Field Evaluation of Detection-Control System

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FOREWORD

Intersections are major components of the roadway system where planned points of conflict occur between road users who need to cross paths. Over the past several years, an average of 21 percent of the fatalities and roughly 50 percent of the serious injuries on the U.S. roadway system occurred at intersections.

Strategies to address intersection safety are diverse and targeted. For isolated rural, high-speed signalized intersections, dilemma zone related angle and rear-end crashes are a major concern. The dilemma zone is defined as a length of roadway on the approach to an intersection, or a time period while driving toward the intersection, within which drivers have difficulty deciding whether to stop or to continue moving when presented with a yellow signal indication.

This report discusses one solution to the above problem called detection-control system (D-CS). D-CS is intended for use at isolated, full-actuated intersections on high-speed roadways where the major road approach has an 85th-percentile speed (or posted speed limit) of 45 mi/h or higher. D-CS requires lane-by-lane vehicle detection on major approaches, and presence detection on minor approaches. Field tests show that D-CS can effectively reduce dilemma zone induced red light running and the frequency of reaching the designated maximum green time for the major road green phase (max-out).

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Research and Development

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16. Abstract
In this research, a field evaluation of the Detection-Control System (D-CS) was conducted at eight sites located in four States. D-CS is similar to a traditional advance detector system in that it uses information from detectors located upstream of the intersection to extend the green phase. However, it differs from traditional advance detector systems because it monitors individual vehicles on the intersection approach on a lane-by-lane basis and on a vehicle length basis. It uses this information to predict the best time to end the major-road through phase. The D-CS software continuously evaluates and updates this prediction in real time. The prediction is based on the number of vehicles currently in (or predicted to soon arrive in) the dilemma zone as well as the number of conflicting phases with a call for service.

Based on the findings to date, D-CS is successful in reducing crashes in almost all cases where it has been evaluated. Crash surrogate measures of effectiveness provide corroborating evidence for this conclusion. Findings from a regression analysis for 1-h periods indicate that the after study periods experienced 82 percent fewer red-light violations, 73 percent fewer vehicles in the dilemma zone, and 51 percent fewer max-outs than the before study periods. State crash data indicate that by combining angle plus rear-end crashes (because of small sample sizes), D-CS reduced crashes by 9 percent. This result is not statistically significant at the 95-percent level. Given the supportive evidence that D-CS improves safety, other controller manufacturers might be willing to include D-CS as an option in their controllers. The Government is already considering ways to encourage signal controller manufacturers to include the D-CS algorithm in their signal controllers.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 1. INTRODUCTION AND BACKGROUND

INTRODUCTION

The objectives of this evaluation study are as follows:

- Verify the detection-control system (D-CS) design objectives through rigorous field instrumentation—at the moment of signal change from green to yellow, no truck should be in the dilemma zone, and no more than one passenger car should be in the dilemma zone.
- Quantify the effectiveness of D-CS in improving safety and reducing dilemma-zone-related crashes, and red-light violations at rural, high-speed, signalized intersections.
- Identify the upper limit of traffic conditions under which D-CS can operate safely and effectively while alternative signal timing strategies may start to fail.

Chapter 2 explains in detail how these research objectives were addressed by four individual studies.

BACKGROUND

High-speed signalized intersections present unique challenges to efforts intended to improve highway safety. Techniques for achieving safety often have an adverse effect on efficiency, and techniques for achieving efficiency sometimes have an adverse effect on safety. For example, efficient operation is achieved when the green phase ends immediately after the queue on the subject intersection approach clears. However, this operation is not always safe because the approach may not be clear at yellow onset, and a driver may be caught in the "dilemma zone." The dilemma zone is a length of roadway on a signalized intersection approach where drivers as a group demonstrate uncertainty about whether to proceed or stop at the onset of yellow. This uncertainty can lead to rear-end, left-turn opposed, or sideswipe collisions.

Traditionally, engineers have used actuated control with multiple advance detectors to provide safe phase termination at high-speed signalized intersections. Research has shown that systems with this type of advance detection can reduce crashes.(1) However, this advance detection often requires a large gap in traffic before it will allow the phase to end. During high-volume conditions, it is often not possible to find this large gap, and thus, traditional advance detection systems frequently extend the green until the maximum limit is reached (i.e., they max-out). Phase termination by max-out eliminates the desired safety benefit of the advance detection system by abruptly ending the phase, regardless of whether the dilemma zone is occupied. It also suggests that the delay to the minor traffic movements has been lengthy. As a result, the safety and operational benefits provided by traditional advance detection systems diminish as traffic volumes increase.

Bonneson et al. developed an alternative dilemma zone detection and control system for the Texas Department of Transportation (TxDOT).(2) The system overcomes the limitations of traditional multiple advance detector systems. The new system, D-CS, intelligently forecasts the best time to end the signal phase based on consideration of vehicle presence in the dilemma zone, vehicle type (i.e., truck or car), and the presence of vehicles waiting for a conflicting phase. At the time this project was getting under way, D-CS had been implemented at eight intersections in Texas and three intersections in Ontario, Canada, and was being planned for other U.S. States.

The functional objectives of D-CS are to both safely and efficiently control the high-speed approaches to an isolated intersection. Safety is measured by D-CS's ability to reduce crashes related to phase termination (e.g., rear-end crash). Efficiency is measured by D-CS's ability to minimize delay to all traffic movements. Bonneson et al. described the manner in which it achieves its functional objectives.[(2)]

The next section includes a brief description of D-CS and a status report on its implementation at Texas intersections. The last section describes the findings from a before-after evaluation of D-CS performance at several Texas intersections.

D-CS

Overview

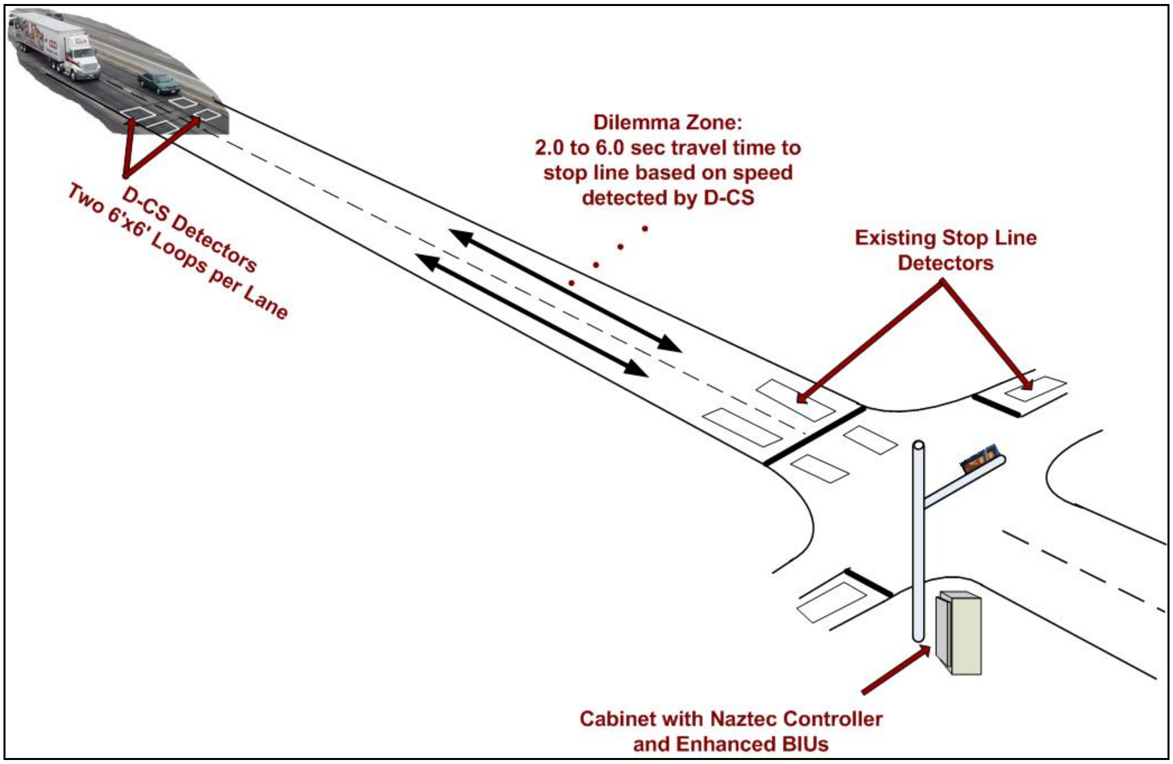
D-CS is similar to a traditional advance detector system in that it uses information from detectors located upstream of the intersection to extend the green. However, it differs from traditional advance detector systems because it monitors individual vehicles on the intersection approach on a lane-by-lane basis and on a vehicle-length basis. It then uses this information to predict the best time to end the major-road through phase. The D-CS software continuously evaluates and updates this prediction in real time. The prediction is based on the number of vehicles currently in (or predicted to soon arrive in) the dilemma zone as well as the number of conflicting phases with a call for service.

More specifically, D-CS monitors each vehicle on the intersection approach and estimates the number of cars and trucks that are in the dilemma zone at the current time and at every 0.5-s interval for a defined future time interval (typically about 3 s into the future). During a user-specified initial time period (typically about 50 s in duration), D-CS will allow phase termination only when no vehicles are in the dilemma zone. Thereafter, the program concludes that traffic flow is too heavy to find a time when the dilemma zone in every lane is clear, so D-CS seeks the least-cost interval. This cost reflects consideration of the count of vehicles in the dilemma zone for each time interval against the increasing delay that will be incurred by vehicles waiting for service on a conflicting phase. For each interval, it computes a cost of phase termination. The D-CS optimization objective during this second time period is to identify the time interval associated with the least cost. It reassesses this cost matrix every 0.5 s, and, when the least-cost time equals the current time, D-CS ends the phase. The program gives trucks an infinitely high cost so that D-CS is discouraged from ending the phase whenever a truck is in the dilemma zone.

Figure 1 shows D-CS and its relationship to the vehicle detection systems at an intersection. D-CS consists of a speed trap that is monitored by an enhanced signal controller.[1] This controller

[1]The D-CS enhanced controller is manufactured by Naztec (as part of Trafficware).

uses the detector output to compute vehicle speed and length. The controller then uses the data to determine the best time to end the phase based on the number and type of vehicles on the major road approach to the intersection, as well as the length of time minor movements have been waiting for service. When the best time to end the phase is determined, the controller ends the phase and transfers service to the next conflicting phase, as defined by the controller ring structure. D-CS uses two detectors in each major-road traffic lane in a speed trap configuration. These detectors are located 800 to 1,000 ft upstream of the intersection on both of the high-speed approaches. (Detector location is flexible in this range and can be adapted to site-specific conditions.)



Source: TTI/Dan Middleton, used with permission.

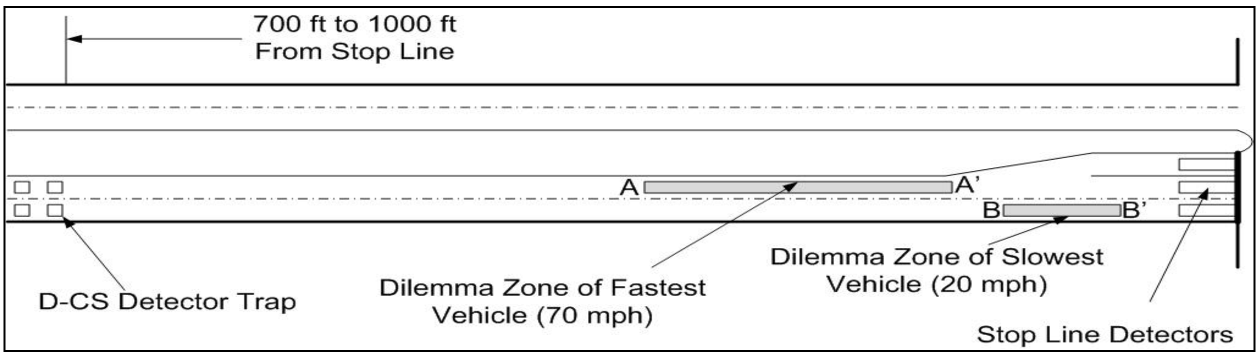
Figure 1. Illustration. D-CS components.[1]

Lane-by-Lane Detection and Vehicle-by-Vehicle Monitoring

A key feature of D-CS is that it can forecast, in real time, when each vehicle in each lane will arrive at and depart from its dilemma zone on the intersection approach. This forecast is based on the D-CS measurement of each vehicle's speed and time of passage at the upstream detector speed trap. The dilemma zone boundaries are defined in terms of travel time to the stop line (i.e., the zone is defined to begin 6-s travel time from the stop line and end 2 s from the stop line).

The real-time nature of D-CS operation allows it to dynamically accommodate changes in speed that occur at the intersection throughout the day, week, and year. Such changes in speed could be the result of legislated changes in speed limit or the result of changes in traffic density over the course of the day. D-CS performance is not compromised when traffic speeds change, as is the case for traditional advance detection systems. This limitation with traditional systems stems from the fact that their detectors are installed at precise locations that correspond to a specified design speed.

To illustrate the implications of the D-CS dynamic dilemma-zone monitoring process, consider the following example. A vehicle traveling at 70 mi/h is at point A in figure 2, and a vehicle traveling at 25 mi/h is at point B. Neither of these vehicles is in its respective dilemma zone, so D-CS could terminate the phase at this instant in time. In contrast, both vehicles are almost certainly in the zone protected by a traditional multiple advance detector system. The D-CS will correctly end the green interval at this point in time, whereas the traditional system will unnecessarily extend the green interval. This example uses an extreme speed differential to make its point; however, the concept applies to the full range of speeds. The monitoring of individual vehicles, on a lane-by-lane basis, allows D-CS to consistently end the phase sooner than the traditional system. Over time, this capability ensures that D-CS will operate with less delay and catch fewer vehicles in the dilemma zone than the traditional advance detector system.



Source: TTI/Karl Zimmerman, used with permission.

Figure 2. Illustration. D-CS detection design.[(1)]

Previous Implementation Status and Site Characteristics

Previous research by Zimmerman and Bonneson resulted in installation of D-CS at eight intersections in Texas as part of a TxDOT Implementation Project.[(1)] All implementation sites were isolated, high-speed signalized intersections of a high-volume major road and a low-volume minor road. D-CS is used to control the major-road through movements at each site. Table 1 lists the sites and their characteristics.

The U.S. 84 and Williams Road site was unsignalized prior to D-CS installation. The operational and safety benefits of D-CS could not be separated from those attributed to the addition of signalization, so this site was excluded from the before-after study. Also excluded from the safety evaluation were the two sites at which D-CS was most recently installed (U.S. 84 and F.M. 2837 and U.S. 59 and F.M. 3129). These sites were excluded because sufficient time had not elapsed by the date of the report to assess the crash history at these sites during the after period.

A before-after study for each of the five sites designated in bold in table 1 indicated that four had some type of advance detection for green extension prior to the installation of D-CS. The advance detection design varied among locations in terms of the type of detectors used (e.g., loop or video) as well as the number and location of advance detection zones. The site at Loop 340 and F.M. 3400 did not have advance detection prior to the installation of D-CS. This site was deactivated on February 27, 2004, because of nearby construction activity.(1) The intersections included in the before-after study had two through lanes on each approach and a 4- to 4.5-s yellow interval duration. The speed limit varied from 45 to 65 mi/h among the sites.

Table 1. Implementation site characteristics.(1)

Implementation Site	Nearest City	Major-Road Characteristics			Years with Signal	D-CS Installation Date
		Name	Through Lanes	Advance Detection[1]		
Loop 340/F.M. 3400	Waco	Loop 340	2	None	> 4	March 2003
U.S. 84/Williams Rd.	Bellmead	U.S. 84	4	Unsignalized	0	October 2003
U.S. 82/F.M. 3092	Gainesville	U.S. 82	4	Loop	> 6	June 2003
U.S. 82/Weber Dr.	Gainesville	U.S. 82	4	VIVDS	> 6	July 2003
U.S. 59/F.M. 819	Lufkin	U.S. 59	4	VIVDS	> 4	June 2004
U.S. 281/Borgfeld Rd.	San Antonio	U.S. 281	4	Loop	1.5	August 2004
U.S. 84/F.M. 2837	Waco	U.S. 84	4	Loop	> 3	January 2005
U.S. 59/F.M. 3129	Domino	U.S. 59	4	VIVDS	> 6	April 2005

[1]Advance detection used prior to the installation of D-CS.
Loop: multiple advance inductive loop detectors.
VIVDS (video imaging vehicle detection system): multiple advance video detection zones.
Note: **Bold** indicates sites evaluated in the before-after study.

PREVIOUS EVALUATION OF D-CS PERFORMANCE

This section summarizes the findings and offers conclusions reached from an in-service evaluation of the operational and safety performance of the D-CS. The following measures of effectiveness were used to evaluate its performance:

- Control delay.
- Stop frequency.
- Red-light violation frequency.
- Crash frequency.

The first two measures provide an indication of the operational efficiency of the system. The latter two are an indication of its effect on safety. A decrease in any (or all) of these measures would be an indication of improved conditions as a result of D-CS installation. The evaluation used a before-after study methodology.

This section consists of two subsections. The first subsection summarizes the findings from the analysis of the before-after study data. Additional details of the study design and analysis techniques are available elsewhere.(3) The second subsection lists the conclusions based on a review of the findings and experiences with D-CS.(1)

Earlier Findings

Table 2 through table 4 summarize the results of the before-after evaluations. The data in table 2 and table 3 were collected during a 4-h before study and a 4-h after study. Table 4 lists the duration of the crash data. As indicated by the data in table 2, intersection operation improved on almost every approach controlled by D-CS. The increase in delays and stops on the southbound approach of U.S. 281 and Borgfeld Road is believed to be due to the significant increase in minor movement traffic volume that was observed in the after period at this site. Overall, D-CS reduced control delay by 14 percent and stop frequency by 9 percent. These reductions are likely the result of the more efficient operation of D-CS relative to the detection and control strategy that was in operation prior to the D-CS installation.

The data in table 3 indicate that the frequency of red-light violations was reduced on all but one approach controlled by D-CS. The increase at this one location was not statistically significant and was rationalized to be a result of random variation in the data. Overall, violations dropped by 58 percent, and violations by truck drivers dropped by about 80 percent. When D-CS replaced an existing multiple advance loop detection system, violations dropped by 53 percent. When D-CS was installed at an intersection that did not previously have advance detection (i.e., Loop 340 at F.M. 3400), violations declined by about 90 percent.

Table 2. Before-after delay and stop frequency comparison.(1)

Site	Approach	Total Control Delay			Total Vehicles Stopping		
		Expected in After Period (hours)	Observed in After Period (hours)	Relative Change[1,2] (percent)	Expected in After Period (vehicles)	Observed in After Period (vehicles)	Relative Change[1,2] (percent)
Loop 340 and F.M. 3400	Northbound	2.0	1.6	-20	289	217	-25*
	Southbound	1.4	1.5	7	230	190	-17
U.S. 82 and F.M. 3092	Eastbound	6.8	6.4	-7	748	654	-13
	Westbound	7.3	6.4	-12	802	711	-11*
U.S. 82 and Weber Dr.	Eastbound	0.4	0.3	-42*	73	51	-30*
	Westbound	0.4	0.2	-44*	75	46	-38*
U.S. 59 and F.M. 819	Northbound	15.7	13.2	-16*	1,324	1,221	-8
	Southbound	14.2	11.5	-19*	1,315	1,237	-6
U.S. 281 and Borgfeld Rd.	Northbound	3.2	1.6	-49*	484	283	-42*
	Southbound	6.5	7.4	13	753	953	26*
Overall		**58.0**	**50.0**	**-14***	**6093**	**5563**	**-9***

[1]Relative change = (after/before -1) x 100.
[2]Negative values denote a reduction.
*Values are statistically significant at the 95-percent level of confidence.

The data in table 4 indicate that the frequency of crashes dropped at all of the intersections at which D-CS was installed. Overall, there was a 39-percent reduction in severe crashes on the two approaches controlled by D-CS. The data suggest that 9 severe crashes (and about 18 property-damage-only crashes) were prevented in the time that D-CS was in operation. If only those crashes that are influenced by D-CS are considered (i.e., rear-end, left-turn opposed, and sideswipe), then D-CS installation accounted for a 50-percent reduction in severe "influenced" crashes.[(1)]

Conclusions Based on Earlier Installations

The objective of the D-CS is to safely control the major-road approaches to an isolated, signalized intersection without creating excessive delay to minor movements. This objective was achieved by developing a system with the following benefits (relative to the traditional multiple advance detector system):

- Reduces the frequency of red-light violations.
- Reduces the frequency of crashes associated with the phase change (e.g., rear-end crashes).
- Reduces delay and stop frequency on the major road.
- Maintains or reduces overall intersection delay.

Table 3. Before-after red-light violation comparison.[(1)]

Site	Approach	Red-Light Violations (all vehicles)[1]			Red-Light Violations (heavy vehicles)[1]		
		Expected in After Period (vehicles)	Observed in After Period (vehicles)	Relative Change[2] (percent)	Expected in After Period (vehicles)	Observed in After Period (vehicles)	Relative Change[2] (percent)
Loop 340 and F.M. 3400	Northbound	13.5	1	-93*	4.3	0	-100
	Southbound	6.6	1	-85*	1.9	1	-46*
U.S. 82 and F.M. 3092	Eastbound	7.6	9	19	1.9	1	-46*
	Westbound	11.8	6	-49*	3.3	1	-69*
U.S. 82 and Weber Dr.	Eastbound	5.2	2	-61*	1.6	1	-37
	Westbound	4.7	2	-57*	1.3	1	-22
U.S. 59 and F.M. 819	Northbound	16.7	7	-58*	3.3	1	-69*
	Southbound	24.2	5	-79*	8.6	0	-100
U.S. 281 and Borgfeld Rd.	Northbound	38.3	19	-50*	1.9	0	-100
	Southbound	22.7	11	-52*	2.1	0	-100
Overall		**151.2**	**63**	**-58***	**30.0**	**6**	**-80***
Loop 340		**20.1**	**2**	**-90***	**6.2**	**1**	**-84***
All sites other than Loop 340		**131.2**	**61**	**-53***	**23.8**	**5**	**-79***

[1]Frequency of red-light violations during study (study duration for each approach listed in table 4).
[2]Relative change = (Obs. After/Exp. After -1) x 100. Negative values of relative change indicate a reduction in violation frequency.
*Values are statistically significant at the 95-percent level of confidence.

Table 4. Before-after severe crash frequency comparison.(1)

Site	Before Study Period		Expected Crashes in After Period	After Study Period		Relative Change[1] (percent)
	Years	Crashes		Years	Crashes	
Loop 340/F.M. 3400	3.0	10	3.8	0.83	3	-21
U.S. 82/ F.M. 3092	3.0	7	4.2	1.67	4	-6
U.S. 82/Weber Dr.	3.0	8	4.3	1.58	2	-53
U.S. 59/F.M. 819	3.0	23	5.2	0.67	3	-42
U.S. 281/Borgfeld Rd.	1.5	13	5.5	0.58	2	-64*
Overall	**13.5**	**61**	**23.0**	**5.33**	**14**	**-39***

[1]Relative change = (Obs. After/Exp. After -1) x 100. Negative values of relative change indicate a reduction in crash frequency.
*Values are statistically significant at the 95-percent level of confidence.

The first two benefits are realized by predicting the time every driver is in his or her dilemma zone and by searching for a time in the near future when the total number of drivers in their respective dilemma zones is at a minimum. This future time is defined as the “best time to end the phase.” In short, D-CS is a dynamic dilemma-zone monitoring system that identifies the dilemma zone for each vehicle in real time and prior to when the information is needed for signal control decisions. D-CS operation differs from that of a multiple advance detector system because the latter system searches for a time when a segment of each approach is clear of vehicles.(1)

The last two benefits identified in the bullet list are realized in two ways. First, they are partly achieved by the D-CS algorithm’s dynamic dilemma-zone monitoring process. This process is often able to find the “best time to end the phase” sooner than a multiple advance detector system. This capability translates into shorter phases and lower overall delay. Second, D-CS does not allow the stop-line detector to extend the phase once the queue has been served. This feature reduces wasted green time at the end of the phase and minimizes delay to waiting vehicles. These benefits are most evident at higher flow rates.

D-CS provides additional safety benefits for trucks. D-CS has the ability to measure the length of approaching vehicles and, using this information, to postpone phase termination whenever long vehicles are in the dilemma zone. Multiple advance detector systems do not provide this sensitivity.(1)

CHAPTER 2. RESEARCH METHODOLOGY

INTRODUCTION

To meet the three objectives stated in chapter 1, the Texas Transportation Institute (TTI) developed the following four studies:

- Study 1: Performance Monitoring of Dilemma Zone Occupancy (addresses objective 1).
- Study 2: Before-After Crash Data Study (addresses objective 2 in part).
- Study 3: Before-After Crash Surrogate Study (addresses remainder of objective 2).
- Study 4: Upper Limit Study (addresses objective 3).

A discussion of these four studies follows.

Study 1: Performance Monitoring of Dilemma Zone Occupancy

This study evaluates the effectiveness of the D-CS algorithm by detecting and comparing the number of vehicles trapped in the dilemma zone, the number of red light runners, and the frequency of max-outs for comparable time periods before and after activation of the D-CS algorithm. Study 1 Scope:

- The study duration was originally intended to use 1 week of before data and 1 week of after data.

- Duration was altered because of excessive time required during analysis to a determined number of hours before and after.

- The study includes existing D-CS sites.

- Data collected include the number and type of vehicles trapped in dilemma zone.

- Eight sites were needed.

Study 2: Before-After Crash Data Study

This study evaluates the safety effect of the D-CS algorithm. Study 2 scope:

- This study is based on data for a 5-year before period and a 2-year after period, depending on cooperation of the local agency and availability of data.

- Data collected include dilemma zone-related crash data.

- Study 2 includes the same eight data collection sites used for the other studies. It uses comparison sites (for which D-CS is not installed but sites are similar to the treatment sites in traffic volumes, roadway characteristics, weather, etc., and are located within the same jurisdictions as the treatment sites).

Study 3: Before-After Crash Surrogate Study

This study is aimed at supplementing Study 2 results. Study 3 scope:

- Study 3 was originally intended to use 1 week of before data and 1 week of after data.

- Because of excessive time required during analysis, duration was altered to a determined number of hours before and after.

- Study 3 collected the following data:

    - Number and type of vehicles trapped in dilemma zone.
    - Red-light violation frequencies.
    - D-CS phase max-out frequencies.

- Eight sites were needed.

Study 4: Upper Limit Study

TTI hoped to find at least one high-volume site to test the upper limit of the D-CS algorithm to determine whether there are conditions under which it does not provide additional protection compared with more traditional procedures. TTI tested variations of the Max1 setting in the controller to study its effect on D-CS performance. Study 4 scope:

- Data collected were the following:

    - D-CS phase max-out frequencies.
    - Number and type of vehicles trapped in dilemma zone.

- One site was needed.

FIELD SITE SELECTION PLAN

TTI developed a site selection plan to conduct the research to evaluate D-CS. The site selection process was limited by the fact that there were only a few sites from which to choose. In fact, it became difficult to reach the original targeted number of eight sites. Some sites that were initially considered as candidate sites were inappropriate because of one or more of the following factors:

- Lack of before crash data.
- Lack of before field data (new signal or signal not installed long enough).
- Lack of support from the operating agency.
- Atypical controller or cabinet, which made installation and/or data collection difficult.

All but two of the selected sites had National Electrical Manufacturers Association (NEMA) TS2 Type I cabinets and Naztec 2070L controllers loaded with the D-CS algorithm and D-CS user interface installed. One of the remaining sites had an Eagle TS2 cabinet, and the final site had a

TS1 cabinet. As a result of these differences, the research team made modest changes to the monitoring equipment.

Site Selection Criteria

The following list includes critical items:

- Equipment running the D-CS algorithm installed and fully operational.
- Willingness of the local transportation department to support research data collection (e.g., provide bucket truck).
- Willingness of the local transportation department to continue operation of D-CS during the 2-year after period.
- Sufficient traffic volume (including sufficient numbers of trucks).
- Traffic signal installed a minimum of 2 years prior to D-CS to ensure before data availability.
- Sites acceptable to both the Government and the research team.

The following list includes items that are desirable but non-critical:

- Newly installed or existing cabinet.
- Sufficient space in the cabinet for research equipment.
- Reasonably good sight distance and geometry on high-speed approaches.
- Properly positioned mounting hardware (e.g., poles) for cameras and Wavetronix™ Advance detectors.
- Sites located reasonably close to TTI headquarters to minimize travel costs.
- Cellular data coverage for continuous operation of wireless routers in cabinets.
- Before detection for dilemma-zone protection.
- Cameras already installed in the optimum locations for D-CS research.

