# Pilot Implementation of a Dynamic All-Red Interval at Signalized Intersections in North Carolina - Phase I Evaluation

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## ABSTRACT

The Dynamic All-Red Extension (DARE) system is designed to reduce crash risk from red light runners by protecting vehicles entering the intersection on the cross street from a set of potential red light violators on the main line. The safety system intervenes in the operation of a traffic signal when it senses a vehicle is likely to violate the red indication of a main line approach by holding the signal controller timing in the all-red clearance interval before switching right of way, thus allowing the offending vehicle time to clear the intersection before the next phase receives a green indication.

North Carolina Department of Transportation has implemented DARE at nine traffic signals across the State since 2011. In this phase of the project, we used yellow light running and red light running as a measure of whether drivers adapt to the installed systems over a 12-month time period, and the frequency and duration of red extensions over a 3-year period as a measure of system operation and performance.

The results suggest there was minimal driver habituation to the system when comparing the pre-installation to 12-month post-installation compliance data results. DARE operated successfully over a 3-year period and remains in operation with minimal surveillance at the study locations. The dynamic lengthening of the all-red interval was not associated with noticeable increases in delay at the rural and isolated study locations.

## INTRODUCTION

Red light running is a serious traffic safety issue. The Insurance Institute for Highway Safety (IIHS) reports that red-light running crashes in 2014 resulted in over 700 deaths and an estimated 126,000 injuries in the United States (1). In locations where red light photo enforcement is not an option, police enforcement can be difficult, especially when violations are very rare. Red light violations rates are estimated between 6 and 29 violations per 100,000 intersection-crossing vehicles (2).

An all-red clearance interval is used to help combat crashes caused by red light running by creating a safety cushion for vehicles entering the intersection on red prior to an opposing movement receiving a green indication. However, a one-second all-red clearance interval may only capture approximately 80 percent of red light violators (3). The remaining 20 percent of red light runners will be entering the intersection when the next phase has a green indication.

Extending clearance timing by a static amount for every cycle may have negative implications, including increased delay and resulting congestion, especially during peak hours (4). In addition, drivers could potentially adapt to a static extension and undo any safety benefits. Based on these concerns, North Carolina Department of Transportation (NCDOT) decided to develop and implement a Dynamic All-Red Extension (DARE) System. Nine systems have been implemented across North Carolina since 2011.

DARE is designed to reduce crash risk from red light runners by protecting vehicles entering the intersection on the cross street from some red light violators on the main line approach. The safety system only intervenes in the operation of a traffic signal when it senses a vehicle is likely to violate the red indication of a main line approach during the red clearance timing interval of that main line approach. The result of the intervention is to hold the signal controller timing in the all-red clearance interval before switching right of way; thus, allowing the offending vehicle time to clear the intersection before the next phase receives a green indication. The all-red extension is variable depending on how late in the yellow and red clearance timing interval the offending vehicle is detected. The intent is for DARE to reduce the crash potential caused by vehicles entering the intersection during the first few seconds of red, without causing driver adaptation.

## PREVIOUS IMPLEMENTATION

The all-red extension strategy has been used in Europe for years, including the LHOVRA system in Sweden and the Speed Assessment (SA)/Speed Discrimination (SD) control strategies in the U.K. Within the U.S. multiple studies have analyzed the theoretical aspects of a dynamic all-red interval over the last decade, including simulation and design (5, 6, 7, 8, 9, 10, 11, 12), but very few installations are known to date. A literature review found two U.S. transportation organizations have implemented and studied a dynamic all-red interval.

The City of Portland, Oregon installed red extensions at eight urban intersections between 2005 and 2009 (13). Inductive loops were placed within the intersection, downstream of the stop line. An extension of the red clearance interval was provided for vehicles that cross the loops during the last half of the yellow interval or during the all-red interval. The design only allowed for two all-red timing options. The default all-red interval was 1 second. If an extension was placed, it was a flat 1.8 second extension, for a total of 2.8 seconds of all-red. A 2012 study showed a reduction in angle crashes using before and after crash data as well as simulation, although multiple other signal upgrades were implemented at the treated intersections and "it is difficult to know accurately the effect of a singular treatment like red extension on safety".

Maryland State Highway Administration (MDSHA) installed a dynamic dilemma zone system at the intersection of US-40 and Red Toad Rd in Cecil County, MD (14). The treated approaches are on US-40, a four-lane divided road with 55-mph speed limit. The treated approaches used a microwave detector system, the Wavetronix SmartSensor Advance, which has a detection range of 875 feet and is capable of providing the location and speed of approaching vehicles in 0.1 second intervals with estimated time of arrival. On US-40, the yellow interval was 5.5 seconds and the default all-red interval was 3 seconds. The all-red interval was then extended by up to an additional 2.5 seconds for vehicles meeting the pre-set thresholds during the default all-red interval. The intersection experienced 89 reported crashes prior to implementation from 2000 to 2010, 40 of which were angle crashes. The angle crashes were dramatically reduced since the system was deployed (15). MDSHA has decided to deploy the system at additional intersections experiencing a similar crash pattern.

Known U.S. installations and published research on installed sites is limited, and there is no research on how the systems may affect driver behavior when installed. This research is intended to provide insight into its installation and long term use and may be the catalyst transportation departments within the U.S. and elsewhere need to consider the dynamic all-red interval a viable and implementable safety countermeasure.

