stop bar. From data visualization, the team verified the stop bar distance from the radar unit (see Figure 11) in each site as shown Table 1.

The data analysis and detector validation tool was used to determine vehicle arrival times and speed data to be used as an input for the trace-driven simulation.

Table 1. Stop Bar Distance from Radar Unit

Site/Direction	Distance
US460/Eastbound	90.7 ft
US460/Westbound	93.3 ft
US220/Northbound	100 ft
US220/Southbound	50 ft

Data Representation

The first objective in data analysis was to answer the question of how much data is representative of the traffic and signal variation in each site, given the high-resolution nature of the collected data (signal and detector changes collected with up to 0.1 s frequency and 1 ms accuracy). The results of a Kolmogorov-Smirnov (KS) Comparison significance test using two months of before data are shown in Table 2.

Table 2. Kolmogorov-Smirnov (KS) Comparison Test Results

Significance Measure	US460		US220	
	Eastbound	Westbound	Northbound	Southbound
P-value for most different days	0.001	0.001	0.051	0.008
P-value for most different weeks	0.018	0.003	0.109	0.668
P-value for 2nd most different weeks	0.0661	0.137	N.A.	N.A.

Table 2 shows that there is a statistically significant difference between days for both sites (P-value less than 0.05). Statistical testing of weeks indicates that there is a significant difference between the most different weeks in the US460 site, but not in the US220 site. A follow up testing of difference between the second most different weeks in the US460 indicates no statistical significance. The KS testing of significant differences between the most different days in the dataset revealed that weekdays were significantly different from weekends. An example of the KS test with significant differences between the two days (solid line and dashed line) with p-value of 0.001 is shown in Figure 13 (the X on the x-axis denotes the volume value and the percentile on the y-axis denotes the corresponding percentile for that X value).

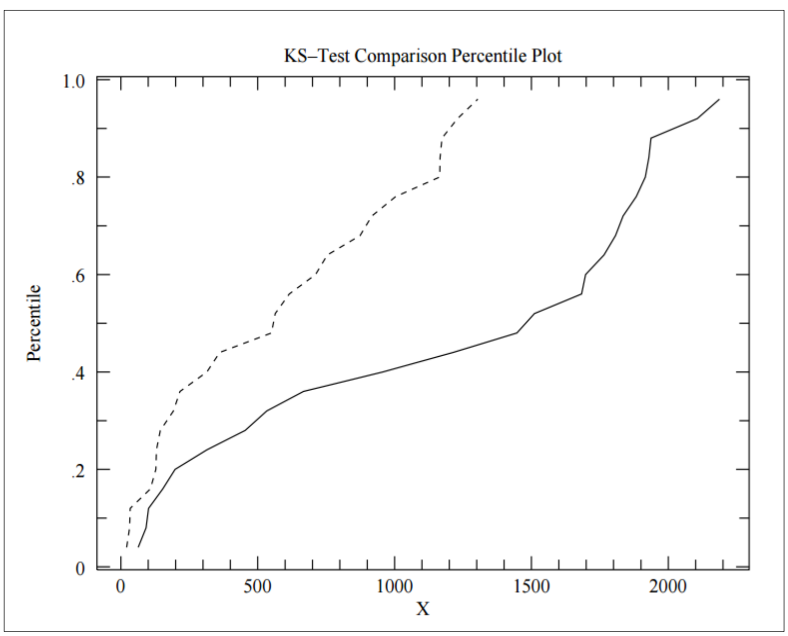


Figure 13. KS-Test Comparison Percentile for 2 Days, Eastbound, US460

The difference between the most different weeks was not significant, except for the US460 site, where the last week of the spring semester was found to be significantly different from the other weeks (because of the proximity of the site to the Virginia Tech campus). It was therefore deemed sufficient to consider a typical week of data analysis as representative, unless a study of specific events was desired. An example of the KS test for weeks is shown in Figure 14.

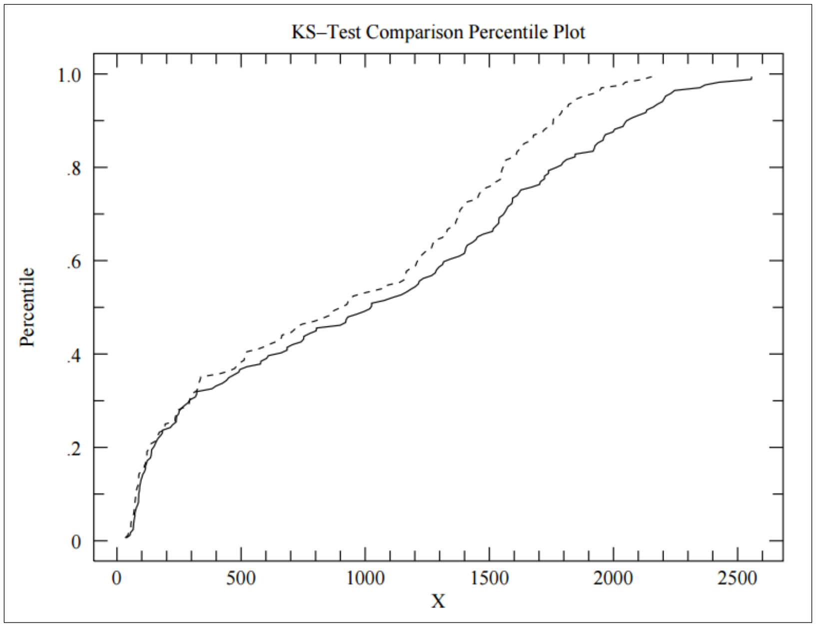


Figure 14. KS-Test Comparison Percentile for 2 Weeks, Westbound, US460

As a result, researchers decided to conduct a detailed comparison for one week of before and after data, using each hour in the day as a data point. Furthermore, an hour-by-hour comparison for a representative day (Wednesday) using each cycle in the hour as a data point was also conducted.

Comparing RLRs Based on Detectors and Radar Data

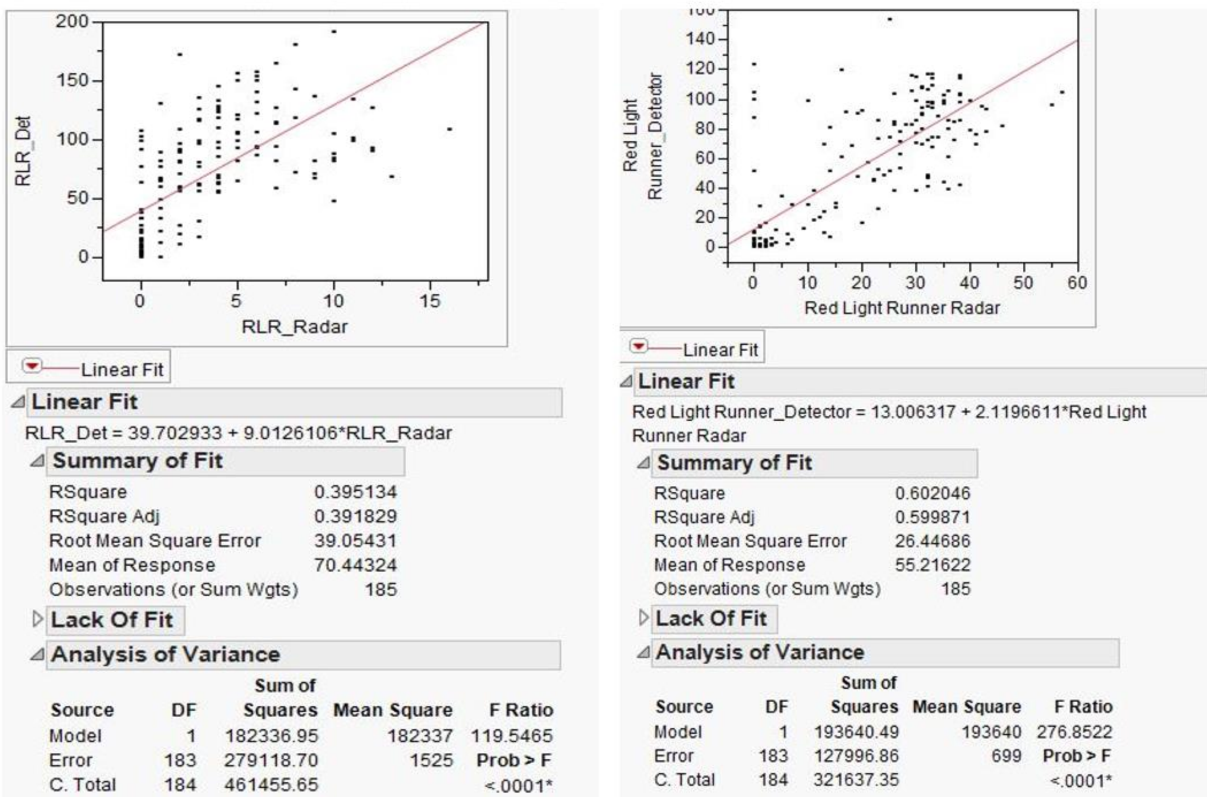
The second objective in data analysis was to develop a relationship between the number of RLRs as identified using radar data (which is more accurate but are available only during the before study) and the number of RLRs identified using video detection data (which are available during both before and after study durations). Since the video detector activations are used for the before-and-after RLR comparison, developing this relationship would shed some light onto the accuracy of the comparison and would also provide a chance for better estimation of the RLR frequency from video detection in future studies at the sites. Regression analysis was used for this purpose.

The number of RLRs identified by video detectors and number of RLRs identified by radar are shown on the y-axis and x-axis, respectively, in Figures 15 and 16. Each one of these two figures shows the result for one site. These results suggest that RLR numbers should only be used for comparison, not as absolute values. The trends seen in the figures are as follows:

1. There is a positive correlation between RLRs identified using radar data and RLRs identified using video detection data.

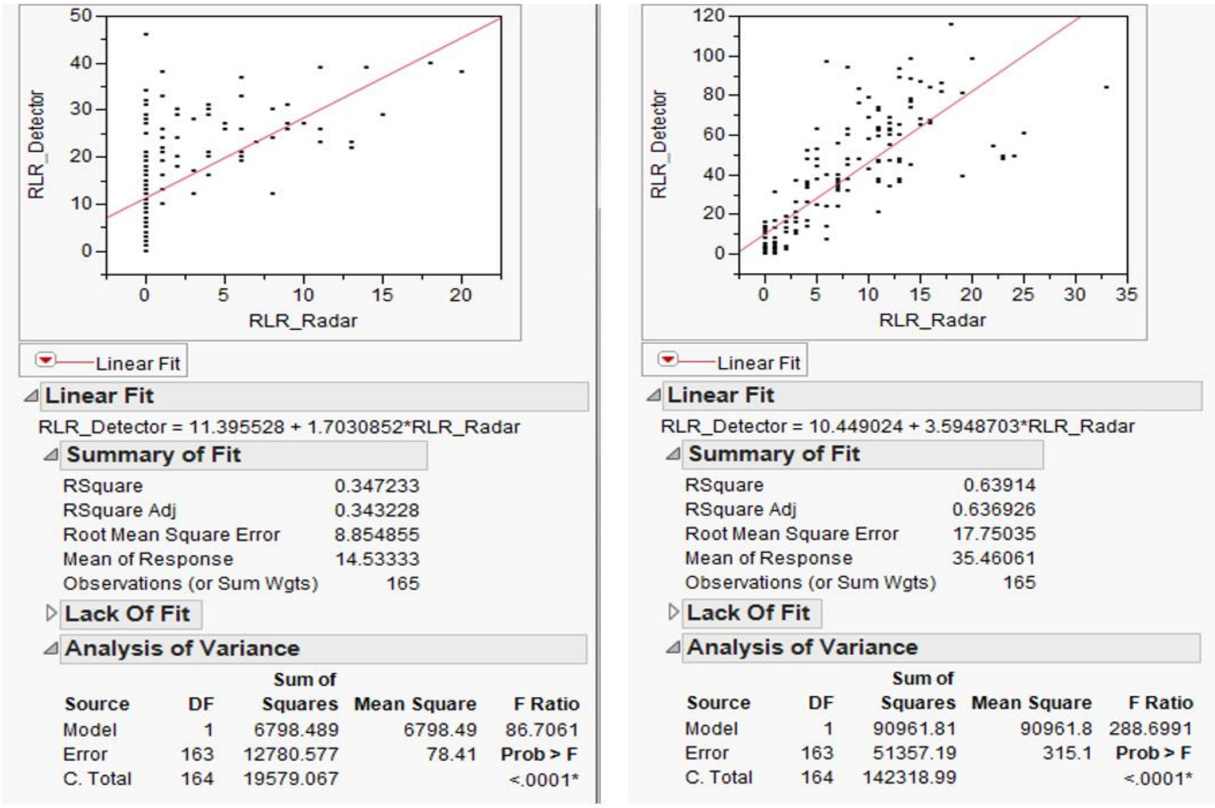
2. There is a wide spread in the data between the two different sites and the two approaches. For example, the number of RLRs identified using video detection is very high on US460 Westbound (almost 10 times the number identified using radar), while on other approaches, the number of RLRs identified using video detection ranges between 2 to 4 times the number of RLRs identified using radar.

3. There seems to be a large number of vehicles flagged as RLRs using video detection even when the radar data flags no vehicles at all. This could be due to either vehicles that creep beyond the stop bar after stopping (activating the video detectors during red) or simply the inaccuracy of video detection. The radar data avoid this limitation because the radar provides the whole trajectory data of each vehicle, including speed information.



(a) Westbound **(b) Eastbound**

Figure 15. Regression Analysis in US460 Site



(a) Northbound **(b) Southbound**

Figure 16. Regression Analysis in US220 Site

Comparing RLRs for the Before and After Studies

Tables 3 and 4 show a comparison of RLRs for the before and after data per day and hour, respectively. The number of RLRs for the after study was normalized for volume by dividing by the after traffic volume and multiplying by the before traffic volume for fair comparison. The tables also show the *p* value and indicate whether the difference in RLRs was significant. As stated in the previous section, these numbers should only be used for comparison and not as absolute values.

Table 3. Normalized Number of Red Light Runners for Before and After Studies per Day

	US460									
	Westbound					Eastbound				
	Before	**After**	**Percent Reduction**	***p* value**	**Significant**	**Before**	**After**	**Percent Reduction**	***p* value**	**Significant**
Sun	1092	1003	8.1	0.837	No	977	224	77.1	<0.001	Yes
Mon	1869	1698	9.2	0.554	No	1411	1106	21.6	0.225	No
Tues	1889	1913	-1.3	0.939	No	1446	1230	14.9	0.403	No
Weds	1947	1502	22.8	0.160	No	1333	390	70.7	0.000	Yes
Thurs	1776	1272	28.4	0.077	No	1360	436	67.9	<0.001	Yes
Fri	1601	1250	22.0	0.245	No	1308	549	58.1	0.001	Yes
Sat	1212	1153	4.9	0.600	No	1132	339	70.1	<0.001	Yes
	11386	9791	14.0			8967	4273	52.3		
	US220									
	Northbound					**Southbound**				
	Before	**After**	**Percent Reduction**	***p* value**	**Signficant**	**Before**	**After**	**Percent Reduction**	***p* value**	**Significant**
Sun	636	187	70.5	0.002	Yes	203	34	83.5	<0.001	Yes
Mon	876	149	83.0	<0.001	Yes	359	64	82.2	<0.001	Yes
Tues	784	194	75.2	<0.001	Yes	371	92	75.1	<0.001	Yes
Weds	943	222	76.5	<0.001	Yes	393	101	74.4	<0.001	Yes
Thurs	891	194	78.2	<0.001	Yes	385	97	74.7	<0.001	Yes
Fri	989	191	80.7	<0.001	Yes	421	71	83.2	<0.001	Yes
Sat	843	177	79.0	<0.001	Yes	291	63	78.5	<0.001	Yes
	5962	1315	77.9			2423	521	78.5		

Overall, using the Wavetronix system resulted in a very large reduction in RLRs (more than 50%) in most of the days, with most of this reduction being statistically significant. The US220 site has a total reduction of about 78% in RLRs, while the US460 site had a total reduction of 52% and 14% for eastbound and westbound traffic, respectively. Further study about the reasons behind these differences is described in the next section. Similar results are shown in hourly reduction in RLRs for a typical day. This can be attributed to the Wavetronix system not catching vehicles in the DZ, and therefore reducing their chance of running the red light in the first place.

Table 4. Normalized Number of Red Light Runners for Before and After Studies per Hour

Hour	US460-Wednesday									
	Westbound					Eastbound				
	Before	After	Percent Reduction	*p* value	Significant	Before	After	Percent Reduction	*p* value	Significant
1	7	1.6	76.8	0.866	No	0	0.0	-	-	-
2	0	1.6	-	0.356	No	2	2.7	-36.1	0.586	No
3	3	0.0	100.0	0.189	No	0	0.0	-	-	-
4	15	1.6	89.2	0.053	No	11	19.1	-73.2	0.896	No
5	62	17.9	71.2	0.266	No	45	2.7	94.0	-	-
6	127	61.7	51.4	0.005	Yes	67	10.9	83.7	0.078	No
7	108	95.8	11.3	0.151	No	82	10.9	86.7	0.006	Yes
8	122	56.8	53.4	0.001	Yes	80	17.7	77.9	0.000	Yes
9	98	68.2	30.4	0.053	No	99	6.8	93.1	0.000	Yes
10	127	64.9	48.9	0.044	Yes	85	12.3	85.6	0.000	Yes
11	118	74.7	36.7	0.000	Yes	95	10.9	88.5	0.000	Yes
12	132	71.4	45.9	0.001	Yes	109	21.8	80.0	0.000	Yes
13	106	61.7	41.8	0.001	Yes	98	12.3	87.5	0.000	Yes
14	130	60.1	53.8	0.000	Yes	68	10.9	84.0	0.000	Yes
15	140	68.2	51.3	0.000	Yes	81	20.4	74.8	0.000	Yes
16	135	64.9	51.9	0.000	Yes	90	31.3	65.2	0.000	Yes
17	118	61.7	47.7	0.001	Yes	99	29.9	69.8	0.000	Yes
18	108	56.8	47.4	0.048	Yes	71	28.6	59.7	0.001	Yes
19	96	73.1	23.9	0.918	No	46	23.1	49.7	0.162	No
20	107	63.3	40.8	0.124	No	51	6.8	86.7	0.014	Yes
21	64	110.4	-72.5	0.225	No	29	43.6	-50.2	0.419	No
22	13	138.0	-961.4	0.000	Yes	18	43.6	-142.0	0.339	No
23	7	94.2	-1245.1	0.008	Yes	6	29.9	-399.1	0.132	No
24	4	68.2	-1604.5	0.011	Yes	1	19.1	-1805.7	0.019	Yes
	1947	1436.7	26.2			1333	415.2	68.9		
	US220-Wednesday									
Hour	Northbound					Southbound				
	Before	After	Percent Reduction	*p* value	Significant	Before	After	Percent Reduction	*p* value	Significant
1	3	2.2	25.3	0.711	No	0	0.0	-	-	-
2	1	0.4	55.2	0.891	No	4	0.4	88.8	0.810	No
3	7	0.0	100.0	0.033	Yes	11	0.4	95.9	0.033	Yes
4	17	0.4	97.4	0.006	Yes	38	1.3	96.5	0.000	Yes
5	19	4.5	76.4	0.040	Yes	43	4.5	89.6	0.007	Yes
6	10	9.9	1.4	0.972	No	24	3.1	86.9	0.036	Yes
7	18	3.6	80.1	0.001	Yes	89	0.4	99.5	0.000	Yes
8	16	1.8	88.8	0.006	Yes	43	0.4	99.0	0.023	Yes
9	29	1.8	93.8	0.001	Yes	47	0.9	98.1	0.000	Yes
10	28	3.6	87.2	0.002	Yes	65	1.8	97.2	0.003	Yes
11	28	2.7	90.4	0.001	Yes	93	2.7	97.1	0.000	Yes
12	31	1.8	94.2	0.001	Yes	79	0.0	100.0	0.001	Yes
13	34	4.5	86.8	0.000	Yes	98	1.8	98.2	0.000	Yes
14	33	4.5	86.4	0.000	Yes	62	2.7	95.7	0.002	Yes
15	32	2.7	91.6	0.000	Yes	61	1.3	97.8	0.001	Yes
16	24	3.1	86.9	0.010	Yes	65	1.8	97.2	0.001	Yes
17	6	3.1	47.7	0.424	No	32	0.9	97.2	0.001	Yes
18	23	2.2	90.3	0.001	Yes	38	0.9	97.6	0.001	Yes
19	11	2.7	75.6	0.204	No	26	0.4	98.3	0.021	Yes
20	7	1.8	74.4	0.155	No	12	0.0	100.0	0.038	Yes
21	8	2.2	72.0	0.112	No	13	0.9	93.1	0.051	No
22	2	4.0	-101.6	0.838	No	0	0.9	-	0.162	No
23	0	2.7	-	0.032	Yes	0	0.0	-	-	-
24	6	4.9	17.9	0.270	No	0	0.9	-	0.161	No
	393	71.2	81.9			943	28.7	97.0		

Safety Surrogate Histograms for US 460

Even though they occur rarely, rear-end collisions are likely to occur because of conflicts caused by DZ-related decisions. To avoid waiting for crashes to occur before doing the analysis, researchers opted to use surrogate safety measures to estimate and assess the safety improvements at each site. Surrogate safety measures found in the literature use input obtained from simulation software to evaluate traffic conflicts. The concepts used in these tools, however, are valuable. For example, the Time to Collision (TTC) provides a good surrogate for the degree of collision risk between each pair of vehicles. The shorter the TTC, the more imminent the collision is, unless drivers adjust their speed in time.