Site Selection Process

Site selection involved finding jurisdictions that were already using D-CS and finding local agencies that were willing to support the research activities. TTI contacted the responsible agencies well in advance of the data collection period to determine their willingness to participate. In some cases, the agencies were using or had been using equipment installed in an earlier TxDOT research project where a personal computer (PC) was loaded with the D-CS algorithm.[2] In one case, TTI replaced a failed PC with a Naztec controller (with permission from the responsible agency). This swap was accompanied by training and other support from Naztec. Of the sites identified in this process, only one had a high volume of traffic for determining the range of D-CS effectiveness (study 4, Upper Limit Study). See chapter 4 for more information.

TTI initially contacted all responsible agencies representing the available sites identified by the Government. States that chose to participate were Florida (three sites), Louisiana (one site), Illinois (two sites), and Texas (two sites); New York and Iowa chose not to participate. TTI also initiated communications with Naztec to encourage support for the project. Having Naztec involved in the project was helpful, but some State transportation department personnel who had not used the Naztec controller were not comfortable installing it before being trained by Naztec. This training activity required more time than originally anticipated.

METHODOLOGY FOR FIELD DATA COLLECTION

The general methodology used in this research began with using the site selection process and identifying candidate sites. Following the tentative selection of sites, researchers contacted the local transportation department to determine the willingness of key officials to support the required activities. The support involved providing onsite assistance with a bucket truck and technical information such as signal controller settings, construction plans, and related documents, and providing crash histories before and after installation of D-CS. In cases where the local transportation department had not used Naztec equipment prior to the research project, the transportation department needed to make a commitment to a different and sometimes unknown brand of hardware for at least the duration of the after test period (about 2 years).

Once the local transportation department made a commitment to support the activity, TTI scheduled a date to be onsite for installing the monitoring equipment. The data collection plan used the same equipment to monitor traffic for studies 1, 3, and 4 during the 1-week before period as during the 1-week after period. Table 5 summarizes the equipment required to monitor two sites simultaneously. The general goal was to monitor traffic for 7 days during the before period (using whatever detection the local transportation department had used before D-CS) and for 7 days during the after period (with D-CS). In a few cases, the data collection exceeded the planned duration for the before period, the after period, or both. In one case, problems caused by a power outage reduced the after period to 5 days instead of the desired 7 days.

Table 5. Summary of traffic monitoring and data storage equipment.

Description	Quantity	Function
Industrial PC	2	Store date, maintain system time
Digital I/O cards	2	Interface peripheral devices with PC
CCD cameras	4	Monitor vehicles approaching, create images for DVR
Video image processors	2	Detect vehicles at detectors past the stop line
Digi™ 4 port serial card	2	Interface peripheral serial devices with PC
Digi™ cellular modem	2	Support remote communication for monitoring sites
Wavetronix™ Advance	4	Monitor vehicle speed and distance from intersection
Videostamp text overlay device	4	Create text on video image (e.g., site name)
DVR	2	Record video of traffic approaching each site

CCD = charge-coupled device.
DVR = digital video recorder.
I/O = input/output.
PC = personal computer.

Installing the equipment at the selected sites required coordination between researchers, the local transportation department, and, in some cases, installation contractors and equipment vendors such as Naztec and Wavetronix™. The local transportation department or its contractor provided a bucket truck for installing cameras and Wavetronix™ Advance detectors. In some cases, the intersections already had cameras installed, but all sites required re-aiming these cameras, installing new cameras, or both. Each additional camera required pulling wire from the cabinet to the camera for power and communication.

Communication required coaxial cables, and power required typical outdoor cables for three-phase AC power. The Wavetronix™ sensors required a Siamese cable with both power and communication in one bundle. TTI ran almost all of the cable overhead because of lack of space in underground conduits. The installer used zip ties to strap the cables to existing span wires for the short duration of the study. Removal of cables from either overhead or conduits was quicker than installation. During the removal, research personnel checked for cable damage and then respooled the cable for use at the next site.

Remote monitoring of equipment following installation required installing a cellular router in each cabinet. In a few cases, TTI also used a remote reboot system in the cabinet to overcome power outages or other short-term problems. The remote system allowed TTI engineers to do the following:

- Monitor the digital video recorder (DVR) to determine whether it was recording accurately.
- Monitor the PC.
- Download data each day.

It was not feasible to monitor the images being recorded by the DVR in real time, although researchers could transfer small segments of video using the Internet to verify proper operation. Replay of larger segments of video required transferring at least one of the two DVRs from the field to TTI headquarters.

SITES SELECTED FOR ANALYSIS

Table 6 lists the sites selected for data collection, their location, cabinet type, and the controller/equipment used at the site.

Table 6. Sites selected for data collection.

Site Description	Near City, State	Cabinet Type	Controller
U.S. 27/Pines Blvd.	Fort Lauderdale, FL	Naztec TS2	Naztec 2070L
U.S. 27/Griffin Rd.	Fort Lauderdale, FL	Naztec TS2	Naztec 2070L
U.S. 27/Johnson St.	Fort Lauderdale, FL	Naztec TS2	Naztec 2070L
U.S. 24/Main St.	Peoria, IL	Naztec TS2	Naztec 2070L
U.S. 24/Cummings Ln.	Peoria, IL	Naztec TS2	Naztec 2070L
LA 3162/LA 3235	New Orleans, LA	Naztec TS2	Naztec 2070L
U.S. 281/E. Borgfeld Dr.	San Antonio, TX	Eagle TS2	Naztec 2070L
U.S. 84/Speegleville Rd.	Waco, TX	Eagle TS1	PC with D-CS

For studies 1, 3, and 4, TTI followed the general sequence of events described above for the field data collection. As soon as the project got under way, TTI ordered the equipment to install and monitor two D-CS sites simultaneously. Chapter 3 provides detailed information on the equipment used. In States that had two or more sites in close proximity to each other, TTI installed two of the sites on the same trip to reduce travel costs. In all cases, the local transportation department had already installed the D-CS inductive loops prior to beginning the before data collection. However, even though TTI had communicated with States weeks in advance to set project requirements, some States had not installed cabinets prior to researchers arriving at the sites. Three reasons for installing inductive loops prior to the research team arriving onsite were as follows:

- To minimize delays following the before data collection and prior to beginning the after data collection.
- To test the (in some cases newly installed) inductive loops for functionality and avoid delays that might otherwise occur when the D-CS was ready for activation and data collection for the after condition.
- To provide a source of vehicle length and speed data to be used as needed during both before and after periods.

Table 7 provides the pertinent dates of signal installation, dates of D-CS installation, and dates when crash data were available from the local agency. In some cases, the operating agency only knew the year. Table 8 lists the days selected for comparison from before to after D-CS installation for all eight sites.

Table 7. Information on sites selected for data collection.

Site	Critical Dates			
	Signal Turned On	D-CS Turned On	Crash History: Before (5 years)	Crash History: After (2 years)
FL: U.S. 27/Pines Blvd.	1975	02/07/09	02/04–01/09	03/09–06/11
FL: U.S. 27/Griffin Rd.	06/01	03/23/09	04/04–03/09	04/09–06/11
FL: U.S. 27/Johnson St.	08/04	03/23/09	08/04–03/09	04/09–06/11
IL: U.S. 24/Main St.	1997	01/19/07	01/02–12/07	02/07–01/09
IL: U.S. 24/Cummings Ln.	1997	01/19/07	01/02–12/07	02/07–01/09
LA: LA 3162/LA 3235	07/05	06/13/09	07/05–05/09	07/09–06/11
TX: U.S. 281/E. Borgfeld Dr.	01/03	08/04	02/03–07/04	09/04–07/06
TX: U.S. 84/Speegleville Rd.	03/01	02/05	01/00–12/04	03/05–02/07

Table 8. Dates for field data collection.

Site Description	Near City, State	Before Dates	After Dates
U.S. 27/Pines Blvd.	Fort Lauderdale, FL	01/24/09–01/30/09	02/07/09–02/13/09
U.S. 27/Griffin Rd.	Fort Lauderdale, FL	03/09/09–03/15/09	03/23/09–03/29/09[1]
U.S. 27/Johnson St.	Fort Lauderdale, FL	03/09/09–03/15/09	03/23/09–03/29/09
U.S. 24/Main St.	Peoria, IL	04/21/09–04/27/09	05/02/09–05/06/09
U.S. 24/Cummings Ln.	Peoria, IL	04/21/09–04/27/09	05/02/09–05/06/09
LA 3162/LA 3235	New Orleans, LA	06/05/09–06/11/09	06/13/09[2]–06/19/09[3]
U.S. 281/E. Borgfeld Dr.	San Antonio, TX	05/30/09–06/08/09	07/20/09[4]–07/27/09
U.S. 84/Speegleville Rd.	Waco, TX	10/07/09–10/14/09	10/28/09–11/05/09[5]

[1]Griffin data incomplete on March 26, 2009.
[2]LA D-CS turned back on about 1 p.m. on June 12, 2009.
[3]June 17 and June 19, 2009, are partial days because of a power outage on June 17 and removal of equipment on June 19.
[4]Delayed because of training by Naztec for TxDOT personnel and a power outage on July 16, 2009.
[5]City of Waco reconnected first loop on phases 2 and 6 (at 111 ft from stop line) on Tuesday, October 27, 2009. TTI disconnected all existing loops on October 23 but later discovered that detection required clearing the queue before D-CS takes over.

Florida Sites

The first three sites installed by the research team at the beginning of the field data collection were in Fort Lauderdale along U.S. 27 at the intersections of Griffin Boulevard, Pines Avenue, and Johnson Street. The initial trips involved three researchers traveling during the weeks of November 17 and December 8, 2008. During the first trip, the research team made progress at both Griffin and Pines intersections, but at the end of the week, neither intersection was ready to begin collecting data. Most of the time spent during that week involved pulling wire from the cabinet to the camera or Wavetronix™ Advance mounting locations. A contractor for the Florida Department of Transportation (FDOT) provided a bucket truck and operator for both weeks.

Delays with Florida installations came from several sources, including some of the equipment purchased for the research project to monitor selected field measures of effectiveness (MOE). The principal agencies at the local level were FDOT, FDOT's consultant, the D-CS installation contractor, and Broward County Transit (BCT) (the traffic signal maintaining agency). Two critical initial problems were local personnel not being trained on the D-CS program in the

Naztec controllers and cabinets not being installed. The training was later provided by Naztec, and BCT pretested the cabinets prior to field installation. Fortunately, the D-CS inductive loops had been installed and were operational when researchers arrived. Local transportation department personnel (BCT, FDOT, and their contract representatives) began to immediately install and wire the cabinets to minimize delays to the research project.

The contractor installed the first cabinet at Griffin within 24 h of the researchers' arrival, but lack of training caused delays in completing cabinet wiring. There were also equipment issues that delayed progress. For example, TTI had purchased new CyberResearch™ industrial computers for use on this project. Because one of them had not arrived before the November trip, TTI used one of its own existing Kontron™ industrial computers. The new CyberResearch™ computers were apparently unable to handle the massive amount of data generated by the Wavetronix™ Advance detectors, whereas the older Kontron™ PC worked flawlessly. The purchase specification for the new computers placed them well ahead of the Kontron™ PCs in all other categories, but researchers finally had to remove the CyberResearch™ PCs from their intended use on this project, resorting instead to the Kontron™ PCs for the remainder of the project.

Naztec provided the necessary training to FDOT and BCT personnel in January 2009. Because BCT was not using similar Naztec equipment anywhere else, the county had no spare or replacement parts in case of failures or damage to cabinets. This became a critical issue in May 2009 when a lightning storm damaged two video cards, four bus interface unit (BIU) cards, and the 2070 controller 2N module in the cabinet at Johnson Street.

The research team encountered other delays during the November trip because of uncertainty on conduit runs and space availability within conduits at both intersections. Knowledgeable local personnel provided field support in spotting lines, but the research team still required more time than originally planned to get the monitoring systems installed. One solution was to run more of the cables overhead, and that option was less stressful on cables used for the research compared with pulling the cables through conduits. The final Griffin wiring was all overhead, and all but one stretch of wiring at Pines was overhead. Over the course of the research project, researchers were able to use Wavetronix™ and camera wiring multiple times by allowing extra length along each wire run. This extra length had to be coiled and strapped overhead (to minimize vandalism), although this took additional time. TTI was able to use the Wavetronix™ wiring purchased at the beginning of the project at all eight sites but was unable to reuse the coaxial cable throughout the project.

On the second trip to Florida, the research team finished all the hardware installation for both Griffin and Pines, but the contractor needed more time to set up cameras and intersection wiring (e.g., D-CS loops). Camera setup was important because TTI planned to use existing video imaging camera systems to detect red-light runners (RLR) by simply adding detection zones just past the stop line in each high-speed approach lane. There was a chance that TTI would have to install additional cameras, but the existing cameras would need to be set up first before that determination could be made. Researchers brought their own setup tool on the second trip, but the contractor needed to re-aim the cameras later.

On the third trip to Florida, TTI was able to finish the installations at Griffin and Pines and begin collecting the before data at these two intersections. BCT personnel agreed to reset the controller when it came time to collect the after data, possibly reducing the need for researchers to travel to the sites. There were also other times when Broward County personnel were helpful in traveling to the sites to check a problem or reboot the system. Multiple power failures at Griffin prompted the research team to add an iBoot device to allow researchers to reboot the system from headquarters in Texas. TTI shipped the device to Broward County for installation, and BCT voluntarily added an uninterrupted power supply to help maintain consistent power to the site.

None of the Florida sites had dilemma-zone protection during the before data collection period. BCT had set up all intersections using stop-line detection, the recall feature in the controllers, or both. This lack of before dilemma-zone detection will be important when analyzing data comparing before with after.

Illinois Sites

Illinois data collection followed the Florida collection. The two Illinois sites were located east of Peoria on U.S. 24—one at the intersection with Cummings Lane and the other at the intersection with Main Street in Washington, IL. The two intersections had almost identical geometry, with two through lanes on each high-speed approach and single-lane left-turn bays on each high-speed approach.

TTI made a total of two trips to the two Illinois sites—one trip for installing the monitoring equipment and the second trip to remove the equipment. The Illinois Department of Transportation (IDOT) had supported the installation of eight cameras under a previous D-CS contract, but three of these cameras were damaged and could not be used. Of the remaining cameras that were operational, the research project needed only two cameras per intersection, so there were enough cameras to conduct the before-after data collection. TTI needed to reorient only two of the remaining cameras at each intersection. TTI removed these cameras following completion of the field data collection at these two sites and shipped them to TTI headquarters.

Louisiana Site

The location of the intersection of LA 3235 and LA 3162 is near the small town of Galliano, LA, in the Lafourche Parish, about 60 mi south of New Orleans. For installation support, TTI contacted the nearest district office of the Louisiana Department of Transportation and Development (LaDOTD) in Houma, LA. LA 3235 is a high-speed roadway with speed limits on each approach at 55 mi/h, although observed local traffic speeds were higher. The D-CS approaches have two through lanes, a left-turn lane for the southbound approach, and a right-turn lane for the northbound approach. Three of the intersection legs serve general purpose traffic, and the fourth leg (eastbound) serves a casino and a convenience store. The only before detection at this intersection was detection at the stop line, so D-CS should significantly improve the safety of the intersection.

Texas Sites

U.S. 281 at E. Borgfeld Drive in San Antonio

The location of this site is at an isolated intersection north of the urbanized area surrounding San Antonio. Peak periods at this site indicated that a significant portion of the traffic was commuter traffic, with heavy inbound movement in the morning hours and heavy outbound movement during the late afternoon hours. The traffic at this site was the heaviest of any of the D-CS data collection sites used in this project and was useful for conducting the upper limit study.

An important aspect of this site involved using the Naztec 2070 controller with a non-Naztec (Eagle) cabinet. Six of the eight sites involved in this research had Naztec controllers and cabinets, so this one offered a good opportunity to test the compatibility of this controller with a different cabinet (the other non-Naztec controller was at the Waco site, described below). During the initial installation of the Naztec controller for data collection around May 30, 2009, the intersection went into flash mode when a detector BIU was unplugged. This occurrence could have been coincidental with removal of the BIU, but Naztec replaced the memory management unit (MMU) anyway and was able to restore normal operation following this change.

TTI completed its normal data collection during the selected before/after period, which ended on July 27, 2009, before another problem occurred related to lightning (according to district personnel). The lightning strike again caused the intersection to go into flash mode. The Naztec controller had operated the intersection successfully for the 8-week period between the installation date of the Naztec controller and the lightning strike. As a temporary fix, district personnel replaced the Naztec controller with the original Eagle controller until Naztec could troubleshoot its 2070 controller. TxDOT shipped the controller back to Naztec during the week of August 17, 2009, to allow Naztec to troubleshoot the problem. Naztec found that the central processing unit (CPU) board had been damaged; a technician from Naztec returned the repaired controller to the district on September 31, 2009. TTI reinstalled its monitoring equipment at the U.S. 281/Borgfeld intersection on October 1, 2009, and began collecting data for the Upper Limit Study.

Upper Limit Study: TTI increased the maximum green setting in the D-CS 2070 controller on November 3, 2009, at the intersection of U.S. 281/Borgfeld to test its upper limit. At this intersection, Naztec and TTI set an initial maximum green of 75 s for phases 2 and 6. After some consideration of adding 80 s and 85 s, TTI selected 85 s and 95 s as the desired additional values to test because of the increased statistical significance in the greater spread.

To prepare for the increased maximum green and possible increase in delay, TTI conducted simulations using the Synchro software. The TxDOT San Antonio District traffic operations engineer mandated that TTI run Synchro to determine the impact of the increased main street green time on overall intersection delay. Even though all decisionmakers realized that Synchro could not simulate D-CS, this was still considered a worthwhile activity because it should at least approximate the increase in delay. Table 9 and table 10 indicate the increased delay based on the Synchro runs. The tabulated values of traffic demand came from TTI counts at the upstream D-CS inductive loops, but TTI had to approximate the side street demand (on Borgfeld Drive) based on loop occupancy values. Based on Synchro results and discussions with the TTI principal investigator regarding how the D-CS algorithm searches for a safe time to end the green phase, the TxDOT traffic operations engineer authorized the increased maximum green settings. Chapter 4 provides the analysis and results of the upper limit study.

U.S. 84 and F.M. 2837 in Waco

The Waco site is at the intersection of U.S. 84 and F.M. 2837 (Old Lorena Road). The location is southwest of Waco and outside the urban area. U.S. 84 is a high-speed roadway with a speed limit of 60 mi/h on each approach and a significant number of trucks. The D-CS approaches have two through lanes, single left-turn lanes, and single right-turn lanes. All four of the intersection legs serve general purpose traffic. Detection prior to D-CS installation consisted of a series of inductive loops upstream for dilemma-zone protection. Dilemma zone detectors were 6-ft by 6-ft loops in each lane at 493, 267, and 111 ft from the stop line. Through lanes on U.S. 84 had no stop-line detection, but left-turn bays did.

Table 9. Synchro results for morning peak at U.S. 281/Borgfeld Dr.

Lane Group	EBL	EBR	NBL	NBT	SBT	SBR	Intersection
Demand (vehicles/h)	253	20	180	398	1400	91	N/A
Delay (75 s)	61.8	0.0	62.0	6.9	33.5	0.1	32.6
LOS	E	A	E	A	C	A	C
Delay (85 s)	63.6	0.0	64.4	6.9	32.8	0.1	32.6
LOS	E	A	E	A	C	A	C
Delay (95 s)	63.4	0.0	65.6	6.9	32.7	0.1	32.6
LOS	E	A	E	A	C	A	C

EBL = eastbound left-turn.
EBR =eastbound right-turn.
LOS = level of service.
NBL = northbound left-turn.
NBT = northbound through.
SBT = southbound through.
SBR = southbound right-turn.
N/A = not applicable.

Table 10. Synchro results for afternoon peak at U.S. 281/Borgfeld Dr.

Lane Group	EBL	EBR	NBL	NBT	SBT	SBR	Intersection
Demand (vehicles/h)	267	20	537	878	1,000	28	N/A
Delay (75 s)	58.4	0.0	117.9	8.7	39.1	0.0	46.0
LOS	E	A	F	A	D	A	D
Delay (85 s)	57.6	0.0	122.9	8.8	39.0	0.0	46.9
LOS	E	A	F	A	D	A	D
Delay (95 s)	55.9	0.0	128.5	9.0	39.4	0.0	48.1
LOS	E	A	F	A	D	A	D

EBL = eastbound left-turn.
EBR = eastbound right-turn.
LOS = level of service.
NBL = northbound left-turn.
NBT = northbound through.
SBT = southbound through.
SBR = southbound right-turn.
N/A = not applicable.

The D-CS site in Waco had a NEMA TS1 cabinet, and City of Waco decisionmakers chose not to replace this cabinet with a TS2 cabinet to accommodate the D-CS, even though they were convinced that D-CS had made a significant difference in improving safety. On the first visit to this site, TTI researchers found that the PC running the D-CS algorithm had failed, so they prepared a replacement PC to be installed in the cabinet. Other TTI researchers had already wired the cabinet for a PC system, reducing the effort required to reinstall D-CS.

The TS1 version of D-CS reads the upstream detector amplifiers directly, so it has to react faster than the TS2 version. The operating system (OS) clock speed is critical. The original TTI research project used Windows 2000 because of the 10-ms OS timer (Windows XP's timer is 15 ms, and earlier Windows OS timers were 55 ms), and that time reduced the speed measurement error. Appendix A has more detailed information on the setup of PCs for TS1 cabinets.

An issue that surfaced immediately following the reinstallation of D-CS at this site was due to not having stop-line detectors on through lanes. The City of Waco technicians had disconnected all previously installed dilemma-zone loops so that only the D-CS loops were connected for main street dilemma-zone protection. The D-CS algorithm does not start to search for gaps in the traffic stream until the termination of the minimum green in the controller or until the stop-line queue is served, whichever is greater. In this case, with the formation of long queues extending past the D-CS loops, the algorithm did not detect gaps appropriately, so it terminated the green phase prematurely with each cycle and forced very long queues to form on the U.S. 84 approaches. The solution involved reconnecting the nearest inductive loops (located at 111 ft from the stop line) and allowing the queue to begin clearing and D-CS to function properly. With reconnection of the closest loops to the stop line, D-CS was able to operate properly. At the first gap-out (or at the end of the minimum green setting, which was usually less), D-CS took over and started looking for gaps to safely end the green phase.

ANALYSIS METHODOLOGY

TTI processed data files collected from field equipment and placed the data in Microsoft Excel files for processing. The amount of data collected at each of the eight sites was enormous, far more than the amount that was actually needed to determine the performance of the D-CS. TTI followed the instructions from the sponsor to collect 7 full days of data but could only analyze a few hours of data from each site to actually compare the before period to the after period. TTI started trying to analyze full days of data, but that was far too time-consuming. The decision based on this realization was to analyze full hours of data until tests of the adequacy of the data indicated that the desired statistical significance had been achieved.

All of the hourly data analysis started with a person watching replay of recorded video to determine RLRs and vehicles caught in the dilemma zone (2 to 6 s from the stop line). The person viewing the video filled in a spreadsheet for each and every signal cycle during the hour based on a predetermined Microsoft® Excel template, from which engineers would subsequently determine actual dilemma-zone violators and RLRs.

The next step in the analysis process involved merging information onto a predetermined worksheet template from the person reviewing video, from phase-status files, from RLR files, and from traffic-volume files (traffic counts of each approach). The data from this worksheet then became part of a final analysis of results based on a regression model technique developed by TTI researchers.

CHAPTER 3. DATA COLLECTION SYSTEM

INTRODUCTION

TTI used a real-time data collection system for assessing the MOEs used to evaluate the performance of the traffic signal system before and after activating the D-CS system at an intersection. The following MOEs were used to evaluate the traffic signal system performance:

- Number of RLRs.
- Number of times a phase reached the max1 green during the day.
- Number of vehicles caught in the dilemma zone at the onset of yellow on main street phases.

The following real-time data elements were among those elements required to calculate the above-mentioned MOEs:

- Change in phase status (green, yellow, red).
- Status of various detectors installed at the intersection.
- Location and travel time to stop line of vehicles on the main approaches at the onset of yellow.
- Video recording of about 7 s before and after the onset of red on main-street approaches to verify the number of RLRs.

TTI used two data collection modules running simultaneously on an industrial PC to collect the real-time data elements required to evaluate the traffic signal system performance. Each data-collection module required several hardware components to collect the necessary data. For example, each intersection required an industrial PC together with enhanced BIUs to interface with TS2 traffic controller cabinets to monitor the change in phase status (green, yellow, red) and status of detectors (D-CS upstream detectors, stop-line detectors, and red-light-running detector) installed at an intersection. The following sections describe in detail the software and hardware components of the data-collection system.

DATA COLLECTION SOFTWARE

The software component of the real-time data collection system consisted of two modules, one developed by TTI and the other by Wavetronix™. The module developed by TTI researchers, called Real-Time Traffic Data Collection System (RTTDCS), served the purpose of monitoring the traffic signal system events and detecting RLRs. Wavetronix™ provided the second data collection module, which facilitated collecting information about vehicles caught in the dilemma zone at the onset of yellow phase. This action required the use of a Wavetronix™ advance sensor installed at the stop line on main street approaches. Both systems ran simultaneously on the same industrial PC and used the PC's system time to timestamp the events and data collected by each system. Consequently, data elements collected by both systems were synchronized because they used the same reference to timestamp the events (i.e., the PC system time).

RTTDCS

TTI researchers developed components of the RTTDCS over a period of time, but refinement of some components occurred in this research project. The RTTDCS interfaces with a traffic controller cabinet (TCC) and monitors the following traffic signal system events at an intersection:

- Phase status (green, yellow, red).
- Detector status (on/off).
- Phase hold.
- Phase on.
- Phase check.
- Ring status bits (A, B, and C).
- Ring force-off.
- Priority preempts.
- Other available input and output events available in a TCC.

Depending on the type of the TCC (i.e., TS2 or TS1), the RTTDCS uses either enhanced BIUs or a digital input/output (I/O) PC card to interface with the TCC. All of the intersections selected for data collection except one (Waco) had TS2 cabinets. Consequently, enhanced BIUs were involved in all cabinets but the one in Waco. An enhanced BIU is similar to a standard BIU except for an additional RS-232 port on the front of the enhanced BIU. TTI researchers used the RS-232 port on the front of the enhanced BIU to monitor special inputs and outputs available on that BIU. For example, TTI used BIU #1 to monitor phase status of phases 1 to 8 in the cabinet. TTI also replaced detector BIUs #1 and #2 in the cabinets with enhanced BIUs to monitor the status of up to 32 detectors in each TS2 cabinet.

To monitor RLRs on main street approaches, TTI researchers installed a video detection camera to monitor the area immediately downstream of the stop line on main street approaches. This action required configuring a RLR detector in each main street approach downstream of the stop line. The RTTDCS monitors the status (on/off) of these RLR detectors. Anytime the RTTDCS detects a change in the status of these detectors while the correspondent main street phase is red, it timestamps and records the RLR events in a daily RLR log file. Also, anytime the RTTDCS detects a change of phase status from yellow to red on main street approaches, it triggers a DVR to record about 7 s of buffered video before and after the start of the red phase from the RLR camera monitoring the approach. TTI used the timestamped RLR events in the log file and the recorded video to verify the number of RLRs at each main street intersection before and after installation of D-CS. The process also involved a video titler whose purpose was to overlay a text message on the video image. This message included the industrial PC timestamp and main street phase status recorded by the DVR from the RLR camera. The reason for overlaying the main street phase status and the PC's timestamp on the recorded video was to simplify the post-processing synchronization of the timestamped events recorded in the RLR log file and video clips recorded by the DVR.

Finally, the RTTDCS receives and logs the contact-closure signal sent by the Wavetronix™ Advance, which indicates whether a vehicle was in the dilemma zone at the onset of yellow. This positioning of each vehicle was necessary for subsequent verification using the recorded video. TTI installed one Advance at the stop line of each main street approach of every evaluated intersection. The Advance has a detection zone area that extends from 100 to 500 ft from the sensor location. The sensor samples the detection zone about every 100 ms and provides the location and speed of every vehicle detected in that zone. The user defines the beginning and end of the dilemma zone as a range in the number of seconds of travel time to the stop line of the approach monitored by the Advance sensor. The Advance sensor uses the installed range of travel times to calculate the dilemma zone of every vehicle detected in its 400-ft zone each time it wakes up. If there is at least one vehicle in this zone expected to arrive in the dilemma zone, the Advance sends a presence signal to the cabinet. The RTTDCS receives the presence signal; timestamps the event; records the vehicle identifier, speed, and distance; and logs the event into the daily log file. Installers used the same Advance configuration parameters as programmed into the D-CS; in other words, the beginning of the dilemma zone was 6 s of travel time from stop line, and the end of the dilemma zone was 2 s of travel time from the stop line on each approach.