## SYSTEM DESIGN

DARE is a hybrid composed of two different sub-systems:

- Oasis/2070 controller
    - Oasis is the standard traffic signal control software used by NCDOT and is equipped with a user programmable logic processor.
    - The 2070 controller is the microcomputer hardware (CalTrans Spec.) that runs the software.
- Northstar Controls model NQ4 Speed Advisory System, using inductive loops

The NQ4 speed advisory system uses two six-foot by six-foot inductive loops spaced approximately 10 feet apart (lagging edge to leading edge) to detect the speed of approaching vehicles. The location of the loop closest to the stop bar is based on the AASHTO Green Book Stopping Sight Distance values given for "Braking Distance on Level" (16). The loops provide outputs, which feed into inputs of the NQ4 logic unit and determine if the preset speed threshold has been violated. The speed threshold varies at each treatment site based on the design speed limit. It is generally equal to 5-mph below the design speed of the treated approaches. Figure 1 provides imagery from the first installation in Ahoskie, NC.

FIGURE 1 Imagery from a treated approach on NC-11 at NC-561 in Ahoskie, NC. The NQ4 system is housed in a separate cabinet next to inductive loops upstream from the stop bar.

If the speed threshold has been violated, the NQ4 triggers an alarm output, which is hardwired to the main controller in the cabinet assembly located at the intersection. This alarm output is operational at all times, even during the green interval. The duration of the alarm output is calculated based on the loop closest to the stop bar getting a vehicle completely through the intersection at the DARE speed threshold. The stop times vary but typically are in the 4.3- to

4.7-second range, which is then rounded up to the nearest whole second due to NorthStar NQ4 output limits.

The AC isolator card provides a DC level signal to the controller, notifying the controller that a vehicle has indeed violated the speed threshold. At this point, this input is fed into the Oasis/2070 controllers' logic processor scheme that allows the controller to determine whether or not to act on the violation. The logic allows the controller to place a stop time only if the controller is currently timing the red clearance interval of the violated approach and any concurrent phase yellow clearance indications are "off." If all conditions are met, the stop order is placed while the alarm output from the NQ4 is active. Since the alarm output could have initiated during the yellow change interval, the stop order would only be placed for the remaining alarm output time while in the red clearance interval. This is the reason the system is termed "dynamic" as the amount of time the red clearance is increased can vary from one cycle to the next. If back to back vehicles violate during the same red clearance interval, the alarm time is reset with each subsequent violation.

The system has two failsafe components built into its operation. First, the controller monitors for a "stuck alarm output." If the alarm output from the NQ4 stops the timing in the red clearance interval for 30 seconds or more, the controller will transition into the flash mode. Secondly, there is a supervisor circuit to ensure that the system is functioning. If at least one violation is not sensed in 24-hour time period, the controller will be placed into flash mode. Entering flash mode ensures the Department is promptly aware of the malfunction rather than possibly waiting months to find the issue during a periodic maintenance review.

Figure 2 provides a simplistic example scenario of DARE on a 55-mph approach where the yellow interval is 5 seconds and the default all-red interval is 1 second. In the example scenario, a vehicle crosses the loops at 3 seconds into the yellow interval. A 5-second stop time is placed on the red interval when the vehicle crosses the loops, which means the vehicle has 2 seconds of remaining yellow, 1 second of default all-red, and 2 seconds of red extension. Therefore, the total all-red interval for this approach during this cycle is 3 seconds.

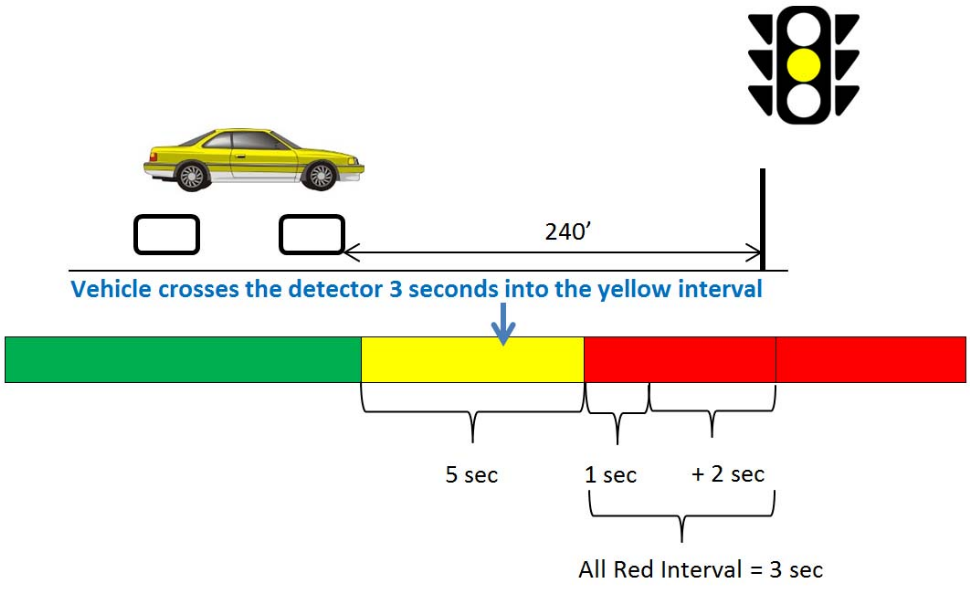


FIGURE 2 Example Scenario

## PROJECT SCOPE

In this phase of the project (Phase I), we determined whether DARE can be installed and function properly in the long term and obtained measures of system performance. We also wanted to determine whether drivers adapt to the system over time and if driver behavior changes after the systems are installed. There was a chance driver behavior could change if motorists routinely ran the red light and encounter lengthened all-red intervals; however, we felt it was more likely for driver behavior to remain relatively unchanged if the red was only extended a handful of times daily in a rural environment and if most drivers did not realize the system was in place.