Although TTC has been widely referenced and used, it had not been directly used in DZ-related studies found in the literature review. In this project, the research team utilized the TTC concept to develop a novel safety surrogate measure called a "safety surrogate histogram" (SSH) of DZ-related conflicts at signalized intersections (Ghanipoor Machiani and Abbas, 2016a, 2016b).

Using the vehicle trajectory data obtained from the radar detection systems, the team measured and plotted the TTC for every two consecutive vehicles on a time-space diagram. Figure 17 illustrates this concept by showing the TTC for two consecutive vehicles (vehicle A is following vehicle B). The TTC is calculated at two points in the figure based on each vehicle's speed. TTC 1 is shorter, indicating a possible imminent collision. At time 2, vehicle A has slowed down with a higher deceleration rate than vehicle B, resulting in a longer TTC. When the TTC values increase with time, the danger of collision subsides.

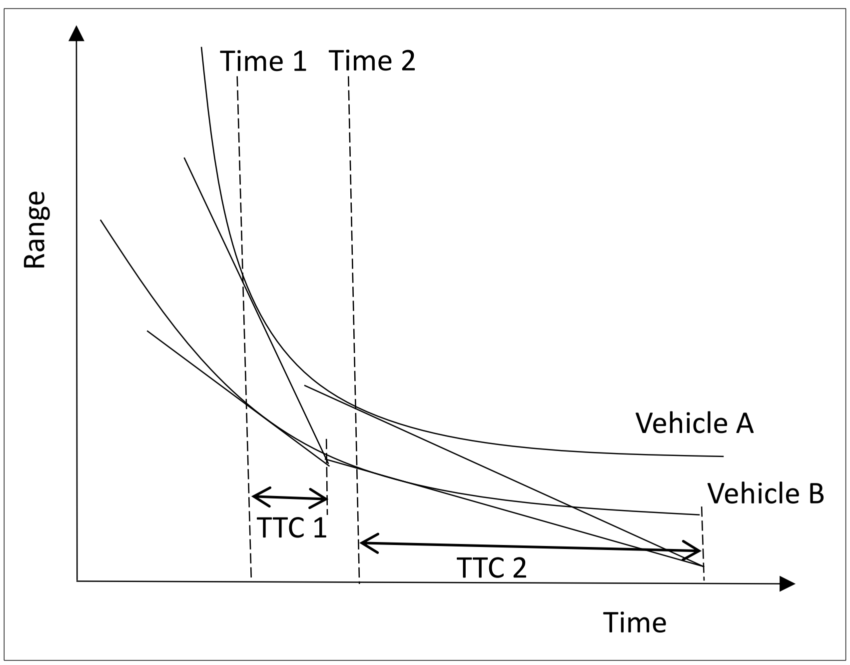


Figure 17. TTC Values Plotted on a Time-Space Diagram

For each pair of vehicles facing a red light, it is expected that the lead vehicle will respond first, slow down, and accelerate again when the green light comes on. The second vehicle will normally respond second and follow almost the same trajectory. This will lead to the TTC value decreasing with time and then recovering smoothly as shown in Figure 18 (Pair B). In situations where the following vehicle has to brake hard to avoid a crash (e.g., driver in the back decides to go, but realizes later that the leading vehicle is stopping), the TTC curve will be steeper, and the TTC value will decrease to lower values, indicating a more dangerous situation (Pair A in Figure 18).

The idea behind the SSH is to show the frequencies of TTC values between 0 and 1 s, 1 and 2 s, etc., that occur during a cycle (the concept could also apply to data from a whole hour). An algorithm goes through each cycle and finds the TTC value for each pair of vehicles each 0.1 s. If the TTC value falls between 2 and 3 s, the histogram entry of bin 3 is incremented (shown in Figure 18 as TTC3++). If the TTC value falls between 1 and 2 s, the histogram bin of 2 s is incremented (shown in Figure 18 as TTC2++), etc. The whole process is illustrated in Figure 18. The figure shows that for each time increment from left to right, the TTC value of any vehicle pair at that time step causes an increase in the corresponding histogram bin. At the end of the cycle (or the hour), the full histogram is drawn for that intersection approach.

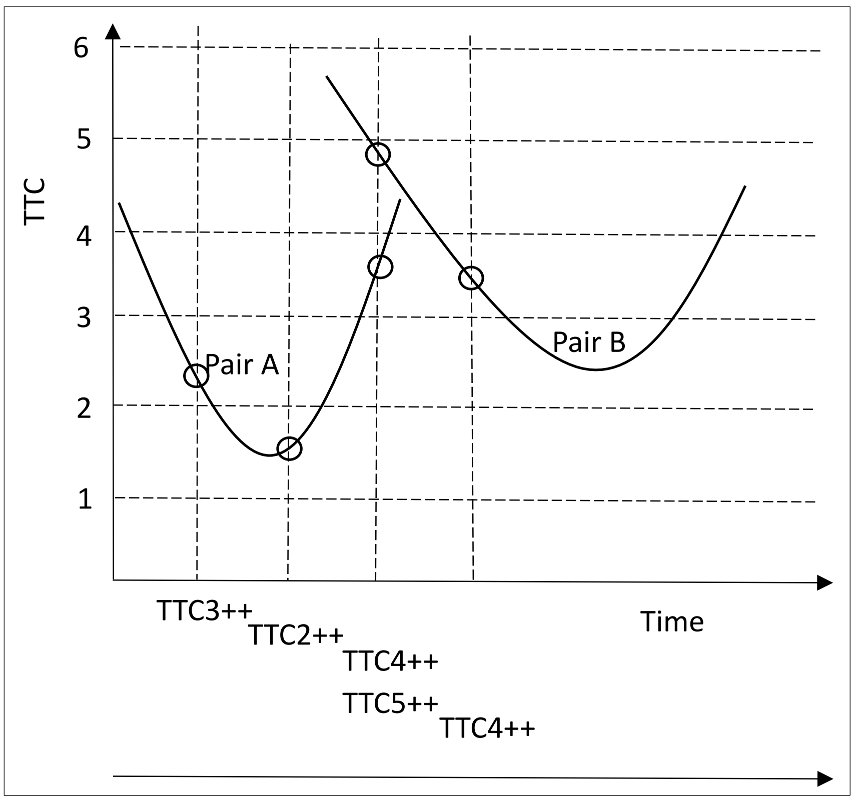


Figure 18. TTC Shape for Two Different Vehicle Pairs

The frequency of each TTC value, especially the smaller values, is important because it indicates how many times a potential crash occurred.

Comparisons between the SSH for different signal timing plans and between the two sites were constructed. Each bin in the SSH shows the TTC frequency normalized by the number of vehicles in each cycle. The SSHs for US460 under shorter red light duration and higher red light duration are shown in Figures 19 and 20, respectively. Trend lines are included in the figures. These figures show the following:

1. All trendlines have positive slopes. That shows, in general, vehicle pairs are more frequently observed with larger TTC, indicating a safe situation.

2. Under shorter red light durations, the TTC values are close to the trend lines, which indicates a linear increase of TTC frequency in relation to the increase in TTC values, as opposed to, for example, a normal distribution of TTC values.

3. Under longer red light durations, for eastbound traffic, the TTC values in the 2, 3, and 4 second bins are more frequent as compared to shorter red light durations. This indicates a longer red light increases the safety of eastbound traffic.

4. The higher TTC values did not increase for westbound traffic under the higher red light duration as compared to the shorter red light duration. This could be due to the effect of the horizontal curve near the intersection on the westbound side. The longer red light causes a longer queue and drivers at the back of the queue have reduced sight distance because of the horizontal curve. Thus, the reduced sight distance counteracted the advantage of a longer red light.

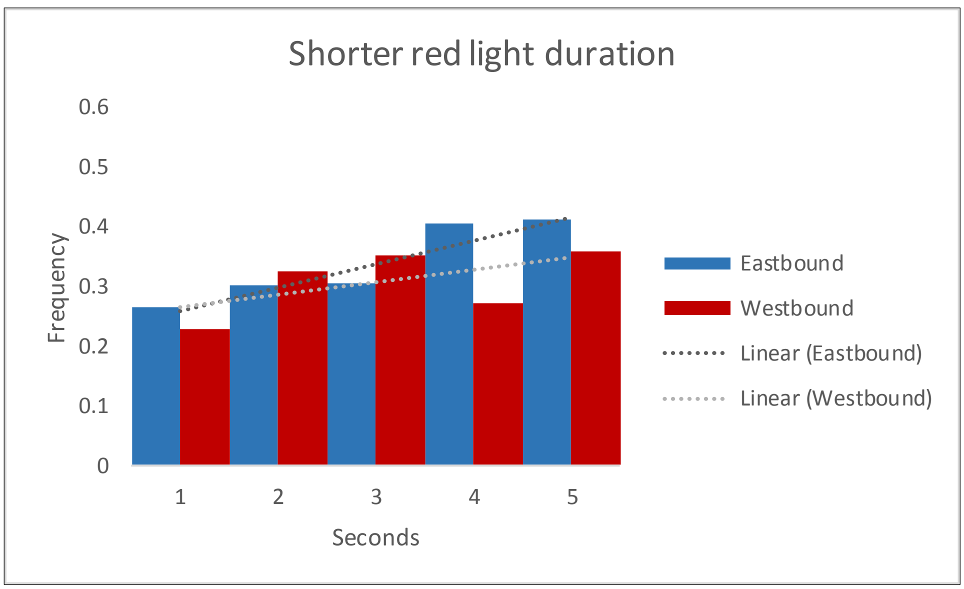


Figure 19. SSH for Shorter Red Light Duration for US460 Eastbound and Westbound

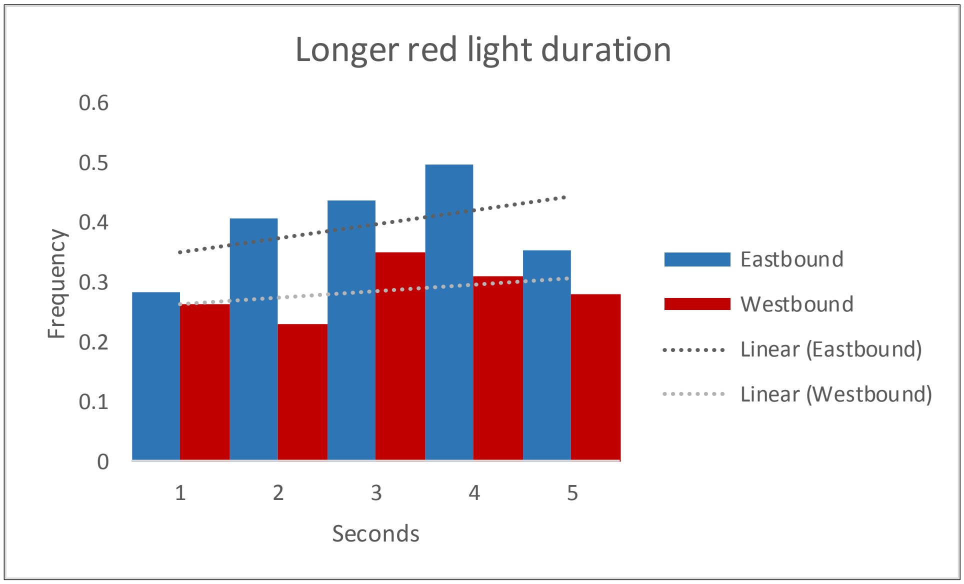


Figure 20. SSH for Longer Red Light Duration for US460 Eastbound and Westbound

Figures 21 and 22 show the SSHs for US460 andUS220, respectively. The presented data were collected on the same day and at the same time of day for each approach. Values are normalized per vehicle and number of cycles to reduce the effect of the volume difference between the two sites.

From the figures, it can be seen that the US460 site has higher SSH frequencies for all TTC values, which indicates a higher potential for safety problems at the US460 site. For both sites, the approaches with a left turning movement, shown in blue, have higher SSH. This is logical because the left turning traffic can disturb the through traffic while weaving through to the left turn bay.

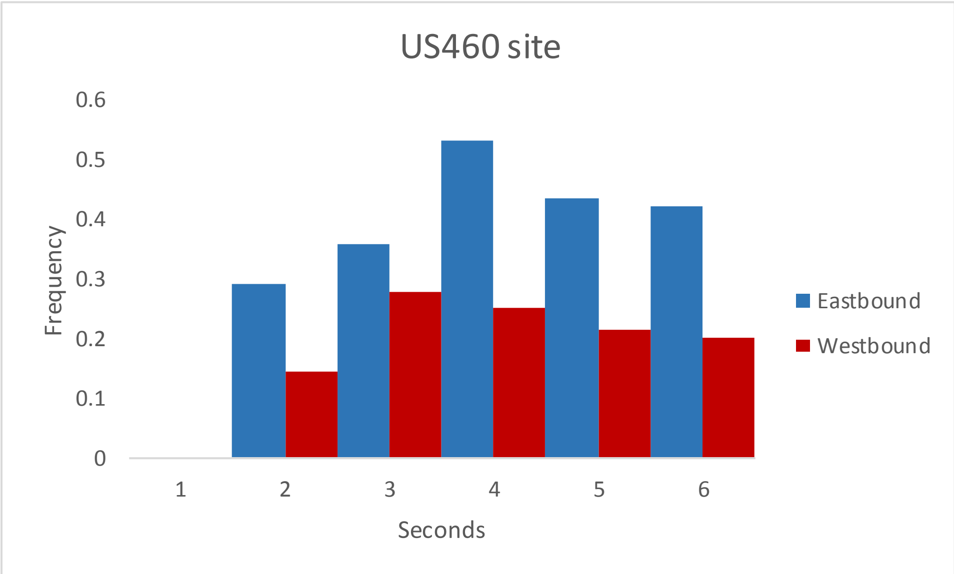


Figure 21. SSH for US460 Site

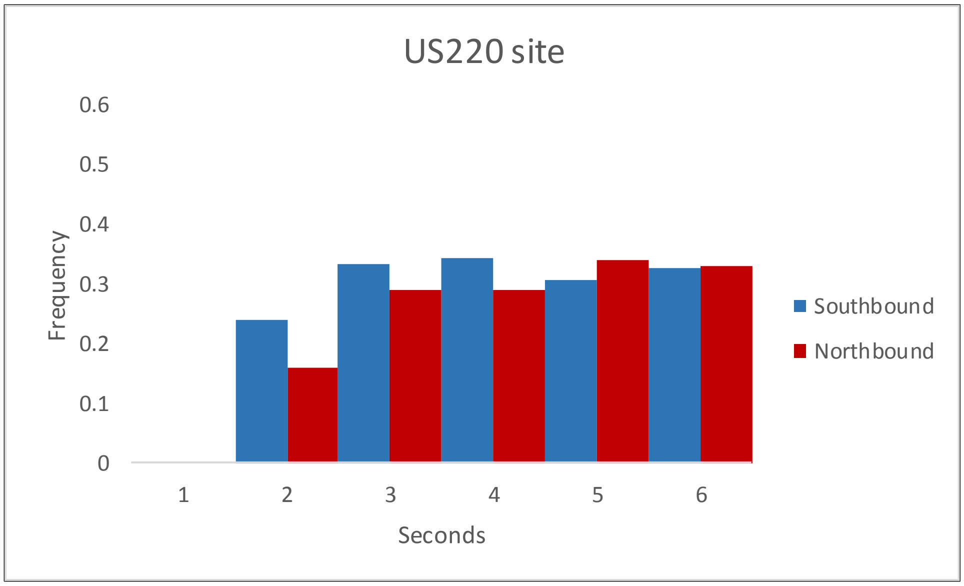


Figure 22. SSH for US220 Site

Developing a Simulation Optimization Platform for DZ Protection Systems

The result of this task was a fully functional simulation optimization software (DZ-Pro) that was implemented using the AnyLogic software platform. The software can simulate any of the three major DZ-protection systems: (1) multi-detector system, (2) green hold/termination system (e.g., D-CS), and (3) radar-based system (e.g., Wavetronix). DZ-Pro is capable of simulating the performance of a given system and optimizing its parameters when applicable (e.g., the location of loops and extension times for a multi-detector system).

Both sites examined in this project were T-intersections as shown in Figure 23. The ring barrier diagram for each of the two sites is shown in Figure 24.