The RTTDCS logs the events and data elements it collects in real time to daily log files, and it closes these log files at midnight every day and immediately opens new files. The daily log files include the following files:

- Phase Status (.PHS files): The RTTDCS saves the change in phase-status events it detects into the phase-status file. For example, when the RTTDCS detects a change in phase status from green to yellow, yellow to red, or red to green, it logs an event into the file indicating the type of change in phase status, along with a time stamp. When the phase status changes from red to green, the RTTDCS writes the following records into the daily phase status file.

- Red-Light Running (.RLR files): Anytime the RTTDCS detects an actuation on the video detectors downstream of the stop line on main street approaches while the corresponding approach phase is red, it timestamps the detector actuation and logs it into the RLR file.

- Detector Status (.SBD files): The RTTDCS logs changes in detector status (on/off) of every detector installed at the intersection into the .SBD file.

- Upstream D-CS Loop Trap (.SPD files): The RTTDCS monitors the D-CS trap loops to detect vehicles and calculate the speed of each vehicle on the main street approaches. The RTTDCS calculates the average speed of each detected vehicle and logs the information into the .SPD file.

- Wavetronix™ Advance (.WAS files): The RTTDCS monitors the Advance (on/off) signal indicating detection of a vehicle in the dilemma zone between 100 and 500 ft from the location of the sensor.

- BIU (.BIU files).

- Detector Failure (.DetFail files).

- Daily Real-Time Log.

The appendixes have a sample of data headers to assist future analysts in understanding the data output.

Wavetronix™ Advance System

Wavetronix™ provided TTI researchers with a software application to intercept real-time speed and distance messages sent by the Wavetronix™ SmartSensor Advance (WSSA) sensor over its RS-232 port. With the help of Wavetronix™ engineers, TTI researchers configured the Advance sensors to send messages over the serial connection about every 100 ms containing the speed and location of every vehicle in the dilemma zone. The Wavetronix™ data collection system receives these real-time messages and logs them into a log file that contained the following information:

- The date.
- The industrial PC system timestamp.
- The vehicle identification.
- The vehicle speed.
- Distance of vehicle from the stop line.
- Vehicle travel time to the stop line.

TTI researchers used the collected information to verify the number of vehicles that were in the dilemma zone on the main street approaches at the onset of yellow.

DATA COLLECTION HARDWARE

Equipment Available from the Government

Table 11 lists the equipment that the Government made available from a previous contract. Besides this list, the Federal Highway Administration (FHWA) had a Naztec 2070 cabinet, a Naztec 2070 controller, and two rolls of coaxial cable. TTI used Government-provided equipment to the extent that was feasible. TTI's proposed budget included costs for PCs other than the ones available from the Government because those PCs (PC-104) did not offer the level of performance needed for efficient completion of the TTI work plan. In fact, the newly purchased PCs were not powerful enough either. As TTI tested the new PCs prior to and during the initial data collection efforts at the first sites in Florida, it became increasingly obvious that the newly purchased PCs would not be able to handle the large amounts of data that would be generated by field data collection units. TTI resorted to its existing Kontron™ industrial PCs to collect and store data throughout the project.

TTI also elected not to use the Traficon™ video detection units, choosing instead to use its own Autoscope™ detectors. The reason for this swap was partly because of greater familiarity with TTI's Autoscope™ video processors and partly because of the additional features offered by the Autoscope™ RackVision systems. TTI had not used Traficon™ video detectors for red-light-running detection prior to this project. TTI provided sufficient equipment (processors, racks, etc.) for two intersections operating simultaneously but used cameras provided by the Government.

Equipment from the list that was useful to TTI included the enhanced BIUs, the video monitor, camera mounting hardware, video quad processors, the black-and-white monitor, and various cables and connectors. In addition to the equipment listed, an earlier contract had resulted in the installation of eight cameras at two Illinois intersections. TTI was able to use four of these cameras during the data collection that occurred during this contract.

Table 11. Equipment list available from FHWA.

Box Number	Shipment Contents
1	10 Data Express hard drives (some labeled as DCS2) 4 100-ft CCTV video power cables 4 high-resolution color quad processors 4 AC/DC switch adapters 4 GPS modules 4 chips (apparently quad processors)
2	3 Naztec BIU power racks
3	2 PC 104s (Sys 3a and Sys 10a) 1 PC 104 case
4	14 plastic bags screws and bands from TRI-M labeled “Container Parts Kit” 1 bag of WinSystems™ cables 7 cables for connecting parts inside PC 104 4 bags of Diamond PC104 prototype board kit 14 Winsystem™ chip cards (about 2 by 2 inches size) 1 stack of chips 2 bags of keys and screws
5	3 Naztec BIU power racks 2 cables
6	9 PC 104 PCs (Sys 11a, 7a, 9a, 1, 8a, 6a, 12a, and 13a)
7	4 camera mounting tubes
8	4 sets of camera mounting brackets
9	1 9-inch B/W monitor
10	2 Naztec/Traficon™ video processors 1 Naztec Pwr/Panel/Video 1 Traficon™ camera adjuster
11	8 BIUs 24 9-pin RS232 cables
12	18 BIUs
13	1 camera
14	1 camera
15	1 camera
16	1 camera

AC/DC = alternate current/direct current.
CCTV = closed-circuit television.
GPS = global positioning system.
TRI-M = TRI-M Technologies Inc.

Equipment Purchased Using Project Funds

Table 12 lists equipment purchased with project funds. Even though TTI specified the two industrial PCs purchased with project funds should be more powerful than ones used for similar research, they were not useful to this project. Upon connecting all the data collection equipment at the first site in Florida, the new PC would typically operate for a short interval and then lock up because of the tremendous flow of data, especially from the Wavetronix™ detectors. TTI resorted to using two existing Kontron™ industrial PCs for the entirety of the field data collection.

Table 12. Equipment purchased with project funds.

Description	Quantity	Unit Price	Total
Industrial PC	2	$1,750.00	$3,500.00
National Instruments™ Digital I/O Cards	2	$780.12	$1,560.24
Digi™ 4 port serial Card	2	$225.42	$450.84
Digi™ cellular modem	2	$1,263.00	$2,526.00
Digi™ modem service (months) (2 units)	14	$100.00	$1,400.00
Wavetronix™ Advance	2	$6,300.00	$12,600.00
Wavetronix™ Advance (loan)	2	—	—
Videostamp text overlay device	4	$224.14	$896.56
DVR (Pelco™)	2	$2,606.00	$5,212.00
Shipping cost estimate	1	$ 200.00	$200.00
Total			$28,345.64

—Not applicable.

Description of Equipment Used

Figure 3 shows a photograph of an equipment cabinet in Florida showing some of the monitoring equipment used for this research, along with the controller and other equipment used to operate the intersection. The following major components were needed in each equipment cabinet:

- Kontron™ industrial computer with six RS-232 serial ports and one 10/100 Ethernet port.
- Digital I/O card: The National Instruments™ peripheral component interconnect (PCI) 6527 digital I/O card with 24 digital inputs and 24 digital outputs.
- Video titler.
- DVR: Pelco™ 5100 series.

The industrial PC triggered the DVR to start recording about 7 s of buffered video before the onset of the red phase and continuing until about 7 s after red. The industrial PC continuously output a timestamp to be recorded on the video in addition to the phase-status indication (i.e., G, Y, or R) from the controller. Ideally, this process required two cameras per approach, for a total of four cameras per intersection. One camera covered the stop-line area while the other covered the area upstream of the stop line. This project required one DVR at each intersection to record video from the four cameras at the onset of red on main street phases.

Researchers used all six of the available serial ports. The system needed two of the serial ports to interface with BIU #1 and the first detector BIU in the cabinet. It used two other serial ports to receive the real-time vehicle information messages from the WSSA sensors. The last two serial ports communicated with the two video titlers to overlay text messages onto recorded video. These text messages included the industrial PC timestamp and main street phase status. The 10/100 Ethernet port allowed remote monitoring of the industrial PC using a cellular modem. Finally, the digital I/O PCI card monitored the RLR video detector status and the presence call from the WSSA sensors indicating the presence of a vehicle in the dilemma zone.

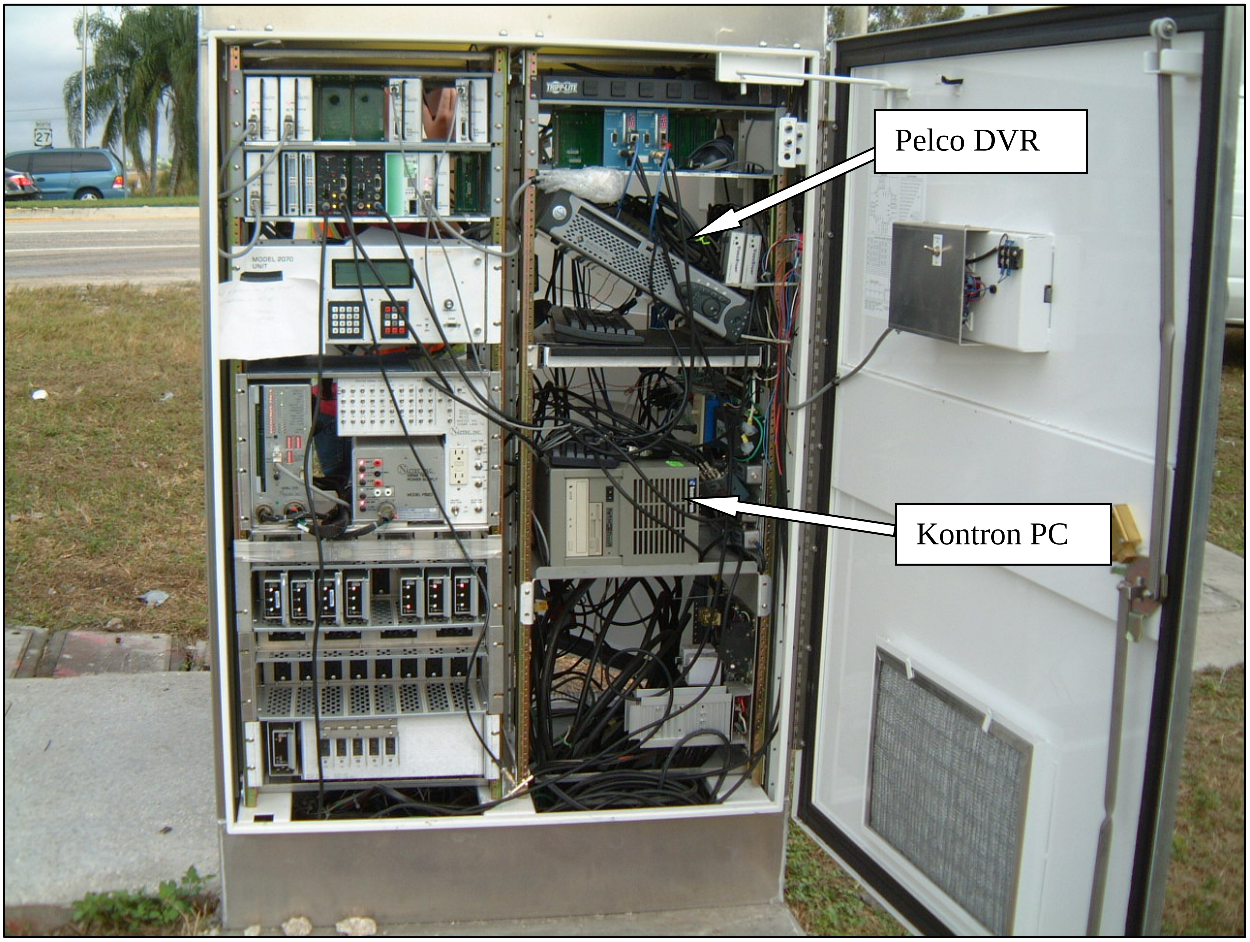


Figure 3. Photo. Naztec cabinet in Florida with D-CS monitoring equipment.

CHAPTER 4. DATA ANALYSIS RESULTS

INTRODUCTION

This chapter begins with descriptions of data collection sites because site details might help explain some of the findings. These details include drawings of the intersection geometry and tables of controller settings for the before and after conditions. The analysis of the actual crash data came near the end of the project. The goal of the traffic data collection was to determine propensity for running, vehicles caught in the dilemma zone, and max-outs. The Upper Limit Study used similar measures of effectiveness as studies 1 and 3. The following four studies were introduced in chapter 1 and explained in chapter 2:

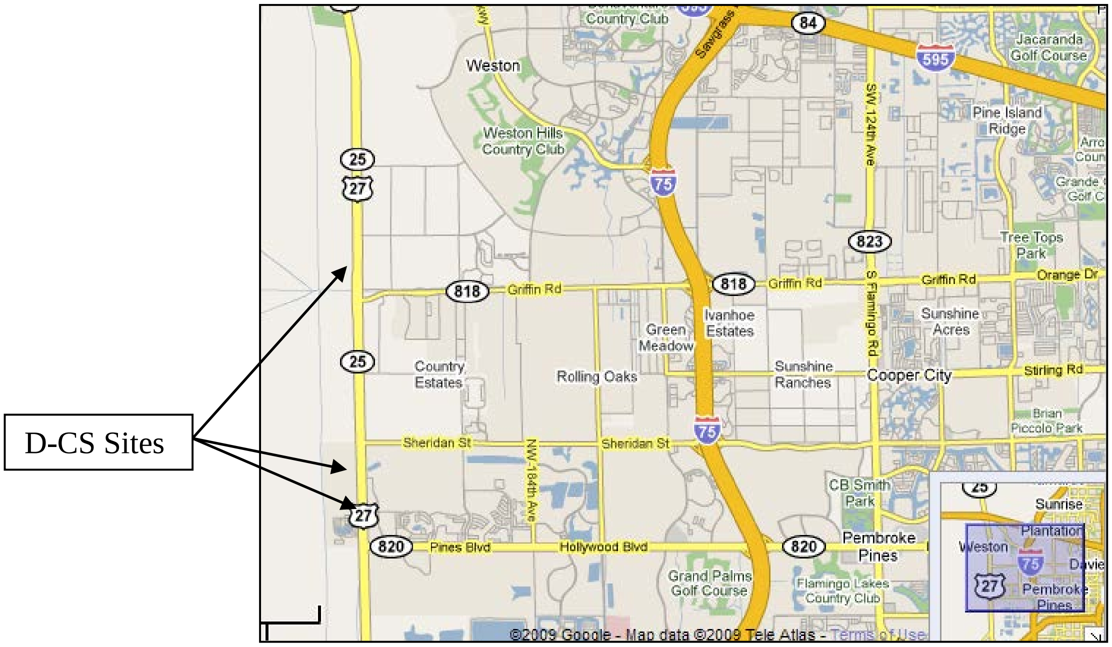
- Study 1: Performance Monitoring of Dilemma Zone Occupancy.
- Study 2: Before-After Crash Data Study.
- Study 3: Before-After Crash Surrogate Study.
- Study 4: Upper Limit Study.

DATA COLLECTION SITES

This chapter contains detailed site information on each of the eight sites to assist in better understanding the results. There is a site map showing geographic information followed by site schematics on each site to present the necessary details for understanding the geometric layout of the intersections and other detectors that were used for the before detection scenario. There is signal timing information on each site in both the before and after conditions. There is discussion about site, detection, and controller features that might have affected the outcome of the before-after comparison. The order of the site information in the remainder of this chapter is alphabetical. Florida (sites 1, 2, and 3) is first, followed by Illinois (sites 4 and 5), Louisiana (site 6), and Texas (sites 7 and 8).

Sites 1, 2, and 3 Information

U.S. 27 is a north-south arterial that lies along the western edge of the city of Fort Lauderdale. The area to the west of U.S. 27 is mostly undeveloped swamps, and to the immediate east is urbanized residential development. Figure 4 shows a map of the local area showing these three intersections. The Pines intersection is a “T” intersection, whereas Griffin and Johnson are four-way intersections. All three intersections have two through lanes on the high-speed U.S. 27 approaches, and all have single left-turn and single right-turn lanes near the intersection. All three intersections have wide medians as shown in figure 5 through figure 7.



Original image: ©2009 Google® Tele Atlas; map annotations provided by TTI.

Figure 4. Map. Fort Lauderdale D-CS sites.[4]

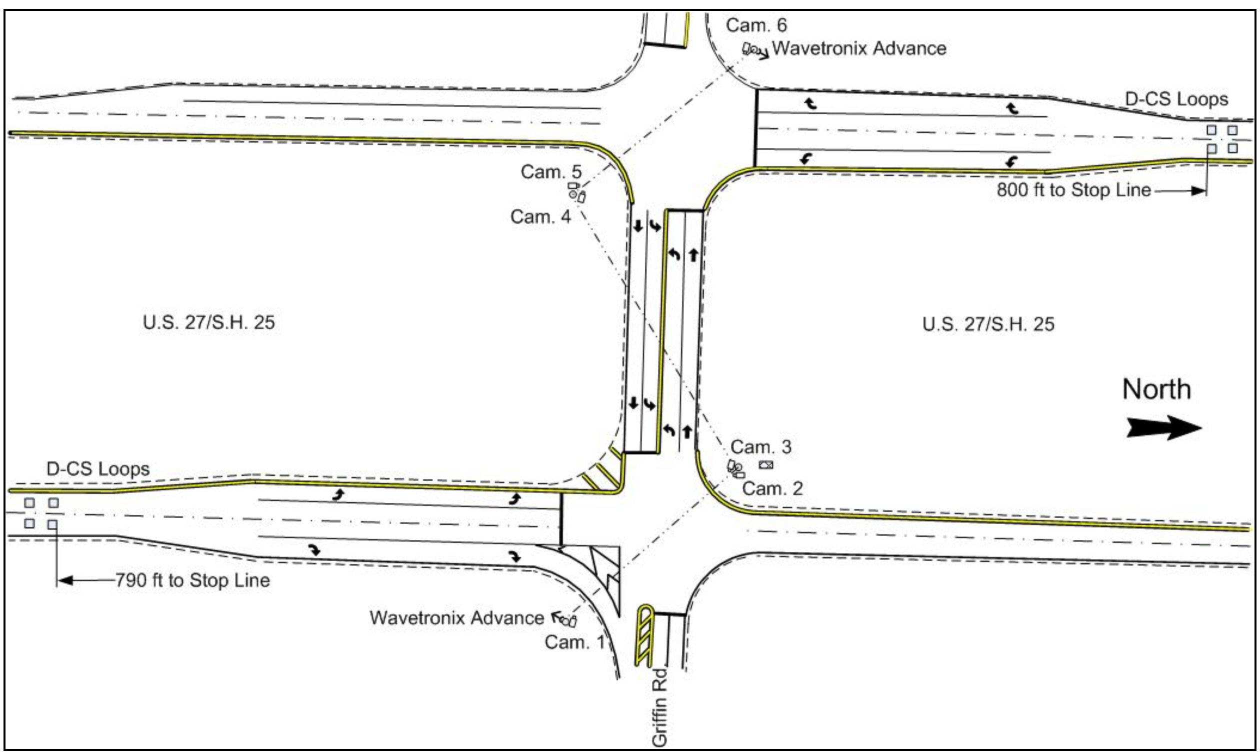


Figure 5. Map. Intersection layout at U.S. 27 and Griffin Rd.

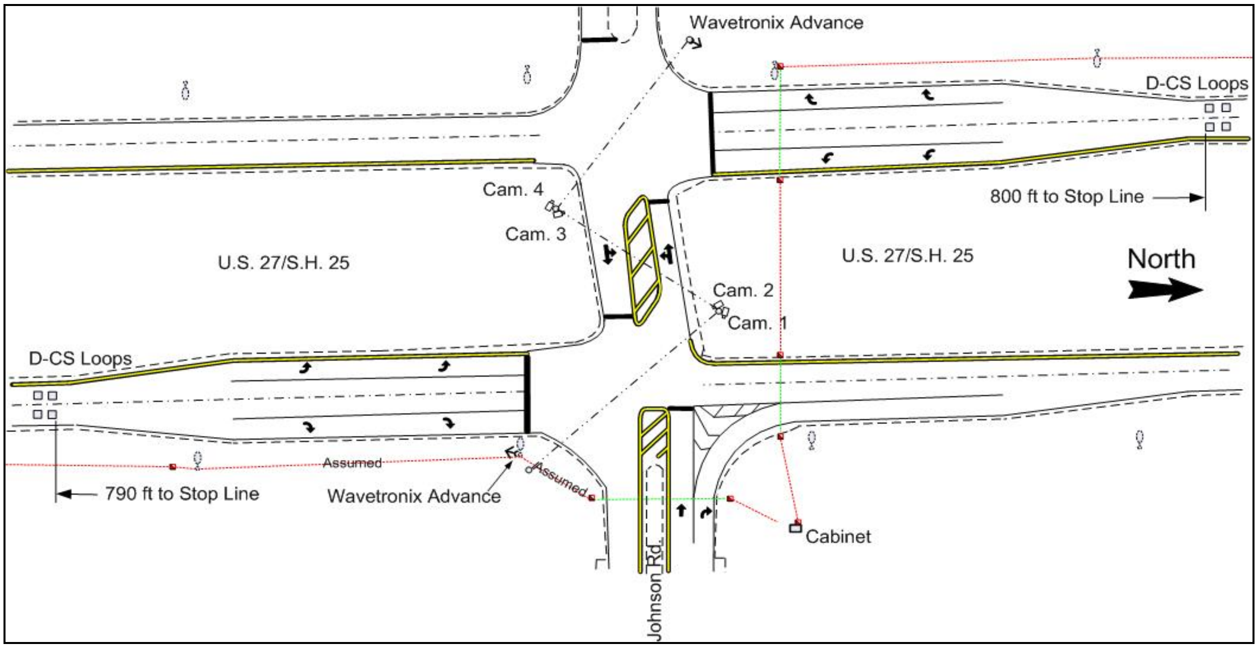


Figure 6. Map. Intersection layout at U.S. 27 and Johnson Rd.

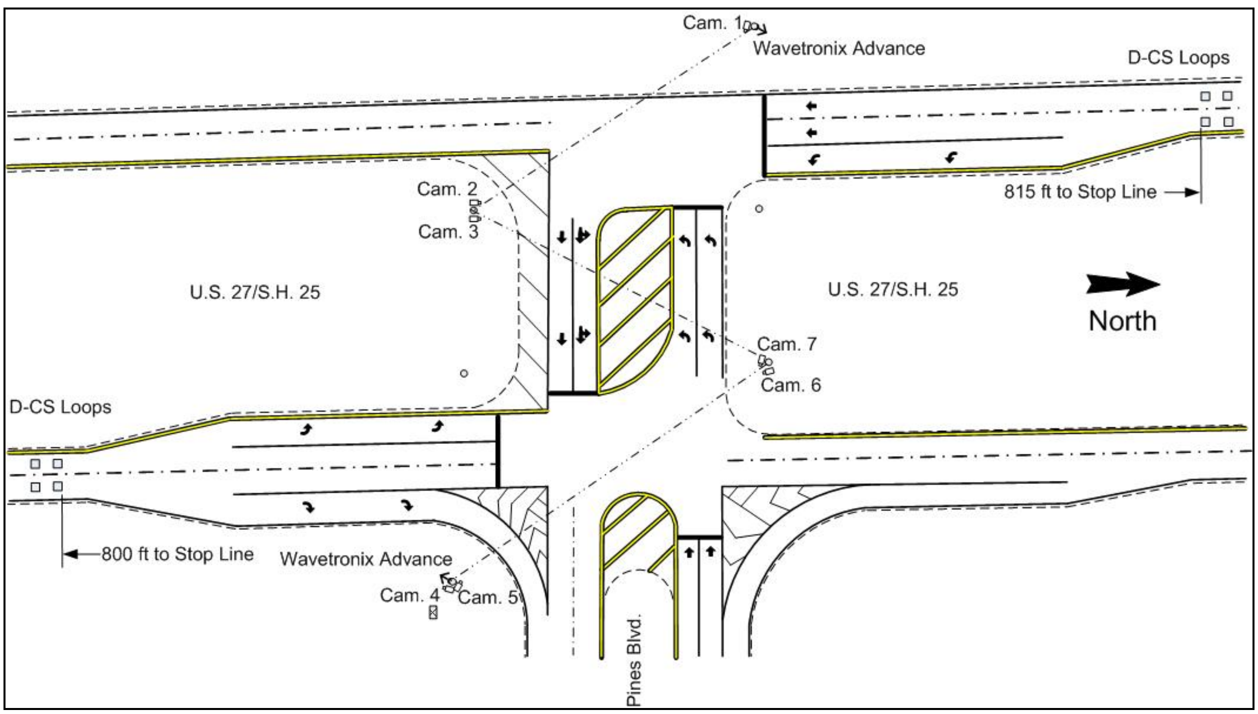


Figure 7. Map. Intersection layout at U.S. 27 and Pines Blvd.

Table 13 through table 18 summarize the controller settings for the three Florida intersections. Figure 8 and figure 9 show the signal phasing sequence for the Pines and Johnson intersections. The Griffin intersection had controller settings that were reasonably straightforward and did not use overlaps like the other two Florida intersections did. The signal phasing at the Pines intersection was an issue because D-CS needs the green phases on the main street approaches

(NEMA phases 2 and 6) to begin simultaneously. BCT officials agreed to change the signal timing to cause these two phases to begin simultaneously and to eliminate one of the overlaps used previously. The other needed element was that the minimum green setting needed to conform to the D-CS recommended minimum of 15 s for approach speed limits of 55 mi/h or higher.[1] If there is no stop-line detection, the minimum green time must be at least sufficient to clear the stopped queue. There was no dilemma-zone detection in the before condition; the only detection used was stop-line detection.

The following definitions apply to table 13 through table 18 and other discussions of controller settings.

The following definitions apply to the before D-CS phase:

- MinGrn (minimum green, or initial green): The shortest possible vehicle green time before any added initial or vehicle extensions.[5]

- Passage (passage time, vehicle extension): When minimum green finishes timing, the green interval is allowed to extend for a length of time equal to maximum time in effect. Actual length of extension period depends on this phase vehicle extension time, frequency of vehicle actuations, and minimum gap setting.[5]

- Max1 and Max2: Maximum green time allowed in the presence of an opposing call. The higher-numbered maximum green selected will be in effect.[5]

- Yel (yellow change interval): the time that the phase yellow indication is displayed following a green indication.[5]

- Red Clearance Interval (or All-Red Interval): The interval at the end of the yellow change interval during which the phase has a red-signal display before the display of green for the following phase. Its purpose is to allow vehicles that entered the intersection on the yellow change interval to clear the intersection prior to the next phase.[6]

The following definitions apply to the after D-CS phase:[1,7]

- TrapDist: TrapDist is the distance from the downstream end of the detector trap to the stop line of the intersection, in feet. The traps should be between 700 and 1,000 ft from the stop line.

- DZArrive: DZArrive is the travel time from the upstream end of the dilemma zone to the stop line, in seconds. The DZArrive time cannot be smaller than DZExit.

- DZExit: DZExit is the travel time from the downstream end of the dilemma zone to the stop line, in seconds. The DZExit time cannot be larger than DZArrival.

- Stage: The maximum green time is divided into two stages, stage 1 and stage 2. The Stage is the percentage of the maximum green time that is allocated to stage 1. Phase termination in stage 1 requires that all dilemma zones are clear. During stage 2, D-CS searches for a time when the number of vehicles in the dilemma zone is at a minimum.

- MaxSpeed (maximum speed): MaxSpeed is the maximum acceptable travel speed to be used by D-CS in mi/h. Speeds detected higher than this value are considered to be errors and are set to the maximum speed.

- MaxLength (maximum length): MaxLength is the maximum acceptable vehicle length for D-CS, in feet. Vehicle lengths reported to D-CS that are longer than the maximum length are considered to be errors, and the maximum length is reported instead.

- ZoneLength: ZoneLength is the measurement between the exit end of the upstream inductive loop and the exit end of the downstream inductive loop, in feet. The minimum zone length is 20 ft, although longer distances are also allowed.

Table 13. Controller settings U.S. 27/Griffin Rd.—before.

	Phase							
Setting	1	2	3	4	5	6	7	8
MinGrn (s)	—	25	—	6	—	25	—	6
Passage (s)	—	2.5	—	2	—	2.5	—	2
Max1 (s)	—	70	—	30	—	70	—	30
Max2 (s)	—	0	—	0	—	0	—	0
Yel (s)	—	5	—	4	—	5	—	4
Red Clearance (s)	—	3	—	2	—	3	—	2

—No data.

Table 14. Controller settings U.S. 27/Griffin Rd.—after D-CS.