The measures of effectiveness (MOE) examined in this phase of the project involve changes in driver compliance, including yellow light runners and red light runners. For both measures, we were interested in the hourly frequency, the rate per entering through vehicle, and the rate per cycle. Additional MOEs are provided to analyze signal operations, including the frequency and duration of red extensions, and a possible range of unnecessary red extensions as a measure of false positives.

When enough time has passed for sufficient evaluation of crash data, we will complete Phase II of the project. In Phase II, we will study whether DARE reduces the number and severity of crashes related to red light running at the pilot intersections.

## SITE SELECTION AND INSTALLATION

The first test site in North Carolina was installed in February 2011 at the intersection of NC-11 and NC-561 in Ahoskie. The site was selected due to a long term pattern of severe injury crashes related to red light running. Multiple countermeasures were tried over the years but the crash trends had not changed. DARE was used on both approaches of NC-11, which is a 45-mph two-lane roadway with an annual average daily traffic (AADT) of 6,600 vehicles per day. The closest inductive loop is placed 240 feet prior to the stop bar. The signal is two-phase with a yellow interval of 5.2 seconds and a default all-red interval of 3.0 seconds. Crashes at this intersection averaged over two red light running crashes per year on NC-11 over the prior 20-year period, including a fatal or serious injury crash every other year. No red light running crashes occurred in the three years after the 2011 changes were implemented. Other changes were made to the signal with the DARE implementation, such as double red signal indication on all signal heads, updating LED “Prepare to Stop” signs on NC 11, and red rest operation. We cannot attribute crash reductions entirely to DARE because of the other countermeasures but found the results impressive. Based on the safety improvements we observed at this location, we decided to implement DARE at additional sites.

After the initial site was implemented, eight additional sites were selected for a pilot study based on a statewide scan of signalized intersections. The list of sites was obtained based on input from NCDOT Regional and Division traffic engineers, as well as an analysis of crash data. We were specifically looking for rural, isolated signals on higher speed facilities with enough reported red light running crashes to allow for post-installation crash analysis evaluation. In the scan, we found red light running crashes at rural, isolated signalized intersections in North Carolina generally occur at a relatively low frequency. The problem is that when they do occur, they are generally high severity crashes. We selected a crash minimum of four angle crashes related to red light running on the major approaches in the prior five-year period. Some potential sites were excluded based on signal compatibility issues, as we decided to only use locations with an existing Oasis/2070 controller. These criteria narrowed down the potential site list to the eight locations listed in Table 1.

| Location Description | County | Treated Approaches | Distance to Loop (ft) | Yellow Interval (sec) | Default Red Interval (sec) | Mainline AADT (vehicles per day) | Mainline Speed Limit (mph) |
|---|---|---|---|---|---|---|---|
| 1. US 17 at US 158/SR 1416 (Northside Rd) | Pasquotank | US 17 - Both | 290 | 5.5-5.6 | 1.0-1.1 | 15,500 | 60 |
| 2. US 52 at US 52 Bus/SR 2011 (Charlie Norman Rd) | Surry | US 52 - Westbound | 240 | 5.1 | 2.0 | 14,500 | 55 |
| 3. US 17/158 at SR 1333 (W. Main St) | Pasquotank | US 17 - Both | 290 | 5.5 | 1.0 | 8,900 | 60 |
| 4. NC 24 at SR 1141/SR 1144 (Hibbs Rd) | Carteret | NC 24 - Both | 240 | 5.3 | 1.1 | 16,000 | 55 |
| 5. US 17 at NC 904 | Brunswick | US 17 - Both | 240 | 5.2-5.3 | 1.0-1.2 | 17,000 | 55 |
| 6. US 70 Bus at SR 2558 (Guy Rd) | Wake | US 70 Bus - Eastbound | 240 | 5.2 | 1.2 | 29,500 | 55 |
| 7. US 601 at NC 268 | Surry | US 601 - Both | 155 | 4.3 | 1.0 | 4,700 | 45 |
| 8. US 17 at SR 1300 (New Hope Rd) | Perquimans | US 17 - Both | 290 | 5.5 | 2.0 | 13,500 | 55 |

TABLE 1 Pilot Study Locations

The locations span across five Divisions in North Carolina and cover the coastal plain, piedmont, and mountain regions. The main line posted speed limits range from 45 mph to 60 mph. The 2011 AADT for the mainline approaches range from approximately 4,700 to 29,500 vehicles per day. The mainline cross sections vary, but a majority are four-lane divided facilities. DARE was installed at the pilot sites between January and October 2013. Both mainline approaches were treated at most sites but two sites were treated on only one mainline approach. It is important to note that no public relations announcements accompanied the installations. All sites currently remain in operation. Figure 3 provides the aerial view for the intersection of US 17 at NC 904, which is representative of the pilot study locations.

FIGURE 3 Aerial View of US 17 at NC 904 (17)

## DRIVER COMPLIANCE RATES

### *Data Collection*

The study uses observational compliance data in an attempt to measure levels of driver adaptation to the red extensions and to detect any subsequent abuse of the system. If there is not driver adaption to the system, we expect driver behavior to remain relatively unchanged while providing increased protection from red light violators. However, if motorists become aware of the red extension and change their behavior, we may see a significant and sustained increase in the number of yellow light and red light runners that could proliferate over time.