Figure 23. Site Layout

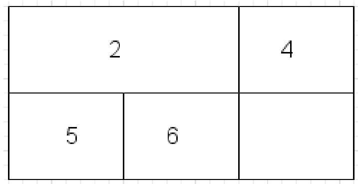


Figure 24. Ring Barrier Configuration

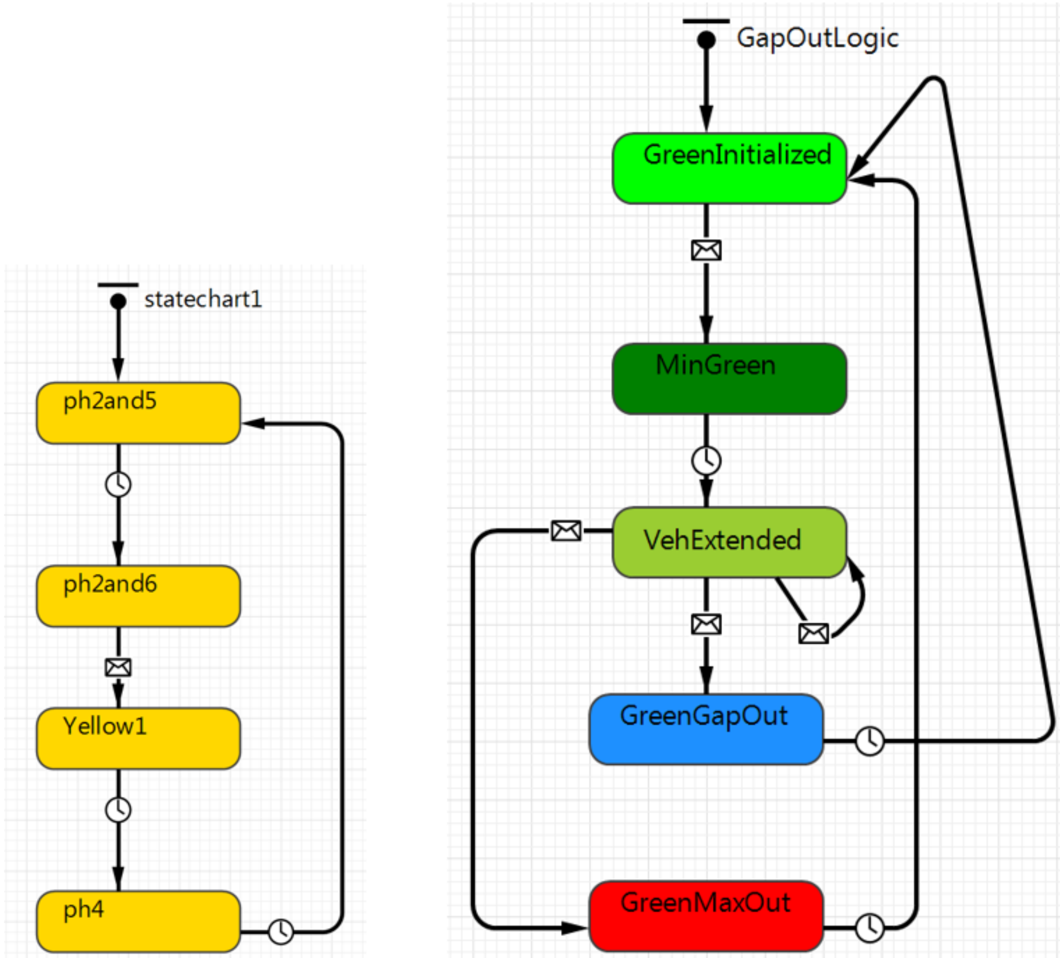
The agent based model of signal control operation is implemented using a state chart for each significant phase state as shown in Figure 25a in correspondance with the ring-barrier diagram, the chart starts with phases 2 and 5. After phase 5 ends (transition between the states in the figure is shown with a clock icon, indicating a timed transition based on phase 5 split duration), it will turn to phases 2 and 6. When the controller's state reaches phases 2 and 6, the gap-out logic will start (transition between states in the figure is shown with a message icon, indicating a conditional transition based on a message received from the gap-out logic to end the phase). After phases 2 and 6 end, the signal for the main stream will turn yellow and then red. The yellow duration is constant for each site, and the red duration represents the all-red period and the phase duration for phase four. After red, the controller's state will turn back to phase 2 and 5 and start a new cycle.

The time duration of phases 2 and 6 is controlled by the gap-out logic, as shown in Figure 25b. This logic starts with the state "GreenInitialized" and waits until the phases reach 2 and 6. The max-out timer will start after phases 2 and 6 start. After the minimum green time, the signal will start the extension process (with a "vehicle extend" input variable). During each extension time, if a new vehicle is detected by a detector, the detector will send an extension call to this gap-out logic (the controller) together with a requested extension time. If the requested extension time is longer than the remaining green time, the remaining green time will be extended to the requested extension time (Equation 4). But if the green time for this phase exceeds the maximum green time, the logic (controller) will no longer answer the extension request, and the phase will end with a max-out. If the max-out timer does not time out, and the remaining green time is equal to zero (which means there is a large gap in traffic), the controller will end the phase with a gap-out.

$$T'_R = \begin{cases} T^i_{Ext} & T^i_{Ext} > T_R \\ T_R & else \end{cases} \qquad \text{[Eq. 4]}$$

where

i: detector number
T^i_{Ext}: vehicle extension time for detector *i*
T_R: green extension for current phase before detector call
T'_R: green extension for current phase after detector call.

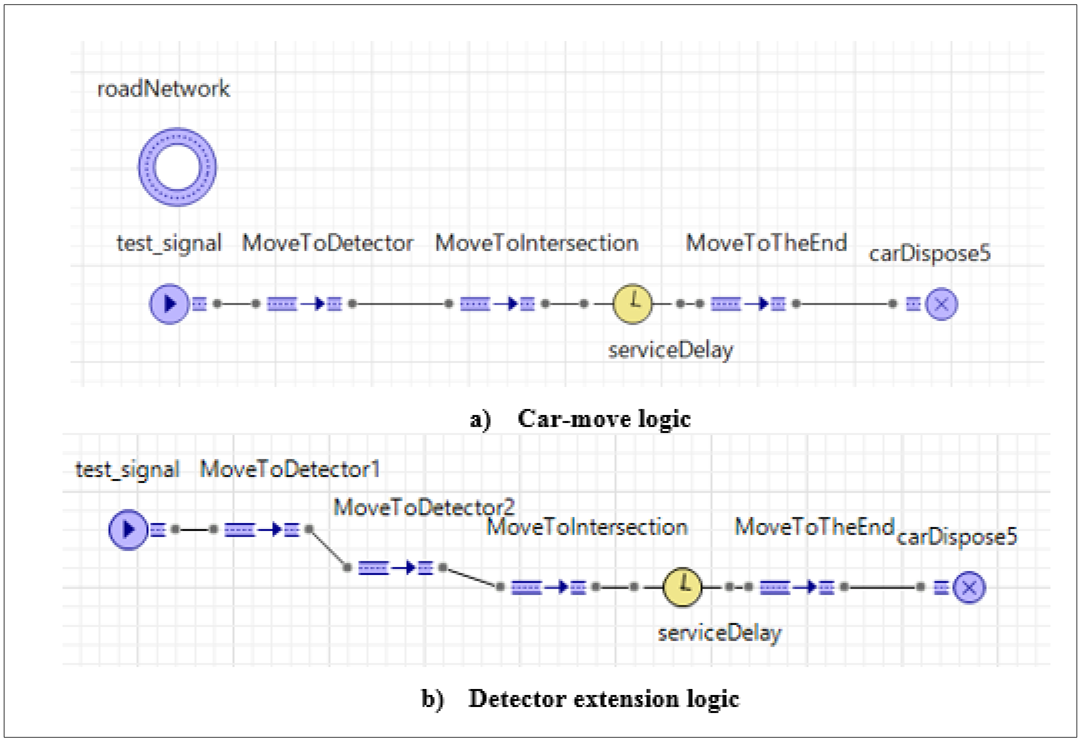


(a) Phase change logic **(b) gap-out logic**

Figure 25. Controller State Chart

To implement a detector logic, the researchers used multiple "Car Move To" functions (blocks) to serve as detectors. After a vehicle is generated, it will be driven to the detector's location, and continue to the next destination (Figure 26a). Before it moves to the next destination, it will trigger the events written in the "Car Move To" block. The events include sending messages to the controller. For the case of green extension/termination simulation (e.g., the D-CS system), the vehicle moves all the way from the first speed trap detector to the stop bar. For the multi-detector system, the researchers let the vehicle drive to the first detector, then to the rest of the detectors one-by-one (Figure 26b). When a vehicle is at the detector's location, it will trigger the events written in the corresponding blocks.

In this work, the event to be triggered on arriving at the detectors is to change the extension time to T_{Ext}^{i} based on the detector number and extend the phase by a vehicle extension.



a) Car-move logic

b) Detector extension logic

Figure 26. Multi-Detector Logic

The timer tool in AnyLogic allows the setup of customized criteria before an action is executed. This tool was used to mimic the Wavetronix operation of monitoring the DZ and placing a call on the controller as long as the DZ is not empty. The user can select which kind of DZ protection they are simulating with a radio button selection, and the developed tool conducts a simulation for the selected system.

Safety Objective Function: Calculating Number of Vehicles in DZ

The current state-of-the-art DZ safety evaluation uses the number of vehicles caught in the DZ as a surrogate measure for assessment purposes. This number is calculated by extrapolating each vehicle path to the stop bar at the onset of yellow to calculate its predicted arrival time. Once the vehicle arrival time at the stop bar is calculated, an evaluation of whether the vehicle is in the DZ is carried out using the prevailing definition of DZ boundaries (2 to 5.5 s for start and end of DZ, respectively). Following this logic, all vehicles on the approach at the onset of yellow are evaluated, and a total count of vehicles caught in DZ is determined. At the end of each simulation run, the researchers use the number of vehicles trapped in DZ divided by the simulation time as the measure of safety.

Optimization

The operation of D-CS and Wavetronix are self-optimized in the sense that each system monitors the DZ and terminates the green when the zone is empty, with the main difference being that D-CS assumes that vehicles travel at a constant speed from the speed trap detector to the stop bar, whereas Wavetronix keeps monitoring vehicles as they approach the intersection. For the case of a multi-detector system, different detector configurations lead to different system performance. For a fair comparison, the multi-detector system needs to be optimized by changing detectors' locations and vehicle extension times. This was achieved using the OptQuest Optimization Engine (Laguna, 2011). The objective of this optimization problem was to minimize the number of vehicles caught in DZ per hour. The variables were detectors' locations and vehicle extension times.

The constraints included the following:

- Detectors' locations are between 10 m (32.8 ft) to the intersection and 140 m (459.3 ft) to the intersection.

- The first (most upstream) detector's distance to intersection is greater than that of the second detector.

- The second detector's distance to intersection is greater than that of the third (nearest) detector.

- The vehicle extension time is between 0.1 s and 4 s.

DZ-Pro can be used to conduct a sensitivity analysis for different traffic volumes and show the performance (i.e., number of vehicles caught in DZ) of each system in the same graph. Figures 27 through 30 show the software optimization, simulation, controller, and traffic animation views, respectively. The three charts on the right in Figure 29 show the following measures with respect to time:

1. Percent of phases ending with a gap-out condition
2. Cumulative number of vehicles in DZ
3. The active phase number in each ring.