	Phase							
Setting	1	2	3	4	5	6	7	8
TrapDist (ft)	—	790	—	—	—	800	—	—
DZArrive (s)	—	6	—	—	—	6	—	—
DZExit (s)	—	2	—	—	—	2	—	—
Stage (percent)	—	65	—	—	—	65	—	—
MaxSpeed (mi/h)	—	70	—	—	—	70	—	—
MaxLength (ft)	—	75	—	—	—	75	—	—
ZoneLength (ft)	—	20	—	—	—	20	—	—

—No data.

Another issue in Florida was the maximum green setting in the Naztec 2070 controller after initiating the D-CS algorithm. The recommended range is 55 to 80 s, but the setting at Pines during field data collection was 50 s.(1) TTI did not check the settings because Naztec had been onsite to provide training and should have set up the controller properly. This error was discovered too late to change it during the field data collection at the Pines intersection. However, TTI checked the other intersections and set the value to 70 s at Griffin and Johnson.

Even though the setting at Pines was lower than the recommended range, the result might still indicate how well it operates under these conditions.

Table 15. Controller settings for U.S. 27/Johnson Rd.—before D-CS.

Setting	Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
MinGrn (s)	6	7	5	6	5	—	—	—
Passage (s)	2	0	2	2	2	—	—	—
Max1 (s)	25	70	18	25	12	—	—	—
Max2 (s)	25	50	18	30	12	—	—	—
Yel (s)	4	5	4	4	4	—	—	—
Red Clearance (s)	2	3	2	2	2	—	—	—

—No data.

Table 16. Controller settings for U.S. 27/Johnson Dr.—after D-CS.

Setting	Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
TrapDist (ft)	—	790	—	—	—	800	—	—
DZArrive (s)	—	6	—	—	—	6	—	—
DZExit (s)	—	2	—	—	—	2	—	—
Stage (percent)	—	65	—	—	—	65	—	—
MaxSpeed (mi/h)	—	70	—	—	—	70	—	—
MaxLength (ft)	—	75	—	—	—	75	—	—
ZoneLength (ft)	—	20	—	—	—	20	—	—

—No data.

Table 17. Controller settings for U.S. 27/Pines Blvd.—before D-CS.

Setting	Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
MinGrn (s)	5	20	5	10	—	—	—	—
Passage (s)	0	3	2	2	—	—	—	—
Max1 (s)	5	50	20	35	—	—	—	—
Max2 (s)	0	0	0	0	—	—	—	—
Yel (s)	4	5	4	4	—	—	—	—
Red Clearance (s)	2	3	2	2	—	—	—	—

—No data.

Table 18. Controller settings for U.S. 27/Pines Blvd.—after D-CS.

Setting	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
TrapDist (ft)	—	800	—	—	—	815	—	—
DZArrive (s)	—	6	—	—	—	6	—	—
DZExit (s)	—	2	—	—	—	2	—	—
Stage (percent)	—	65	—	—	—	65	—	—
MaxSpeed (mi/h)	—	70	—	—	—	70	—	—
MaxLength (ft)	—	75	—	—	—	75	—	—
ZoneLength (ft)	—	20	—	—	—	20	—	—

—No data.

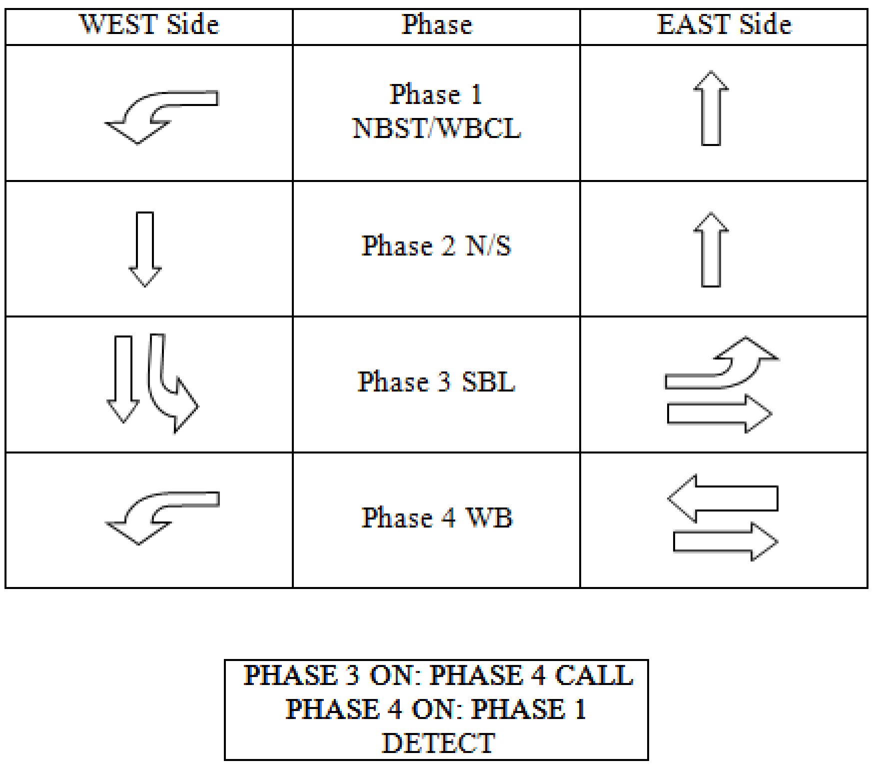


Figure 8. Chart. Phase sequence for U.S. 27/Pines Blvd.

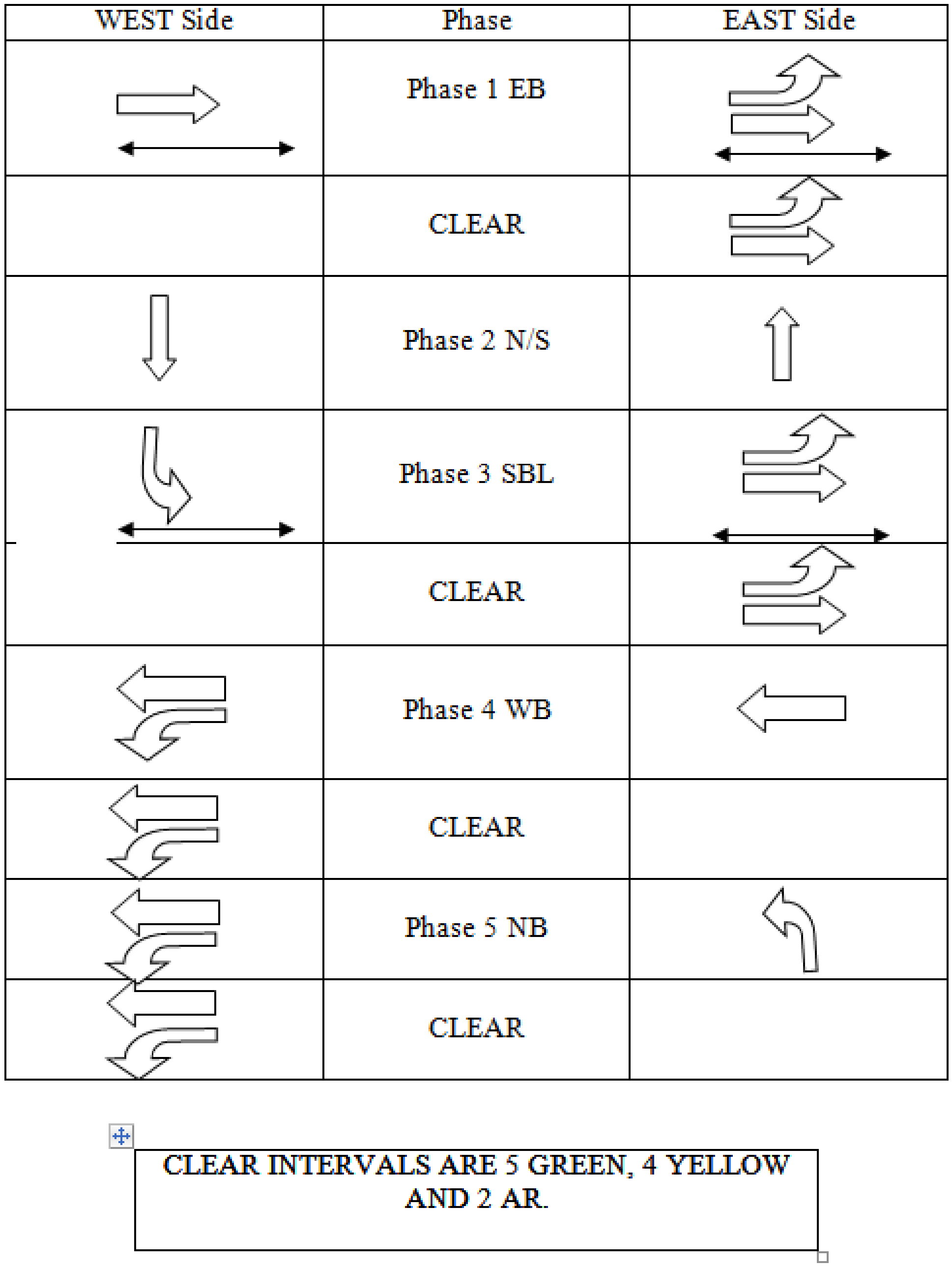
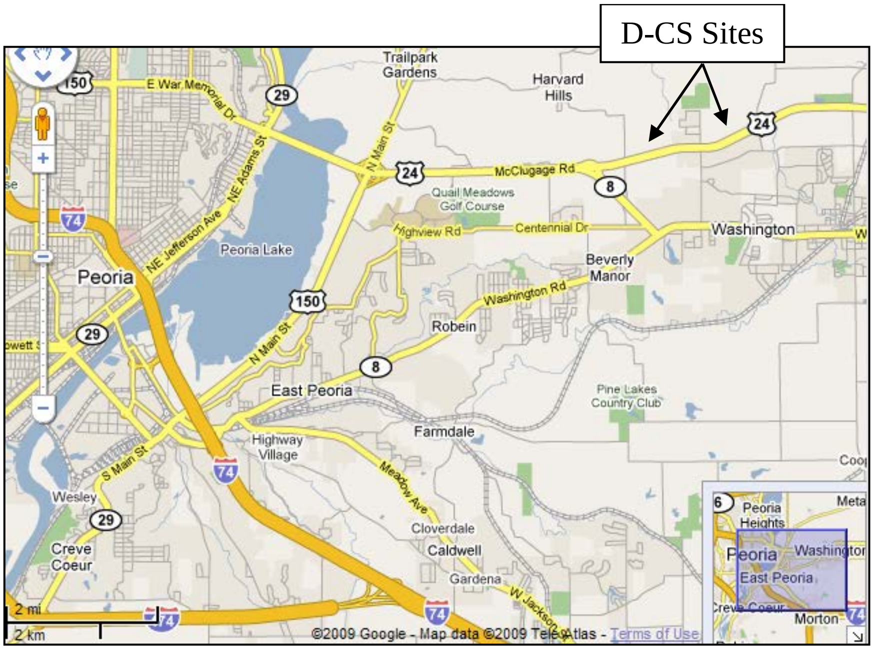


Figure 9. Chart. Phase sequence for U.S. 27/Johnson St.

Sites 4 and 5 Information

Illinois data collection followed Florida. The two Illinois sites were located east of Peoria on U.S. 24—one at the intersection with Cummings Lane and the other at the intersection with Main Street near Washington, IL. Figure 10 shows an area map indicating the location of the two Illinois sites. The two intersections had almost identical geometry, with two through lanes on each high-speed approach and single lane left-turn bays on each high-speed approach. Figure 11 and figure 12 show the intersection details. Table 19 through table 22 provide controller settings.



Original image: ©Google® Map Data 2009 Tele Atlas; map annotations provided by TTI.

Figure 10. Map. Washington, IL, D-CS sites.[(8)]

Challenges to Data Collection

IDOT used a single 6-ft by 6-ft inductive loop located about 5 s travel time upstream of the intersection for dilemma-zone detection at the Cummings and Main intersections. These loops were all still operational for collecting the before data. The distances from the D-CS loops to the stop line were 1,000 ft in all cases. Vehicular speeds at these sites adhered closely to the speed limit of 55 mi/h. Traffic at these intersections appeared to be primarily commuter traffic, with a pronounced peak in the morning and afternoon periods.

One of the challenges to the before data collection at the Illinois sites was loss of power, resulting in loss of some controller settings. Upon restoration of power, IDOT personnel noticed the problem with controller settings and worked with TTI personnel to get the appropriate settings reloaded. IDOT apparently set a relatively high value for passage time in the before condition to ensure clearance of the stopped queue, even though the only detector was 330 ft from the stop line. A question arose in trying to reset the passage time regarding how much time would be appropriate. TTI research personnel convinced IDOT to reduce it to 5 s.

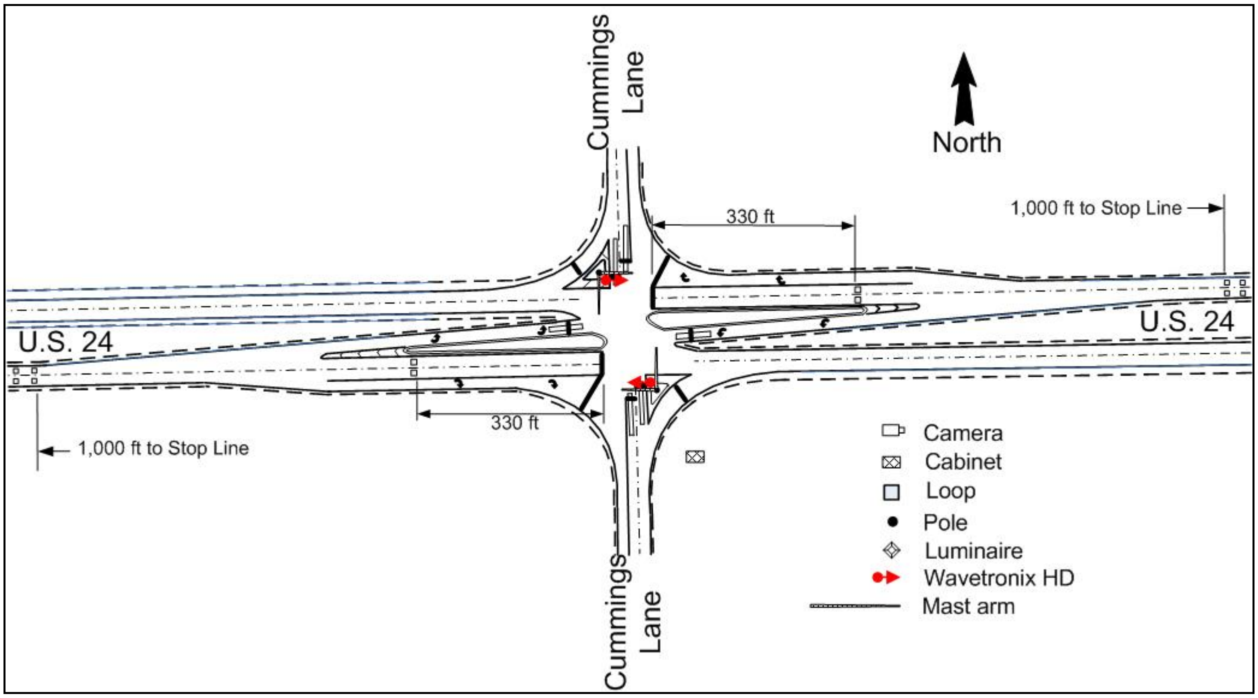


Figure 11. Map. Intersection layout at U.S. 24 and Cummings Ln.

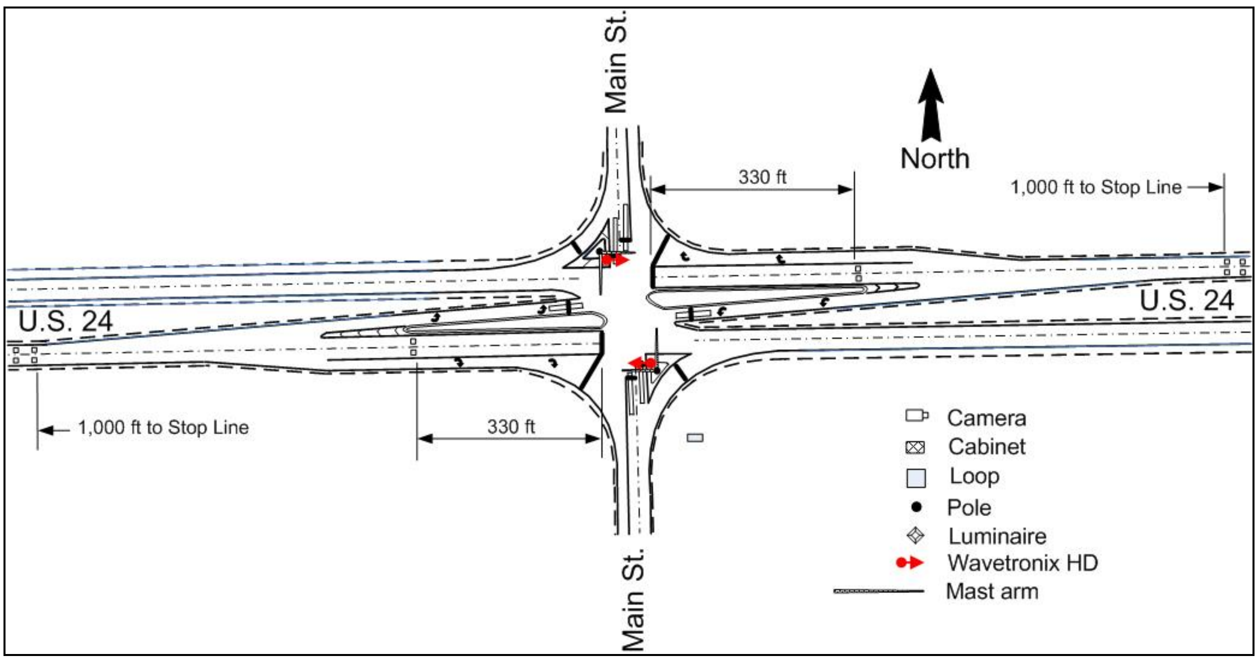


Figure 12. Map. Intersection layout at U.S. 24 and Main St.

Table 19. Controller settings for U.S. 24/Cummings Ln.—before D-CS.

Setting	Phase							
	1	2	3	4	5	6	7	8
MinGrn (s)	4	15	—	10	4	15	—	10
Passage (s)	2	6	—	2	2	6	—	25
Max1 (s)	20	65	—	25	20	65	—	2
Max2 (s)	25	60	—	30	25	60	—	30
Yel (s)	3.5	5	—	4.5	3.5	5	—	4.5
Red Clearance (s)	1.5	1.7	—	2.2	1.5	1.7	—	2.2

—No data.

Table 20. Controller settings for U.S. 24/Cummings Ln.—after D-CS.

Setting	Phase							
	1	2	3	4	5	6	7	8
TrapDist (ft)	—	1,000	—	—	—	1,000	—	—
DZArrive (s)	—	6	—	—	—	6	—	—
DZExit (s)	—	2	—	—	—	2	—	—
Stage (percent)	—	75	—	—	—	75	—	—
MaxSpeed (mi/h)	—	70	—	—	—	70	—	—
MaxLength (ft)	—	75	—	—	—	75	—	—
ZoneLength (ft)	—	20.3	—	—	—	20.2	—	—

—No data.

Table 21. Controller settings for U.S. 24/Main St.—before D-CS.

Setting	Phase							
	1	2	3	4	5	6	7	8
MinGrn (s)	4	15	—	10	4	15	—	10
Passage (s)	2	6	—	2	2	6	—	25
Max1 (s)	20	65	—	25	20	65	—	2
Max2 (s)	25	60	—	30	25	60	—	30
Yel (s)	3.5	5	—	4.5	3.5	5	—	4.5
Red Clearance (s)	1.5	1.7	—	2.2	1.5	1.7	—	2.2

—No data.

Table 22. Controller settings for U.S. 24/Main St.—after D-CS.

Setting	Phase							
	1	2	3	4	5	6	7	8
TrapDist (ft)	—	1,000	—	—	—	1,000	—	—
DZArrive (s)	—	6	—	—	—	6	—	—
DZExit (s)	—	2	—	—	—	2	—	—
Stage (percent)	—	75	—	—	—	75	—	—
MaxSpeed (mi/h)	—	70	—	—	—	70	—	—
MaxLength (ft)	—	75	—	—	—	75	—	—
ZoneLength (ft)	—	20.3	—	—	—	20.2	—	—

—No data.

Site 6 Information

Figure 13 shows an area map indicating the location of the Louisiana site, which is the intersection of LA 3235 and LA 3162. The location is near the small town of Galliano, LA, in the Lafourche Parish, about 60 mi south of New Orleans. LA 3235 is a high-speed roadway with speed limits on each approach at 55 mi/h, although observed local traffic speeds were higher. The D-CS approaches have two through lanes, a left-turn lane for the southbound approach, and a right-turn lane for the northbound approach. Three of the intersection legs serve general purpose traffic, and the fourth leg (eastbound) serves a casino and a convenience store. The only before detection at this intersection was at the stop line, so D-CS should significantly improve the safety of the intersection. Figure 14 shows the geometric layout of the intersection, indicating the location of detectors used for field data collection. Table 23 and table 24 provide controller settings for the before and after conditions.

A challenge at this site was an apparent conflict in the cabinet between the serial ports on the PC running the TTI software and the extra unused BIUs being turned on. After turning these extra BIUs off and operating with only the needed BIUs, the TTI data collection system ran normally. Solving this problem required an additional trip by one TTI person to meet Naztec personnel at the site. A second challenge was being able to monitor side street demand to determine how many legitimate max-outs occurred. In the before data collection, LaDOTD had set the main street phases to maximum recall (i.e., the main street phases were maxing out during each cycle of the day in the before data collection). LaDOTD was using an Autoscope™ mini-hub connected to the controller bus, which precluded the TTI equipment from monitoring the side street detectors in the after data collection. Therefore, determining the number of max-outs was not possible. However, the intersection functioned as it did prior to the installation of the D-CS equipment, which was important in determining before-after differences.

Original image: ©Google® Map Data 2009 Tele Atlas; map annotation provided by TTI.

Figure 13. Map. Louisiana D-CS site.(9)

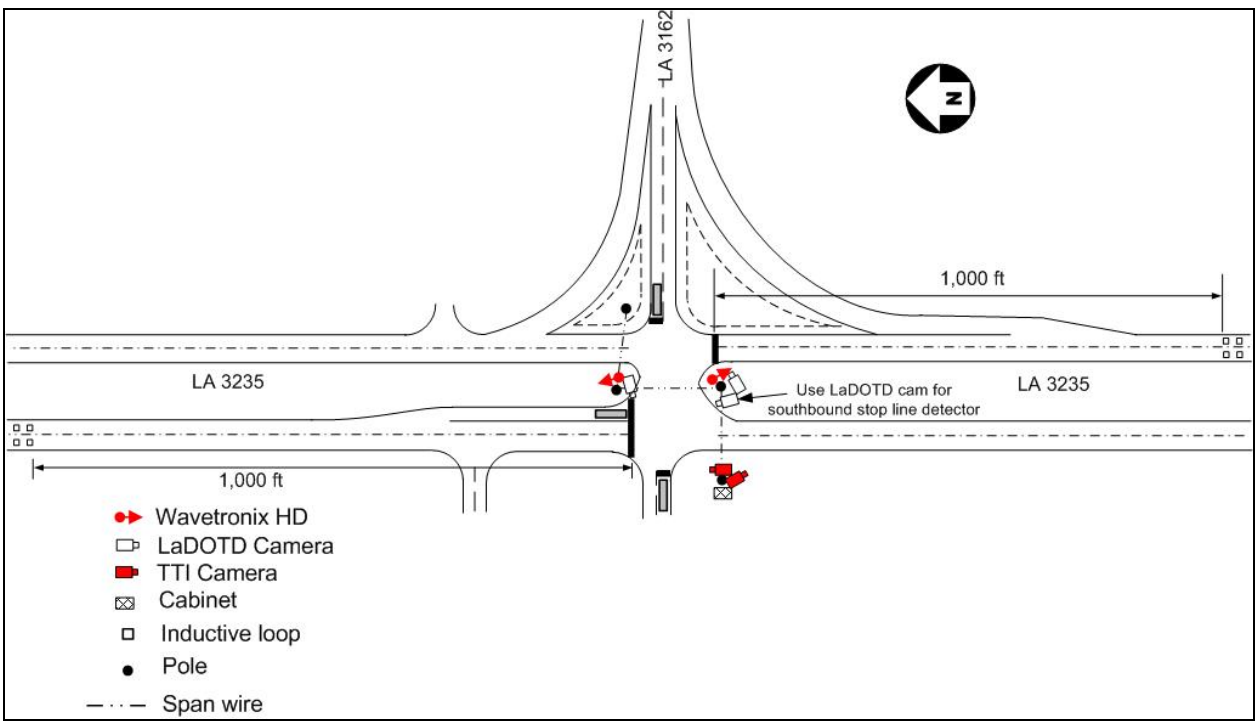


Figure 14. Map. Intersection layout at LA 3235 and LA 3162.

Table 23. Controller settings for LA 3235/LA 3162—before D-CS.

Setting	Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
MinGrn (s)	6	15	5	10	5	15	5	10
Passage (s)	1.5	2	1	1.5	1	2	1	1.5
Max1 (s)	15	75	25	25	25	75	25	35
Max2 (s)	15	75	50	25	50	75	50	35
Yel (s)	5.8	5.8	3.5	4.3	3.5	5.8	3.5	4.3
Red Clearance (s)	1	1	1.5	1.2	1.5	1	1.5	1.2

Table 24. Controller settings for LA 3235/LA 3162—after D-CS.

Setting	Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
TrapDist (ft)	—	1,000	—	—	—	1,000	—	—
DZArrive (s)	—	6	—	—	—	6	—	—
DZExit (s)	—	2	—	—	—	2	—	—
Stage (percent)	—	75	—	—	—	75	—	—
MaxSpeed (mi/h)	—	75	—	—	—	75	—	—
MaxLength (ft)	—	80	—	—	—	80	—	—
ZoneLength (ft)	—	20.5	—	—	—	20.5	—	—

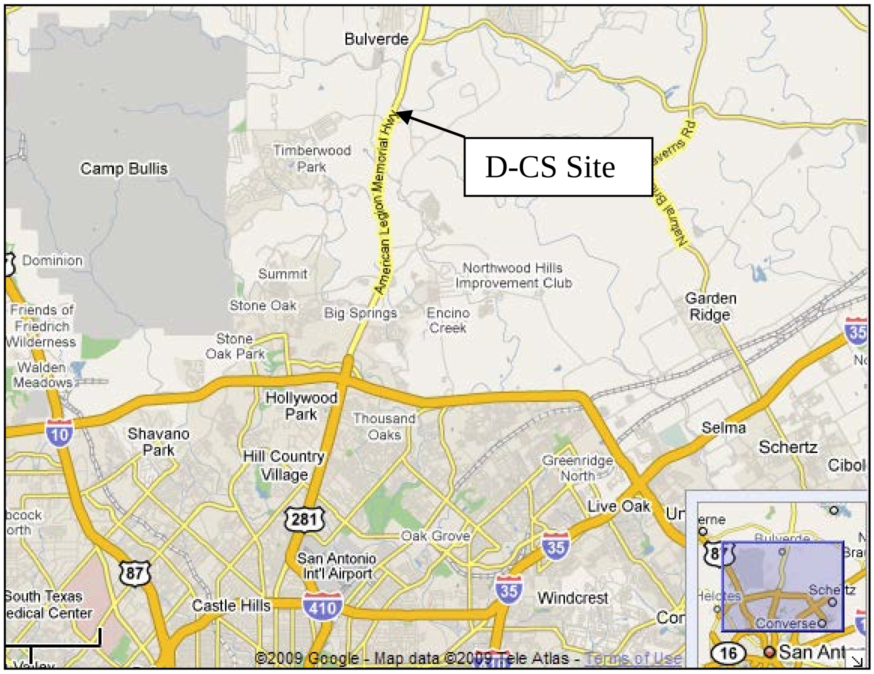
—No data.

Sites 7 and 8 Information

U.S. 281 at E. Borgfeld Drive in San Antonio

Figure 15 shows an area map indicating the location of the San Antonio site. The location is an isolated intersection north of the urbanized area surrounding San Antonio. Peak periods at this site indicated that a significant portion of the traffic was commuter traffic, with heavy inbound movement in the morning hours and heavy outbound movement during the late afternoon hours. This traffic was the heaviest of any of the D-CS data collection sites used in this project and was useful for conducting the Upper Limit Study.