Compliance data were collected prior to installation and at the 1-month, 3-month, 6-month and 12-month marks after installation. In the before period, data were collected on two 13-hour days on each treated approach. Therefore, up to 52 hours of before period data were collected at the intersections with two treated approaches. In the after period, data were collected on two 13-hour days at the 1-month after period mark and on at least one 13-hour day for each of the remaining after period marks on each treated approach. Therefore, up to 130 hours of after period data were collected at intersections with two treated approaches. In all, we collected over 1,000 hours of data to determine how the countermeasure may affect vehicle compliance.

Compliance data were collected using cameras mounted to signal poles or other nearby fixed objects. The cameras were located as inconspicuous as possible on the roadway shoulder. The cameras were positioned to capture the signal indication and the stop bar for the approach being counted. Data were collected on weekdays with 20 percent chance of rain or less forecasted.

In North Carolina, a driver can legally enter the intersection during the yellow interval; therefore, a red light violation only occurs if a driver enters the intersection after the onset of red. For purposes of our study, a yellow light runner is defined as a vehicle that crosses the stop bar with a yellow signal indication and a red light runner is defined as a vehicle that crosses the stop bar with a red signal indication. Vehicles that creeped over the stop bar on red just prior to the green signal indication or vehicles that were decelerating and happened to stop immediately past the stop bar were not considered red light runners. We only collected data on vehicles traveling straight and completely through the intersection, and did not consider left or right turning vehicles. We observed no significant changes in driver population, speed limits, or road geometry from the before to after periods.

DARE was not operational for several weeks of the after period at two intersections. In both cases it impacted one of their post-installation time periods. Site 5, US-17 at NC-904, was not operating at the 3-month after period and Site 6, US-70 Bus at SR 2558 (Guy Rd), was not operating at the 1-year after period. Because the issues were brief, we decided to leave these sites in the compliance study and only excluded the single affected time period.

Site 8, the intersection of US-17 at SR-1300 (New Hope Rd), is excluded from the compliance study because DARE was not operational for three months, affecting the 3-month and 6-month after periods. The system was repaired shortly after the 6-month after period and has been operational since that time.

### *Results*

Compliance rates before and after DARE installation were compared using two-sided unpaired *t*-tests. Differences in compliance rates post-installation were declared significant for *p*-values less than 0.05. The results are provided as the average per site per treated approach.

Table 2 summarizes the yellow light running (YLR) results. Although it is not the most important measure of effectiveness, YLR was observed to measure potential changes in driver behavior from a very large sample. Over 6,900 YLR were observed in the study.

| Time Period | Observation Period (hours) | Number of Observations | Average YLR/Hour | Average YLR/ 1,000 veh | Average YLR/ Cycle |
|---|---|---|---|---|---|
| **Site 1** | | | | | |
| Pre-installation | 52 | 663 | 12.75 | 36.29 | 0.312 |
| 1 Month Post-installation | 52 | 608 | 11.69 | 32.91 | 0.262 |
| 3 Month Post-installation | 26 | 286 | 11.00 | 35.15 | 0.239[a] |
| 6 Months Post-installation | 26 | 264 | 10.15[a] | 27.92[a] | 0.232[a] |
| 12 Months Post-installation | 52 | 595 | 11.44 | 31.77[a] | 0.258[a] |
| **Site 2** | | | | | |
| Pre-installation | 26 | 87 | 3.35 | 17.09 | 0.058 |
| 1 Month Post-installation | 26 | 62 | 2.38 | 5.52[a] | 0.044 |
| 3 Month Post-installation | 13 | 22 | 1.69[a] | 3.74[a] | 0.032[a] |
| 6 Months Post-installation | 13 | 48 | 3.69 | 7.79[a] | 0.071 |
| 12 Months Post-installation | 13 | 49 | 3.77 | 7.82[a] | 0.069 |
| **Site 3** | | | | | |
| Pre-installation | 52 | 287 | 5.52 | 27.81 | 0.112 |
| 1 Month Post-installation | 49 | 220 | 4.49 | 22.52[a] | 0.096 |
| 3 Month Post-installation | 26 | 145 | 5.58 | 29.04 | 0.112 |
| 6 Months Post-installation | 26 | 170 | 6.54 | 31.24 | 0.132 |
| 12 Months Post-installation | 50 | 256 | 5.12 | 24.93 | 0.105 |
| **Site 4** | | | | | |
| Pre-installation | 52 | 227 | 4.37 | 8.99 | 0.103 |
| 1 Month Post-installation | 52 | 248 | 4.77 | 9.73 | 0.109 |
| 3 Month Post-installation | 26 | 144 | 5.54 | 11.34 | 0.129 |
| 6 Months Post-installation | 26 | 146 | 5.62 | 11.44 | 0.136 |
| 12 Months Post-installation | 26 | 126 | 4.85 | 11.06 | 0.112 |
| **Site 5** | | | | | |
| Pre-installation | 52 | 706 | 13.58 | 30.93 | 0.424 |
| 1 Month Post-installation | n/a | n/a | n/a | n/a | n/a |
| 3 Month Post-installation | 26 | 293 | 11.27 | 25.43 | 0.219[a] |
| 6 Months Post-installation | 26 | 327 | 12.58 | 24.83[a] | 0.270[a] |
| 12 Months Post-installation | 26 | 221 | 8.50[a] | 21.71[a] | 0.155[a] |
| **Site 6** | | | | | |
| Pre-installation | 18 | 97 | 5.39 | 5.01 | 0.217 |
| 1 Month Post-installation | 24 | 142 | 5.92 | 6.53 | 0.248 |
| 3 Month Post-installation | 12 | 76 | 6.33 | 7.11 | 0.290 |
| 6 Months Post-installation | 12 | 72 | 6.00 | 7.26 | 0.243 |
| 12 Months Post-installation | n/a | n/a | n/a | n/a | n/a |
| **Site 7** | | | | | |
| Pre-installation | 52 | 106 | 2.04 | 16.44 | 0.031 |
| 1 Month Post-installation | 52 | 90 | 1.73 | 14.35 | 0.025 |
| 3 Month Post-installation | 26 | 44 | 1.69 | 15.03 | 0.025 |
| 6 Months Post-installation | 26 | 40 | 1.54 | 15.04 | 0.024 |
| 12 Months Post-installation | 26 | 48 | 1.85 | 17.75 | 0.028 |