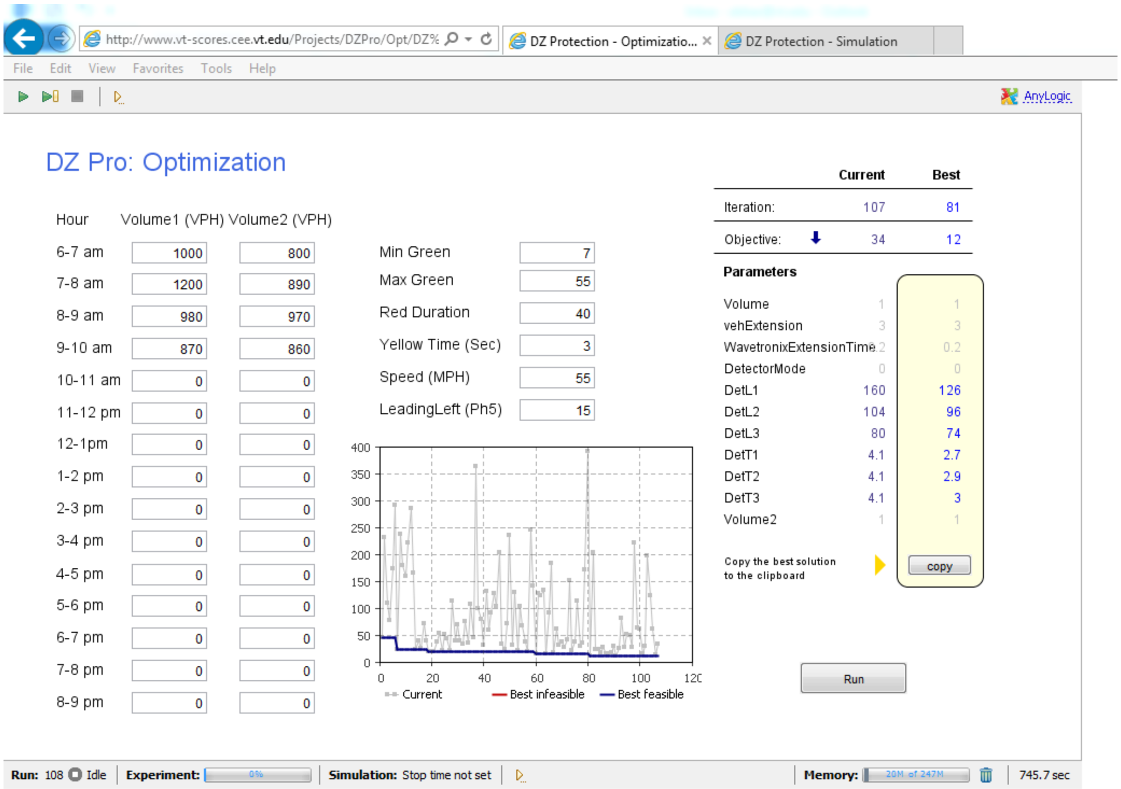


Figure 27. DZ-Pro Optimization Screen

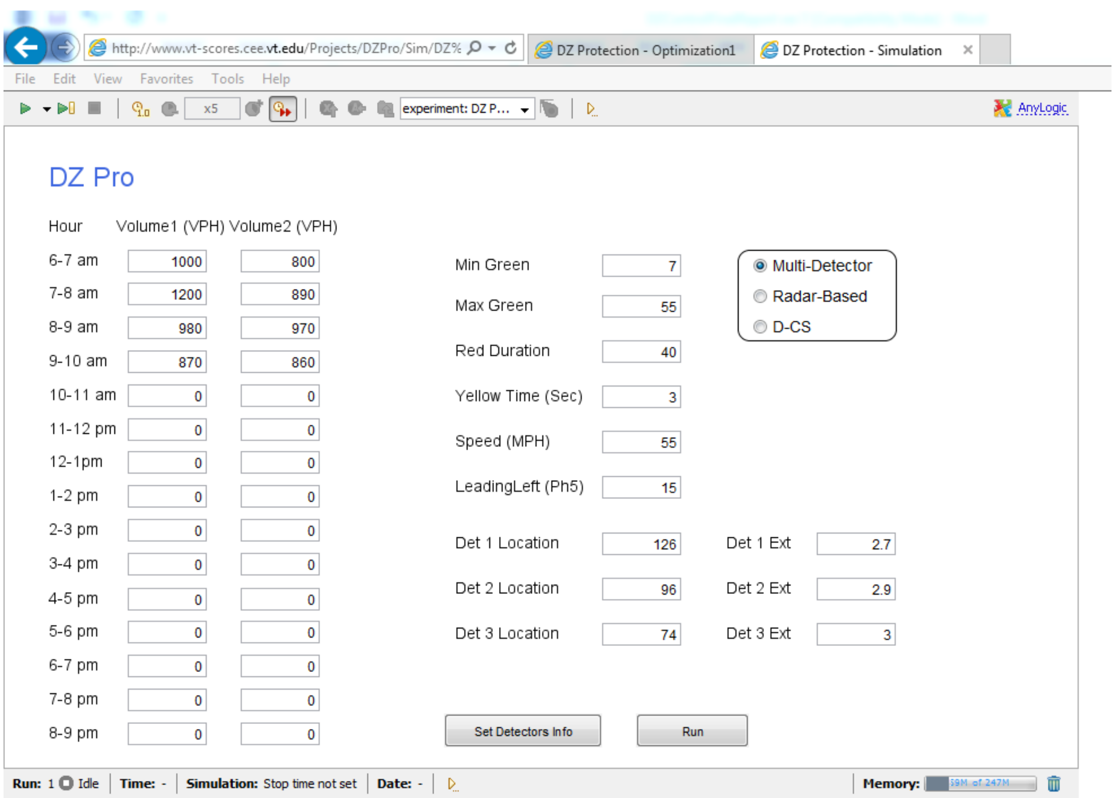


Figure 28. DZ-Pro Simulation Screen

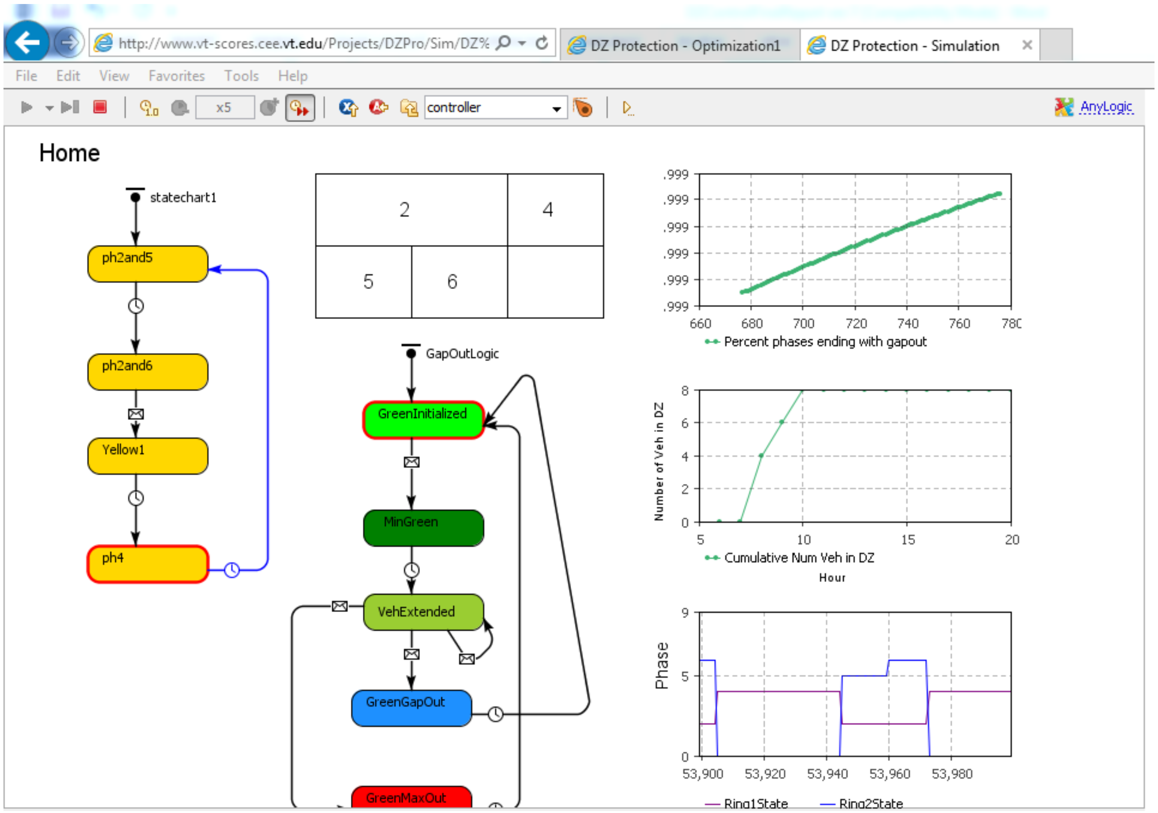


Figure 29. DZ-Pro Controller Simulation and Output

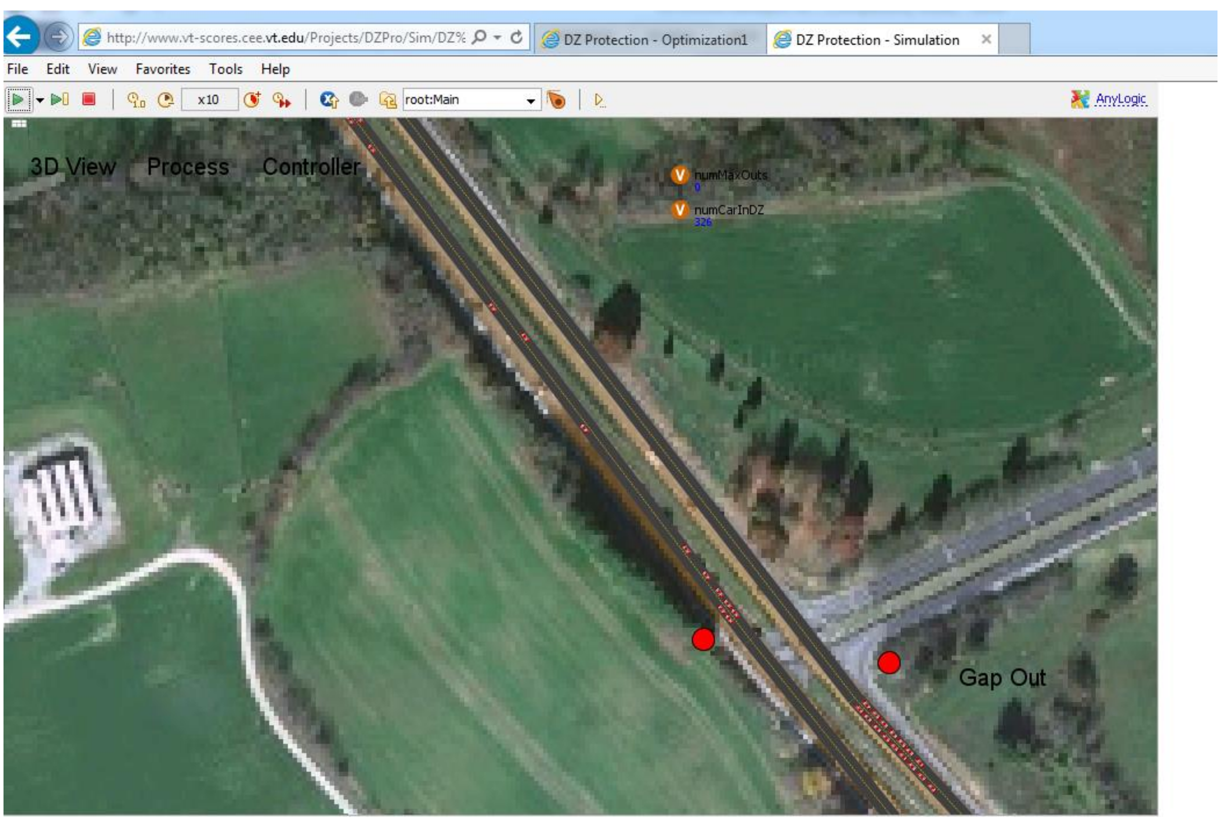


Figure 30. DZ-Pro Traffic Simulation Screen

Comparing the Performance of Different DZ Protection Systems using Trace-Driven Simulation

Trace-driven simulation conducted using each of the three DZ protection systems for a sample day revealed a clear advantage of the radar-based system. The results indicate that for this whole-day simulation, the radar-based system could avoid trapping any vehicle in the DZ. The multi-detector system traps a total of about 480 vehicles in a whole day. Figures 31 and 32 show screen shots of the DZ-Pro animation for the radar-based and multi-detector systems, respectively. The chart in each figure shows the cumulative number of vehicles caught in DZ as a function in time.

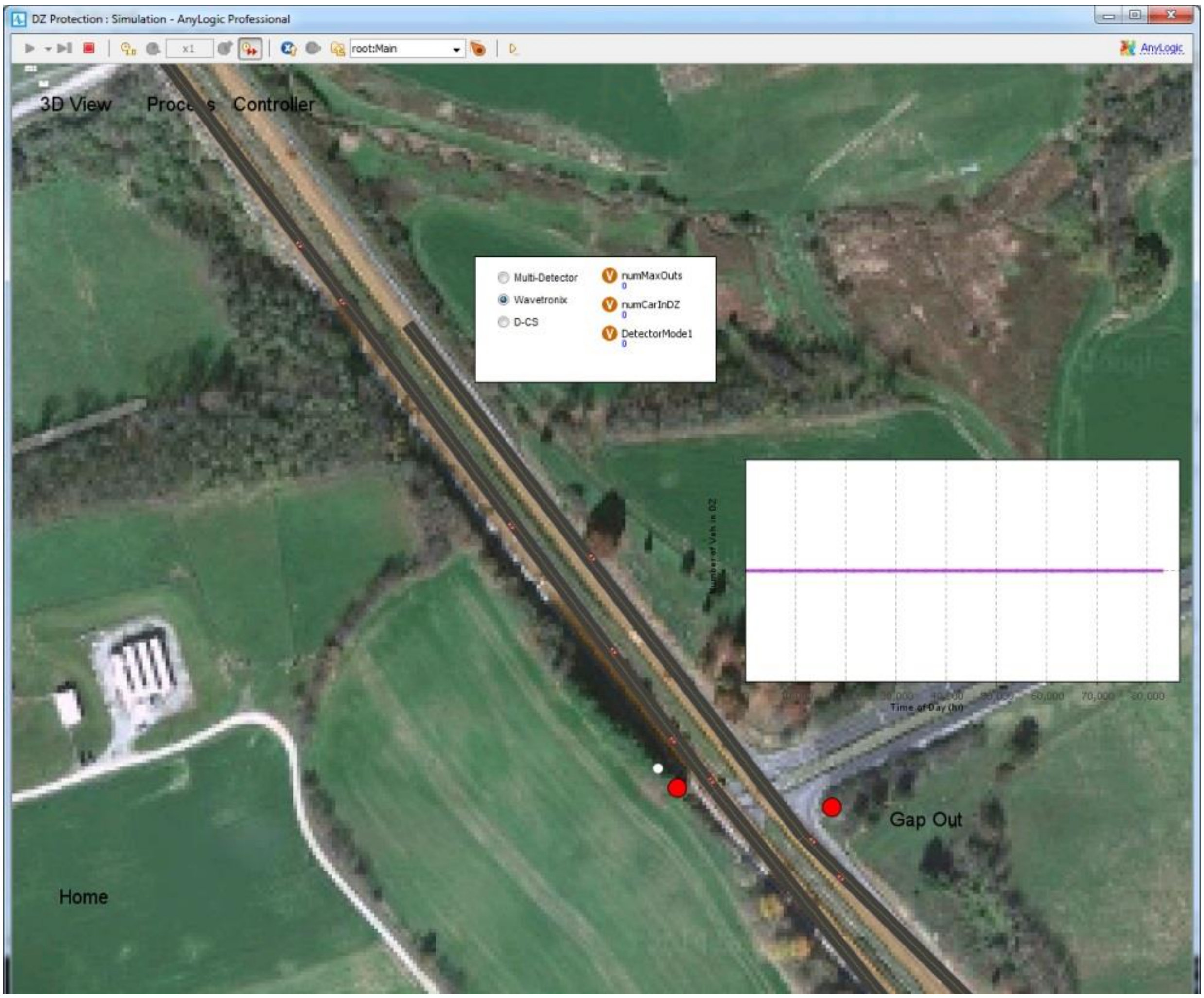


Figure 31. Radar-Based Trace-Driven Simulation

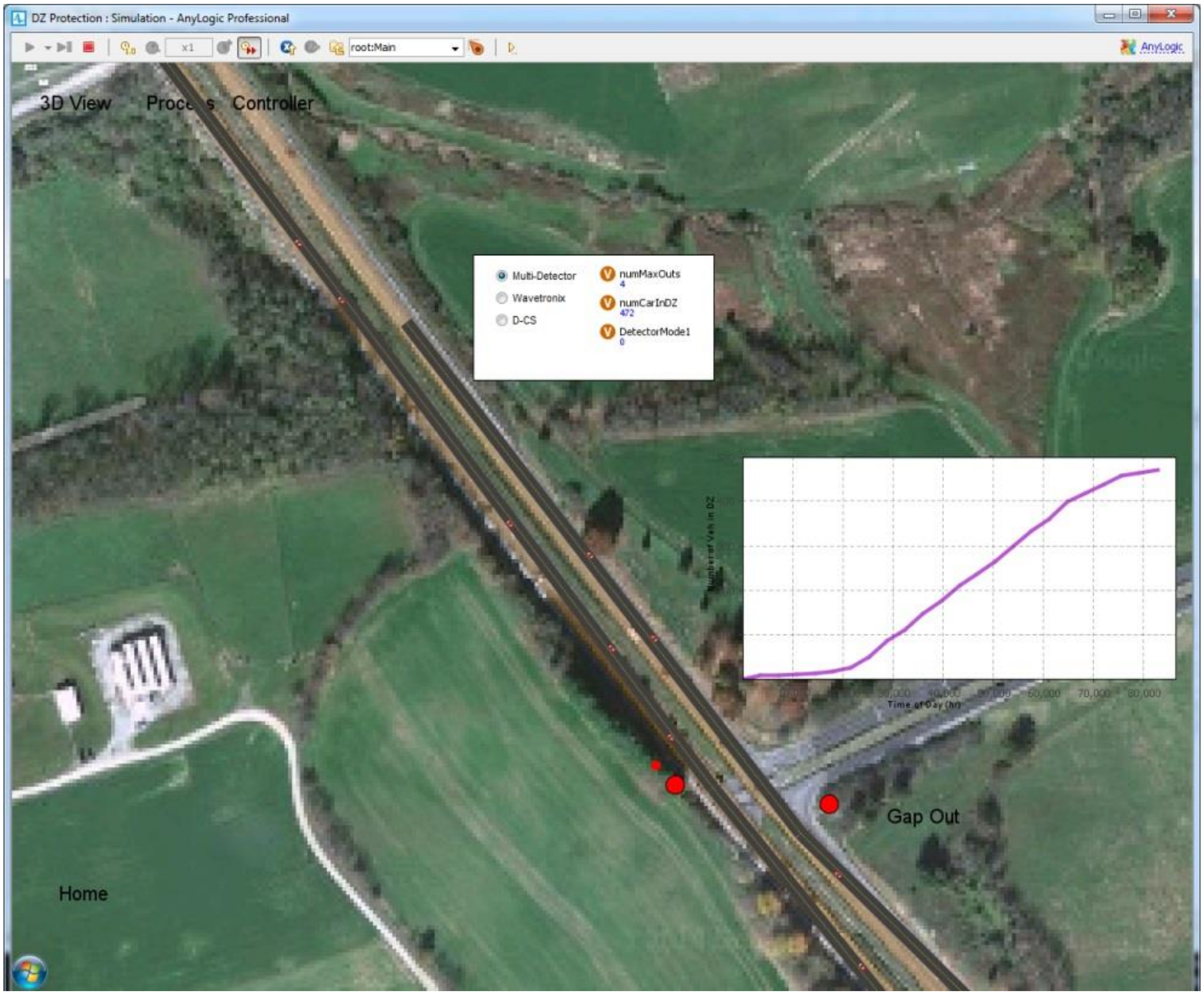


Figure 32. Multi-Detector Trace-Driven Simulation

Developing General Guidelines for Selection of DZ Protection Systems

The main purpose of this project was to provide general guidelines for using advanced control features to address DZ issues at high speed signalized intersections, with the focus on:

1. Providing guidelines for optimal design of existing actuated controller systems
2. Evaluating and providing guidelines for the use of green hold and termination systems
3. Providing a comparison of each DZ protection method
4. Providing guidelines on the integrated use of CABs with DZ protection systems.

Development of each one of these items is described here. Examples of using DZ-Pro are also provided to help VDOT engineers optimize, evaluate, and select suitable systems for different circumstances.

Developing Guidelines for Optimal Design of Existing Actuated Controller Systems

The objective of this subtask is twofold: (1) provide an illustrative comparison between existing guidelines for multi-detector design and (2) provide an example for using DZ-Pro optimizer for a particular field situation.

The first objective was achieved in two steps. In the first step, an optimized detector design for an average arrival rate of 780 vehicles/hour/direction was obtained using a ten-hour simulation run in each optimization iteration. After 500 iterations, the optimizer obtained the minimum number of vehicles caught in DZ per hour. Figure 33 shows the number of vehicles caught in DZ on the y-axis and the corresponding iteration number on the x-axis. The optimized configuration resulted in three detectors placed at 370 ft, 292 ft, and 207 ft upstream of the stop bar with vehicle extension equal to 3.2 s, 1.9 s, and 2.6 s, respectively.

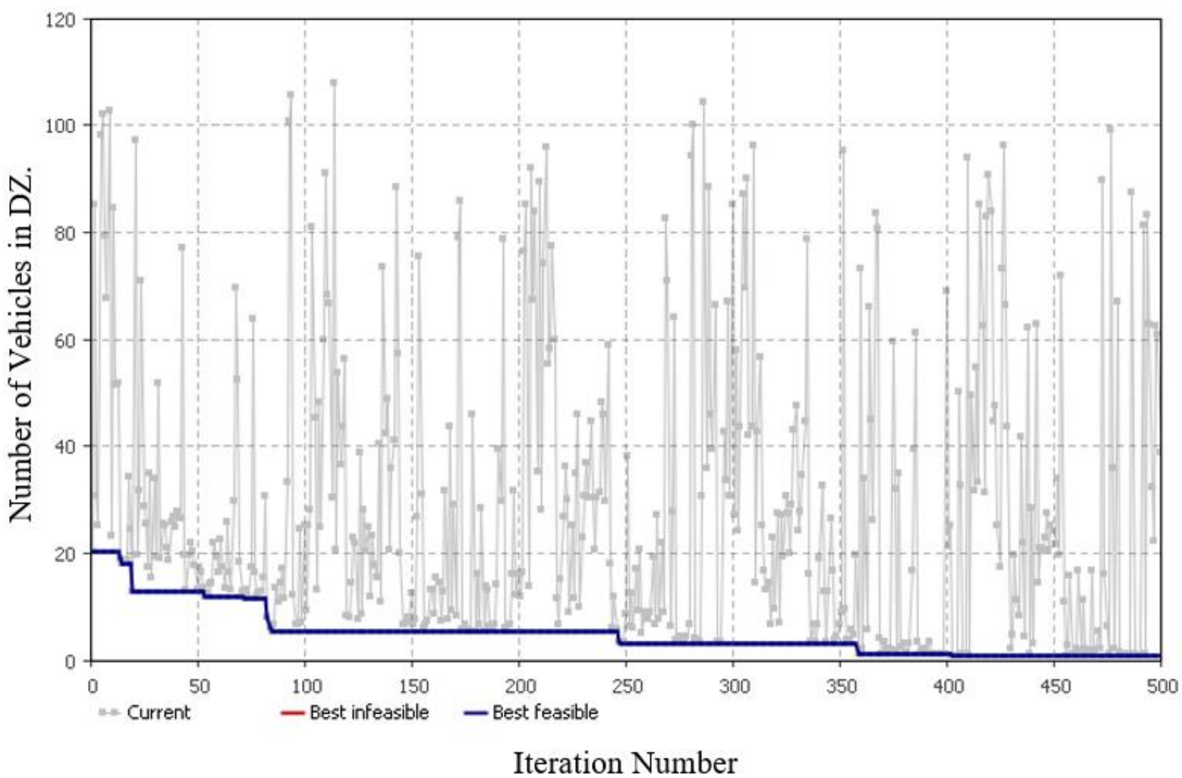


Figure 33. Detectors' Configuration Optimization

In the second step, a comparison between different detector designs was conducted by running each prevailing detector design, and the optimized design, for volumes ranging between 0 and 3000 vehicles per hour per direction. It should be noted, however, that the "optimized design" was the design optimized for an average field condition of 780 vehicles/hour/direction.

The results of the evaluations are shown in Figure 34. The performance of each multi-detector design under different traffic volumes is plotted in this figure. The unit of flow is vehicles/hour/direction. The figure shows that different multi-detector designs perform differently under different volume conditions. From this figure, it can be seen that in a low volume conditions, the optimized configuration leads to a lower number of vehicles caught in the DZ per hour, which means a safer scenario and a better performance of the DZ protection system. The SSITE's configuration is best when the volume is between 1000 and 1750 vehicles/hour/approach. Bonneson's configuration is best when the flow is between 1750 and 2000 vehicles/hour/approach. Sackman's design is best when the volume is above 2000 vehicles/hour/approach.