Figure 16 shows the geometric layout of the intersection. The three-way intersection has two through lanes on the U.S. 281 approaches, while Borgfeld Drive has one lane in each direction away from the intersection. At the intersection, the northbound and eastbound approaches have left-turn bays. The U.S. 281 approaches had a series of seven inductive loops (each loop crossing both lanes) for dilemma-zone protection with distances from the stop line of 48, 93, 157, 239, 321, 425, and 534 ft. Table 25 through table 27 provide the controller settings for the original Eagle controller, the Naztec 2070 controller with the before settings, and the Naztec 2070 controller with the D-CS settings, respectively. Naztec representatives were supposed to enter settings in their controller (table 26) to replicate the operation of the original Eagle controller (table 25).



Original image: ©Google® Map Data 2009 Tele Atlas; map annotation provided by TTI.

Figure 15. Map. San Antonio, TX, D-CS site.[10]

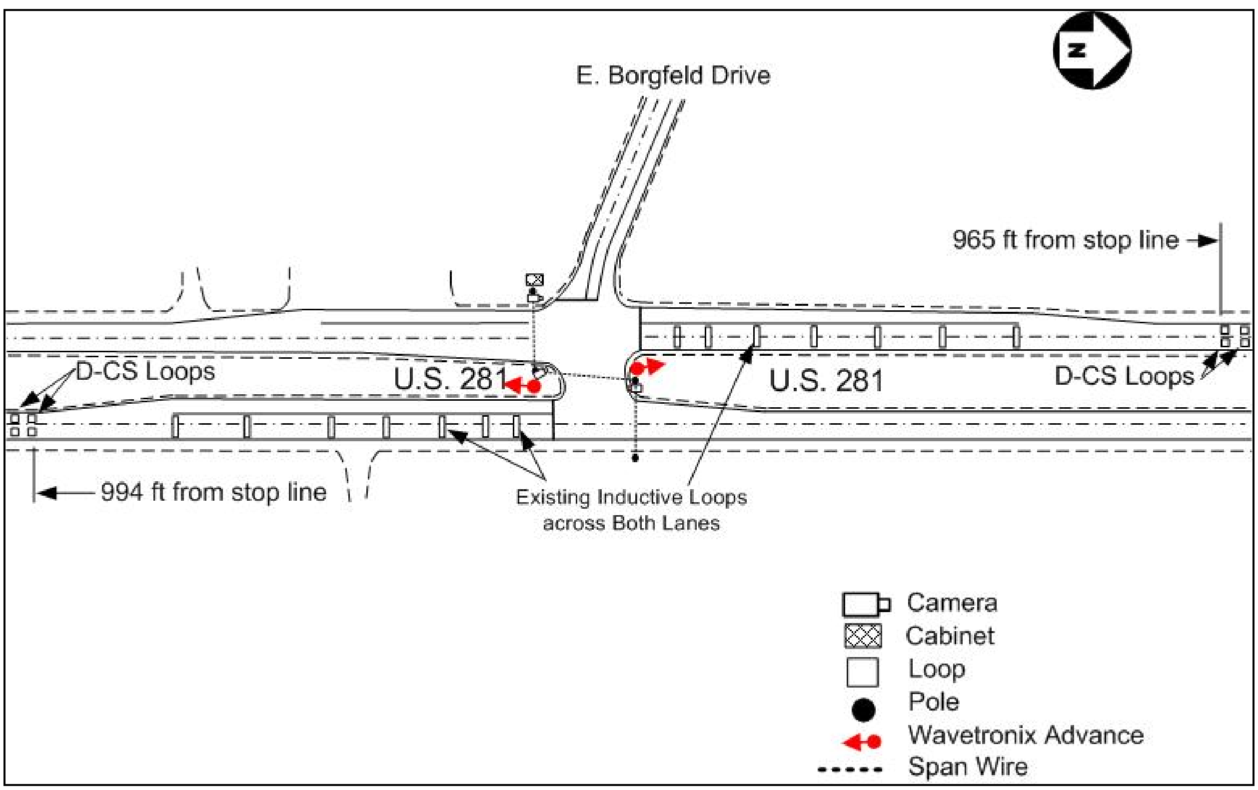


Figure 16. Map. Intersection layout at U.S. 281/E. Borgfeld Dr.

Table 25. Controller settings for U.S. 281/Borgfeld Dr.—before D-CS, Eagle controller.

Setting	Phase							
	1	2	3	4	5	6	7	8
MinGrn (s)	6	20	—	—	—	20	—	8
Passage (s)	5	10	—	—	—	10	—	0
Max1 (s)	30	55	—	—	—	55	—	30
Max2 (s)	30	65	—	—	—	65	—	30
Yel (s)	5	5.8	—	—	—	5.8	—	4.3
Red Clearance (s)	1.4	1.9	—	—	—	1.9	—	1.8

—No data.

Table 26. Controller settings for U.S. 281/Borgfeld Dr.—before D-CS, Naztec controller.

Setting	Phase							
	1	2	3	4	5	6	7	8
MinGrn (s)	6	20	—	—	—	20	—	8
Passage (s)	5	10	—	—	—	10	—	0
Max1 (s)	30	75	—	—	—	75	—	30
Max2 (s)	30	65	—	—	—	65	—	30
Yel (s)	4.7	5.8	—	—	—	5.8	—	4.3
Red Clearance (s)	1.6	1.9		—	—	1.9	—	1.8

—No data.

Table 27. Controller settings for U.S. 281/Borgfeld Dr.—after D-CS, Naztec controller.

Setting	Phase							
	1	2	3	4	5	6	7	8
TrapDist (ft)	—	965	—	—	—	994	—	—
DZArrive (s)	—	6	—	—	—	6	—	—
DZExit (s)	—	2	—	—	—	2	—	—
Stage (percent)	—	60	—	—	—	60	—	—
MaxSpeed (mi/h)	—	70	—	—	—	70	—	—
MaxLength (ft)	—	65	—	—	—	65	—	—
ZoneLength (ft)	—	20	—	—	—	19	—	—

—No data.

An important aspect of this site involved using the Naztec 2070 controller with a non-Naztec (Eagle) cabinet. Six of the eight sites involved in this research had Naztec controllers and cabinets, so this site offered a good opportunity to test the compatibility of this controller with a different cabinet (the other non-Naztec controller was at the Waco site, described below). During the initial installation of the Naztec controller for beginning data collection about May 30, 2009, the intersection went into flash mode when a detector BIU was unplugged. This occurrence could have been coincidental with removal of the BIU, but Naztec replaced the MMU anyway and was able to restore normal operation following this change.

TTI completed its normal data collection during the selected before/after period, which ended on July 27, 2009, before another problem occurred related to lightning (according to district personnel). The lightning strike again caused the intersection to go into flash mode. The Naztec controller had operated the intersection successfully for the 8-week period between the installation date of the Naztec controller and the lightning strike. As a temporary fix, district personnel replaced the Naztec controller with the original Eagle controller until Naztec could troubleshoot its 2070 controller. TxDOT shipped the controller back to Naztec during the week of August 17, 2009, to allow Naztec to troubleshoot the problem. Naztec found that the CPU board had been damaged; a technician from Naztec returned the repaired controller to the district on September 31, 2009. TTI reinstalled its monitoring equipment at the U.S. 281/Borgfeld intersection on October 1, 2009, and began collecting data for the Upper Limit Study.

Upper Limit Study: TTI increased the maximum green setting in the D-CS 2070 controller on November 3, 2009, at the intersection of U.S. 281/Borgfeld to test its upper limit. At this intersection, Naztec and TTI set an initial maximum green of 75 s for phases 2 and 6. After some consideration of adding 80 and 85 s, TTI selected 85 and 95 s as the desired additional values to test because of the increased statistical significance in the greater spread.

U.S. 84 at Speegleville Road in Waco

Figure 17 shows an area map indicating the location of the Waco site, which is at the intersection of U.S. 84 and Speegleville Road. The location is southwest of Waco and outside the urban area. U.S. 84 is a high-speed roadway with a speed limit of 60 mi/h on each approach and a significant number of trucks. The D-CS approaches have two through lanes, single left-turn lanes, and single right-turn lanes. All four of the intersection legs serve general purpose traffic. Detection prior to installation of D-CS being installed consisted of a series of inductive loops upstream for dilemma-zone protection. Dilemma-zone detectors were 6-ft by 6-ft loops in each lane at 493, 267, and 111 ft from the stop line. Through lanes on U.S. 84 had no stop-line detection, but left-turn bays did. Figure 18 shows the geometric layout of the intersection, indicating the location of detectors used for field data collection.

Original Image: ©Google® Map Data 2009 Tele Atlas; map annotation provided by TTI.

Figure 17. Map. Waco, TX, D-CS site.(11)

The D-CS site in Waco had a NEMA TS1 cabinet, and City of Waco decisionmakers chose not to replace this cabinet with a TS2 cabinet to accommodate the D-CS, even though they were convinced that D-CS had made a significant difference in improving safety. On the first visit to this site, TTI researchers found that the PC running the D-CS algorithm had failed, so they prepared a replacement PC to be installed in the cabinet. Other TTI researchers had already wired the cabinet for a PC system, reducing the effort required to reinstall D-CS.

An issue that surfaced immediately following the reinstallation of D-CS at this site was due to not having stop-line detectors on through lanes. The City of Waco technicians had disconnected all previously installed dilemma-zone loops so that only the D-CS loops were connected for main street dilemma-zone protection. The D-CS algorithm does not start its search for gaps in the traffic stream until the termination of the minimum green in the controller. In this case, with the formation of long queues extending past the D-CS loops, the algorithm did not detect gaps appropriately, so it terminated the green phase prematurely with each cycle. The solution involved reconnecting the nearest inductive loops (located 111 ft from the stop line) and allowing the queue to begin clearing and for D-CS to function properly. With reconnection of the closest loops to the stop line, D-CS was able to function properly. At the first gap-out (or at the end of the minimum green setting, which was usually sooner), D-CS took over and started looking for gaps to safely end the green phase. Table 28 and table 29 provide the controller settings for the U.S. 84/Speegleville Road intersection.

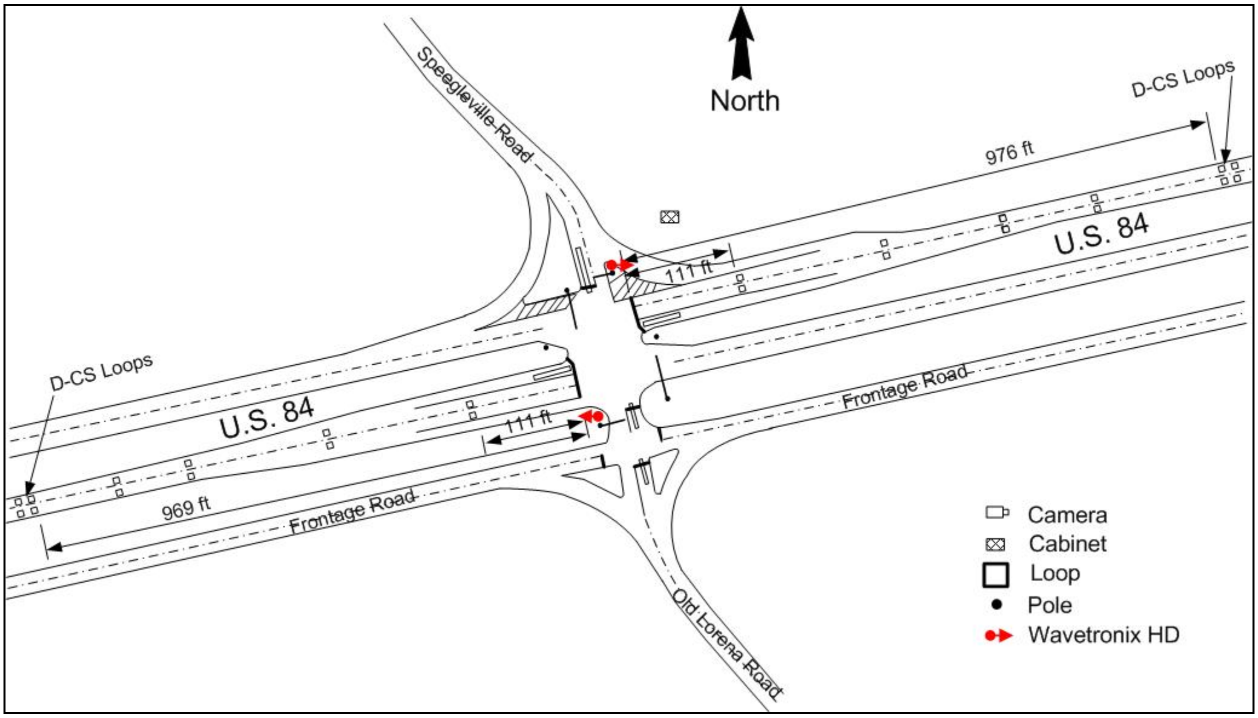


Figure 18. Map. Intersection layout at U.S. 84/Speegleville Rd.

Table 30 summarizes the speed limit and the dilemma-zone detection type used before installation of D-CS, stop-line detection, and distance to D-CS loops. Obviously, the best comparison of D-CS was with systems that had at least reasonably adequate dilemma-zone protection in the before condition. Therefore, the best comparisons are with Illinois and Texas sites.

Table 28. Controller settings for U.S. 84/Speegleville Rd.—before D-CS.

Setting	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
MinGrn (s)	4	15	—	4	3	15	4	4
Passage (s)	30	30	—	15	15	40	30	15
Max1 (s)	15	70	—	15	15	70	30	15
Max2 (s)	30	65	—	—	—	65	—	30
Yel (s)	4	4.5	—	4.5	4	4.5	4	4.5
Red Clearance (s)	1	2.5	—	2.5	1	2.5	1	2.5

—No data.

Table 29. Controller settings for U.S. 84/Speegleville Rd.—after D-CS.

Setting	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
TrapDist (ft)	—	969	—	—	—	976	—	—
DZArrive (s)	—	6	—	—	—	6	—	—
DZExit (s)	—	2	—	—	—	2	—	—
Stage (percent)	—	60	—	—	—	60	—	—
MaxSpeed (mi/h)	—	70	—	—	—	70	—	—
MaxLength (ft)	—	75	—	—	—	75	—	—
ZoneLength (ft)	—	20	—	—	—	19	—	—

—No data.

Table 30. Site summary information.

Site Description	Speed Limit (mi/h)	Dilemma Zone Detection Used During Before Period	Stop Line Detection	Distance to D-CS Loops[1]	Phase
U.S. 27/ Pines Blvd.	55 (NB) 55 (SB)	None	Video	800 ft (NB) 815 ft (SB)	2 6
U.S. 27/ Griffin Rd.	55 (NB) 55 (SB)	None	Video	790 ft (NB) 800 ft (SB)	2 6
U.S. 27/ Johnson St.	55 (NB) 55 (SB)	None	Video	790 ft (NB) 800 ft (SB)	2 6
U.S. 24/ Main St.	55 (EB) 55 (WB)	One loop/approach[2]	Video	1,000 ft (EB) 1,000 ft (WB)	2 6
U.S. 24/ Cummings La.	55 (EB) 55 (WB)	One loop/approach	Video	1,000 ft (EB) 1,000 ft (WB)	2 6
LA 3162/ LA 3235	55 (NB) 55 (SB)	None	Video	1,000 ft (NB) 1,000 ft (SB)	2 6
U.S. 281/ E. Borgfeld Dr.	65 (NB) 65 (SB)	Multiple loops 7 sets	Loops	994 ft (NB) 965 ft (SB)	6 2
U.S. 84/ Speegleville Rd	60 (EB) 60 (WB)	Multiple loops 3 sets[3]	Loops	969 ft (EB) 976 ft (WB)	2 6

[1]Measured from stop line to trailing edge of exit loop.
[2]Single 6-ft by 6-ft loop located at 405 ft (about 5-s travel time) from stop line.
[3]City of Waco used distances from the stop line of 111, 267, and 493 ft.

TRAFFIC DATA ANALYSIS

Most of the results presented in this section were generated by human observers watching replay of recorded video of vehicles at each of the eight intersections. The monitoring system in each case involved a video camera/processor system to detect RLRs and a second (redundant) system that monitored vehicles caught in the dilemma zone. At each site, the process defined the dilemma zone as a range in travel time from 2 to 6 s. The redundant monitoring system consisted of two components: 1) the inductive loop pairs used for the D-CS, and 2) a Wavetronix™ Advance radar detector for each high-speed approach. The camera providing data to the video image processor also served as a surveillance camera to assist observers in verifying RLRs and vehicles in the dilemma zone. The inductive loops provided vehicle length and speed, and the radar detectors monitored speed and distance to each vehicle on the approach. TTI researchers were able to read the data stream from the radar detector's serial port that updated speed and distance for each approaching vehicle every few milliseconds. This continuous stream of data provided enough information on approaching vehicles to serve as its own prediction of vehicles in the dilemma zone.

The following results are categorized according to the four studies. Studies 1 and 3 are similar, so results are combined into one section. Results from study 4, the Upper Limit Study, also come later in this section. Results from study 2 will come later in the final report at the end of the project because final crash data will not be available until that time.

Studies 1 and 3 Results

Table 31 and table 32 provide summary statistics describing the variables in the before-after database. The data in each row of either table reflect about 1 h of data collection for one signal phase at the associated intersection location. The data in table 31 indicate that the study observed more than 1,300 signal cycles at six locations. During these cycles, 88 vehicles entered the intersection within 6 s following the change in signal indication from yellow to red. Collectively, the intersections had both very low and very high traffic flow rates (120 to 1,512 vehicles/h). They also experienced a wide range in cycle length (57 to 127 s). These wide ranges added a desired breadth in the range of conditions represented in the database.

As a first step in the analysis of the data, analysts computed red-light violation rates for each intersection approach, resulting in computation of two rates. The first rate is expressed in terms of red-light-running events per 1,000 vehicles. The second rate represents the number of red-light-running events per 10,000 vehicle-cycles, where "cycles" represents the average number of cycles per h during the period for which vehicles are counted. The use of "vehicle-cycles" is based on previous research demonstrating that exposure for red-light violations should be based on the count of vehicles and the count of cycles.(3) Table 32 includes both of these rates.

The overall average rates at the study locations are 5.3 red-light violations per 1,000 vehicles and 1.1 red-light violations per 10,000 vehicle-cycles. This number is the average for all sites where the rate in column 4 of table 32 is computed using total red-light running events divided by the total approach vehicles, and the rate in column 5 is computed using the equation in footnote C. The former rate is at the higher end of a range found in the literature (3.0 to 5.3 violations per 1,000 vehicles). Specifically, data reported by Kamyab et al. indicate an average rate of 3.0 violations per 1,000 vehicles.(6) Data reported by Baguley indicate an average rate of 5.3 violations per 1,000 vehicles.(7) Bonneson and Son reported 4.1 violations per 1,000 vehicles and 1.0 violations per 10,000 vehicle-cycles.(3)

Table 31. Before-after database summary—total observations.

Location	Study Hour and Phase	Study Period	Cycles	Flow Rate,[1] vehicles/h	Cycle Length[2]	Number of Vehicles in Dilemma Zone,[1] Vehicles	Number of Max-Outs[1]	Number of Red-Light Violations,[1] Vehicles
U.S. 27/ Griffin Rd.	17:00 Ph. 6	Before	56	493	65	23	0	9
		After	46	475	79	7	0	1
	7:00 Ph. 6	Before	52	560	69	26	0	8
		After	43	502	84	2	1	0
U.S. 27/ Johnson St.	8:00 Ph. 2	Before	40	402	89	15	4	7
		After	40	324	89	3	0	0
	13:00 Ph. 2	Before	37	401	94	17	0	9
		After	39	388	89	1	0	0
U.S. 24/ Main St.	10:00 Ph. 2	Before	62	137	58	0	0	1
		After	58	120	60	0	0	0
U.S. 24/ Cummings Ln.	7:00 Ph. 6	Before	57	696	63	5	0	3
		After	54	663	66	3	0	0
	8:10 Ph. 6	Before	63	537	57	9	0	3
		After	60	577	59	0	0	0
	17:10 Ph. 2	Before	57	534	62	—	0	2
		After	49	551	72	—	1	0
	16:00 Ph. 2	Before	57	622	63	—	0	2
		After	48	617	75	—	0	1
LA 3162/ LA 3235	14:20 Ph. 6	Before	31	836	113	5	—	2
		After	53	845	68	9	—	1
	13:10 Ph. 6	Before	30	361	118	9	0	3
		After	54	359	66	7	0	1
U.S. 84/ Speegleville Rd.	7:00 Ph. 2	Before	34	1465	107	52	20	13
		After	28	1512	127	13	7	4
	8:10 Ph. 2	Before	46	582	78	—	6	3
		After	41	601	89	—	0	1
	16:30 Ph. 6	Before	41	885	91	—	0	10
		After	35	896	106	—	2	4
Total		Before	663	8511	81	161	30	75
		After	648	8430	81	45	11	13
Percent Change[3]			-2.3	-1.0	0.0	-72	-63	-83
Total			1,311	16,941	81	206	41	88

[1]Flow rate and counts include both passenger cars and heavy vehicles.
[2]Cycle length in the total rows represents an average length (not a sum).
[3]Percent change = 100 x (after/before - 1.0).
—Data not available.

Table 32. Before-after database summary—red-light-running violation rates.

Location	Study Hour	Study Period	RLRs per 1,000 Vehicles	RLRs per 10,000 Vehicle-Cycles
U.S. 27/Griffin Rd.	17:00	Before	18.4*	3.3
		After	2.1	0.5
	7:00	Before	14.6	2.7
		After	0.0	0.0
U.S. 27/Johnson St.	8:00	Before	17.9	4.4*
		After	0.0	0.0
	13:00	Before	23.8*	6.1*
		After	0.0	0.0
U.S. 24/Main St.	10:00	Before	7.4	1.2
		After	0.0	0.0
U.S. 24/Cummings Ln.	7:00	Before	4.4	0.8
		After	0.0	0.0
	8:10	Before	5.7	0.9
		After	0.0	0.0
	17:10	Before	3.9	0.7
		After	0.0	0.0
	16:00	Before	3.3	0.6
		After	1.7	0.3
LA 3162/LA 3235	14:20	Before	2.5	0.8
		After	1.2	0.2
	13:10	Before	8.8	2.8
		After	2.9	0.5
U.S. 84/Speegleville Rd.	7:00	Before	9.0	2.6
		After	2.8	0.9*
	8:10	Before	5.3	1.1
		After	1.7	0.4
	16:30	Before	11.1	2.8
		After	4.5*	1.3
Overall Average Rates Based on Total Observations for All Sites		Before	9.0	1.9
		After	1.6	0.3
Percent Change[1]			-82	-82
Average[2]			5.3	1.1

[1]Percent change = 100 x (after/before - 1.0).
[2]RLRs per 10,000 vehicle-cycles = count of red-light violations x 10,000 x Σ study hours / (Σ vehicles x Σ cycles).
*Values exceed the average rate by a factor of 2.0 or more.

The red-light violation rates listed in table 32 provide some indication of the extent of red-light violations at the intersections studied. The vehicle-based rates listed in column 4 indicate that three locations exceeded the average rate for the corresponding study period by a factor of 2.0 or more. The rates listed in column 5 indicate that three locations exceeded the corresponding average rate by 2.0 or more. Clearly, there is some discrepancy regarding which locations are the most problematic. This discrepancy illustrates the importance of considering both volume and number-of-cycles when computing the red-light violation rate for location-based comparison or evaluation. The vehicle-cycle-based rate logically represents a more reliable measure of the propensity for red-light violation than the vehicle-based rate because it accounts for two measures of exposure to a red-light violation.

Statistical Analysis Method

A preliminary examination of the data indicated that they are neither normally distributed nor of constant variance, as is assumed when using traditional least-squares regression. Under these conditions, the generalized linear modeling technique is appropriate because it accommodates the explicit specification of an error distribution using maximum-likelihood methods for coefficient estimation.

The distribution of violation frequency can be described as negative binomial because there are two different sources of variability. One source of variability stems from the differences in the mean frequency *m* among the otherwise similar intersection approaches. The other source stems from the randomness in frequency at any given site, which follows the Poisson distribution. The variance of the negative binomial distribution is seen in figure 19:

$$V(x) = E(m) + \frac{E(m)^2}{k}$$

Figure 19. Equation. Variance of distribution.

Where:

$V(x)$ is the variance of the distribution.

x is the observed violation frequency for a given approach having an expected frequency of $E(m)$ and dispersion parameter k.

Researchers used the GENMOD regression procedure in the statistical analysis system software to estimate the model coefficients.[(12)] This procedure is often used to calibrate regression models using count data with a large amount of variability (e.g., crash frequency).

Model Calibration

The regression analysis indicated that relationships existed between red-light violation frequency and exposure (expressed as the ratio of flow rate to cycle length), location, and the type of detection-and-control system used. Findings indicate that the regression coefficient associated with each of these factors was significant at a level of confidence that exceeded 95 percent. As a result of this analysis, the linear regression terms were specified in the model using the formulation in figure 20.

$$E[R] = \left(\frac{Q}{C}\right)^{b_1} \times e^{(b_0 + b_2 I_{cummings} + b_3 I_{after})}$$

Figure 20. Equation. Expected red-light-running frequency.

Where:

$E[R]$ = expected red-light-running frequency, vehicles/h.

Q = approach flow rate, vehicles/h.

C = cycle length, s.

$I_{Cummings}$ = indicator variable (= 1.0 for U.S. 24/Cummings Lane location; 0.0 otherwise).

I_{after} = indicator variable (= 1.0 for data from the after study period, 0.0 otherwise).

This analysis also applied the equation shown to model dilemma-zone frequency and max-out frequency. In each case, the process substituted the corresponding dependent variable for $E[R]$ in figure 20.

Red-Light Violation Model Results

The regression analysis indicated that the calibrated model accounted for most of the variability in the data. The U.S.24/Cummings Lane location required one location-specific indicator variable because this location experienced less than one-half of the violations of the other locations, all other factors considered. The model variables explain the differences among the other locations.

Table 33 shows the statistics related to the calibrated red-light-running model. The calibrated coefficient values can be used with figure 20 to predict the hourly red-light-running frequency for a given intersection approach. The analysis found that a dispersion parameter k of 54.9 yielded a scaled Pearson χ^2 of 1.07. The Pearson χ^2 statistic for the model is 25.7, and the degrees of freedom are 24 (= n-p-1 = 28-3-1). Because this statistic is less than $\chi^2_{0.05, 24}$ (= 36), the hypothesis that the model fits the data cannot be rejected. A measure of model fit that is appropriate for negative binomial error distributions is R_K^2, as developed by Miaou.(13) The interpretation of this statistic is the same as for the coefficient of determination R^2 (i.e., that values near 1.0 suggest a very good fit to the data). R_K^2 for the calibrated model is 0.98.

Table 33. Calibrated red-light violation model statistical description.

Model Statistics		Value		
RK^2:		0.98		
Scaled Pearson χ^2:		1.07		
Pearson χ^2:		25.7 (χ20.05, 24 = 36)		
Dispersion Parameter k:		54.9		
Observations:		28 h		
Range of Model Variables				
Variable	**Variable Name**	**Units**	**Minimum**	**Maximum**
Q	Approach flow rate	vehicles/h	120	1,512
C	Cycle length	s	57	127
Calibrated Coefficient Values				
Variable	**Definition**	**Value**	**Standard Deviation**	**t-statistic**
b0	Intercept	-7.895	2.378	-3.3
b1	Effect of exposure	0.970	0.269	3.6
b2	Effect of U.S. 24/Cummings Lane location	-1.374	0.340	-4.0
b3	Effect of change in detection and control	-1.733	0.309	-5.6

The last rows of table 33 list the regression coefficients for the model. The *t*-statistic shown indicates that all coefficients are significant at a 95-percent level of confidence or higher. A negative coefficient for b_3 indicates that red-light violations were less frequent during the after period. Based on the model structure, this coefficient can be converted into an equivalent reduction percentage of 82 percent (= 100 [1 - $e^{-1.733}$]). Thus, the analysis indicates that the after study periods experienced 82 percent fewer red-light violations than the before study periods. This reduction factor is consistent with the average change in violation rates shown at the bottom of table 32.

Researchers assessed the fit of the model through the graphical comparison of the observed and predicted red-light-running frequencies as shown in figure 21. The trend line in this figure does not represent the line of best fit; rather, it is a "$y = x$" line. The data would fall on this line if the model predictions exactly equaled the observed data. The trends shown in this figure indicate that the model is able to predict the red-light violation frequency without bias.