[a] Denotes a statistically significant (p < .05) change from pre-installation to post-installation conditions.

TABLE 2 Summary of Yellow Light Runner (YLR) Data

Comparing the before period to the 12-month after period, only one site (Site 5) experienced a statistically significant change in YLR/hour from the before to the 12-month after period. The change at this site was associated with a decrease. All statistically significant changes in YLR were associated with decreases.

The frequency of YLR varied drastically between sites. Site 7 averaged the lowest YLR/hour, ranging from 1.54 – 1.85 during the post-installation periods. Site 7 has the lowest approach speed limits (45 mph) and lowest mainline AADT (4,700). Site 1 averaged the highest YLR/hour, ranging from 10.15 – 11.69 during the post-installation period. Site 1 has the highest approach speed limits (60 mph) and a mainline AADT of 15,500.

Table 3 summarizes the red light running (RLR) results. A total of 485 RLR were observed in the study. Comparing the before period to the 12-month after period, no site experienced a statistically significant change in RLR/hour. There were some statistically significant changes associated with an increase in RLR in the earlier post-installation periods at Sites 2 and 5, which diminished by the 12-month post-installation period. Site 5 experienced a statistically significant increase in RLR/hour at the 3-month and 6 month post-installation period but data was not obtained at the 1-month post-installation period. Site 2 experienced a statistically significant increase in RLR/hour at the 1-month and 6-month post-installation periods but a decrease in RLR/hour at the 3-month post-installation period. A contributing factor to fluctuations in the compliance data from one time period to another may be due to random variations in the data that occur from one day to the next. Reviewing over 1,000 hours of data enabled us to gather a maximum one week snapshot of compliance data per intersection over a 12-month period.

The frequency of RLR varied drastically between sites. Site 7 averaged the lowest RLR/hour, ranging from 0.10 – 0.35 during the post-installation periods. Site 7 also averaged the lowest YLR/hour, as mentioned above. Site 5 averaged the highest RLR/hour, ranging from 0.69 – 1.58 during the post-installation periods. Site 5 has an approach speed limit of 55 mph and a mainline AADT of 17,000 (the second highest in the study). Variability in the compliance rates between intersections is likely created by differences in location characteristics, travel speeds, system parameters, driver demographics, and entering volumes.

| Time Period | Observation Period (hours) | Number of Observations | Average RLR/Hour | Average RLR/ 1,000 veh | Average RLR/ Cycle |
|---|---|---|---|---|---|
| **Site 1** | | | | | |
| Pre-installation | 52 | 18 | 0.35 | 0.94 | 0.008 |
| 1 Month Post-installation | 52 | 25 | 0.48 | 1.48 | 0.011 |
| 3 Month Post-installation | 26 | 8 | 0.31 | 1.01 | 0.007 |
| 6 Months Post-installation | 26 | 12 | 0.46 | 1.32 | 0.010 |
| 12 Months Post-installation | 52 | 25 | 0.48 | 1.28 | 0.011 |
| **Site 2** | | | | | |
| Pre-installation | 26 | 15 | 0.58 | 2.58 | 0.010 |
| 1 Month Post-installation | 26 | 30 | 1.15[a] | 3.02 | 0.021[a] |
| 3 Month Post-installation | 13 | 5 | 0.38 | 1.05 | 0.007 |
| 6 Months Post-installation | 13 | 16 | 1.23[a] | 2.78 | 0.023[a] |
| 12 Months Post-installation | 13 | 12 | 0.92 | 2.01 | 0.017 |
| **Site 3** | | | | | |
| Pre-installation | 52 | 11 | 0.21 | 1.00 | 0.004 |
| 1 Month Post-installation | 49 | 15 | 0.31 | 1.45 | 0.006 |
| 3 Month Post-installation | 26 | 6 | 0.23 | 0.94 | 0.004 |
| 6 Months Post-installation | 26 | 10 | 0.38 | 1.95 | 0.007 |
| 12 Months Post-installation | 50 | 15 | 0.30 | 1.64 | 0.006 |
| **Site 4** | | | | | |
| Pre-installation | 52 | 18 | 0.35 | 0.85 | 0.008 |
| 1 Month Post-installation | 52 | 19 | 0.37 | 0.73 | 0.008 |
| 3 Month Post-installation | 26 | 11 | 0.42 | 1.04 | 0.010 |
| 6 Months Post-installation | 26 | 10 | 0.38 | 1.02 | 0.009 |
| 12 Months Post-installation | 26 | 9 | 0.35 | 0.82 | 0.007 |
| **Site 5** | | | | | |
| Pre-installation | 52 | 30 | 0.58 | 1.32 | 0.017 |
| 1 Month Post-installation | n/a | n/a | n/a | n/a | n/a |
| 3 Month Post-installation | 26 | 41 | 1.58[a] | 3.64[a] | 0.030[a] |
| 6 Months Post-installation | 26 | 34 | 1.31[a] | 3.16[a] | 0.027 |
| 12 Months Post-installation | 26 | 18 | 0.69 | 1.79 | 0.012 |
| **Site 6** | | | | | |
| Pre-installation | 18 | 10 | 0.56 | 0.59 | 0.020 |
| 1 Month Post-installation | 24 | 19 | 0.79 | 1.31 | 0.028 |
| 3 Month Post-installation | 12 | 6 | 0.50 | 0.42 | 0.026 |
| 6 Months Post-installation | 12 | 8 | 0.67 | 0.98 | 0.017 |
| 12 Months Post-installation | n/a | n/a | n/a | n/a | n/a |
| **Site 7** | | | | | |
| Pre-installation | 52 | 9 | 0.17 | 1.45 | 0.003 |
| 1 Month Post-installation | 52 | 5 | 0.10 | 0.70 | 0.001 |
| 3 Month Post-installation | 26 | 9 | 0.35 | 3.32 | 0.005 |
| 6 Months Post-installation | 26 | 3 | 0.12 | 1.07 | 0.002 |
| 12 Months Post-installation | 26 | 3 | 0.12 | 1.10 | 0.002 |