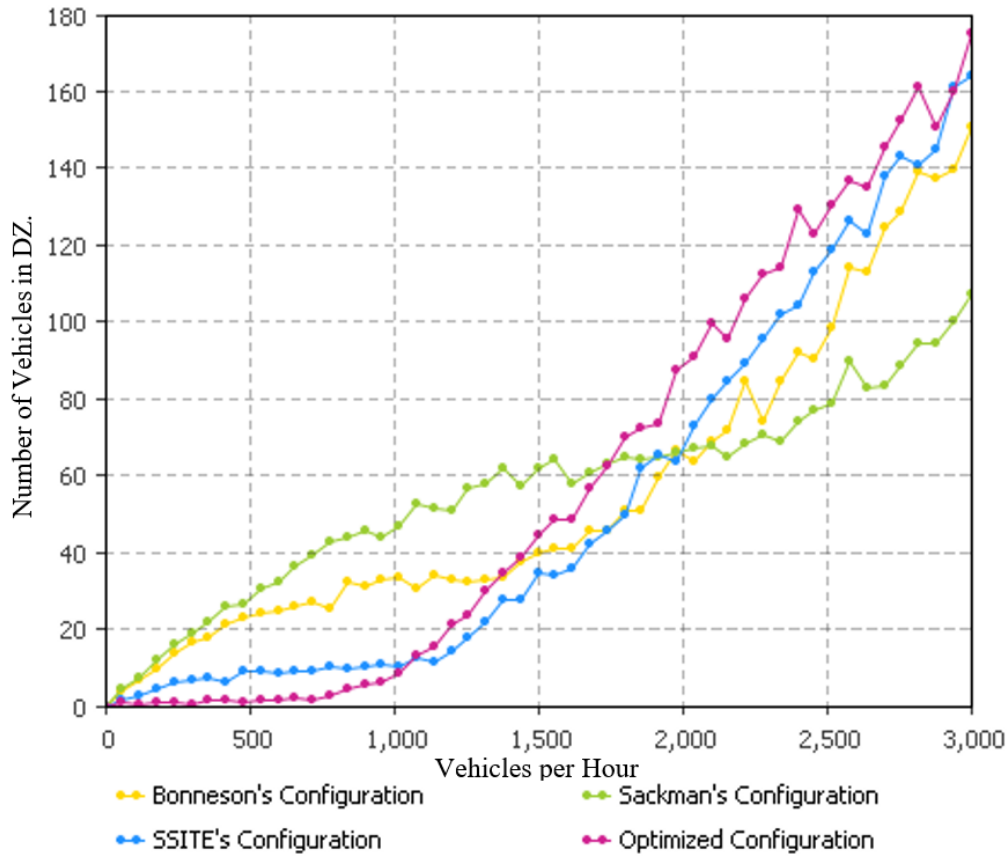


Figure 34. Multi-Detector System Optimization Results

The second objective was to provide an example of using DZ-Pro optimizer. This was important because traffic volume varies during the day, and therefore, the optimization process should take the daily volume profile into account. Since daily profiles at different sites can vary widely, it is important for VDOT engineers to optimize the detector configuration for the daily volume profile of the specific site under consideration. The following examples show how to use DZ-Pro optimizer for this purpose.

Example 1:

At a T-intersection, the speed limit is 55 mph in the main street (Phase 2 and 6). The controller setting is given as follows: Phase 2 and 6 minimum green is 7 seconds and maximum green is 60 seconds. Phase 5 split is 20 seconds. Phase 4 split plus the all-red duration of phases 2 and 6 is 45 seconds. The NEMA ring-barrier diagram is shown in Figure 35.

The typical traffic volume daily profile for each direction is shown in Table 5. What are the optimal detector configurations and the vehicle extension for a multi-detector DZ protection system?

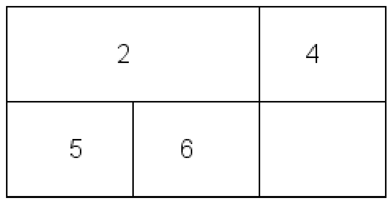


Figure 35. NEMA Diagram for Example 1

Table 5. A Typical Traffic Volume Profile for Each Direction at the Site

Hour	Volume 1 (VPH)	Volume 2 (VPH)
6-7 am	700	400
7-8 am	1000	500
8-9 am	1500	900
9-10 am	1400	800
10-11 am	800	700
11-12 pm	700	700
12-1 pm	600	600
1-2 pm	500	500
2-3 pm	500	500
3-4 pm	600	700
4-5 pm	700	800
5-6 pm	700	1300
6-7 pm	800	1200
7-8 pm	800	1000
8-9 pm	800	800

Solution:

Navigate to the DZ Pro Optimization link at http://www.vt-scores.cee.vt.edu/Projects/DZPro/Opt/DZ%20Protection.html as shown in Figure 36.

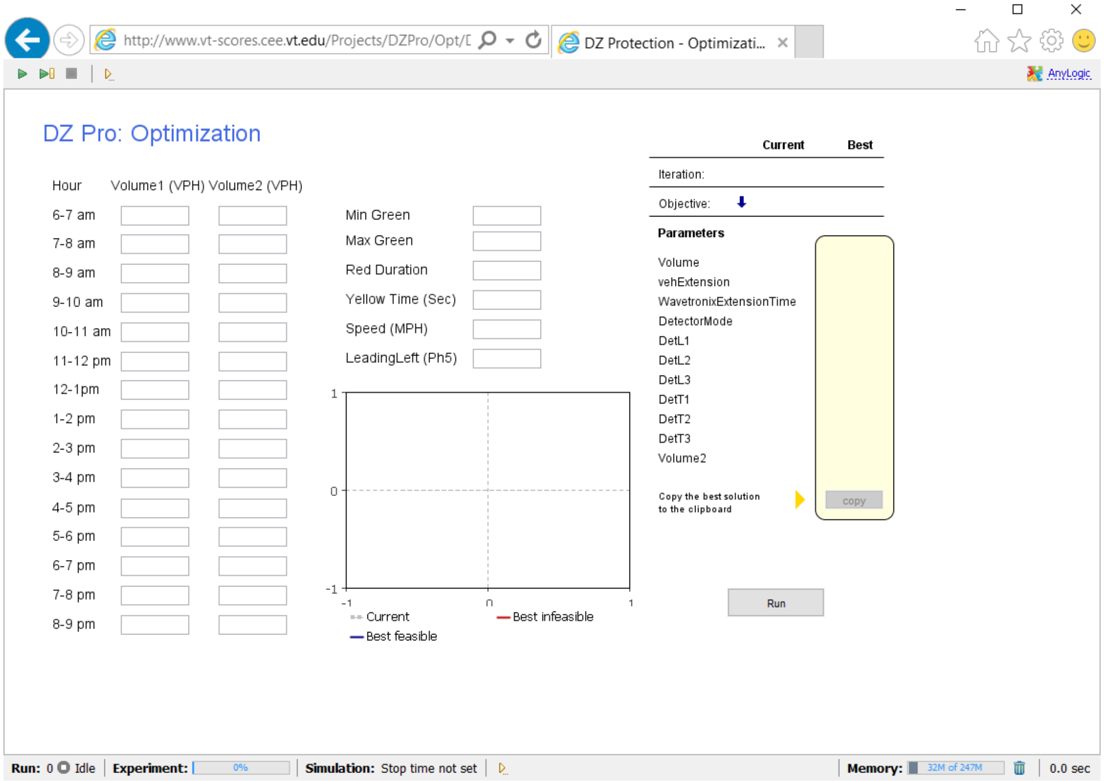


Figure 36. DZ-Pro Optimization

Enter the daily volume profile values in the corresponding text boxes (Figure 37).

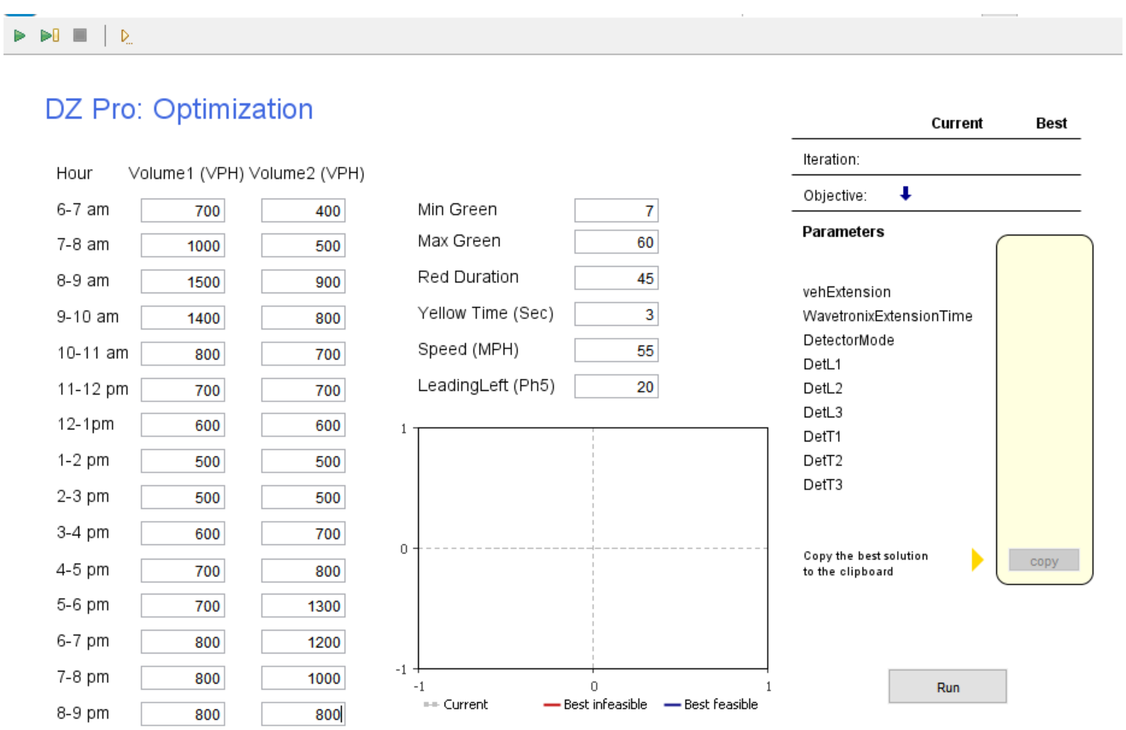


Figure 37. Entering Daily Volume Profile Values in DZ-Pro Optimization

Click the “Run” button to run the optimization. Wait until the end of the optimization experiment. The results shown in the column of “Best” are the optimal configuration (Figure 38).

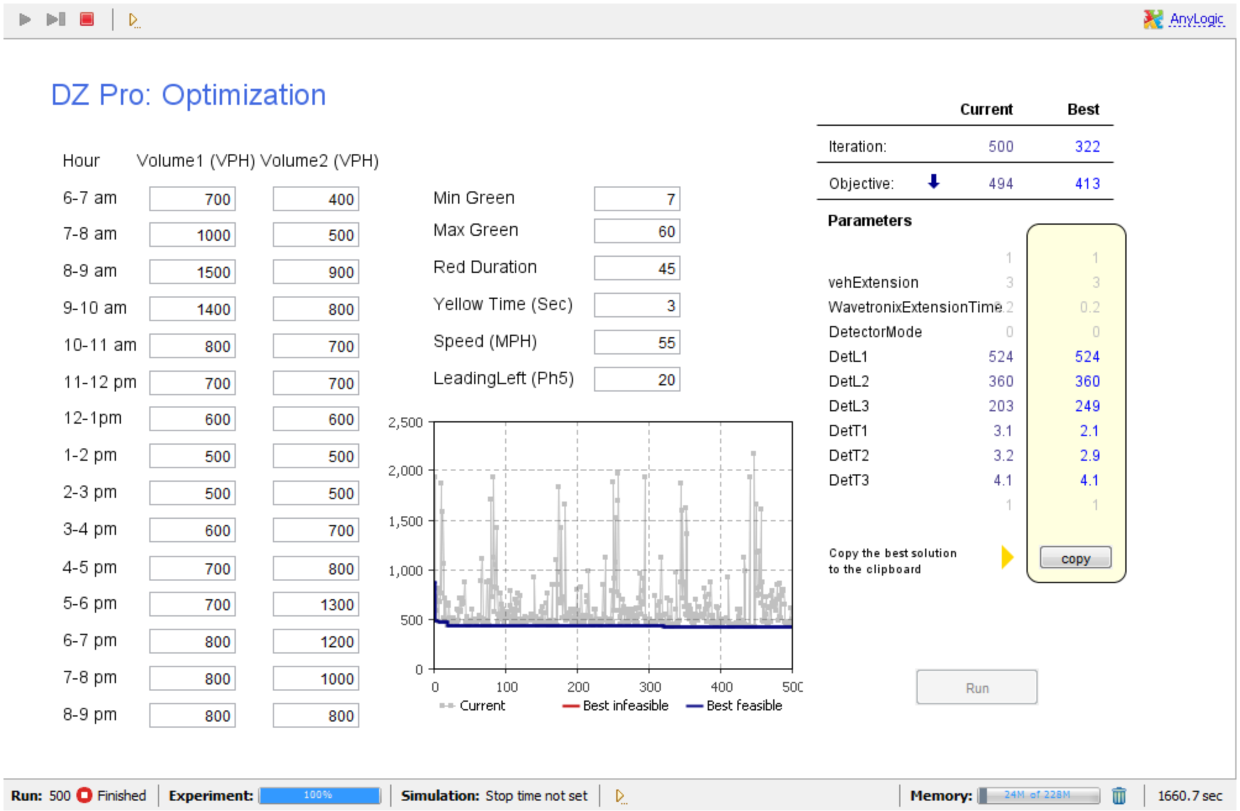


Figure 38. Results of DZ Pro Optimization

Note the resulting optimal multi-detector design (524, 360, and 249 ft for locations, and 2.1, 2.9, and 4.1 seconds for vehicle extension for each of the detectors) and the corresponding minimum number of vehicles caught in DZ (413 vehicles during the 15-hour period).

Example 2:

In example 1, what if the intersection was not a T-intersection?

Solution:
Same as example 1, except the following:

1. The red duration should be entered as the summation of phases (3 and 4), or (7 and 8), whichever is greater, plus the all-red time for phases 2 and 6.

2. The leading left should be entered as the difference between phase 1 and phase 5.

Example 3:

In example 1, what if traffic volume was collected for few hours only (e.g., peak hours only)?

Solution:
If a volume value is missing, enter zero in its place. This will speed up the simulation but will also exclude the effect of that hour from the analysis. By all means, one should try to obtain as much data as one can.

Developing Guidelines for the Use of Green Hold and Termination System

Green hold/termination systems have been implemented in some controllers. They require an advance speed trap detector in each direction and are mostly self-optimized; they track individual vehicle speeds and hold the green as long as vehicles exist in DZ. Once the DZ is empty, they terminate the green. However, green hold/termination systems assume simplified vehicle trajectories (no car-following models or interaction with signal shockwave), and their benefits are lower with higher traffic volumes. In the following section, the researchers provide examples for evaluating a green hold/termination system for the same varying traffic volume profile used in the previous section and then compare its performance to the multi-detector system and the radar-based system. It should be noted that different volume profiles would lead to different results, and therefore the DZ-Pro tool should be used for evaluation purposes.

Example 4:

Using the same intersection information described in example 1, evaluate the use of a green hold/termination system (e.g., D-CS). What are the benefits and limitations of such a system?

Solution:
A green hold/termination system is "self-optimized" in the sense that it uses only an advance speed trap detector to obtain individual vehicle speeds to calculate an individual vehicle's DZ. The system monitors the DZ and ends the green only when the DZ is empty. To assess the benefits and limitation of a green hold/termination system for a given site, the DZ-Pro simulation tool should be used.

1. Navigate to the DZ Pro Simulation link at http://www.vt-scores.cee.vt.edu/Projects/DZPro/Sim/DZ%20Protection.html.

2. Enter the daily volume profile values and select the "D-CS" radio button (Figure 39).

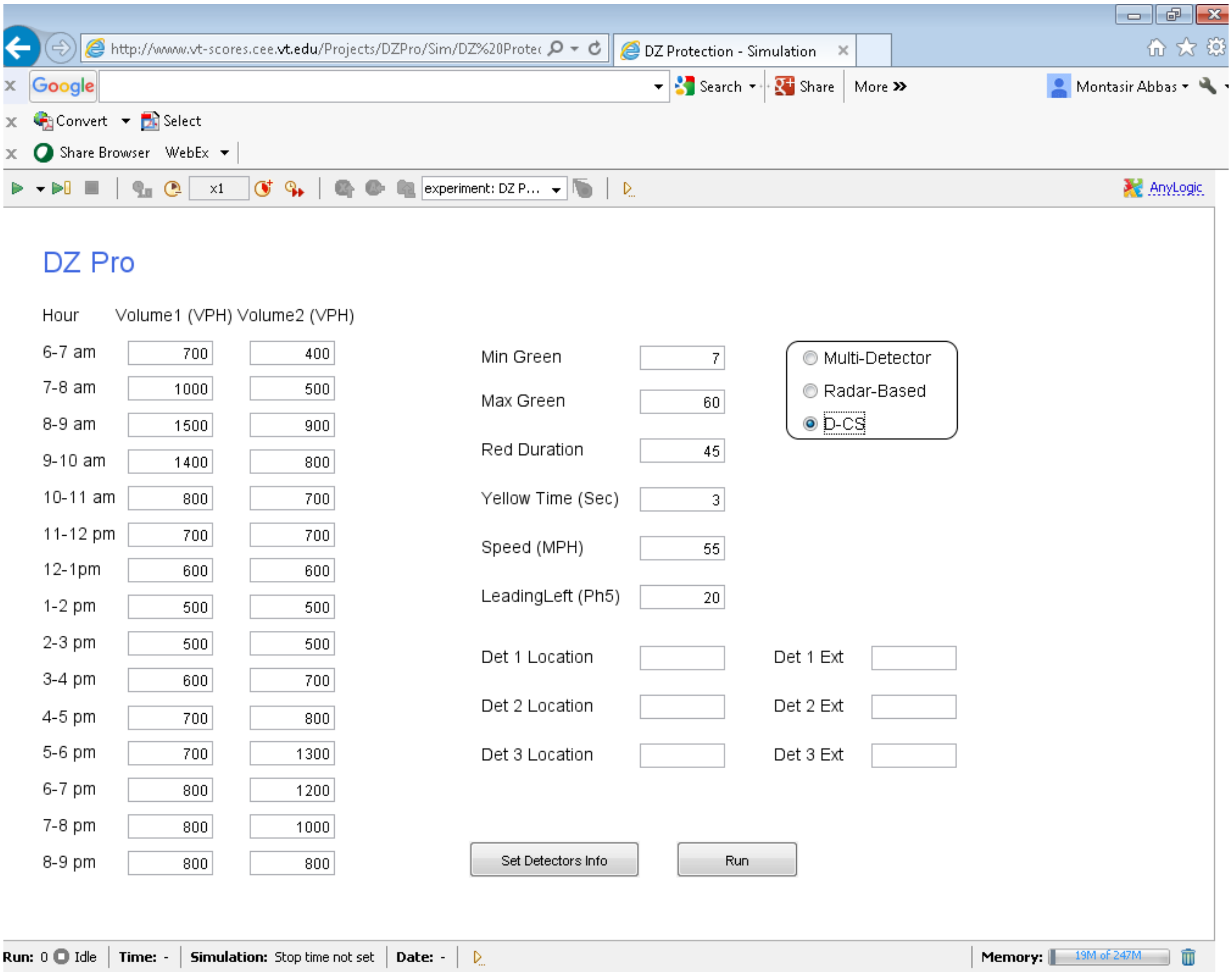


Figure 39. Entering Daily Volume Profile Values in DZ-Pro Simulation

Run the simulation and observe the animation screen if desired (Figure 40).