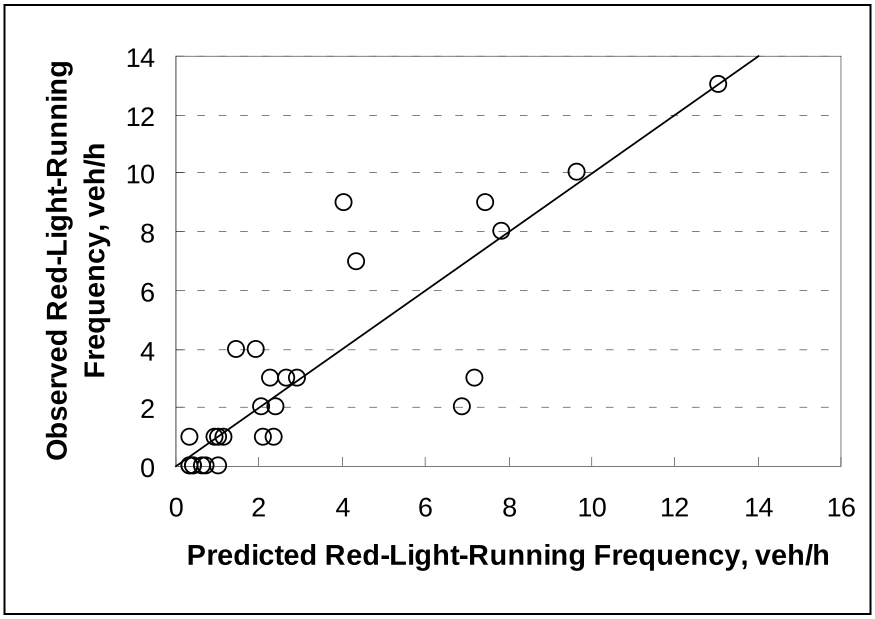


Figure 21. Graph. Comparison of observed and predicted red-light-running frequency.

Dilemma Zone Model Results

The model used for the dilemma-zone frequency analysis was the same as used for the red-light violation model. The regression analysis indicated that the calibrated model accounted for most of the variability in the data. Again, one location-specific indicator variable was needed to account for the U.S.24/Cummings Lane location. This location experienced less than one-half of the dilemma-zone count compared with the other locations, all other factors considered. The model variables explain differences among the other locations.

Table 34 shows the statistics related to the calibrated dilemma zone model. The calibrated coefficient values can be used with figure 20 to predict the hourly number of vehicles in the dilemma zone at yellow onset for a given intersection approach. A dispersion parameter *k* of 6.2 yielded a scaled Pearson χ^2 of 1.07. The Pearson χ^2 statistic for the model is 19.7 and the degrees of freedom are 20 (= *n*-*p*-1 = 24-3-1). Because this statistic is less than $\chi^2_{0.05, 20}$ (= 26), the hypothesis that the model fits the data cannot be rejected. R_K^2 for the calibrated model is 0.87. This value suggests that the model explains most of the variability in the data.

The last rows in table 34 show the regression coefficients for the model. The *t*-statistic shown indicates that all coefficients are significant at a 95-percent level of confidence or higher. A negative coefficient for b_3 indicates that there were fewer vehicles caught in the dilemma zone during the after period. Based on the model structure, this coefficient can be converted into an equivalent reduction percentage of 73 percent (= 100 [1 - $e^{-1.317}$]). Thus, the analysis indicates that the after study periods experienced 73 percent fewer vehicles in the dilemma zone than the before study periods.

Table 34. Calibrated dilemma zone model statistical description.

Model Statistics		Value		
RK^2:		0.87		
Scaled Pearson χ^2:		1.07		
Pearson χ^2:		19.7 (χ20.05, 20 = 26)		
Dispersion Parameter k:		6.2		
Observations:		20 h		
Range of Model Variables				
Variable	**Variable Name**	**Units**	**Minimum**	**Maximum**
Q	Approach flow rate	vehicles/h	120	1,512
C	Cycle length	s	57	127
Calibrated Coefficient Values				
Variable	**Definition**	**Value**	**Standard Deviation**	**t-statistic**
b0	Intercept	-10.912	2.745	-4.0
b1	Effect of exposure	1.376	0.274	5.0
b2	Effect of U.S. 24/Cummings Lane location	-1.621	0.381	-4.3
b3	Effect of change in detection and control	-1.317	0.266	-5.0

Researchers assessed the fit of the model through the graphical comparison of the observed and predicted dilemma-zone counts as indicated in figure 22. The trend line in this figure does not represent the line of best fit; rather, it is a "$y = x$" line. The data would fall on this line if the model predictions exactly equaled the observed data. The trends shown in this figure indicate that the model is able to predict the dilemma-zone count without bias.

Max-Out Model Results

The model used for the max-out frequency analysis was the same as used for the red-light violation model. The regression analysis indicated that the calibrated model accounted for most of the variability in the data. The U.S.24/Cummings Lane location required one location-specific indicator variable. This location experienced very few max-outs relative to the other locations. Model variables explain differences among the other locations.

Table 35 shows the statistics related to the calibrated max-out model. The calibrated coefficient values can be used with figure 20 to predict the hourly max-out frequency for a given intersection approach. A dispersion parameter k of 0.43 yielded a scaled Pearson χ^2 of 1.19. The Pearson χ^2 statistic for the model is 26.3, and the degrees of freedom are 22 (= n-p-1 = 26-3-1). Because this statistic is less than $\chi^2_{0.05, 22}$ (= 34), the hypothesis that the model fits the data cannot be rejected. R_K^2 for the calibrated model is 0.72. This value suggests that the model explains much of the variability in the data.

The last rows of table 35 show the regression coefficients for the model. The *t*-statistic shown indicates that all coefficients but one are significant at a 95-percent level. The coefficient b_3 for "effect of a change in detection and control" was not statistically significant.

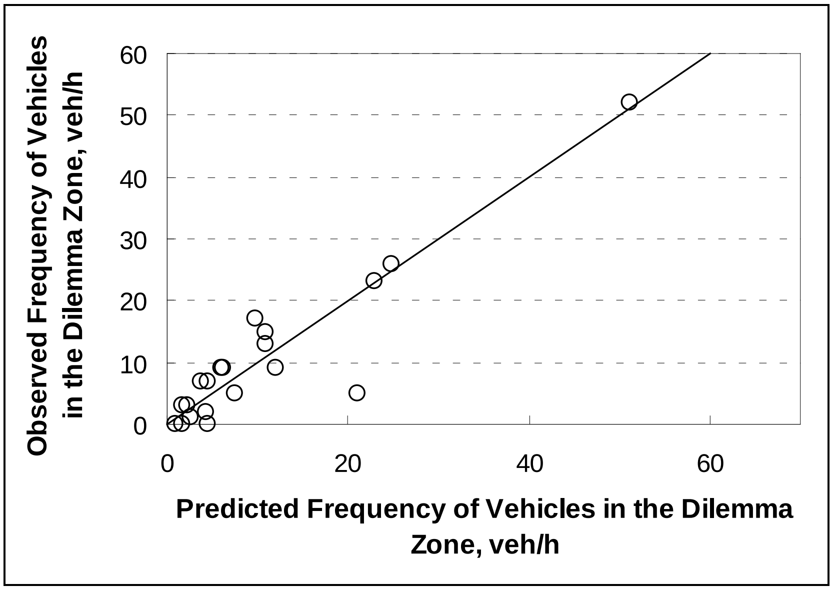


Figure 22. Graph. Comparison of observed and predicted number of vehicles in the dilemma zone.

Table 35. Calibrated max-out model statistical description.

Model Statistics		**Value**		
RK^2:		0.72		
Scaled Pearson χ^2:		1.19		
Pearson χ^2:		26.3 (χ20.05, 22 = 34)		
Dispersion Parameter k:		0.43		
Observations:		22 h		
Range of Model Variables				
Variable	**Variable Name**	**Units**	**Minimum**	**Maximum**
Q	Approach flow rate	vehicles/h	120	1512
C	Cycle length	s	57	127
Calibrated Coefficient Values				
Variable	**Definition**	**Value**	**Standard Deviation**	**t-statistic**
b0	Intercept	-25.971	9.942	-2.6
b1	Effect of exposure	2.635	0.983	2.7
b2	Effect of U.S. 24/Cummings Lane location	-3.063	1.296	-2.4
b3	Effect of change in detection and control	-0.722	0.866	-0.8

A negative coefficient for b_3 indicates that max-outs were less frequent during the after period. Based on the model structure, this coefficient can be converted into an equivalent reduction percentage of 51 percent (= 100 [1 - $e^{-0.722}$]). Thus, the analysis indicates that the after study periods experienced 51 percent fewer max-outs than the before study periods. However, this percentage varied widely among locations, and it was relatively infrequent at all locations (except the U.S. 84/Speegleville Road location). For these reasons, it appears that the change in detection and control reduces max-out frequency, but the trend is not known with certainty. The available data make it impossible to rule out the possibility that the max-out frequency actually increased in the after period.

Researchers analyzed the fit of the model through the graphical comparison of the observed and predicted max-out frequencies as indicated in figure 23. The trend line in this figure does not represent the line of best fit; rather, it is a "$y = x$" line. The data would fall on this line if the model predictions exactly equaled the observed data.

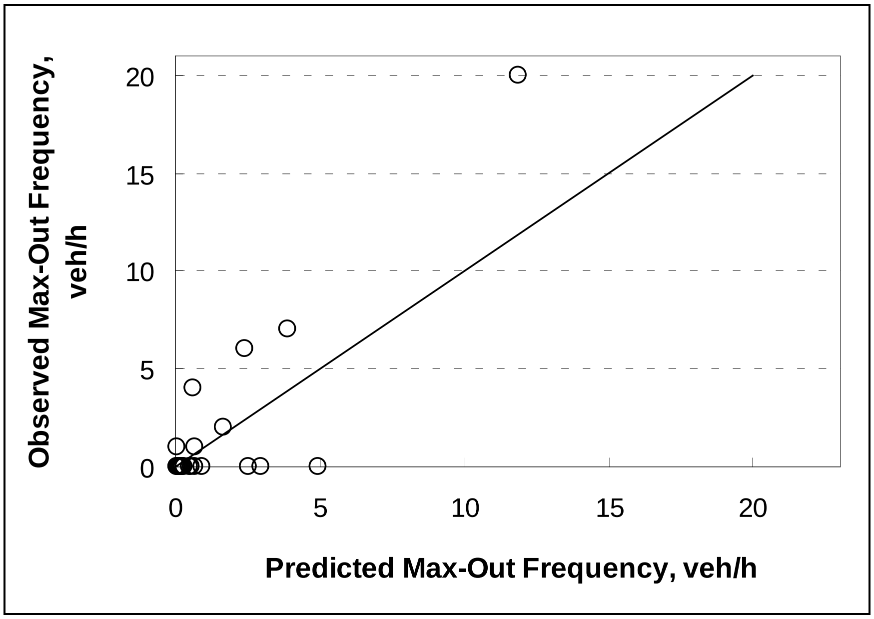


Figure 23. Graph. Comparison of observed and predicted max-out frequency.

Study 4 Results

Table 36 summarizes the findings of the upper limit comparison of different maximum green settings of 75, 85, and 95 s. The results indicated in this tabular summary are followed by statistical analysis. Visual observation of the results does not make a compelling case indicating improvement in the standard MOEs except for phase 6 max-outs. Phase 2 max-outs remain constant because the northbound through movement is impeded less often (only by phase 8) than phase 6. There is no apparent trend in RLRs from these data.

Table 36. Upper Limit Study summary.[1]

	Max1: 75 s		Max1: 85 s		Max1: 95 s	
Date	10/28/09	10/29/09	11/04/09	11/05/09	11/11/09	11/12/09
Phase 2 Max-Out	1	0	1	0	0	1
Total No. Phase 2 Cycles/Day	874	871	852	862	875	859
Phase Average Green (s)	68	68	69	68	67	68
Phase6 Max-Out	16	13	6	9	4	3
Total No. Phase6 Cycles/Day	615	609	590	573	584	610
Phase 6 Average Green (s)	114	118	121	126	122	118
Phase 8 Max-Out	11	8	8	12	9	10
Total No. Phase 8 Cycles/Day	615	609	590	573	584	610
Phase 8 Average Green (s)	10	10	11	11	11	11
MP Phase2 LL RLRs	6	5	3	4	1	6
MP Phase2 RL RLRs	6	9	5	5	5	3
MP Phase6 LL RLRs	5	0	2	1	2	1
MP Phase6 RL RLRs	3	5	5	4	5	2
Total MP	20	19	15	14	13	12
MOP Phase2 LL RLRs	6	5	1	1	5	3
MOP Phase2 RL RLRs	2	2	8	4	5	6
MOP Phase6 LL RLRs	2	2	0	1	3	2
MOP Phase6 RL RLRs	7	6	4	2	5	4
Total MOP	17	15	13	8	18	15
EP Phase2 LL RLRs	1	3	4	1	1	4
EP Phase2 RL RLRs	3	3	3	6	7	4
EP Phase6 LL RLRs	7	4	0	4	2	0
EP Phase6 RL RLRs	3	5	5	9	2	3
Total EP	14	15	12	20	12	11
EOP Phase2 LL RLRs	0	1	3	2	1	2
EOP Phase2 RL RLRs	3	4	5	7	2	2
EOP Phase6 LL RLRs	0	2	0	0	0	0
EOP Phase6 RL RLRs	1	2	0	3	1	1
Total EOP	4	9	8	12	4	5
Total Peak RLRs	34	34	27	34	25	23
Total Off-Peak RLRs	21	24	21	20	22	20
Total RLR Per Day	55	58	48	54	47	43
RLR Percent Reduction Per Day			13	7	15	26

[1]AM peak 6–9; PM peak 4–8.
Blank cell = base condition.
EOP = evening off peak.
EP = evening peak.
LL = left lane.
MOP = morning off peak.
MP = morning peak.
RL = right lane.

Table 37 provides summary statistics describing the variables in the upper-limit database. The data in each row of this table reflect about 1 h of data collection for 1 signal phase at the U.S. 281/E. Borgfeld Drive location. The data in table 37 indicate that the research project observed more than 300 signal cycles at this location. During these cycles, the subject phase terminated by max-out for 14 signal cycles. The traffic flow rate ranged from 1,255 to 1,450 vehicles/h, and the cycle length ranged from 91 to 109 s.

The last column of table 37 indicates that the sample size is somewhat small, having only 14 observations during the collective set of study hours. The trend in the data (shown in the last few rows of the last column) indicates that the max-out frequency decreased with increasing maximum green duration. The number of max-outs decreased by 43 percent when operating the intersection with an 85-s maximum green compared with a 75-s maximum green. The number of max-outs decreased 57 percent when operating at a 95-s maximum green, compared with a 75-s maximum green.

Table 37. Upper-limit database summary—total observations.

Location	Maximum Green, s	Study Hour	Cycles	Flow Rate,[1] vehicles/h	Cycle Length,[2] s	Number of Max-Outs[1]
U.S. 281/ E. Borgfeld Dr.	75	17:10	39	1,407	93	0
		17:00	36	1,281	101	3
		16:00	38	1,290	95	4
	85	17:20	35	1,428	101	3
		17:10	38	1,303	91	1
		16:20	38	1,291	93	0
	95	17:20	35	1,255	98	0
		16:00	34	1,288	107	1
		17:00	33	1,450	109	2
Total	75	all	113	3,978	96	7
	85	all	111	4,022	95	4
	95	all	102	3,993	105	3
Percent Change 75 to 85[3]			-1.8	1.1	-1.1	-43
Percent Change 75 to 95[3]			-9.7	0.4	9.0	-57
Total			326	11,993	81	14

[1]Flow rate and counts include both passenger cars and heavy vehicles.
[2]Cycle length in the total rows represents an average length (not a sum).
[3]Percent change = 100 x (after/before - 1.0).

The statistical analysis used a model similar to figure 20 but with an additional variable for maximum green duration. The results of this analysis indicate that the trend in the last column of table 37 was not statistically significant. Thus, it appears that a longer maximum green setting may reduce max-out frequency, but the trend is not known with certainty. The available data make it impossible to rule out the possibility that the max-out frequency actually increases with maximum green duration.

The original intent for the Upper Limit Study was to compare the MOEs—red-light running, vehicles caught in the dilemma zone, and max-out frequency—to those caused by traditional detection, accounting for any variations in traffic or other conditions. The only comparison that was available for this intersection was comparing the before data from the existing inductive loops with the after data with D-CS, both with Max1 set at 75 s, which was done in the earlier comparisons. Further analysis using simulation would be the only way to evaluate the desired increase in demand and determine at what volume D-CS is no longer able to provide adequate dilemma-zone protection.

Study 2 Results

The primary objective of study 2 was to evaluate before-after crash data to determine the effectiveness of D-CS in reducing motor vehicle crashes at signal-controlled intersections. The section reports on a statistical analysis to evaluate the effectiveness that D-CS had on all (TOT), fatal and injury (FI), and angle plus rear end (angle plus RE) crashes. The reason some categories were combined was to increase the sample size.

Methodology

The research team used a before-after study to evaluate the safety effectiveness of D-CS at the eight selected sites. The evaluation used the comparison group method with correction for traffic flow to overcome some of the problems with a simple or naïve before-after study. This method uses a comparison group that has influencing factors similar to those of the treated group. The following assumptions underlie this approach:[13]

- The factors that affected safety have changed in the same way from before the improvement to after the improvement for both the treatment and the control groups.
- The changes in the various factors influence the safety of the treatment and the control groups in the same manner.

The results from this approach are considered more accurate and reliable than the simple before-after study because the new approach can account for external causal factors. Although this approach can improve the weakness of the simple method through careful selection ofng the comparison groups, it is still subject to the regression-to-the-mean (RTM) bias because it predicts the expected number of target crashes of a site based on the before-period crash number only. RTM refers to the tendency for a fluctuating characteristic of an entity to return to a typical value in the period after an extraordinary value has been observed.[16]

The comparison group method considers only the factors that are unidentified, unmeasured, and not understood.[14] If a before-after study is planned, information about traffic flow in the before and after periods should always be secured.[14] Because the effect of change in traffic flow on safety may be large, it is important to try to account for it directly and explicitly. Harwood et al. used a variation of the comparison group approach, which makes the traffic volume adjustment using a regression relationship between crash frequency and traffic volume. The before-after study uses the following steps:[16]

Step 1. Define the target crashes.

Safety of D-CS is measured in terms of its ability to reduce crashes related to phase termination (e.g., rear-end and angle crashes). The target crashes are the types of crashes that are likely influenced by D-CS.

Step 2. Define the comparison group.

The comparison group method uses sites that are similar to the treated entities but without D-CS installation. Comparison group crashes are useful in explaining factors other than D-CS that might have influenced the safety of an intersection. In each case, the operating agency offered sites that were similar to the treated sites.

Step 3. Predict the expected number of crashes and variances for after period.

This information is required to account for factors other than the treatment that affect safety but are either not measured or the influence of which on safety is not known. The expected number of after period crashes and their variance for site *i* had the treatment not been implemented at the treated site is shown in figure 24:

$$\widehat{\pi} = \hat{r}_d \hat{r}_T \hat{r}_{tf} K \text{ and}$$
$$V\widehat{A}R(\widehat{\pi}) = r_d^2 \widehat{\pi}^2 \left(\frac{1}{K} + V\widehat{A}R\{\hat{r}_T\}/r_T^2\right)$$

Figure 24. Equation. Expected number of crashes and variances for after period.

Where:

$\hat{r}_d$ = the ratio of duration of after period to the duration of before period.

$\hat{r}_T$ = the ratio of after to before target crashes at comparison sites = (N/M)/(1=1/M).

$\hat{r}_{tf}$ = the ratio of the functional relationship between traffic flow and safety in the before period to that in the after period = $f(A_{avg})/f(B_{avg})$.

K = total crash counts during the before period in a treated site.

M = total crash counts during the before period in a comparison site.

N = total crash counts during the after period in a comparison site.

A_{avg} = expected traffic volume (averaged over the number of years) in the after period.

B_{avg} = expected traffic volume (averaged over the number of years) in the before period:

$$V\hat{A}R\{\hat{r}_T\}/r_T^2 \cong 1/M + 1/N$$

Step 4. Compute the sum of the predicted crashes over all treated sites and its variance.

It is widely recognized that the safety effect of a treatment varies from one site to another. Thus, instead of a single site, one would like to know the average safety effect of the treatment for a group of sites. The expected number of after-period crashes and their variances for a group of sites had the treatment not been implemented at the treated sites is given in figure 25:

$$\hat{\pi} = \sum_{i=1}^{n} \hat{\pi}_i \text{ and}$$

$$\mathrm{Var}(\hat{\pi}) = \sum_{i=1}^{n} \mathrm{Var}(\hat{\pi}_i)$$

Figure 25. Equation. Sum of predicted crashes and its variance.

Where:

n = total number of sites in the treatment group.

$\hat{\pi}$ = expected after-period crashes at all treated sites had there been no treatment.

Step 5. Compute the sum of the actual crashes over all treated sites.

For a treated site, the crashes in the after period are influenced by the implementation of the treatment. The safety effectiveness of a treatment is known by comparing the actual crashes with the treatment to the expected crashes without the treatment. The actual number of after-period crashes for a group of treated sites is given in figure 26:

$$\hat{\lambda} = \sum_{i=1}^{n} L_i$$

Figure 26. Equation. Sum of actual crashes for treated sites after period.

Where:

L_i = total crash counts during the after period at site i.

Step 6. Compute the unbiased estimate of safety-effectiveness of the treatment and its variance.

The "index of effectiveness (θ)" is defined as the ratio of what safety was with the treatment to what it would have been without the treatment. The parameter $\hat{\theta}$ gives the overall safety effect of the treatment and is seen in figure 27.

$$\hat{\theta} = \frac{\left(\frac{\lambda}{\pi}\right)}{\left(1 + \frac{\mathrm{Var}(\hat{\pi})}{\hat{\pi}^2}\right)}$$

Figure 27. Equation. Index of effectiveness.

The percent increase in the number of target crashes owing to the treatment is calculated by 100(1 - $\hat{\theta}$) percent. If $\hat{\theta}$ is less than 1, then the treatment has a positive safety effect. The estimated variance and standard error of the estimated safety-effectiveness are shown in figure 28 and figure 29:

$$\mathrm{Var}(\hat{\theta}) = \hat{\theta}^2 \frac{(1/L + \mathrm{Var}(\hat{\pi})/\hat{\pi}^2)}{(1 + \mathrm{Var}(\hat{\pi})/\hat{\pi}^2)^2}$$

Figure 28. Equation. Variance of estimated safety-effectiveness.

$$\mathrm{s.e.}(\hat{\theta}) = \sqrt{\mathrm{Var}(\hat{\theta})}$$

Figure 29. Equation. Standard error of safety-effectiveness.

The approximate 95-percent confidence interval for θ is given by adding and subtracting 196$s.e.(\hat{\theta})$ to $\hat{\theta}$. If the confidence interval contains the value 1, then no significant effect has been observed.

Data Description

Table 38 summarizes the number of crashes occurring in the four States by the following metrics:

- Treatment period (before D-CS and after D-CS).
- Length of analysis period (duration in years).
- TOT crashes.
- Severity of crashes (FI).
- Type of crashes related to D-CS (angle plus RE).

All sites except one (U.S. 281/E. Borgfeld in Texas) have a comparison site, although in most cases, more than one treatment site uses the same nearby comparison site.

Table 38. Number of crashes at treatment and comparison sites.

State	Category	Site	Period	AADT	Duration (year)	TOT	FI	Angle Plus RE
FL	Treatment	U.S. 27/Griffin Rd.	Before	17,225	4.2	12.0	2.0	4.0
			After	19,350	2.2	13.0	1.0	3.0
	Comparison	NW138	Before	41,875	4.2	67	23.0	31.0
			After	34,500	2.3	38	10.0	14.0
	Treatment	U.S. 27/Johnson Rd.	Before	17,225	4.2	16.0	2.0	3.0
			After	19,200	2.3	10.0	0.0	0.0
	Comparison	NW138	Before	41,875	4.2	67	23.0	31.0
			After	34,500	2.3	38	10.0	14.0
	Treatment	U.S. 27/Pines Blvd.	Before	19,925	4.2	19.0	2.0	6.0
			After	18,600	2.3	11.0	0.0	0.0
	Comparison	SR997/Krome Ave.	Before	23,000	4.2	33.0	15.0	19.0
			After	19,150	2.3	12.0	3.0	5.0
IL	Treatment	U.S. 24/Main St.	Before	9,730	5.0	20.0	3.0	10.0
			After	11,150	2.0	9.0	2.0	5.0
		U.S. 24/Cummings Ln.	Before	12,700	5.0	30.0	6.0	16.0
			After	14,025	2.0	15.0	2.0	11.0
	Comparison	IL29/Rench Rd.	Before	21,100	5.0	17.0	5.0	14.0
			After	21,100	2.0	14.0	3.0	14.0
LA	Treatment	LA 3235/LA 3162	Before	6,700	3.8	7.0	2.0	7.0
			After	6,700	2.0	3.0	0.0	2.0
	Comparison	LA20-Mel	Before	10,833	3.8	18.0	3.0	16.0
			After	13,067	2.0	3.0	0.0	3.0
TX	Treatment	U.S. 84/ Speegleville Rd.	Before	22,250	3.8	9.0	4.0	5.0
			After	22,220	2.2	7.0	3.0	3.0
	Comparison	Lp340	Before	5,310	3.8	15.0	7.0	15.0
			After	5,310	2.2	4.0	1.0	4.0
	Treatment	U.S. 281/E. Borgfeld Dr.	Before	30,500	1.5	33.0	16.0	32.0
			After	31,750	2.0	40.0	19.0	40.0
	Comparison	N/A	Before	N/A	N/A	N/A	N/A	N/A
			After	N/A	N/A	N/A	N/A	N/A

AADT = annual average daily traffic.
N/A = not applicable.

Analysis Results

Safety performance functions (SPF) are used to develop a relationship between the number of crashes and daily traffic data. This study develops the SPFs with the crash and traffic data in the before period. Table 39 shows the summary of statistics for these crashes and annual average daily traffic (AADT). The number of observations is not the number of intersections independent spatially but the number of intersections independent temporally (e.g., a year). As a result, an intersection may produce several data points depending on the number of years of data collected.

Table 39. Summary statistics of crashes and traffic flow.

Variable	Minimum	Maximum	Mean	Standard Deviation	Sum
TOT	0	19	4.19	3.45	226
FI	0	9	0.87	1.61	47
Angle Plus RE	0	18	2.15	3.21	116
AADT	5,310	31,000	16,425.19	6,137.97	—

—No data.

The Poisson-gamma (i.e., negative binomial) model is the most common type of model used by transportation safety analysts for modeling traffic crashes. This model is preferred over other mixed-Poisson models because the gamma distribution is the conjugate of the Poisson distribution. The Poisson-gamma model has the following model structure: the number of crashes Y_{it} for a particular i^{th} site and time period t when conditional on its mean μ_{it} is Poisson distributed and independent over all sites and time periods, as shown in figure 30.

$$Y_{it} \mid \mu_{it} \sim Po(\mu_{it})$$

Figure 30. Equation. Number of crashes based on the Poisson-gamma model.

Where:

$i = 1, 2, \ldots, i$, and $t = 1, 2, \ldots, t$

The mean of the Poisson is structured as shown in figure 31:

$$\mu_{it} = f(X; \beta)\exp(e_{it})$$

Figure 31. Equation. Mean of the number of crashes.

Where:

f = function of the covariates (X).

β = vector of unknown coefficients.

e_{it} is the model error independent of all the covariates.

The functional form used for the model in this study is as shown in figure 32:

$$\mu_{it} = e^{\beta_0} \times Y \times AADT^{\beta_1}$$

Figure 32. Equation. Functional form of safety performance.

Where:

Y = number of years of crash data.

β_i = a vector of unknown coefficients (to be estimated) (i = 0,1).

Table 40 summarizes the estimation results for all three crash types. In general, the sign and magnitude of the regression coefficients in table 40 are logical and consistent with previous research findings.

Table 40. Parameter estimation for SPF.

Parameter	Inferred Effect of…	TOT		FI		Angle Plus RE	
		Value	***t*-statistic**	**Value**	***t*-statistic**	**Value**	***t*-statistic**
β_0	Intercept	-6.8143	-3.0	-11.4937	-2.4	-4.9924	1.4
β_1	AADT	0.8667	3.7	1.1868	2.4	0.6160	1.7
α	Dispersion parameter	0.2286	2.6	1.1365	2.2	1.1508	3.4
AIC	Akaike information criterion	254.6		143.5		218.9	

The coefficients in table 40 were combined with the equation in figure 32 to obtain the crash mean of each crash type:

The form of each model is shown in figure 33, figure 34, and figure 35:

$$\mathrm{TOT} = \mathrm{e}^{-6.8143} \times \mathrm{AADT}^{0.8667}$$

Figure 33. Equation. SPF for TOT crashes.

$$\mathrm{FI} = \mathrm{e}^{-11.4937} \times \mathrm{AADT}^{1.1868}$$

Figure 34. Equation. SPF for FI crashes.

$$\mathrm{Angle} + \mathrm{RE} = \mathrm{e}^{-4.9924} \times \mathrm{AADT}^{0.6160}$$

Figure 35. Equation. SPF for angle plus RE crashes.