[a] Denotes a statistically significant ($p < .05$) change from pre-installation to post-installation conditions.

TABLE 3 Summary of Red Light Runner (RLR) Data

Figure 4 provides details on time into red for the 374 RLR observed in the post-installation periods. A large majority of RLR entered the intersection within the first second of red, which concurs with past research (3). Eighty-two percent of RLR entered the intersection less than 1 second into red; 17 percent entered the intersection between 1 to 5 seconds into red; and less than 1 percent entered the intersection at 5 seconds or greater into red.

DARE is targeting the group of RLR entering the intersection after the default all-red interval (varies from 1 to 2 seconds on the treated approaches) and generally captures vehicles entering the intersection up to 4-5 seconds into red. The end time varies slightly based on the specific intersection approach speeds and system design. We observed 44 RLR targeted by DARE in the post-installation periods, which comprised 12 percent of the RLR sample during this time, as shown shaded in red in Figure 4. Trucks, which include buses, light single unit trucks, and large tractor/semi-trailers, were overrepresented in the RLR targeted by DARE, comprising 52 percent of the post-installation sample.

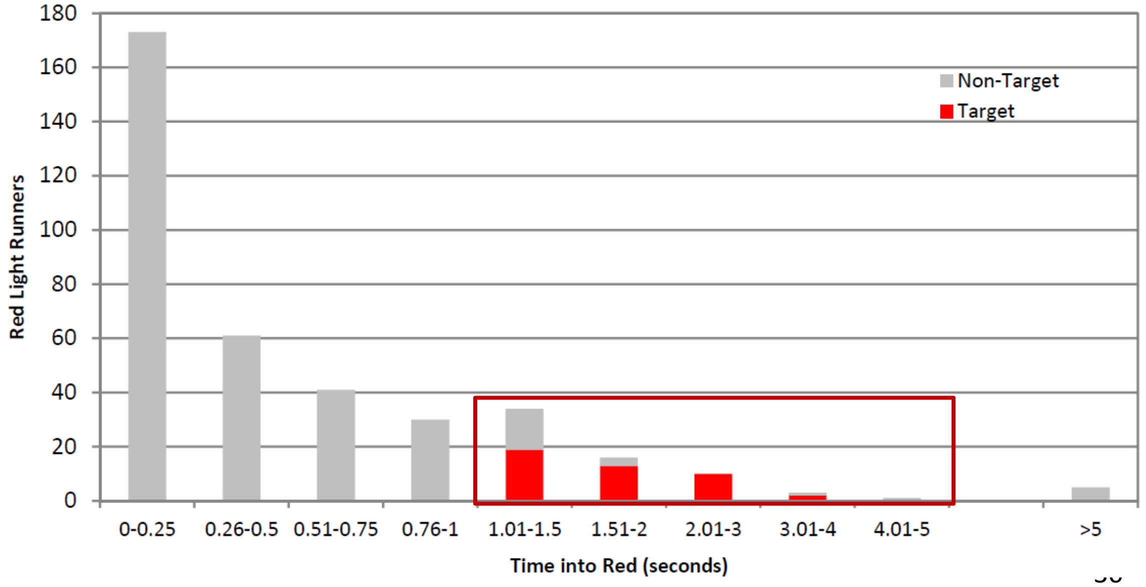


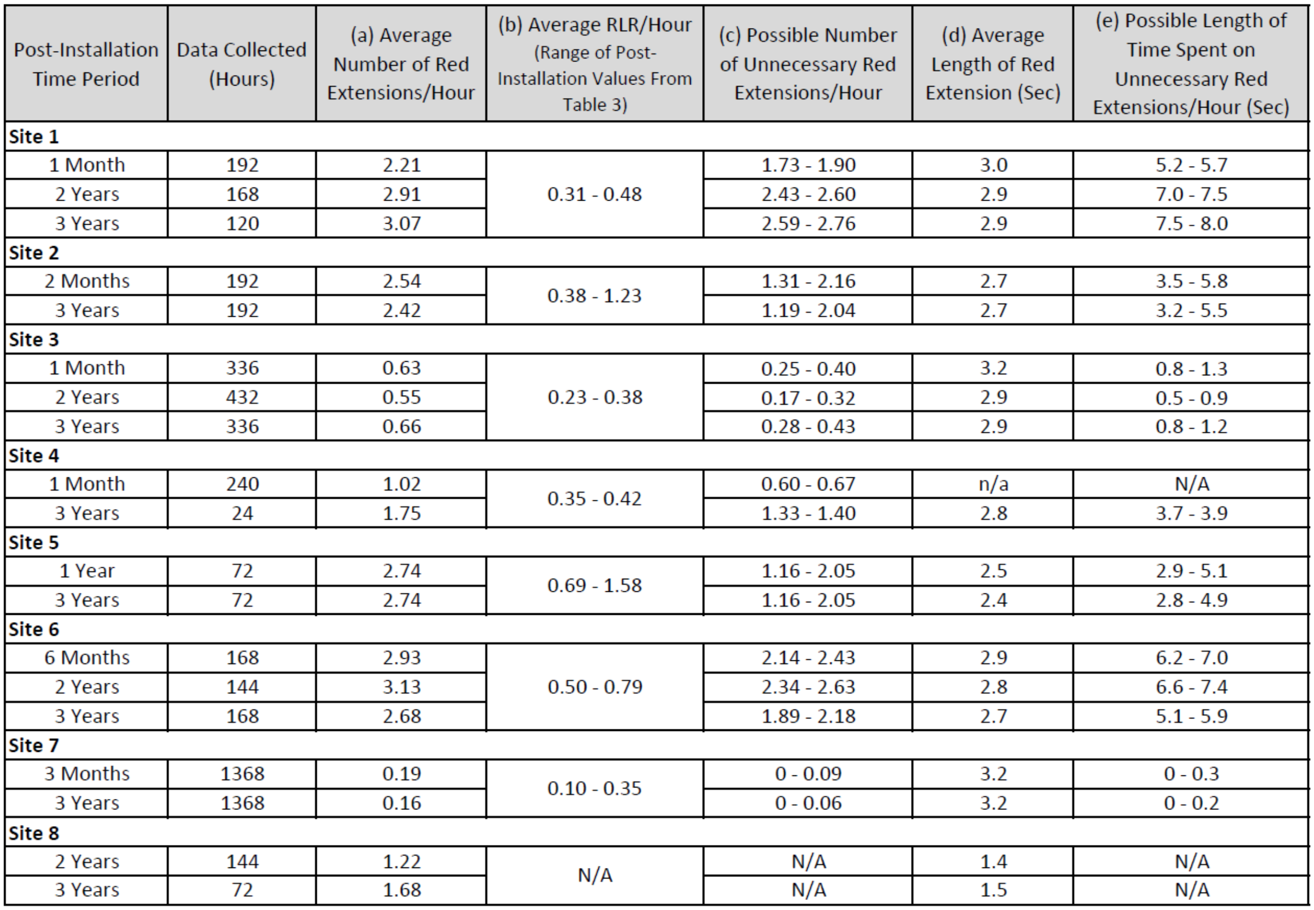
FIGURE 4 Time into Red – Post-Installation