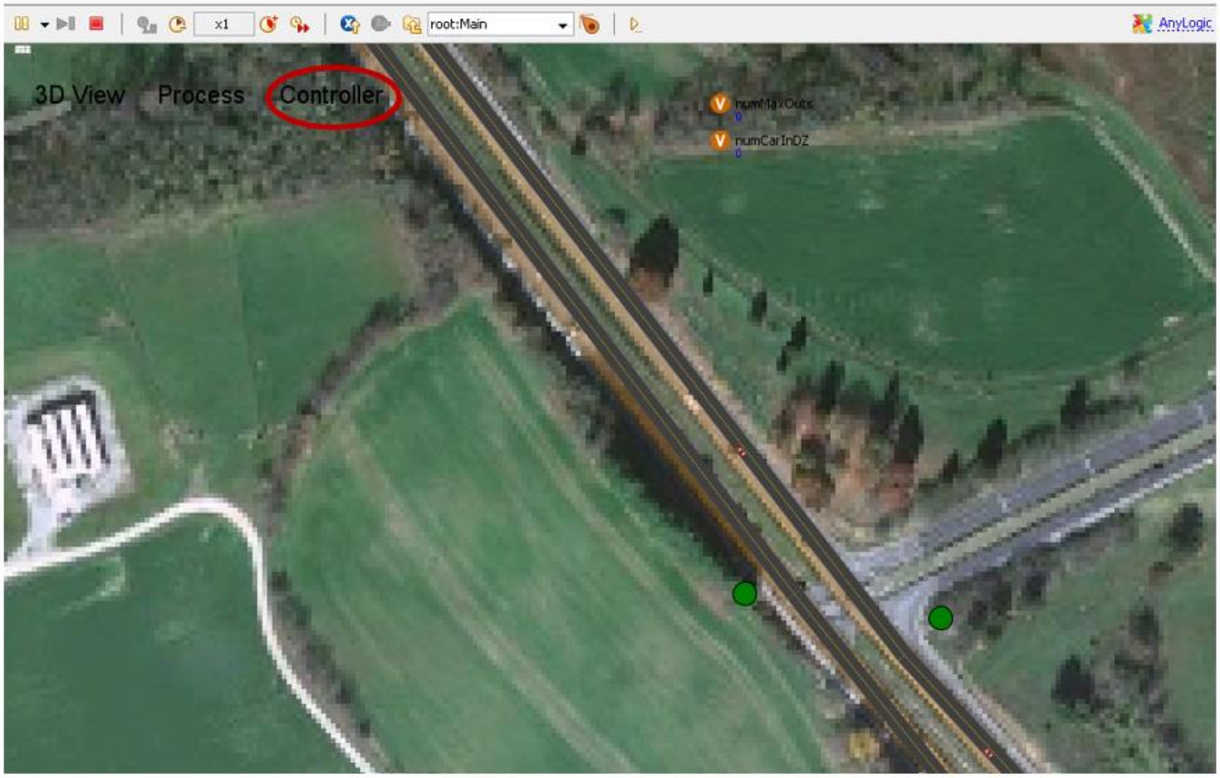


Figure 40. Animation Screen of DZ-Pro Simulation Tool

Click on "controller" to navigate to the current controller state, phase diagram, and output summary (Figure 41). Click on the button to run the simulation at maximum speed.

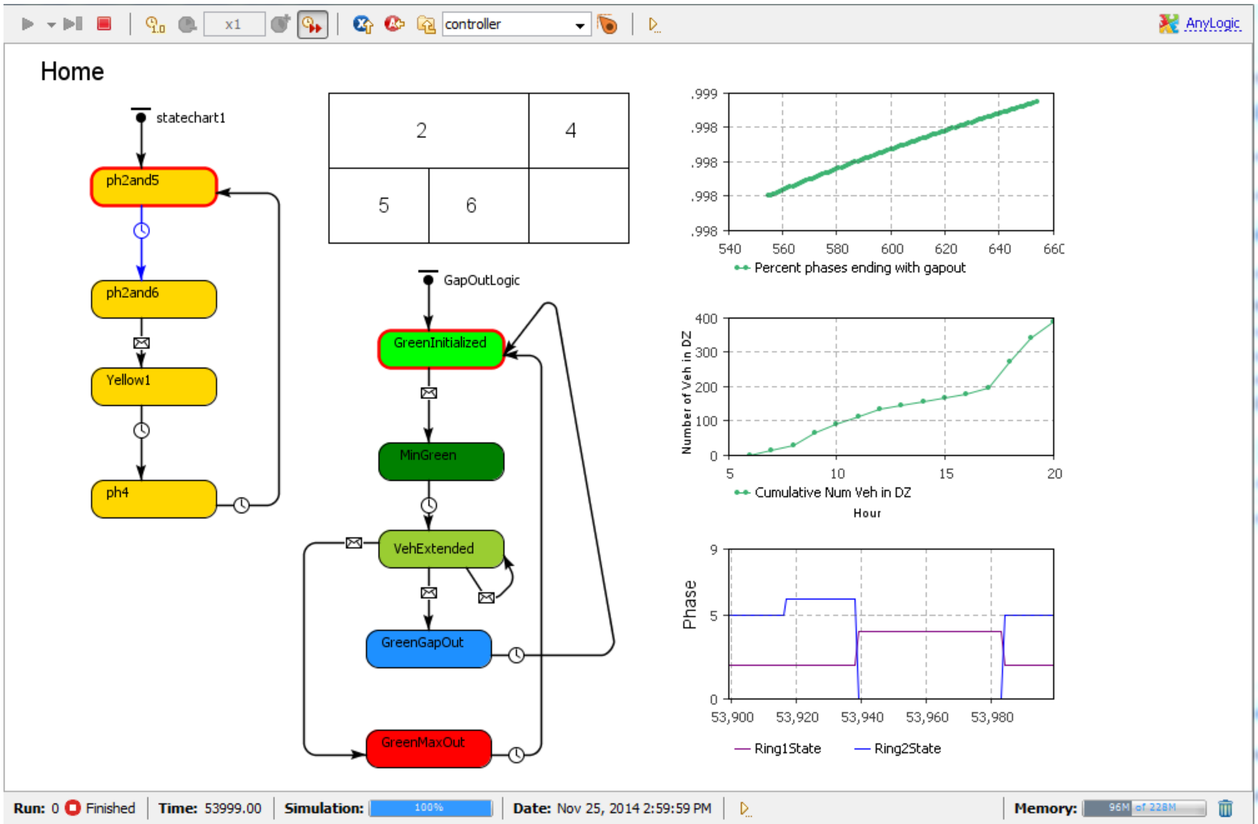


Figure 41. Controller Screen of DZ-Pro Simulation Tool

Observe the three charts on the right of the controller screen. The charts show the following measures with respect to time:

1. Percent of phases ending with a gap-out condition
2. Cumulative number of vehicles in DZ
3. The active phase number in each ring

It can be observed that a high percentage of cycles are ending in a gap-out. The chart shows a rolling horizon of the latest cycles in the simulation. Earlier cycles (during hours with higher traffic volumes) might have ended in max-out. The charts are dynamic and results can be seen during the simulation to observe the effect of traffic volume on each output.

It can also be observed that the number of vehicles caught in DZ was increasing during the day. This could be an indication that the traffic volume profile examined in this case was resulting in lower system efficiency because of vehicles changing speed as they approach the intersection.

Finally, the ring diagram shows which phase is active in each ring as the simulation progresses. This chart is meant to provide insight into the controller operation and validate the whole simulation process.

Example 5:

Using the same intersection information described in the previous example, evaluate the benefit of using multi-detector and radar-based systems in comparison to the green hold/termination system.

Solution:

1. Enter the daily volume profile values and select the "Multi-Detector" radio button.

2. Enter the detector locations and extension times, click on "Set Detectors Info," and run the simulation (Figure 42).

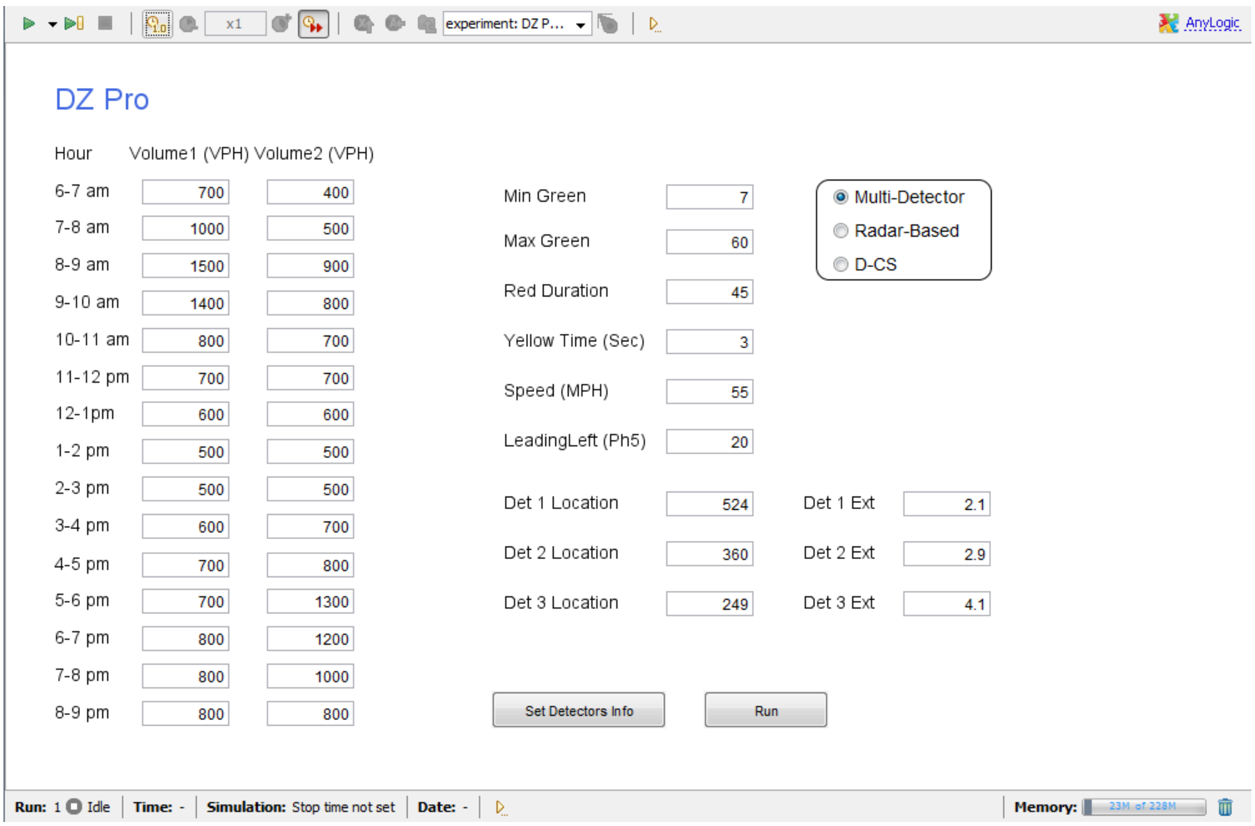


Figure 42. Entering Daily Volume Profile Values in DZ-Pro with Multi-Detector Simulation

Click on "controller" to navigate to the current controller state, phase diagram, and output summary (Figure 43). Click on the  button to run the simulation at maximum speed.

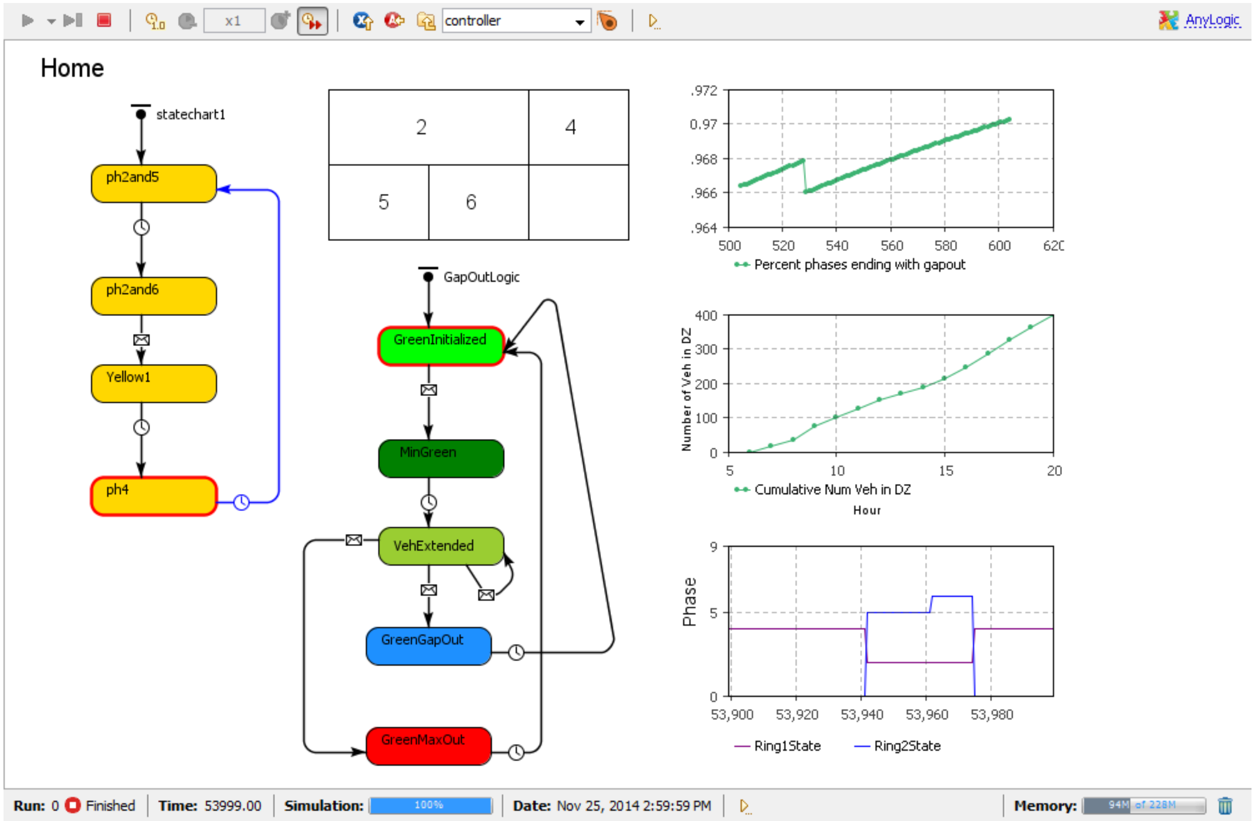


Figure 43. Controller Screen of DZ-Pro Simulation Tool with Multi-Detector Run

1. Observe the three charts on the right of the controller screen. It can be observed that the percentage of cycles ending in a gap-out and the number of vehicles caught in DZ are somewhat similar to the results obtained with the D-CS run. However, the number of vehicles caught in DZ is increasing with a slower rate during the last hours. This is due to the fact that the multi-detector design was optimized for this particular volume profile, taking into account the effect of downstream shockwaves and queues.

2. Enter the daily volume profile values, select the "Radar-Based" radio button, and run the simulation (Figure 44).

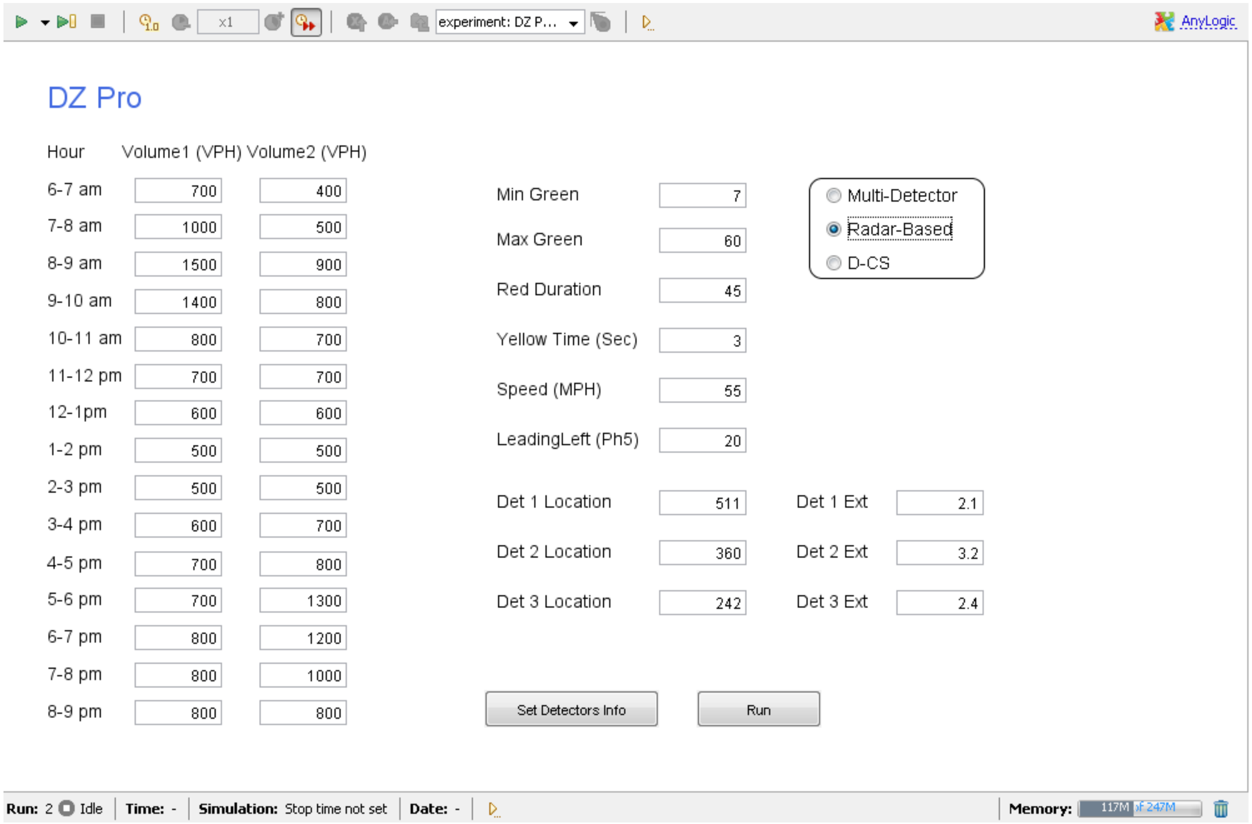


Figure 44. Entering Daily Volume Profile Values in DZ-Pro with Radar-Based Simulation

Click on controller to navigate to the current controller state and speed up the simulation. Observe the three charts on the right of the controller screen (Figure 45). Now, the number of vehicles caught in DZ is zero. In this example, the radar-based system is superior to both other systems.