Safety Effects of D-CS

Table 41 presents the average safety effect of D-CS based on crash data. The average safety effect of D-CS is known from the unbiased estimate of index of effectiveness ($\hat{\theta}$). If this value is less than 1, then D-CS has a positive effect on safety (improves safety). The analysis results suggest that D-CS has no effect on TOT and FI crashes and produces a reduction of 9 percent for angle plus RE crashes. The standard deviation of this estimate of average safety effect is 15 percent, so at a 95-percent confidence level, the result is not significant. This result can be attributed to the small sample size. Achieving a significant result at the 5-percent level would require a larger number of treated sites, a longer period of crash data collection, or both.

Table 41. Average safety effect of D-CS based on crash data.

Measure	Description	TOT	FI	Angle Plus RE
$\hat{\lambda}$	Number of crashes observed during the after period[1]	108.0	30.0	66.0
$\hat{\pi}$	Expected number of crashes during after period had red light cameras not been installed	107.6	29.0	71.6
$Var(\hat{\pi})$	Variance of $\hat{\pi}$	84.22	29.73	65.93
$\hat{\theta}$	Unbiased estimate of index of effectiveness	1.00	1.00	0.91
$\sigma(\hat{\theta})$	Standard error of $\hat{\theta}$	0.13	0.25	0.15
$100(\hat{\theta} - 1)$	Percent increase in the number of crashes[1]	0	0	-9
$(\theta_{lower}, \theta_{upper})$	95 percent confidence interval for θ	(0.75, 1.25)	(0.50, 1.49)	(0.61, 1.20)

[1]A negative value represents a decrease, while a positive value represents an increase in crashes.

CHAPTER 5. D-CS IMPLEMENTATION GUIDE

INTRODUCTION

TTI developed D-C S to improve the safety of high-speed, signalized intersections. This system uses a unique detector configuration to monitor approaching vehicles and hold the green until they are safely clear of the intersection, as well as provide some priority for trucks. This installation guide provides an overview of D-CS operations and offers guidance to installing agencies on controller settings and field installation procedures.

Overview of D-CS

D-CS is similar to a traditional advance detector system in that it uses information from detectors located upstream from the intersection to extend the green. However, it differs from the traditional advance detector system because it processes vehicle speed and length information to find the best time to terminate the major road through phase. This time is based on a forecast of the number of vehicles that will be in the dilemma zone[2] in the immediate future, as well as the number of minor movements waiting for service. D-CS reevaluates this information continuously and updates it in real time.

D-CS uses a two-loop detector trap in each approach lane to obtain the necessary information about vehicles approaching the intersection. Each detector trap is located 700 to 1,000 ft upstream of the intersection. The exact location is not critical. However, distances nearer 1,000 ft are better because they provide D-CS with a larger time horizon for evaluating future arrivals to the dilemma zone.

A key feature of D-CS is that it can predict, in real time, when each vehicle will arrive at and depart from its dilemma zone on the intersection approach. This feature takes advantage of the fact that the dilemma-zone boundaries are defined in terms of travel time to the stop line. D-CS measures each arriving vehicle's speed, forecasts its dilemma-zone arrival and departure times, and holds the green phase when a vehicle is in its dilemma zone.

D-CS ALGORITHM

This section describes the logic used in the detection-control algorithm, primarily through the use of three flowcharts. The first flowchart, figure 36, indicates the two components of D-CS: a vehicle-status component and a phase-status component. The primary function of the vehicle-status component is to monitor the output from the classifier and record each vehicle's time of arrival at and departure from the dilemma zone. This component repeats its checks every 0.05 s. The primary function of the phase-status component is to determine the best time to end the phase and then send the appropriate instructions to the signal controller. This component repeats its function every 0.05 s. The next section describes each component in more detail.

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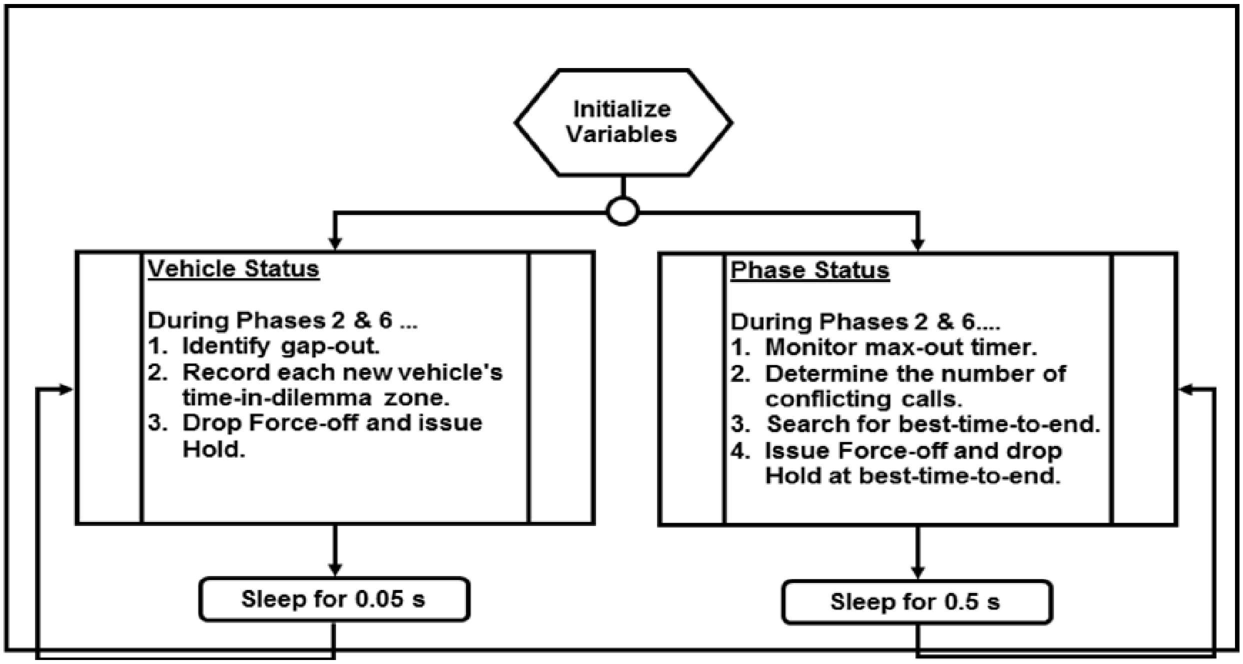
[2]The dilemma zone represents a length of roadway on the intersection approach within which drivers are collectively indecisive regarding whether to stop or continue when presented with a yellow signal indication. The upstream edge of this zone is typically defined as 5.5 s travel time from the stop line. The downstream edge of this zone is typically defined as 2.5 s travel time from the stop line.



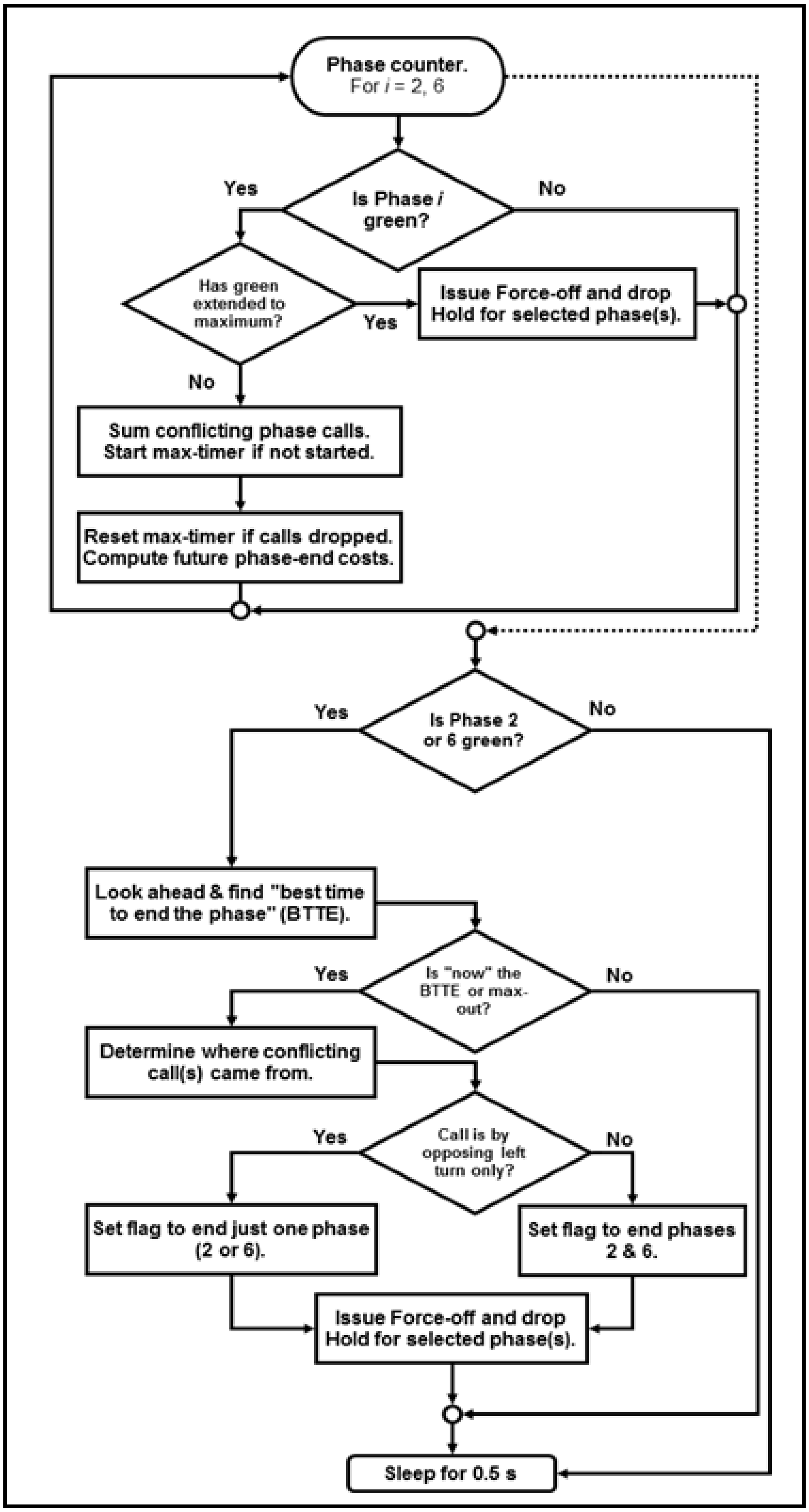
Source: TTI/Karl Zimmerman, used with permission.

Figure 36. Chart. Detection-control algorithm flowchart.[(2)]

Vehicle Status Component

Figure 37 shows the vehicle status component of the algorithm. It sequentially checks the detector output (via the classifier) for each approach lane served during the major road signal phase (i.e., phases 2 and 6). The algorithm only takes action when the subject phase is in service (i.e., showing a green indication). At the start of each phase, it resets the system variables to zero and issues a phase Hold command to the controller. While the phase is green, this component processes vehicles measured by the classifier and adds them to a “dilemma zone matrix” representing the number and length of vehicles present during each second within the look-ahead time interval.

If a vehicle is traveling faster and will arrive behind a slower vehicle, the vehicle status component adjusts the faster vehicle’s speed to equal that of the slower vehicle. Its arrival time at and departure time from the dilemma zone lags that of the slower vehicle by 1.5 s. This algorithm is most applicable to single-lane intersection approaches and high-volume multilane approaches. Its use at low-to-moderate volume multilane approaches is generally conservative because it will always assume a car-following mode when, in fact, faster drivers may pass slower drivers.



Source: TTI/Karl Zimmerman, used with permission.

Figure 37. Chart. Vehicle-status component algorithm flowchart.[(2)]

Phase-Status Component

Figure 38 shows the phase-status component of the D-CS algorithm. This component checks the dilemma zone matrix during the major road through phase. The algorithm only takes action when the subject phase is in service (i.e., showing a green indication). While the phase is green, the algorithm monitors a maximum green setting internal to the algorithm. If this maximum is reached, this component immediately causes a phase termination by dropping all phase Hold commands and issuing a Force-Off command for both rings.

The phase-status component is primarily concerned with monitoring the dilemma zone matrix and finding the "best time to end the phase" (BTTE) based on the current look-ahead interval. This interval is defined as the travel time between the detection zone and the beginning of the dilemma zone for a vehicle traveling in the 99th-percentile speed. When the detection zone is located 1,000 ft from the stop line and the 99th-percentile speed is 70 mi/h, the look-ahead time is approximately 2.8 s.

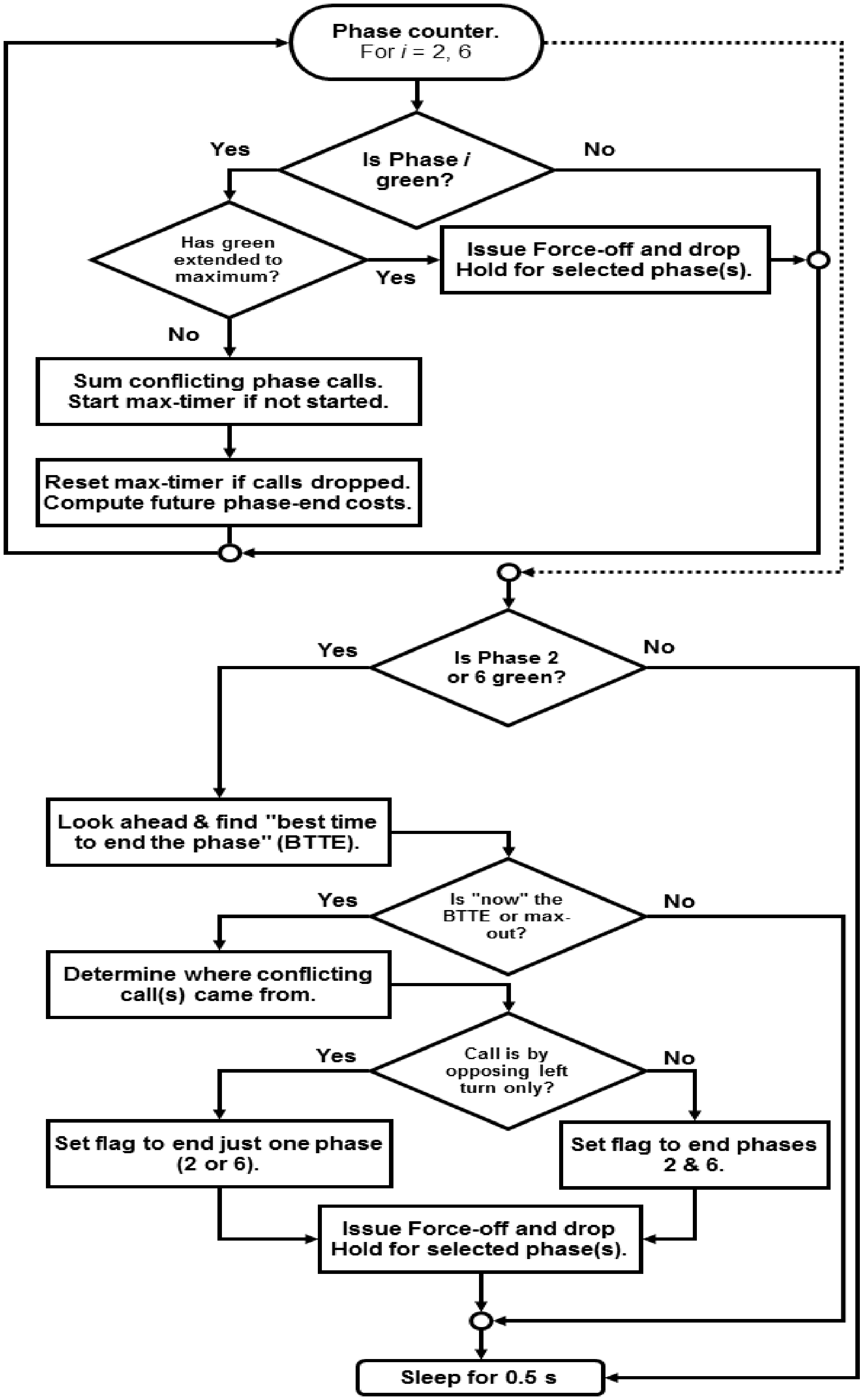
Determination of the BTTE is based on two checks. The first check requires that the dilemma zone contain fewer vehicles than a specified maximum value for any current or future time interval. All intervals that have the same (or fewer) number of vehicles than the maximum value are candidates to be the BTTE.

The algorithm uses two maximum values. The first portion of the phase (or stage) uses one maximum value, and the last stage of the phase uses a second value. The maximum value is established at zero during the first stage. However, during the second stage, the maximum value is relaxed to allow up to one passenger car (no trucks) per lane in the dilemma zone. This "relaxation" of the maximum value is intended to prevent the phase from maxing out while still limiting the number of vehicles caught in the dilemma zone to a minimum value.

Implications of D-CS

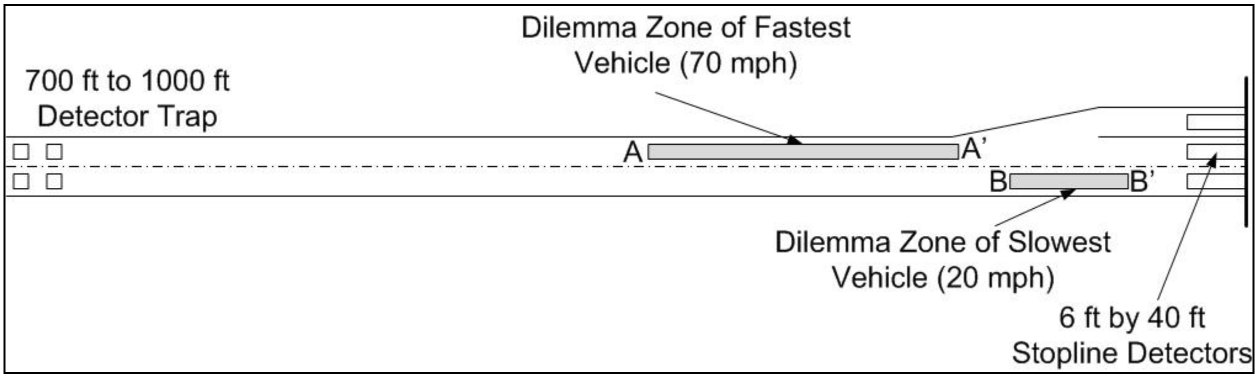
To illustrate the implications of D-CS's dynamic dilemma zone monitoring process, consider the following example. A vehicle traveling at 70 mi/h is at point A in figure 39, and a vehicle traveling at 20 mi/h is at point B. Neither vehicle is in its respective dilemma zone, so D-CS could terminate the phase at this instant in time. In contrast, both vehicles are almost certainly in the zone protected by the traditional multiple advance detector system, and both vehicles would unnecessarily extend the phase. As a result, a D-CS controlled phase could end at this point in time, whereas the traditional system would continue to extend the green interval. This example uses an extreme speed differential to make its point. However, the concept applies to the full range of speeds and allows D-CS to consistently end the phase sooner than the traditional system. Over time, this capability ensures that D-CS will operate with less delay and catch fewer vehicles in the dilemma zone than the traditional advance detector system.

The real-time nature of D-CS operation allows it to dynamically accommodate changes in speed that occur at the intersection throughout the day, week, and year. Its performance is not compromised when traffic speeds change, as would be the case for traditional advance detection systems because their detectors are precisely located for a specified design speed.



Source: TTI/Karl Zimmerman, used with permission.

Figure 38. Chart. Phase-status component algorithm flowchart.[(2)]



Source: TTI/Karl Zimmerman, used with permission.

Figure 39. Illustration. Comparison of dilemma zones for fast and slow vehicles.[(1)]

In short, D-CS is designed to dynamically identify the dilemma zone for each vehicle, in real time, and predict the best time to terminate the phase. This design allows D-CS to provide safe and efficient signal operation for the full range of intersection traffic volumes and speeds. To assist the installer, the following narrative provides guidance on some of the controller settings to set up D-CS. This guidance is specific to the Naztec 2070 controller.

D-CS Input Screens

The Naztec 2070 controller has the following two input screens for D-SC:

- Speed detectors.
- Lane setup.

There is also a status screen for monitoring D-CS operation.

Speed Detectors

D-CS uses a pair of detectors in each lane in a speed trap configuration. Each speed trap is set up in the speed detector screen, accessed by MM -> 5 (Detectors) -> 8 (V/O-Speed) -> 2 (Speed Detectors). Table 42 shows an example speed detector screen. Each row describes one speed trap. Speed traps 1, 2, 3, and 4 are defined in figure 39. The following screens provide an explanation of the values shown for each speed trap. D-CS can monitor one speed trap per lane in as many as eight lanes, so the maximum number of speed traps is also eight.

Table 42. Speed detector screen.[1]

	UpDet	DnDet	ZoneLen	Loop/CarLen
1	9	10	20.0	6.0
2	11	12	20.0	6.0
3	13	14	20.0	6.0
4	15	16	20.0	6.0
5	—	—	0.0	0.0
6	—	—	0.0	0.0
	—	—	0.0	0.0

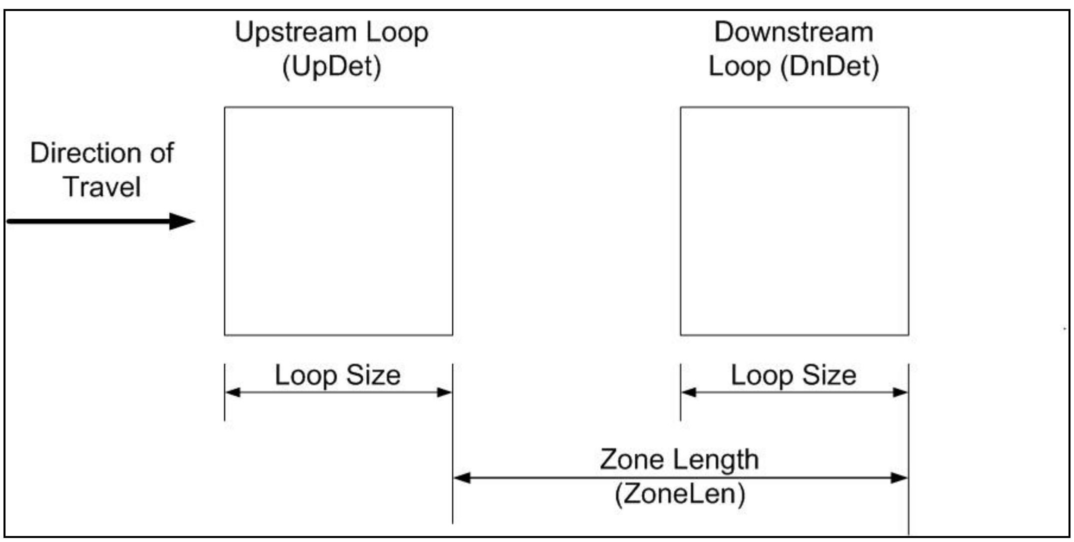
—No data.

UpDet

UpDet is the detector channel number for the upstream detector in a speed trap (figure 40).

DnDet

DnDet is the detector channel number for the downstream detector in the trap (figure 40).



Source: TTI/Karl Zimmerman, used with permission.

Figure 40. Illustration. Speed trap configuration.[1]

ZoneLen

ZoneLen is the distance from the downstream end of UpDet to downstream end of DnDet in feet. The minimum ZoneLen is 20 ft, although a longer trap may be used if desired.

Loop/CarLen

Loop/CarLen is the size of the UpDet and DnDet detector loops, in feet.

For D-CS to function properly, both loops in each trap must be the same size.

Lane Setup

The lane setup is performed after the detector traps are assigned. The lane setup screen is accessed by MM -> (Detectors) -> 8 (V/O-Speed) -> 4 (DCS Menu) -> 1 (table 43).

Table 43. Lane setup screen.[1]

DCS Setup	Lane1	Lane2	Lane3	Lane4	>
Phase	2	2	6	6	
SpeedTrap	1	2	3	4	
TrapDistance	1,000	1,000	1,000	1,000	
DZArrival	6.0	6.0	6.0	6.0	
DZExit	2.0	2.0	2.0	2.0	
StagePercent	70	70	70	70	
MaxSpeed	70	70	70	70	
MaxLength	65	65	65	65	

Lane1, Lane2, Lane3…

Each lane controlled by D-CS has a detector trap assigned to it. As many as eight approach lanes can be monitored by D-CS.

Phase

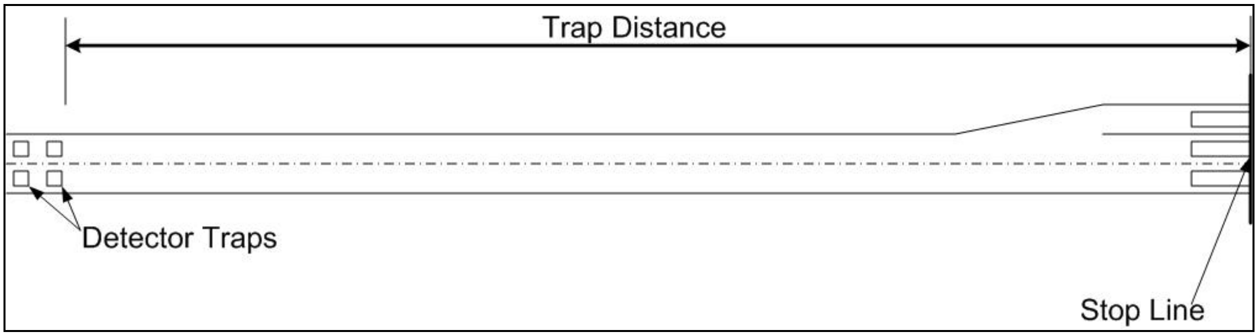
Phase is the D-CS controlled phase associated with this lane.

SpeedTrap

SpeedTrap is the speed trap number assigned to this lane from the speed detector screen.

TrapDistance

TrapDistance is the distance from the downstream end of the detector trap to the stop line of the intersection, in feet (figure 41). The traps should be located between 700 ft and 1,000 ft from the stop line.



Source: TTI/Karl Zimmerman, used with permission.

Figure 41. Illustration. Trap distance measurement.[1]

DZArrival

DZArrival is the travel time from the upstream end of the dilemma zone to the stop line, in seconds. The DZArrival time cannot be smaller than DZExit.

DZExit

DZExit is the travel time from the downstream end of the dilemma zone to the stop line, in seconds. The DZExit time cannot be larger than DZArrival.

StagePercent

The maximum green time is divided into two stages. Stage 1 occurs first, followed by stage 2. The StagePercent is the percentage of the maximum green time that is allocated to stage 1. Phase termination during this stage requires that all dilemma zones are clear (i.e., no vehicles are in the dilemma zone). The balance of the maximum green time is allocated to stage 2. During stage 2, D-CS searches for a time when the number of vehicles in the dilemma zone is at a minimum. It terminates the phase when this minimum is reached.

MaxSpeed

MaxSpeed is the maximum acceptable vehicle speed for D-CS, in mi/h. Vehicle speeds reported to D-CS that are faster than the maximum speed are considered to be errors, and the maximum speed is reported instead.

MaxLength

MaxLength is the maximum acceptable vehicle length for D-CS, in feet. Vehicle lengths reported to D-CS that are longer than the maximum length are considered errors, and the maximum length is reported instead.

Status

The Naztec 2070 controller also has a D-CS status screen so a user can monitor D-CS operation in the field. This screen is accessed by MM -> 8 (V/O-Speed) -> 4 (DCS Menu) -> 7 (Status) (table 44).

Each column's entries have the data for one phase. Non-zero values in the last five rows indicate that phases 2 and 6 are the D-CS controlled phases.

PhaseOn

PhaseOn indicates whether this phase is (X) or is not (.) currently active. A phase is "active" when it is timing the green, yellow, or all-red intervals. In the example, the active phases are phases 2 and 6.

Table 44. Status screen.[1]

D-CS Setup	1	2	3	4	5	6	7	8
PhaseOn	.	X	.	.	.	X	.	.
PhsCall	.	.	.	X	.	.	X	.
DCSActv	.	X	.	.	.	X	.	.
EGWUsed	0	16	0	0	0	16	0	0
Thrshold	0	0	0	0	0	0	0	0
Holding	.	X	.	.	.	X	.	.
QueClear	.	X	.	.	.	X	.	.

