GUIDELINES ON INTEGRATED USE OF CONTROLLER ACTUATED BEACONS WITH DILEMMA ZONE PROTECTION SYSTEMS

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ABSTRACT
Several research studies have been conducted on the effectiveness of Controller Actuated Beacons (CABs) near isolated high-speed signalized intersections, indicating that CABs are generally effective in reducing accidents. However, while drivers approaching the intersection during flashing CABs might anecdotally accelerate or decelerate depending on their time/distance to the stop bar, the literature lacks guidance on quantifying this behavior and accounting for it in the use of DZ protection systems in the presence of CABs. This paper focuses on analyzing and identifying key variables that can result in a change in a vehicle trajectory as it approaches intersections with flashing CABs, and develop guidelines for the use of DZ-protection systems in these cases. The findings of this work include identifications of conditions when drivers accelerate and get trapped in DZ due to the CAB operation and provide guidance on placement of CABs and change in DZ-protection boundaries to avoid these situations.

Keywords: Controller Actuated Beacons, Dilemma Zone, High-resolution data, radar-based, signal control.
INTRODUCTION
Past research shows that approximately 45 percent of all crashes in the United States occur at intersections (1-3), with a major proportion of these crashes occurring due to dilemma zones (DZs) related behavior. This usually occurs because drivers may misjudge whether the clearance interval is enough to complete their stop-or-go decision safely (2).

On the other hand, several research studies have been conducted on the effectiveness of Controller Actuated Beacons (CABs) near isolated high-speed signalized intersections, indicating that CABs are generally effective in reducing accidents (4-6). However, while drivers approaching the intersection during flashing CABs tend to either accelerate or decelerate depending on their time/distance to the stop bar, the literature lacks guidelines on the use of DZ protection systems in a way that accounts for this driver behavior in the presence of CABs.

This paper focuses on analyzing and identifying key variables that can result in a change in a vehicle trajectory as it approaches intersections with flashing CABs, and develop guidelines for the use of DZ-protection systems in these cases.

We start by providing a definition of DZ and DZ-protection systems, followed by a brief description of the field data collection, and data analysis conducted in this work. Finally, we conclude the paper by presenting our findings and provide concluding guidelines and remarks.

OBJECTIVES
The work presented in this paper was funded as a part of a project that aims to provide general guidelines for using advanced control features to address DZ issues at high speed signalized intersections. This paper focuses on presenting guidelines on the integrated use of controller-actuated beacons (CABs) and their operational guidelines when used with DZ protection systems, taking into account the anticipated driver response due to the presence of the CABs.

BACKGROUND AND SYNTHESIS OF PAST RESEARCH
Dilemma Zone Definitions
DZ can be defined based on physical equations that determine whether a vehicle can stop before the stop bar if a maximum deceleration rate is applied, or pass through the intersection within the clearance interval using its current speed. This definition is usually referred to as type I DZ, and can be eliminated by designing the clearance interval correctly (7, 8). The other definition of DZ (type II) is based on driver perception of the clearance interval, their vehicle’s capabilities, etc. This type of DZ is usually defined based on percentage of drivers that stop at certain travel time values to the intersection (90% and 10% for beginning and end of DZ boundaries, respectively). Different researchers found different DZ boundaries based on the definition above, but it’s usually around 5.5 and 2 seconds for the beginning and end of DZ, respectively (9-13).

DZ Protection Systems
Various DZ-protection systems have been developed in the recent years, including point-detection based algorithms such as the D-CS (14-16), LHOVRA (17), and MOVA (18), the Platoon Identification Algorithm [PIA] (19), and Wavetronix systems (20). These systems work to minimize DZ-related safety measures in real time, such as the number of vehicles caught in a DZ. Other measures of safety can be used with these systems after the fact to evaluate their effectiveness. These measures include the number of yellow and red light violators, and stop-line encroachment, etc (21). Most of these real-time DZ protection systems (if not all) assume a simplified constant-speed based vehicle trajectory, and can therefore deviate from optimality if
that assumption was not true. The change in driver behavior due to the presence of CAB therefore needs to be quantified and accounted for to achieve optimal operation of DZ-protection and CABs.

**Effect of Controller Activated Beacons (CABs)**

McCoy and Pesti (22) evaluated the combination of advance detection (AD) and Advance Warning Flashers (AWF) on DZ related behavior. 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 (5) 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. (23) 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 (24) in Utah, the Advance Warning for the End of Green Signal (25) in Texas, and the Integrated Platoon Priority System (26) 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 Illustration of Integrated use of Control Algorithms and Driver Warning Systems**

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 11 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 due to 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.

The Virginia Department of Transportation (VDOT) has guidelines (TE348) indicating that (27):

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.

To gain further understanding of these guidelines, Figure 1 shows a conceptual illustration of the CAB working mechanism, showing two example vehicle trajectories with their DZ shown with thick lines. In this figure, vehicle 1 passes 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 by subtracting 5.5 seconds and 2.0 seconds from point B, respectively.

There are several details that should be noted in this regard:

**FIGURE 1 Conceptual illustration of DZ shift due to CAB.**

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.
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, and then subtracting up to 2 seconds (time to the end of DZ) as illustrated in Figure 1.

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. This is why field data analysis is needed to clarify and quantify the actual driver behavior in the study sites.

Data analysis was therefore 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- How does the presence of CAB affect the DZ protection systems? What guidelines can be provided for this purpose?