The study involved the review of a large amount of video data. Even so, there were no crashes and too few observable vehicle conflicts to evaluate. In the after period we observed six RLR entering the intersection too late for an extension. Three were police or emergency vehicles with the lights on, one involved a vehicle stopping before proceeding through the intersection on red, and two were near miss events. In the near miss events, the vehicles entered the intersection at six seconds and nine seconds into red and a vehicle was entering the intersection from the cross street. Due to the rural, isolated conditions of the pilot sites, most observed RLR involved a single vehicle. Only 3% of post-installation RLR observations involved back-back RLR receiving red extensions.

## SYSTEM OPERATION

Signal logs were obtained by field personnel after DARE was installed to monitor the system operation over a longer duration of time, and to ensure the system could function with minimal surveillance for a 3-year period. The signal logs allowed us to track the average number of red extensions/hour and the average length of the red extension. We analyzed this information at several post-installation periods for each site. The average number of red extensions/hour differs from the average RLR/hour summarized in the compliance study because it includes all activations of DARE, even those that may cross the stop bar with a yellow signal indication or those that may have stopped (false positives).

Table 4 summarizes the following information: (a) average number of red extensions/hour, (b) average RLR/hour (range of post-installation values from Table 3), (c) possible number of unnecessary red extensions/hour, (d) average length of red extension (sec), and (e) possible length of time spent on unnecessary red extensions/hour (sec). The results are provided as the average per site per treated approach.