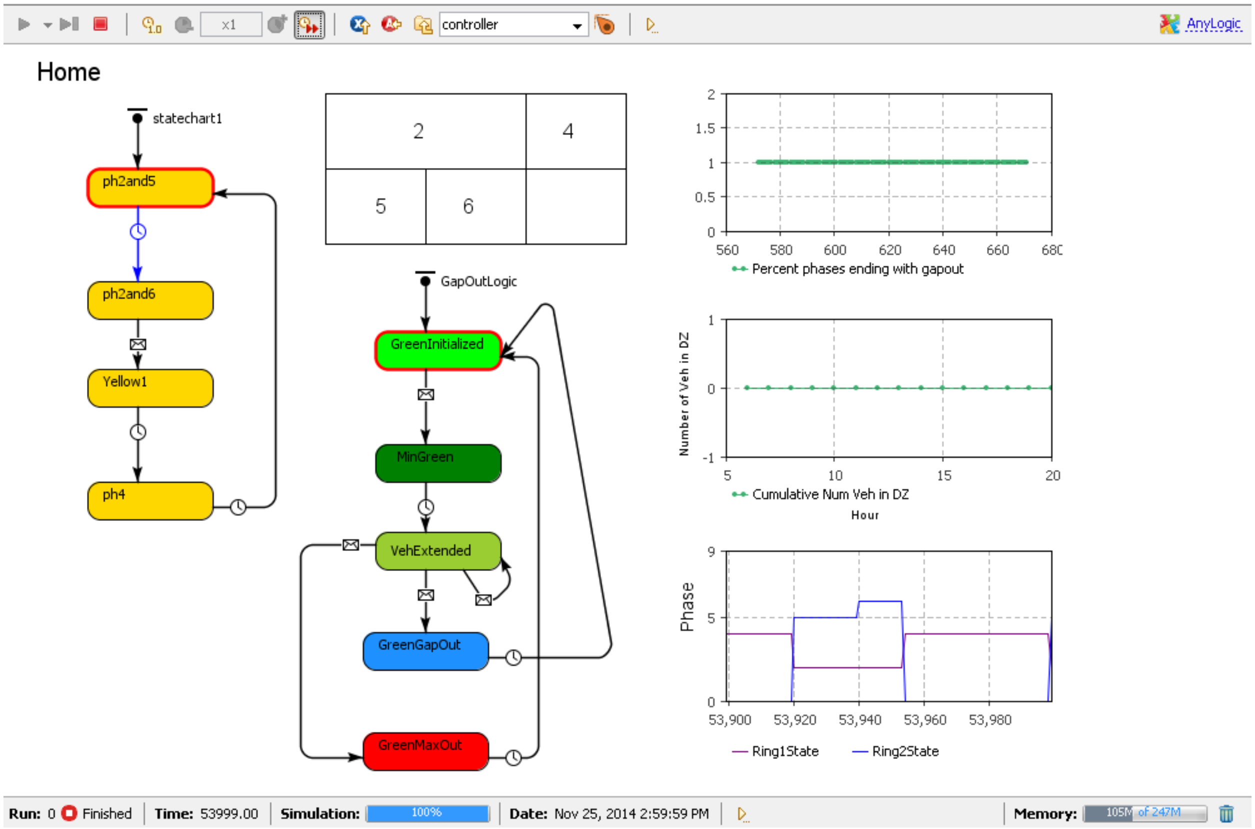


Figure 45. Controller Screen of DZ-Pro Simulation Tool with Radar-Based Run

Comparison of DZ Protection Systems

For guidelines regarding the DZ protection system type, the team ran the simulation with different volumes for the three DZ protection systems examined. The optimized detector design was used as an example for the multi-detector system (for the given volume profile shown in example 1). Figure 46 shows the results of the volume variation experiment. The radar-based system outperforms the green hold/termination system and the multi-detector system in all traffic volumes. The green hold/termination system outperforms the multi-detector system until about 1200 vehicle/hour/direction. After that, the green hold/termination system performs poorly because of its inability to take queue backup into account (Figure 47).

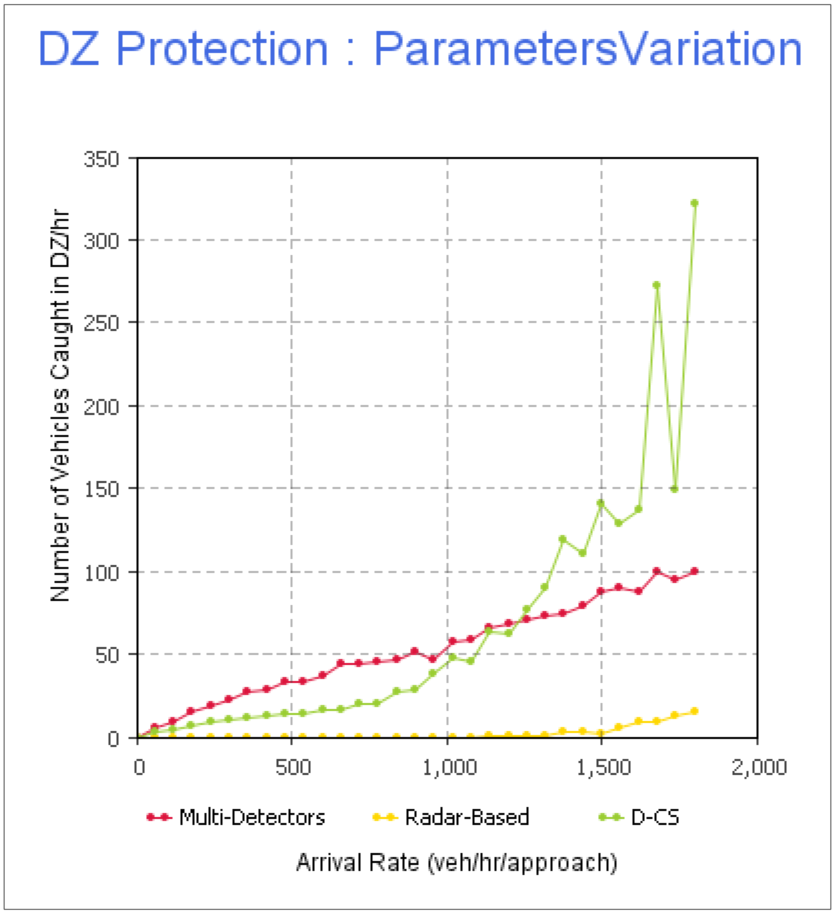


Figure 46. System Comparison with Volume Variation

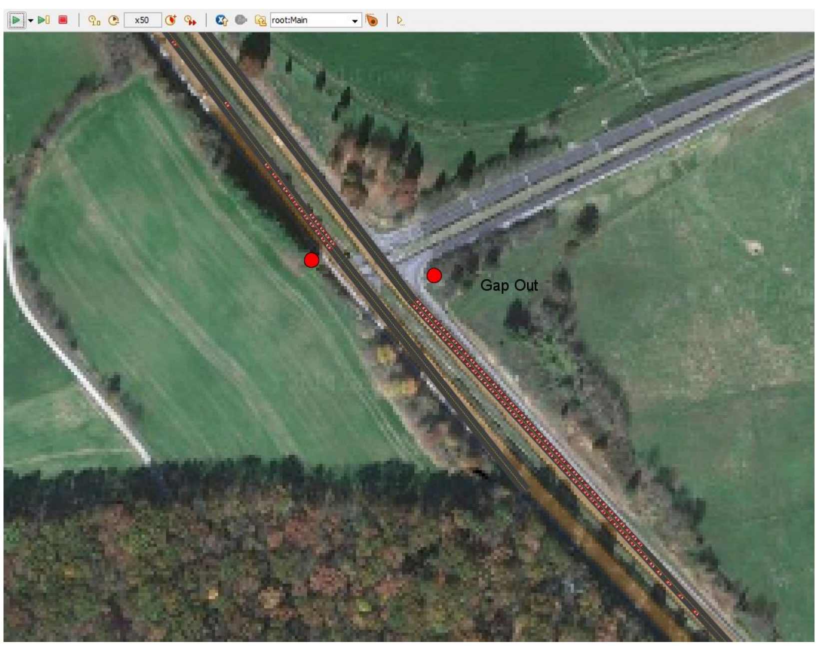


Figure 47. Queue Backup with Green Hold/Termination System with High Traffic Volume

Developing Guidelines on the Integrated Use of CABs with DZ Protection Systems

The objective of this subtask was to answer three questions: (1) what is the effect of CABs on driver behavior near the DZ, (2) how are the DZ boundaries affected by the CAB operation, and (3) what are the guidelines for the integrated use of CABs with DZ protection systems?

Effect of CABs on Driver Behavior near the DZ

As discussed earlier in this report, a driver who approaches the signal and sees the flashing beacon might decelerate to stop at the light or accelerate to "beat the light." This decision will result in a new anticipated arrival time at the intersection, and therefore a new estimated start and end of DZ for that particular driver. To answer the question of how the CABs affect the driver behavior near the DZ, vehicle trajectories from the US220 site were extracted and analyzed to study the effect of CAB activation on the change in driver behavior. The US220 site data were used in this analysis for two reasons:

1. The lower speed limit at the US220 site (compared to the US460 site) means that vehicles with large Time to Intersection (TTI) values are closer in range to the stop bar. Hence, selecting the site with a lower speed limit would ensure that a wider range of vehicles' TTI is captured within the Wavetronix radar range.

2. The Wavetronix radar coverage on the US460 site was considerably lower because of the short line of sight on the westbound approach, in addition to the higher speed limit and actual drivers' speeds near the intersection.

A response surface analysis was performed using JMP software to develop a model as shown in Figures 48 and 49. The JMP Profiler tool was then used to plot the relationship between the maximum acceleration/deceleration value and each of the input variables in the model. These models were used to gain more insight into the effect of CAB operation by changing the values of some variables (using the sliders shown on the x-axes in Figure 50) and observing the effect of that change on the predicted maximum acceleration/deceleration in vehicle trajectories as is described here.

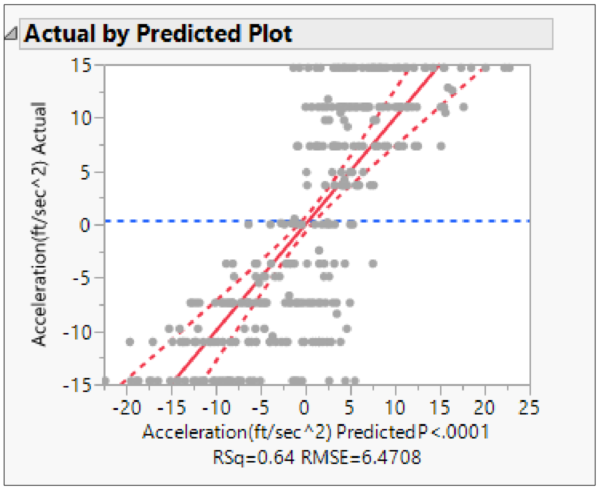


Figure 48. Predicted Driver Acceleration Model in the Presence of CABs

Summary of Fit

RSquare	0.640591
RSquare Adj	0.611185
Root Mean Square Error	6.470786
Mean of Response	0.399027
Observations (or Sum Wgts)	358

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	27	24627.479	912.129	21.7842
Error	330	13817.455	41.871	Prob > F
C. Total	357	38444.935		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.806138	3.652756	0.22	0.8255
T(sec)	-2.401908	0.452111	-5.31	<.0001*
TTI(sec)	-1.936614	0.389678	-4.97	<.0001*
Speed(mph)	-0.073384	0.070597	-1.04	0.2993
Range(ft)	0.0415912	0.006106	6.81	<.0001*
Delta_Accn(ft/sec^2)	0.8522606	0.059244	14.39	<.0001*
Hour	-0.079317	0.077866	-1.02	0.3091
(T(sec)-2.14078)*(T(sec)-2.14078)	0.0986518	0.125282	0.79	0.4316
(T(sec)-2.14078)*(TTI(sec)-2.59878)	0.1510253	0.10221	1.48	0.1405
(TTI(sec)-2.59878)*(TTI(sec)-2.59878)	0.0754328	0.021658	3.48	0.0006*
(T(sec)-2.14078)*(Speed(mph)-43.7151)	-0.048131	0.033774	-1.43	0.1551
(TTI(sec)-2.59878)*(Speed(mph)-43.7151)	0.0074258	0.017839	0.42	0.6775
(Speed(mph)-43.7151)*(Speed(mph)-43.7151)	0.0069303	0.003185	2.18	0.0303*
(T(sec)-2.14078)*(Range(ft)-295.746)	-0.003173	0.003039	-1.04	0.2973
(TTI(sec)-2.59878)*(Range(ft)-295.746)	-0.010925	0.002296	-4.76	<.0001*
(Speed(mph)-43.7151)*(Range(ft)-295.746)	-0.000826	0.000589	-1.40	0.1613
(Range(ft)-295.746)*(Range(ft)-295.746)	7.9614e-5	3.288e-5	2.42	0.0160*
(T(sec)-2.14078)*(Delta_Accn(ft/sec^2)+0.33599)	-0.120758	0.046348	-2.61	0.0096*
(TTI(sec)-2.59878)*(Delta_Accn(ft/sec^2)+0.33599)	-0.068647	0.036797	-1.87	0.0630
(Speed(mph)-43.7151)*(Delta_Accn(ft/sec^2)+0.33599)	-0.008989	0.007256	-1.24	0.2162
(Range(ft)-295.746)*(Delta_Accn(ft/sec^2)+0.33599)	-8.954e-5	0.000671	-0.13	0.8939
(Delta_Accn(ft/sec^2)+0.33599)*(Delta_Accn(ft/sec^2)+0.33599)	-0.008827	0.004332	-2.04	0.0424*
(T(sec)-2.14078)*(Hour-11.852)	-0.078552	0.0554	-1.42	0.1572
(TTI(sec)-2.59878)*(Hour-11.852)	-0.027858	0.045141	-0.62	0.5376
(Speed(mph)-43.7151)*(Hour-11.852)	0.0016138	0.010386	0.16	0.8766
(Range(ft)-295.746)*(Hour-11.852)	0.0009641	0.000899	1.07	0.2843
(Delta_Accn(ft/sec^2)+0.33599)*(Hour-11.852)	-0.007236	0.011812	-0.61	0.5405
(Hour-11.852)*(Hour-11.852)	0.0083859	0.014277	0.59	0.5573

Figure 49. JMP Response Surface Model for Predicting Driver Acceleration

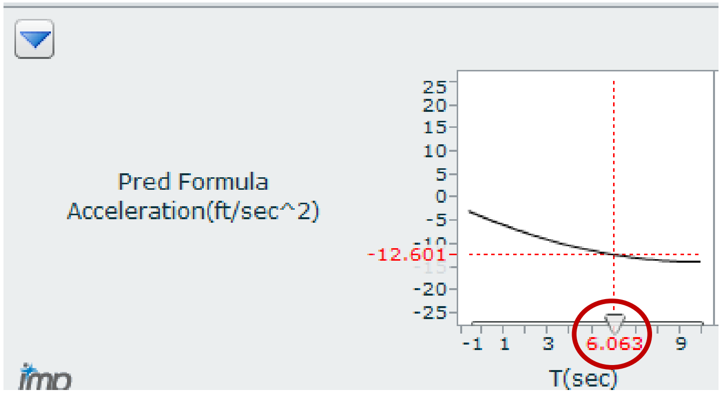


Figure 50. Using Sliders in JMP Profiler

Figure 51 illustrates the meaning of each variable used in the CAB effect analysis. T is measured from the time the vehicle had the maximum acceleration/deceleration in its trajectory to the onset of yellow. TTI is the time to intersection based on vehicle speed and distance at the onset of yellow. The overlap shown in the figure is the difference between the time the CAB started flashing and the onset of yellow.

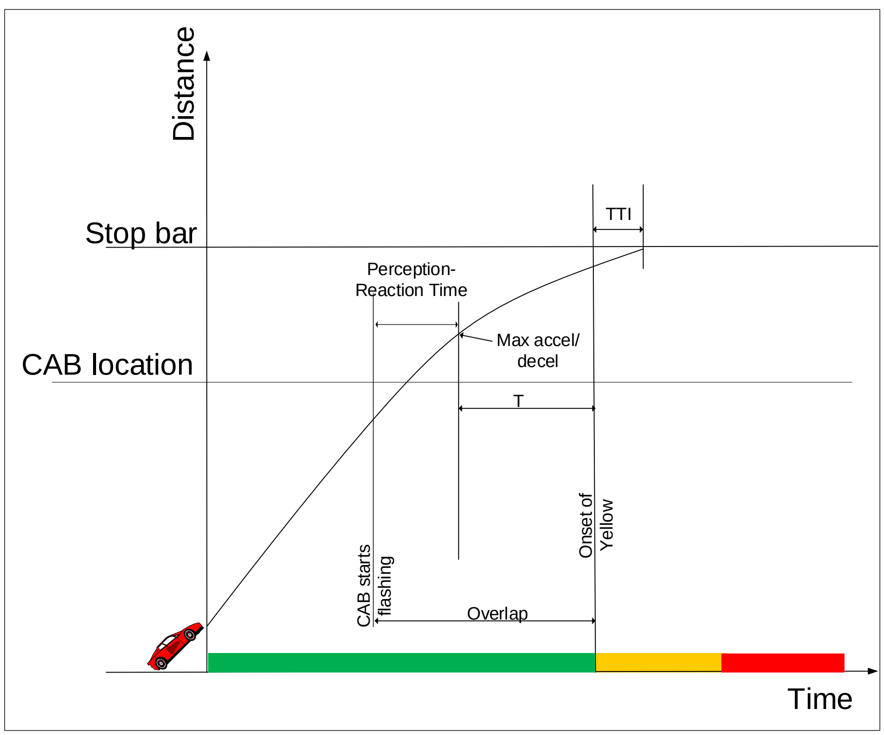


Figure 51. Illustration of Independent and Response Variables in CAB Analysis

It should be noted that:

1. Since T is the time difference between the point of maximum acceleration/deceleration in a vehicle trajectory and the onset of yellow, T values greater than the overlap time (6 seconds) would not be due to the flashing CABs. Drivers of vehicles that experience their largest acceleration/deceleration at T values

greater than the overlap time have not actually seen the flashing CABs at that moment yet (those vehicles would be driving during the green and they could be accelerating or decelerating because they are approaching a signal). In fact, T values related to the flashing CABs should be equal to the overlap time minus the driver perception-reaction time. The same rationale applies to the examined ranges (distance between vehicles and the stop bar). The expected range should be equal to the distance between the stop bar and the location where the driver sees the flashing CAB minus the distance the vehicle travels during the driver's perception-reaction time.

2. The profiler trend line for a given variable changes according to the changes in other variables. Therefore, it is important to keep other variables within a meaningful range for the examined scenario.

3. There are so many combinations of variables and so many trends that it could be almost impossible to look at all different combinations. For this reason, the team focused on looking at responses of interest (vehicle before, within, and after the boundaries of DZ at the onset of yellow) in an attempt to shed more light onto the underlying causes of these situations.

4. New boundaries of DZ may result from the presence of a flashing CAB. This is the second part of this analysis. So for the first part of the analysis, the team was aware that the traditional boundaries of 2 and 5.5 seconds from arrival to the stop bar might not apply to all sites. Therefore, more conservative ranges were used to examine the three possible outcomes mentioned in point 3.

The three examined scenarios were as follows:

1. First, by changing the TTI value to values that are before the beginning of the DZ at the onset of yellow (an 8.4-second value is shown in Figure 52), it can be observed that all T values are corresponding to a deceleration decision (acceleration trend line shows negative values for all T values less than 6 seconds). The interpretation of this is that vehicles that were not caught in DZ because they have not entered their DZ yet have decelerated as a response to the flashing CABs (since T is the time between the onset of yellow and a vehicle's largest change in acceleration/deceleration value).