DEVELOPING GUIDELINES ON THE INTEGRATED USE OF CABS WITH DZ-PROTECTION SYSTEMS

Field Data Collection
Field data were collected at two T-intersections in Virginia, one in Ridgeway (located at US 220 and Route 87) and one in Blacksburg (located at US 460 and Southgate Drive) as shown in Error! Reference source not found. FIGURE 2 {Abbas, 2016 #73}. The speed limit for the
Ridgeway site is 45 mph, and for Southgate site is 65 mph, with a reduced speed limit of 55 mph near the intersection.

![Image](image1.jpg)

**FIGURE 2** Study sites.

The research team used the Virginia Tech Signal Control & Operations Research and Education System (VT-SCORES) Signal Control Intelligent Adaptive Module (SCIAM) system (FIGURE 3) to connect to and collect high-resolution field data and Wavetronix Radar trajectories remotely (28-31).

![Image](image2.jpg)

**FIGURE 3** Third generation VT-SCORES data collection system.
Methodology
A dataset of the 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. This data was further used to test the statistical significance of each variable with respect to. Response surface analysis was conducted to develop a model between the max acceleration and all independent variables and their interactions.

Analyzing the Effects of CABs on Driver Behavior
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 was 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 due to 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 FIGURE 4 and FIGURE 5. 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 6) and observing the effect of that change on the predicted maximum acceleration/deceleration in vehicle trajectories as will be described below.

![Actual by Predicted Plot](image)

**FIGURE 4** 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
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<td>38444.935</td>
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</table>

### 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   | <0.001* |
| TTl(sec)                      | -1.936614 | 0.389678  | -4.97   | <0.001* |
| Speed(mph)                    | -0.073384 | 0.070597  | -1.04   | 0.2993 |
| Range(ft)                     | 0.0415912 | 0.006106  | 6.81    | <0.001* |
| Delta_Accn(ft/sec^2)          | 0.8522060 | 0.059244  | 14.39   | <0.001* |
| 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)*(TTl(sec)-2.59878) | 0.1510253 | 0.10221   | 1.48    | 0.1405 |
| (TTl(sec)-2.59878)*(TTl(sec)-2.59878) | 0.0754328 | 0.021659  | 3.48    | 0.0006* |
| (T(sec)-2.14078)*(Speed(mph)-43.7151) | -0.048131 | 0.033774  | -1.43   | 0.1515 |
| (TTl(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 |
| (TTl(sec)-2.59878)*(Range(ft)-295.746) | -0.010925 | 0.002296  | -4.76   | <0.001* |
| (Speed(mph)-43.7151)*(Range(ft)-295.746) | -0.000826 | 0.000509  | -1.40   | 0.1513 |
| (Range(ft)-295.746)*(Range(ft)-295.746) | 7.9514e-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* |
| (TTl(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 | 0.00671   | -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 |
| (TTl(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 5** JMP Response Surface Model for predicting driver acceleration.
FIGURE 6 Using sliders in JMP profiler.

FIGURE 7 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 7 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 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.

Analysis and Findings
The research team classified the effect of CABs into three scenarios (shown in Figure 8). The following paragraphs explains the finding related to each scenario.

a) Examining Vehicles not yet in DZ at the onset of Yellow

b) Examining Vehicles caught in DZ at the onset of Yellow

c) Examining Vehicles that passed their DZ at the onset of Yellow

FIGURE 8 Using JMP profiler to examine vehicle trajectories.
1. First, by sliding the TTI profiler 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 8a), it can be observed that all T values for these vehicles that have not yet entered their DZ when the signal turned yellow, are negative. 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).

2. Second, by changing the TTI profiler value to fall within the DZ at the onset of yellow (a 4-second value is shown in Figure 8b), 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. Since their T values suggest that their maximum acceleration occurred at 2 seconds or less from the onset of yellow, 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 around the design 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, which 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.

3. Third, by changing the TTI value to a value less than the end of DZ (about 0.9 seconds in Figure 8c), it can be seen that vehicles with T values less than 4.9 seconds accelerated (and were able to clear the DZ given the 0.9 seconds TTI at the onset of yellow). 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 (cannot control which vehicles accelerate early and which ones accelerate later), the recommendation that the DZ protection system should avoid trapping vehicles near the CAB region still holds.

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.

**CONCLUSIONS AND FUTURE WORK**

This paper presented work that used high-resolution field data to examine the effect of installing CABs near intersections and develop guidelines on how the CAB induced driver behavior can be accounted for in DZ-protection systems. The results showed the following:

- The anecdotal observation that some drivers would decelerate and some would accelerate when the CAB is activated was found to be true. In addition, it was observed that this behavior is similar to the driver response to the onset of yellow in the absence of CABs, i.e., drivers that are far from the CAB would decelerate, and drivers that are close to the CAB when it starts flashing accelerate.

- Drivers that ended up being trapped in DZ even though they accelerated when seeing the flashers were those drivers who were physically close to the CAB when it started flashing, yet they reached their maximum acceleration about 2 seconds from the onset of yellow (i.e., they were accelerating slowly).
It is therefore recommended that:

- 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. This can happen if the CAB is placed beyond the reach/effect of DZ-protection systems (e.g., when using radar-based systems).

- Real-time DZ-protection system that base their protection range on travel time calculation should be configured to extend its range to cover the distance of the CAB to avoid trapping vehicles near the CAB. This means that the presence of the CAB slightly changes the concept of Type II DZ-protection to include the physical distance in addition to the travel time to intersection.

An extension to this research should include development of real-time DZ protection systems that explicitly account for the driver behavior profiler model presented in this paper. Future work could also look into the optimal design of the overlap time to account for the driving behavior on the vicinity of CABs.

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REFERENCES


27. VDOT, TE-348 - *Virginia Department of Transportation*. 2007, VDOT.