| Post-Installation Time Period | Data Collected (Hours) | (a) Average Number of Red Extensions/Hour | (b) Average RLR/Hour (Range of Post-Installation Values From Table 3) | (c) Possible Number of Unnecessary Red Extensions/Hour | (d) Average Length of Red Extension (Sec) | (e) Possible Length of Time Spent on Unnecessary Red Extensions/Hour (Sec) |
|---|---|---|---|---|---|---|
| **Site 1** | | | | | | |
| 1 Month | 192 | 2.21 | 0.31 - 0.48 | 1.73 - 1.90 | 3.0 | 5.2 - 5.7 |
| 2 Years | 168 | 2.91 | | 2.43 - 2.60 | 2.9 | 7.0 - 7.5 |
| 3 Years | 120 | 3.07 | | 2.59 - 2.76 | 2.9 | 7.5 - 8.0 |
| **Site 2** | | | | | | |
| 2 Months | 192 | 2.54 | 0.38 - 1.23 | 1.31 - 2.16 | 2.7 | 3.5 - 5.8 |
| 3 Years | 192 | 2.42 | | 1.19 - 2.04 | 2.7 | 3.2 - 5.5 |
| **Site 3** | | | | | | |
| 1 Month | 336 | 0.63 | 0.23 - 0.38 | 0.25 - 0.40 | 3.2 | 0.8 - 1.3 |
| 2 Years | 432 | 0.55 | | 0.17 - 0.32 | 2.9 | 0.5 - 0.9 |
| 3 Years | 336 | 0.66 | | 0.28 - 0.43 | 2.9 | 0.8 - 1.2 |
| **Site 4** | | | | | | |
| 1 Month | 240 | 1.02 | 0.35 - 0.42 | 0.60 - 0.67 | n/a | N/A |
| 3 Years | 24 | 1.75 | | 1.33 - 1.40 | 2.8 | 3.7 - 3.9 |
| **Site 5** | | | | | | |
| 1 Year | 72 | 2.74 | 0.69 - 1.58 | 1.16 - 2.05 | 2.5 | 2.9 - 5.1 |
| 3 Years | 72 | 2.74 | | 1.16 - 2.05 | 2.4 | 2.8 - 4.9 |
| **Site 6** | | | | | | |
| 6 Months | 168 | 2.93 | 0.50 - 0.79 | 2.14 - 2.43 | 2.9 | 6.2 - 7.0 |
| 2 Years | 144 | 3.13 | | 2.34 - 2.63 | 2.8 | 6.6 - 7.4 |
| 3 Years | 168 | 2.68 | | 1.89 - 2.18 | 2.7 | 5.1 - 5.9 |
| **Site 7** | | | | | | |
| 3 Months | 1368 | 0.19 | 0.10 - 0.35 | 0 - 0.09 | 3.2 | 0 - 0.3 |
| 3 Years | 1368 | 0.16 | | 0 - 0.06 | 3.2 | 0 - 0.2 |
| **Site 8** | | | | | | |
| 2 Years | 144 | 1.22 | N/A | N/A | 1.4 | N/A |
| 3 Years | 72 | 1.68 | | N/A | 1.5 | N/A |

TABLE 4 Summary of System Operation Data

A possible range of hourly false positives, (c), was calculated as (a) - (b). The possible length of time that may be spent on unnecessary red extensions per hour, (e), was then calculated as (c) x (d). These results provide insight into the possible impact of false positives on signal operations at each of the pilot sites.

Comparing the average number of red extensions/hour, (a), to the average RLR/hour, (b), there appeared to be a high proportion of false positives at the DARE sites. This was expected due to the conservative design used at the pilot sites: fixed point detection, detection placed hundreds of feet from the intersection, and speed thresholds below the posted speed limit. But when a length of time, (d), is attributed to the possible number of unnecessary red extensions/hour, (c), the results showed the additional delay created by unnecessary red extensions, (e), is likely trivial, possibly ranging from 0 – 8 seconds per hour per treated approach at the pilot sites.

## DISCUSSION AND CONCLUSION

Comparing the before period to the 12-month after period, none of the sites experienced a statistically significant change in RLR/hour. Two of seven sites experienced statistically significant changes associated with an increase in RLR in earlier post-installation periods that diminished by the 12-month post-installation period. Comparing the before period to the 12-month after period, one site experienced a statistically significant change in YLR/hour from the before to the 12-month after period, although the change was associated with a decrease in YLR. All statistically significant changes in YLR were associated with decreases. There appears to be minimal driver habituation to the system when comparing the pre-installation to 12-month post-installation compliance data results.

Because the pilot locations are rural and isolated, the dynamic lengthening of the all-red interval has not been associated with noticeable increases in delay. Due to the conservative design, the systems generally produced a high proportion of false positive red extensions but the results showed the amount of time spent on unnecessary red extensions is likely trivial, possibly ranging from 0 – 8 seconds per hour per treated approach at the pilot sites. Caution should be exercised at sites in urban areas or in a more congested environment where the system may be triggered on a much more frequent basis, as there may be more delay and a higher likelihood for driver adaptation. A less conservative design might be considered in cases where too many extensions may negatively affect signal operations.

A major finding was DARE can operate and work as designed for an extended period of time. We have monitored the study locations for multiple years after installation, and the systems are still operational. There have been some maintenance issues but they appear to be general signal maintenance issues, and not specifically related to the DARE system. We decided to implement a supervisor circuit (which looks for a minimum of one violation during a 24 hour time period) to ensure the system is functioning, especially if the location is rural and isolated. There is minimal risk with the system. If it's not working and a supervisor circuit is not in place, the signal will revert to the standard red interval.

Since there was not a statistically significant change in red light running at the final compliance study period, while providing increased protection from red light runners, we anticipate a reduction in angle crashes. The DARE system is not going to capture all crashes related to red light running, but it is providing extra protection against angle crashes caused by a specific group of mainline red light running vehicles. By annualizing the number of red light runners targeted by DARE that were observed in the after period compliance study, one could expect over 500 red light runners per treatment potentially targeted by DARE every year. DARE has great potential to improve safety at a number of signalized intersections.

As designed, DARE is a low cost solution. The cost is approximately $5,000 per approach. Costs are kept to a minimum by using inductive loops for detection and by tweaking the existing controllers. Radar detection units could also be used, but likely at a higher cost. The benefit-cost of DARE could be high if a safety improvement is realized, considering the low installation costs and the high costs associated with severe-injury red light running crashes. We plan to study crash data in Phase II of this project and hope to develop crash reduction factors associated with the countermeasure.

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