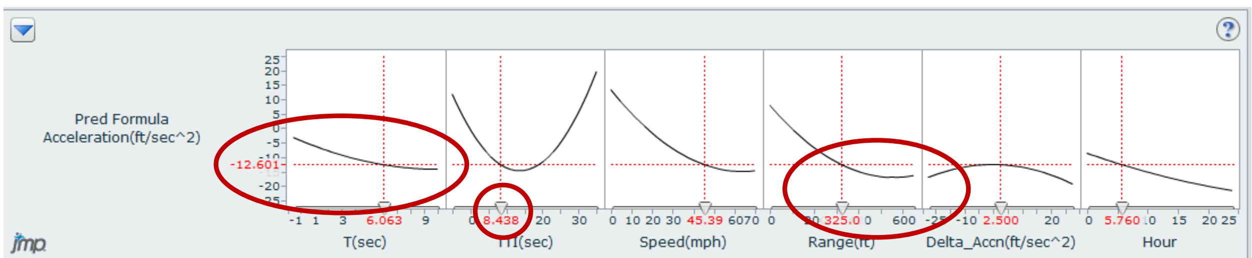


Figure 52. Using JMP Profiler to Examine Vehicles Not Yet in DZ at the Onset of Yellow

2. Second, by changing the TTI value to fall within the DZ at the onset of yellow (a 4-second value is shown in Figure 53), it can be observed that vehicles with T values

less than 2 seconds accelerated, while vehicles with higher T values decelerated. However, the figure also shows that only vehicles with ranges greater than 325 feet accelerated. Their T values suggest that their maximum acceleration occurred at 2 seconds or less from the onset of yellow as they were approaching the intersection. This means those vehicles were close to the CAB when it started flashing. This calculation is based on the following estimates: vehicles that continued travelling with the same speed for 4 seconds before accelerating traveled 264 feet on average (66 ft/sec times 4 seconds). Adding this distance to the 325 feet results in 589 feet; this is greater than but close to the 510-foot distance to the CAB location. These vehicles accelerated, but their accelerations were not high enough for them to clear their DZ. This suggests that the DZ protection system should be designed so that it does not trap vehicles near the CAB region.

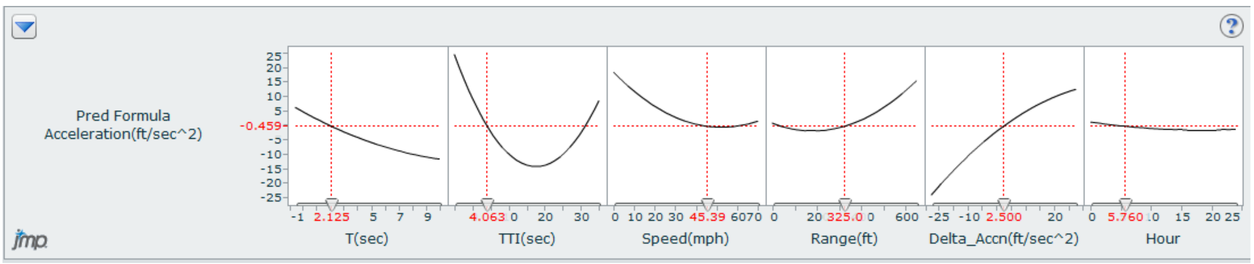


Figure 53. Using JMP Profiler to Examine Vehicles Caught in DZ at the Onset of Yellow

3. Third, by changing the TTI value to a value less than the end of DZ (about 0.9 seconds in Figure 54), it can be seen that vehicles with T values less than 4.9 seconds accelerated and cleared the DZ. The difference between this case (a safer case with vehicles clearing their DZ before the onset of yellow) and the previous case is that vehicles that accelerated did that early on. Since the driver behavior is not controllable, the recommendation that the DZ protection system should avoid trapping vehicles near the CAB region still holds.

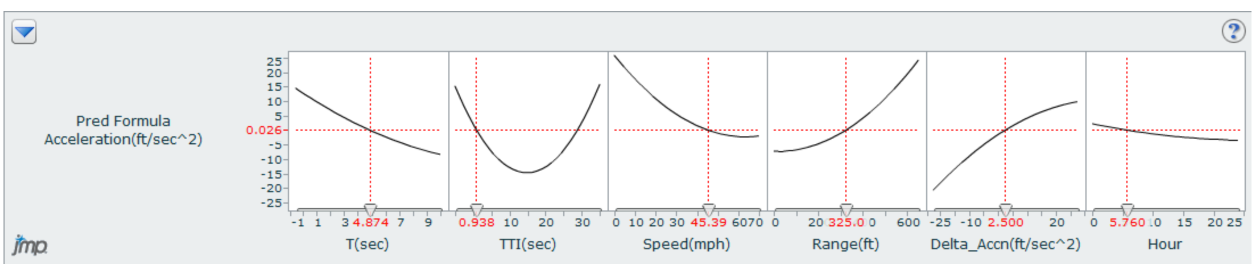


Figure 54. Using JMP Profiler to Examine Vehicles That Passed Their DZ at the Onset of Yellow

All three scenarios show that some vehicles accelerate and some decelerate in the presence of a flashing CAB. Some of these vehicles ended up not entering their DZ at the onset of yellow and some had cleared the DZ already. Moving the onset of yellow to the left or to the right within its feasible window (shown in Figure 55) might result in catching vehicles in their DZ if not done based on predicted vehicle trajectories. Therefore, the guidelines on calculating the overlap should not be modified. Rather, a recommendation is made for DZ protection developers to include a trajectory prediction feature to account for CAB operation in their systems.

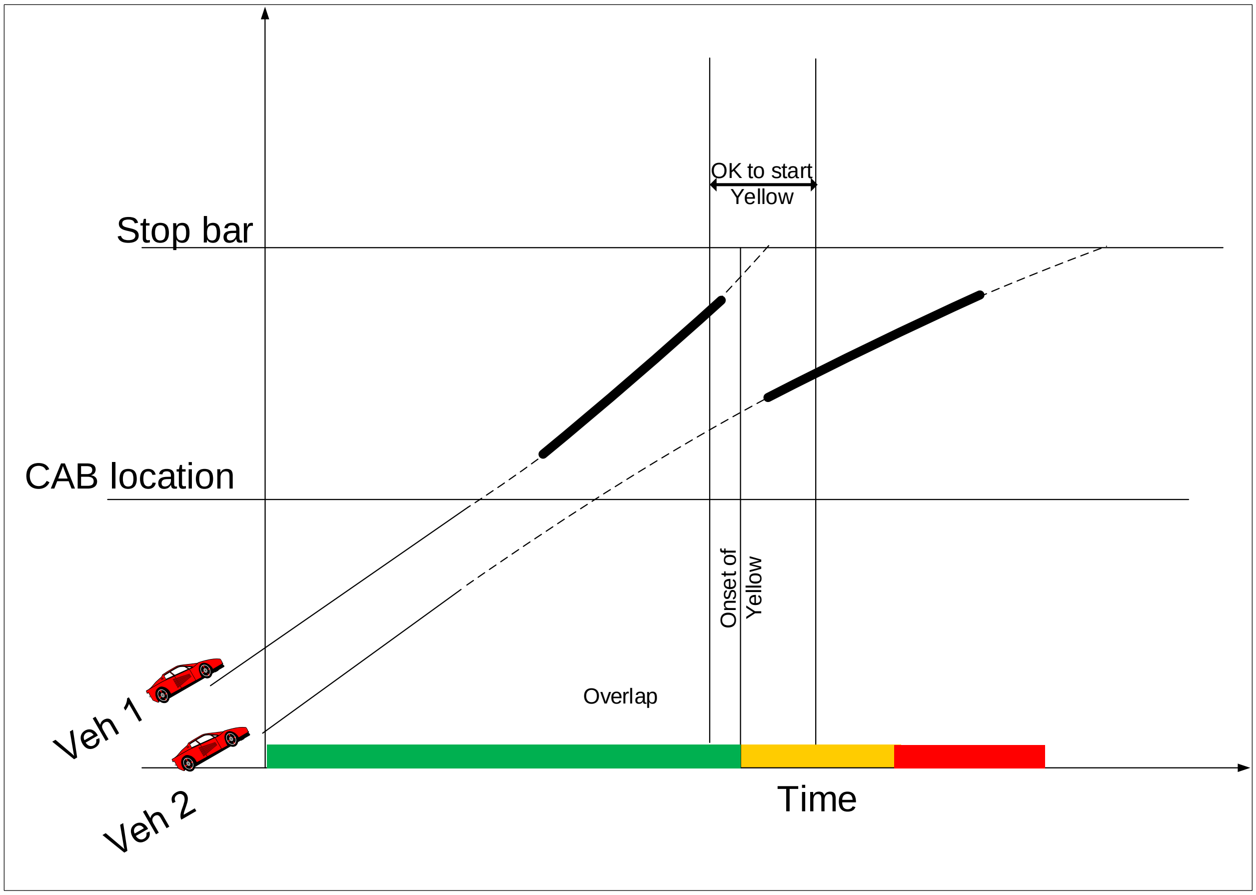


Figure 55. Conceptual Illustration of the Effect of Earlier or Later Yellow Onsets

DZ Boundaries Affected by the CAB operation

The preceding analysis does not consider the change in behavioral regime (i.e., the change in drivers' perception of DZ because they have been warned by the flashers) or the new DZ boundaries attributable to that change of perception. In order to determine whether the DZ boundaries changed because of the CAB operation, research was conducted to determine the TTI values corresponding to the 90th and 10th percentiles of the distribution of percent vehicles stopping versus vehicles' TTI values at the onset of yellow. Vehicle trajectories were extracted and categorized based on their TTI values. Next, for each TTI value, the percent of vehicles stopping was calculated. A set of all TTI values and their corresponding percent of vehicles stopping were plotted for each site, as shown in Figures 56 and 57.

Different distributions were used to fit each plot, and the distribution with the best goodness of fit was selected in each case. Based on the plotted diagram and the fitted distribution, the 90th and 10th percentile of the stopping vehicles were extracted from the fitted lines. Corresponding TTIs for 90% and 10% of the stopping vehicles for the US220 site (Ridgeway) for different directions are shown in Table 6. As shown in the table, the 10th percentile of the stopping vehicles is 2.6 and 1.1 (mean=1.85, variance=1.12) for different directions for the Ridgeway site. The 90th percentile of the stopping vehicles was 8.9 and 7.8 (mean=8.35, variance=0.60).

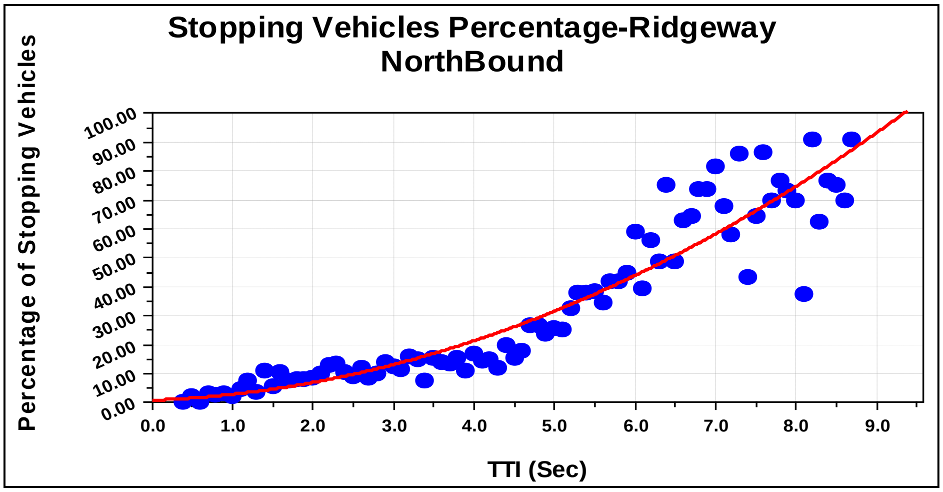


Figure 56. Percentage of Stopping Vehicles Based on Their TTI for US220 Northbound

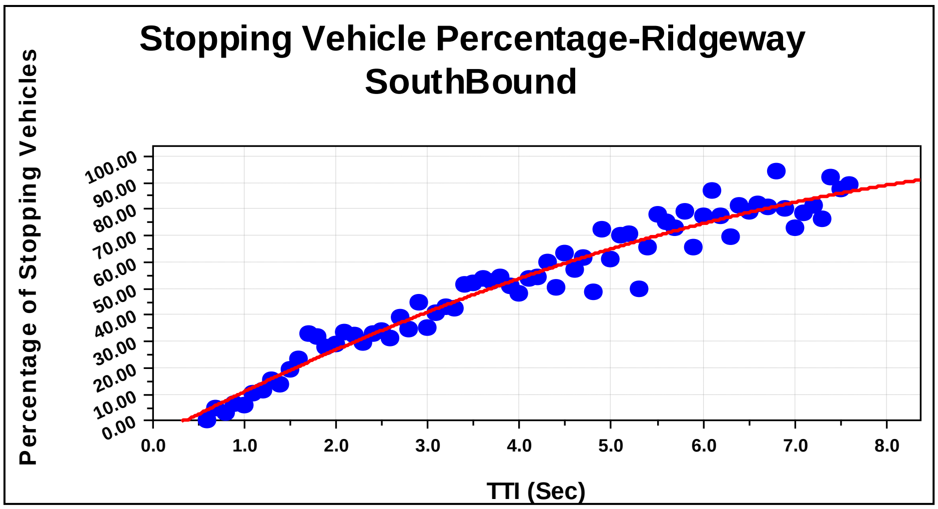


Figure 57. Percentage of Stopping Vehicles Based on Their TTI for US220 Southbound

Table 6. Corresponding TTIs for 10% and 90% of Stopping Vehicles for Each Direction, US220 (Ridgeway) Site

Direction	10% of the Stopping Vehicles	90% of the Stopping Vehicles
Northbound	2.6	8.9
Southbound	1.1	7.8

These values indicate that the beginning and end of DZ in presence of flashing CABs are different from values cited in the literature (2 sec and 5.5 sec for beginning and end of DZ, respectively). However, it should be noted that the question of whether vehicles caught in DZ after being warned by the flashing CABs are exposed to the same danger levels of those caught in DZ without the CAB warnings remains unanswered.

Guidelines

Based on the discussion and findings, the research team presents the following guidelines.

Selection of Most Appropriate DZ Protection Method

- When sight distance (line of sight) is not an issue, radar-based DZ systems outperform both green extension and multi-detector systems under all volume conditions.

- Where radar is not appropriate, multi-detector systems are more effective than green extension systems over a greater range of volumes.

- At low volumes (less than 1200 vph/direction), the D-CS system is slightly better than the multi-detector system.

Optimal Design of Existing Actuated Controller Systems

- The optimal detector spacing locations and vehicle extension parameters for multi-detector actuated control systems will vary based on the volume conditions at the site. In general, SSITE's configuration is best when volume is between 1000 and 1750 vph/direction. Bonneson's configuration is best when volume is between 1750 and 2000 vph/direction. The Sacksman design performs best when volume exceeds 2000 vph/direction.

- Given that volume can vary significantly throughout the day, an optimization tool such as the DZ-Pro tool developed in this effort is recommended for use in determining the best configuration overall.

Use of Green Hold and Termination Systems

- The green hold/termination system is effective for locations with volumes up to 1,200 vph/direction. Beyond this volume threshold, the system performs poorly because of its inability to account for queue backups.

Integrated Use of CABs and DZ Protection Systems

- In general, the use of CABs will result in a longer dilemma zone. As a result, the DZ-protection system should be designed to include this additional distance.

- When a CAB is used, it should be placed as close to the intersection as feasible to reduce the risk of trapping vehicles in the dilemma zone.

- When a CAB is used because of restricted line of sight on the approach to the intersection, radar-based DZ-protection systems should not be used.

CONCLUSIONS

- *The optimal multi-detector loop setup will vary depending on traffic volume.* Using a volume profile representative of an average day will mitigate this challenge.

- *Radar-based protection and green-termination are superior to the multi-loop system, with the radar-based system providing the most DZ protection.* This is attributed to the capability of the radar-based system to monitor vehicle speeds continuously and act accordingly, whereas the green hold/termination system assumes constant vehicle speeds.

- *Red light violations were reduced by up to 80% by implementing radar-based DZ protection systems at the test sites.*

- *An optimization tool (DZ-Pro) was developed in this study.* The tool was instrumental in this study and should be used to design optimal multi-detector systems.

- *DZ-Pro can be used to simulate any of the three DZ protection systems evaluated in this study to estimate the number of vehicles caught in the DZ if a system was used with a given daily volume profile.* This should help VDOT engineers evaluate different systems.

- *VDOT Memo TE348 results in a 2-second valid window for presenting the onset of yellow*. Moving the onset of yellow to the left or to the right within its feasible window (shown in Figure 55) might result in catching vehicles in their DZ if not done based on predicted vehicle trajectories.

- *The state-of-the-practice metric for evaluating DZ protection systems is the number of vehicles caught in the DZ.* This metric does not take into account the interaction between vehicles inside the DZ (e.g., one vehicle in a DZ might not be as dangerous as two vehicles in a DZ). The research team developed a new metric (safety surrogate histograms) to address this limitation. This new metric is better used with real-time data to improve safety at problematic sites. It can also be used off-line to prioritize intersections for safety improvement projects.

RECOMMENDATIONS

1. *The Virginia Transportation Research Council (VTRC) in partnership with VDOT's Traffic Engineering Division (TED) should sponsor a 1-day workshop on the use of simulation-optimization tools, such as DZ-Pro, to configure detector and control parameters.* The workshop will be scheduled once the details of the statewide central system are more clearly defined.

2. *Dependent on the outcome of the workshop in Recommendation 1, VDOT's TED should work with VTRC to make any needed modifications to the draft guidelines provided in this report. After modifications are made, VDOT's TED should evaluate the feasibility of implementing the guidelines provided in this report, especially at sites with a history of rear-end and right-angle crashes.*

BENEFITS AND IMPLEMENTATION

Benefits

Implementation of the research findings of this project would be beneficial to VDOT in several ways. The application of guidelines for addressing DZ issues at sites with high rates of RLRs and rear-end and right-angle crashes will result in the following:

1. a reduction in the number of RLR occurrences
2. a reduction in vehicle crashes at traffic signals
3. safer control of traffic signals.

Specifically, implementation of Recommendation 1 would provide VDOT staff with working knowledge of a tool to assist in the optimal configuration of detector and control parameters specifically relating to DZ protection.

Implementation of Recommendation 2 would help to provide consistency across the state in how DZ issues are addressed.

Implementation

Implementation of Recommendation 1 will center on the development and delivery of a workshop that will be presented to signal staff from the VDOT regions. Particular focus will be on signal technicians responsible for the day-to-day operations of the traffic signals. VTRC and members of the technical review panel for this study will work with the researchers to develop the workshop materials, focusing on the topics critical to identifying DZ issues at intersections and selecting and designing the optimum DZ protection system for a given site. The workshop will be offered at least one time in person and will be recorded for future viewing if appropriate. The initial workshop will be offered within 1 year of the implementation of the new statewide central signal system.

Implementation of Recommendation 2 will rely on feedback and experience from the workshop to modify the draft guidelines included in this report. After modification, VDOT's TED will work with the regions and districts to develop a plan for incorporation of the guidelines into the signal design process. Given the coming implementation of a statewide traffic signal central system, additional considerations may be necessary. As a result, implementation will be postponed until after the roll-out of that system.

ACKNOWLEDGMENTS

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