PhsCall

PhsCall indicates whether this phase has (X) or does not have (.) a call for service. In the example, phases 4 and 7 have calls for service.

DCSActv

DCSActv indicates whether D-CS is (X) or is not (.) active for this phase. D-CS is "active" when it is searching for a safe time to terminate the phase. D-CS can only be active for two of the eight phases at any one time, and only when those two phases are green. In the example, D-CS is active on phases 2 and 6.

EGWUsed

EGWUsed is the current total vehicle length in the dilemma zone. If the total length value shown is 16, then one 16-ft vehicle is currently in the dilemma zone for the corresponding phase. If 32 is shown, then two vehicles are in the dilemma zone, and so on.

Thrshold

Thrshold is the maximum total vehicle length in the dilemma zone at the time of phase termination. Thrshold can have the following two different states for an active D-CS phase:

- When D-CS is in stage 1, Thrshold is 0.
- When D-CS is in stage 2, Thrshold is greater than 0.

There are three ways to terminate a D-CS controlled phase:

- In stage 1.
- In stage 2.
- By max-out.

EGWUsed and Thrshold can be used together to determine how each D-CS controlled phase ended. To terminate a phase in stage 1 or stage 2, the EGWUsed value must be less than or equal to Thrshold. In stage 1, D-CS requires that all dilemma zones must be clear before the phase is allowed to terminate. For this reason, Thrshold is set to 0 during stage 1, and the EGWUsed must equal 0 in each lane before the phase can be terminated.

In stage 2, D-CS relaxes the requirement that all dilemma zones must be clear to terminate the phase. In this stage, a phase can be terminated when there is no more than one passenger car in the dilemma zone. To provide truck priority, D-CS maintains the requirement in stage 2 that all dilemma zones be clear of trucks (defined as vehicles with length of 25 ft or more). For this reason, Thrshold is set to 24 during stage 2, and the EGWUsed must be less than 24 in each lane before the phase can terminate.

When the maximum green limit is reached, the phase is terminated (i.e., maxes out), regardless of the Thrshold or EGWUsed values.

Holding

Holding indicates whether D-CS is (X) or is not (.) holding the phase in its green interval. This variable will show both indications while an active D-CS controlled phase is timing, depending on whether vehicles are in the dilemma zone. It will show (.) when the phase terminates.

QueClear

QueClear indicates whether or not D-CS has determined that the stopped queue has cleared. D-CS will not terminate a phase until the stopped queue clears. D-CS checks one of two different conditions to determine whether the queue has cleared. These two conditions are as follows:

- Gap out of a presence detector near the stop line.
- The end of minimum green, whichever occurs later.

If presence detection is not provided near the stop line, the end of minimum green is used exclusively to make this determination.

Recommended D-CS Settings

D-CS has relatively few input settings. However, some key settings are interrelated, and their values must be adjusted in combination to optimize D-CS operation. The key D-CS settings are as follows:

- Dilemma-zone boundaries (DZArrival and DZExit).
- Maximum green.
- Stage 1 percentage.
- Minimum green.

Recommendations for each of these settings are discussed below.

Dilemma Zone Boundaries (DZArrival and DZExit)

Research studies have shown that the dilemma zone begins at 5.5 s of travel time from the stop line and ends at 2.5-s travel time from the stop line. The physical location of the dilemma zone can be easily identified when the vehicle travels at a constant speed. D-CS makes this assumption when it determines the location of each vehicle's dilemma zone. This determination is made soon after the vehicle crosses the detector trap. In fact, studies have shown that most drivers maintain a relatively constant speed on the intersection approach, so the assumption is reasonable. However, drivers may occasionally alter their speed on the intersection approach after crossing the detector trap. For this situation, it is recommended that 0.5 s be added to the dilemma zone arrival time and that 0.5 s be subtracted from the dilemma zone exit time. Therefore, the recommended value for DZArrival is 6 s, and the recommended value for DZExit is 2 s.

Maximum Green

The maximum green setting for D-CS should be somewhat longer than the typical maximum green setting used at an isolated intersection with conventional detection and control. D-CS requires this longer maximum green duration to find the safest time to terminate the phase and provide adequate truck priority. However, D-CS is highly efficient in finding safe termination times and rarely extends the green interval to its maximum limit. Research studies have shown that delay is lower with D-CS operation than with conventional detection and control.

The recommended maximum green setting for D-CS is equal to the sum of the stage 1 and stage 2 durations. Stage 1 should be as long as the typical maximum green setting, which may range from 35 to 60 s, depending on the location. Stage 1 should always be longer than the longest queue clearance time to maximize the safety benefits of D-CS. The recommended stage 2 duration is about 20 s. Hence, the maximum green setting should range from 55 to 80 s, with larger values in this range preferred for the reasons stated in the previous paragraph.

Stage 1 Percentage

The stage 1 percentage is the ratio of the stage 1 duration divided by the length of the maximum green duration, expressed as a percentage. As noted previously, stage 1 should range from 35 to 60 s, and the maximum green duration should range from 55 to 80 s. Therefore, the stage 1 percentage should ideally range from 65 to 75 percent, but it should not be less than 60 percent.

Minimum Green

D-CS operation is very sensitive to the length of the minimum green for the phases it controls. There are two reasons for this sensitivity. First, D-CS does not control the intersection until after queue clearance or the end of minimum green, whichever occurs later. D-CS uses the stop line detectors to determine whether the queue has cleared. However, a slow-starting vehicle may create a gap in the queue large enough to gap out the detector even though the queue has not cleared. This situation can result in premature phase termination by D-CS.

Second, the D-CS algorithm assumes that the distance from the detector trap to the stop line is clear of vehicles at the start of the green interval. It has no knowledge of vehicle presence on the intersection approach at the start of this interval and cannot extend the green interval for them. Thus, the minimum green duration must be sufficiently long enough to allow any moving vehicle that is between the detector trap and the stop line at the start of the green interval to reach the inside edge of the dilemma zone before the minimum green expires. If this opportunity is not available, D-CS may terminate the phase prior to this vehicle being served.

To avoid these two situations, the minimum green duration should be at least 15 s for phases with approach speed limits of 55 mi/h or higher. The minimum green duration should be at least 17 s for phases with approach speed limits of 45 or 50 mi/h. Longer minimum green times may be used, although a minimum green time greater than or equal to the stage 1 duration is not recommended.

If presence detection is not available in the vicinity of the stop line, then the minimum green must be long enough to allow the stopped queue to adequately clear. Otherwise, D-CS may end the phase before the stopped queue clears. If D-CS ends a phase before the queue clears and no presence detection is available, it is likely that subsequent phases may also end before the queue clears. This pattern will persist until the queue is able to clear within the minimum green. This situation is undesirable and should be avoided if possible, either with a long minimum green or the addition of presence detection near the stop line.

If volume density operation is being used, the 15-s (or 17-s) recommended minimum green for D-CS operation must be supplied even if no actuations occur during the yellow and red intervals.

Summary

Table 45 summarizes the recommended values of the D-CS settings described in this section. The recommended values for the minimum green duration are the minimum recommended values for reliable D-CS operation.

Table 45. D-CS recommended settings.(1)

Setting	Recommended Value
DZArrival	6 s
DZExit	2 s
Maximum green duration	55 to 80 s (larger values will improve D-CS performance)
Stage 1 percentage	65 to 75 percent preferred, but not less than 60 percent
Minimum green duration	Minimum of 15 s for approach speed limits of 55 mi/h or higher Minimum of 17 s for approach speed limits of 45 mi/h or 50 mi/h Larger values may be needed if presence detection is not available near the stop line.

INDUCTIVE LOOP FIELD INSTALLATION PROCESS

This section contains the procurement, installation, and performance requirements for D-CS. The distance between the loops and the stop line does not have to be precisely defined and is not dictated by speed. It is best to install the loops between 700 and 1,000 ft upstream of the stop line. Distances nearer 1,000 ft are encouraged because they are better from the standpoint of providing some improvement in system performance, but they are not critical if they are difficult to achieve. For example, if a culvert or driveway is located at 850 ft and would be expensive to cross, then installing the loops at 840 ft is acceptable.

Vehicle Detection System Components

The text of the following section was originally published in *Intelligent Detection-Control System for Rural Signalized Intersections* and has been adapted for this report.(2)

Materials and Hardware

Inductive Loop Detectors: The D-CS uses two 6-ft by 6-ft inductive loops in each through travel lane, placed upstream of the intersection. A special feature of this design is that each loop has six turns of wire. The detector loop wire is stranded copper No. 14 AWG XHHW cross-linked-thermosetting-polyethylene insulated conductor conforming to IMSA 51-3.(2)

Detector Loop Lead-In Cable: One lead-in cable is provided for each loop detector. A special feature of this design is that the cable is shielded twisted No. 12 AWG. Otherwise, the design meets all of the requirements of IMSA 50-2.

Loop Amplifier: A two-channel loop amplifier (or detector unit) is provided for each pair of inductive loop detectors (i.e., one amplifier per through travel lane). These loop amplifiers may be stand-alone or rack mounted. The amplifier should be operated in the "fast response" mode. This mode minimizes the lag time associated with call filtering and thereby improves the accuracy of D-CS speed estimation.

Installation and Testing of D-CS Loop Detectors

There are two loops per travel lane. The spacing of the loops are 20 ft from trailing edge to trailing edge, and the loops are centered in each through lane.(2) The trailing edge of the trailing loop is at a distance from the stop line specified on the plan sheets. A special feature of this design is that each loop is provided with its own lead-in cable to the cabinet.

Inductive Loop Layout: Each loop layout is 6 ft by 6 ft square with 8.5 ft between each pair of diagonally opposite corners. When cutting the pavement, the contractor should not deviate more than 0.5 inches from the chalk line on leading edges of loops and no more than 1 inch on all other sides of the square loops. A special feature of this design is that the contractor should round the corners to a minimum of a 1-inch radius for the full depth of the cuts.(2) All sharp edges at corners and elsewhere should be removed. The contractor should not create excessive "gaps" at loop corners. All saw cuts should be filled with loop sealant flush with the pavement surface.

Inductive Loop Saw Cuts: The saw cut depth allows six turns of loop wire to be placed such that each turn in the leading edge of each loop is "stacked" on the previous turn. Each successive wire turn touches the one installed below it (or before it), and the wire turns remain contiguous following application of the loop sealant. A backer rod is not required. The contractor should install all turns in a clockwise direction and mark the beginning end on each loop.

The saw cuts should be vertical and at least wider than the diameter of the loop wire, up to a maximum of 0.25 inches. The top wire may be as much as 1.5 inches below the surface but not less than 1.0 inch below the surface. The saw cut depth should be a minimum of 2.5 inches and a maximum of 3 inches, measured at any point along the loop perimeter.(2)

The width of home-run saw cuts should be at least 0.25 inches wider than twice the diameter of the loop wire, up to a maximum of 0.5 inches. The top wire in the home-run cut may be as much as 1.5 inches below the surface, but not less than 1 inch below the surface.(2)

Wire Twists in Home-Run Cut: A special feature of this design is that the contractor should twist loop wire leads a minimum of five twists per ft from feeder slot to the first ground box.

Testing Loop Wires: The contracting agency should test all loop wires at the first ground box prior to the contractor applying loop sealant. If any failures are discovered in the loop wire conductor, the contractor will be required to replace the loop wire.

Loop Sealant: The contractor should completely encapsulate the loop conductors with sealant both in the loop proper and along the wire leads. A minimum of 1 inch of sealant should be provided between the top of the conductors and the top of the saw cut.[(2)] The contractor should fill saw cuts completely with sealant such that it is flush with the top of the saw cuts. The sealant should be either 3-M loop sealant or TA-500.

Installation and Testing of D-CS Lead-In Cable

A special feature of this design is that each loop is provided with its own lead-in cable to the cabinet.

Loop Lead-In Cable: A special feature of this design is that the loop lead-in cables are long enough to extend from the first ground box to the cabinet without splicing. Some additional length should be provided to allow sufficient slack to make connections at each end.

The contractor should pull the lead-in cables from the first ground box to the cabinet. The shield should be left unconnected, insulated at the splice point, and grounded only in the control cabinet until inspected by the contracting agency. If the led-in cable fails testing, the contractor should remove the defective cable and replace it.

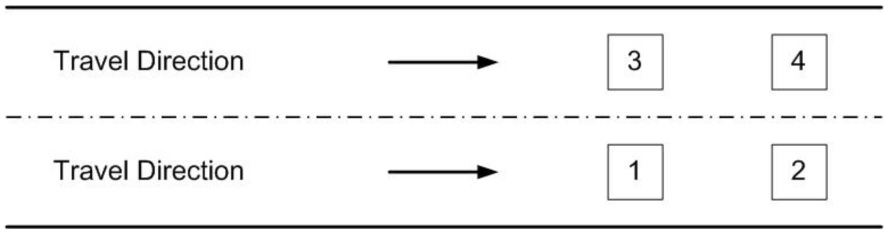
Cable Splices: A special feature of this design is that there is only one splice between the loop and the cabinet. That one splice is in the first ground box and connects the loop to the lead-in cable. The contractor should solder and seal all connections in the first ground box with 3-M Scotchcast.

Ground Boxes: The ground boxes should be consistent with the local operating agency's specifications for ground boxes.

Conduit: The lead-in cable should be inside a conduit that is in conformance with the local operating agency's specifications.

Installation and Testing of D-CS Loop Amplifiers

The loop amplifiers (or detector units) for the D-CS should be installed as stand-alone or rack-mounted. Each loop should be assigned to a separate amplifier channel. These channels should be dedicated solely for the use of D-CS (i.e., they should not also be assigned to other signal phases). Loop amplifier function should be tested according to local agency requirements. Figure 42 and table 46 show a recommended setup for a Reno A&E model S-1200-SS detector unit.



Source: TTI/Karl Zimmerman, used with permission.

Figure 42. Illustration. Numbering of inductive loops in the roadway.[(1)]

Table 46. Settings for Reno A&E model S-1200-SS.[(1)]

Detector	Channel	Frequency[1] (KHz)	Sensitivity Setting[2]	Fast Response[3]
1	1	1 or 2	4	On
2	2	7 or 8	4	On
3	3	7 or 8	4	On
4	4	1 or 2	4	On

[1]Goal with frequency is to have 5 KHz separation between loops in adjacent lanes.
[2]Set sensitivity as high as possible without causing loop to "stick" in the on mode. Too low a value will result in missed trucks. Typical values are 4 to 6.
[3]Not on by default; used for speed trap applications.

APPLICATION CONSIDERATIONS

The D-CS is intended for use at isolated, full-actuated intersections on high-speed roadways. The intersection should consist of a major road and a minor road where the major road approach has an 85th-percentile speed (or posted speed limit) of 45 mi/h or higher. The agency must install detection zones for the system in each lane of both major road approaches, and the intersection must operate in isolation of other adjacent signalized intersections. A left-turn bay is required for each major road approach, and a right-turn bay (or full-width shoulder) is desirable.

The installing agency should consider using D-CS at new intersections meeting the above requirements whenever multiple advance detection might otherwise be a good fit. For existing intersections with multiple advance detectors, decisionmakers should consider replacing the existing system with D-CS when the existing system's design life is finished.

Extensive simulation and field study have shown that the system is able to function safely and efficiently for all levels of traffic demand. However, its performance degrades with frequent turning activity from the major road approaches. For this reason, its benefits will diminish as the total turn percentage (i.e., the sum of the left-turn percentage and the right-turn percentage) increases. Performance has been acceptable when the turn percentage is less than 40 percent.

Other conditions that make D-CS even more desirable are as follows:

- Higher than normal truck traffic.
- Locations where approach speeds vary significantly.

- Locations with high crash rates.

The types of crashes to be particularly mindful of are angle plus RE crashes.

Table 47 summarizes the criteria discussed above and the recommended threshold values that justify the use of D-CS. The last two entries in this table, truck traffic and crash frequency, are considered important, but the other criteria are more critical in determining when to use D-CS.

Table 47. Guidance on the use of D-CS.

Criterion	Threshold
Isolated full-actuated intersection	N/A
Intersection of major road and minor road	N/A
85th-percentile speed (or speed limit)	> 45 mi/h
Total turn percentage (right plus left)	< 40 percent
Truck traffic	> 10 percent in off-peak hours, > 5 percent in peak hours
Crash rates for rear-end and right angle	> similar intersections in the area

N/A = not applicable.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

This chapter uses the results and analyses from earlier chapters to formulate conclusions and recommendations based on results of the four studies. The goal of the traffic data collection was to determine propensity for red-light running and vehicles caught in the dilemma zone. The following conclusions are organized beginning with those related to the methodology and followed by conclusions related to field data collection elements of the research. The recommendations are the final section.

CONCLUSIONS

The objectives of this evaluation study were as follows:

- Objective 1: Verify the D-CS design objectives through rigorous field instrumentation—at the moment of signal change from green to yellow, no truck should be in the dilemma zone, and no more than one passenger car should be in the dilemma zone.

- Objective 2: Quantify the effectiveness of D-CS in improving safety and reducing dilemma-zone-related crashes and red-light violations at rural, high-speed, signalized intersections.

- Objective 3: Identify the upper limit of traffic conditions under which the D-CS can operate safely and effectively when alternative signal timing strategies may start to fail.

To meet the three research objectives, TTI developed the following four studies:

- Study 1: Performance Monitoring of Dilemma Zone Occupancy (addresses objective 1).
- Study 2: Before-After Crash Data Study (addresses objective 2 in part).
- Study 3: Before-After Crash Surrogate Study (addresses remainder of objective 2).
- Study 4: Upper Limit Study (addresses objective 3).

TTI conducted studies 1 and 3 simultaneously by collecting field data at eight sites in four States (Florida, Illinois, Louisiana, and Texas). During study 4 (an extension of studies 1 and 3) data were collected at a high-volume site to determine whether an upper limit exists to the demands placed on the D-CS algorithm. MOEs for studies 1, 2, and 4 were the number of RLRs, the number of vehicles caught in the dilemma zone at the onset of yellow, and max-out frequency. Study 2 simply involved a comparison of the number and types of crashes from the before D-CS period (desirably 5 years) to the after D-CS period (desirably 2 years).

Related to Methodology

The methodology used for this research involved collecting a redundant set of data using different systems to ensure capture of the critical data. The industrial PC in the controller cabinet at each intersection recorded the data from the Wavetronix™ Advance detectors, the inductive loop actuations from the D-CS loops, and video detector outputs from detection zones placed just past the stop line at each main street approach. The methodology also included video cameras and DVRs for recording video of each main street approach. Data from the enhanced BIUs provided the controller state for post-processing of data. The major problem at the first site was that the CyberResearch™ industrial PCs was unable to handle the massive amounts of data being transferred for storage via its serial ports. The research team resorted to using two of its own Kontron™ industrial PCs, which worked flawlessly throughout the entire project.

TTI also used a cell modem in each controller cabinet to facilitate remote communication with each site. Attempting this project without such communication capabilities would have been unwise. The wireless modem allows the researchers to remotely access the site and download data. Otherwise, a researcher has to go to the site, manually download the data, and restart the data-logging process. Even with this capability in place, TTI still had to request local transportation department support occasionally to do a power cycle, install firmware upgrades, or complete other relatively simple tasks. In Florida, the sites experienced several power outages, prompting the local transportation department to install an "iBoot" device to be able to execute a power cycle remotely.

Each transportation department was willing to provide bucket-truck support for installation and removal of equipment. Attempts to pull cables through existing conduits were usually unsuccessful, so researchers resorted to running cables overhead and zip-tying them to existing cables during the few weeks the systems were in place. By using this methodology, researchers were able to reuse the same cables for all sites.

TTI attempted to collect at least 7 days of before data and 7 days of after data at each site. In a few cases, scheduling or other conflicts precluded collecting the full 7 days. This amount of data still far exceeded the amount actually needed and created challenges in manipulating files during the data analysis phase, especially when combined with all the different data elements being collected. For example, Microsoft® Excel (2007 and later) has a physical limit of one million lines of data. Many of the sites had so much data that one 24-h period exceeded this limit, requiring analysts to split files into multiple segments.

The primary system for identifying vehicles in the dilemma zone consisted of two Wavetronix Advance detectors—one for each main street approach. The detector tracks vehicles approaching the detector from 500 ft away until they reach about 100 ft away. TTI used the serial data stream to determine when vehicles were in the dilemma zone (defined as 2 s to 6 s travel time to the stop line). The output from the detectors provides the distance and speed of each vehicle it detects. Even though these sensors are accurate and worked very well for this purpose, their output (scanning each approach every few milliseconds) is probably what overwhelmed the CyberResearch™ computers. Another challenge from these detectors was the fact that they do not distinguish between trucks and cars. Because D-CS is designed to favor trucks, this research had to rely on the D-CS loops and their vehicle length determination to identify trucks (defined as vehicles more than 30 ft in length).

Cameras for video recording usually served a dual role—providing video to be recorded and serving as the count device for RLRs and total intersection approach counts. To detect RLRs, installers placed a detection zone just past the stop line. A detection occurring just past the onset of the red phase triggered a red-light running event, but the analysis process still verified these supposed events. For example, a vehicle stopping just beyond the stop line might trigger the detector but was not actually an RLR. Also, a vehicle's headlight "sweep" at night from an opposing phase could trigger an unintended detection that might otherwise appear as an RLR.

Video recording was not continuous because of the enormous storage requirement. Researchers decided to purchase two DVRs with high-end features to limit the amount of video recorded. They chose a DVR with alarm capabilities so that the onset of red would trigger the recording to begin. Field personnel programmed each DVR to begin recording 5 s prior to the beginning of the red phase and 6 s after the beginning of the red phase. With this much lead-in video, post-processing of the video allowed viewers to watch vehicles on the approach several hundred feet before arriving at the stop line. There were several cases of RLRs entering the intersection very late in this recorded period, but such blatant violations were not counted against D-CS because no detection scheme would have likely prevented such results.

The data analysis methodology required the use of an exposure measure, so TTI needed to count the traffic passing straight through the intersection. Video detectors placed at the stop line provided such a count, but a weakness of video detectors with regard to counting was that they could not accurately distinguish between cars and trucks at night because of the nighttime algorithm's use of headlights instead of the full vehicle length as in the daytime. The inductive loops at about 1,000 ft from the intersection were more accurate, but counts at that location would include turning traffic. Therefore, TTI chose to use the video counts and not try to distinguish trucks from cars.

Matching data from multiple systems requires use of a common clock time. The most likely source for the components used to collect the data would be the PC in the cabinet, although not all devices in the cabinet were capable of using its clock. For example, the DVR had its own clock and was independent from the PC and related systems. However, researchers bypassed this issue by using VideoStamp devices, which caused the timestamp from the PC to be recorded on the video image, facilitating post-coordination with other data even if the DVR clock was significantly different from the PC clock. The VideoStamp device has an RS-232 port to receive the timestamp from the PC and an RCA video input to receive the video input recorded by the DVR. Without this device, the most appropriate approach was to synchronize all clocks either physically at the start of data collection and periodically afterward, or to find common points that could be associated with each system, such as the start of the red phase.

The methodology at the data collection sites was as consistent as researchers could feasibly make it. However, there were differences by site that affected the results and how the results should be interpreted. For example, some sites had no before dilemma-zone protection. In other words, some sites had no upstream detection whatsoever. All three Florida sites and the Louisiana site fit this category. Obviously, D-CS should reduce RLRs, vehicles caught in the dilemma zone, and the number of vehicle crashes at these sites compared with those with dilemma-zone protection prior to D-CS being installed. Better evaluation of D-CS would come from its comparison at sites with the more traditional dilemma-zone protection such as those in Texas and Illinois. In this study, the researchers evaluated before/after crash data at the evaluation sites and comparison sites. To assess effectiveness of D-CS in reducing dilemma zone-related red-light running and crashes, it is better to perform side-by-side comparison of D-CS with other dilemma zone protection technologies at the same location.

TTI followed instructions from the sponsor and began investigating red-light running, dilemma-zone encroachments, and max-outs for all days of both the before and after period. However, after many days of watching video to verify dilemma-zone encroachments and completing only a few days of actual data evaluation, the research team concluded that project resources were insufficient to complete the project this way. Continuing would provide hour-by-hour or day-by-day comparisons, but that became impractical. Therefore, researchers began using a different approach that required comparison based on the number of signal cycles at each intersection and used the count of vehicles as an exposure factor. The number of RLRs, the number of vehicles caught in the dilemma zone, and the number of max-outs were still the variables of interest in this procedure, but the procedure was not nearly as onerous as the previous labor-intensive approach. This procedure, which used a regression analysis methodology, also accounts for differences in traffic volume, site features, cycle length, and other known factors. It would have accounted for weather as well, but there were no weather conditions that were thought to affect the outcomes.

Related to Crash Surrogate Measures

Researchers began the data analysis using 24-h periods and developing before-after comparisons on that basis. Evaluating this quantity of data was not necessary, and resources were not available to continue and complete all sites on that basis. However, this document presents the limited partial results for information. Based on the partial analysis using 24-h data, TTI found that the number of RLRs always decreased with the use of D-CS compared with the before treatments.

Table 48 summarizes these results for weekdays only; weekend results might be different. Results in Illinois are especially important because the two sites there were the only ones in this evaluation group with reasonably adequate dilemma-zone protection before D-CS was installed. The other sites had no dilemma-zone protection before D-CS. Dilemma-zone results improved for cars with the use of D-CS as well, but results for trucks were different in this sample. The number of trucks in the dilemma zone were the same in before to after periods at the Cummings Lane site, and they increased from one in the before to three in the after condition at the Main Street site.

Table 48. Summary of partial 24-h operations data.

Site	Condition	RLR		Dilemma Zone	
		Trucks	Cars	Trucks	Cars
U.S. 24/Cummings Ln.	Before	26	157	5	109
	After	3	10	5	72
U.S. 24/Main St.	Before	34	110	1	68
	After	1	12	3	23
LA 3235/LA 3162	Before	39	42	—	—
	After	31	28	—	—
U.S. 27/Griffin Rd.	Before	179	111	—	—
	After	117	77	—	—

—No data.

Because of resource constraints, researchers stopped the 24-h data analysis and resorted to a methodology using regression analysis. Results of the regression analysis indicated that D-CS decreased red-light running, the number of vehicles in the dilemma zone, and the number of max-outs. Findings from 28 1-h periods indicate an 82-percent reduction in RLRs, a 73-percent reduction in vehicles caught in the dilemma zone, and a 51-percent reduction in max-outs.

Related to Upper Limit Study

The statistical analysis used for the Upper Limit Study using data from U.S. 281/Borgfeld Drive near San Antonio, Texas, indicated that the max-out frequency decreased with increasing maximum green duration from 75 to 85 to 95 s. However, this trend was not statistically significant. The field effort related to the Upper Limit Study was originally planned as a precursor to simulation. It would have served the role of model calibration as well as determining the effect of increasing maximum green. However, project resources were insufficient to do both.

Related to Crash Data Analysis

Chapter 1 provides crash results based on an earlier evaluation of D-CS at five sites in Texas. There was a 39-percent reduction in severe crashes on the two approaches controlled by D-CS. The data suggest that 9 severe crashes (and about 18 property-damage-only crashes) were prevented during the time that D-CS was operating. If just those crashes that are influenced by D-CS are considered (i.e., rear-end, left-turn opposed, and sideswipe), then D-CS installation accounted for a 50-percent reduction in severe "influenced" crashes.[1]

The more recent crash data analysis using comparison sites suggests that D-CS had no effect on TOT and FI crashes and produces a reduction of 9 percent for angle plus RE crashes. The standard deviation of this estimate of average safety effect is 15 percent, so at a 95-percent confidence level, the result is not significant. This result can be attributed to the small sample size. Achieving a significant result at the 5 percent level would require a larger number of treated sites, a larger period of crash data, or both.

RECOMMENDATIONS

TTI recommends that D-CS be viewed as a viable solution to improving intersection safety at high-speed, isolated intersections. Its emphasis on trucks is a salient feature that makes it unique in comparison with other types of dilemma-zone protection. Agencies that would not consider above-ground detection for dilemma zones should have an option available to them such as D-CS (because D-CS has relied on inductive loops). However, there are reasons to investigate non-loop options for D-CS, including wireless communications and above-ground detectors such as side-fire radar detectors, which can provide speed and length. Some agencies are already minimizing the installation of detectors in the pavement in favor of non-intrusive options, so this approach would improve the chances of D-CS becoming more universally applicable and perhaps less expensive.

The TTI research team encountered a fair amount of concern within State and local transportation agencies about installing Naztec controllers in cases where the local agency had no experience with this controller. The Government is in the process of approaching other manufacturers to encourage implementation of the D-CS algorithm. TTI engineers had contacted other manufacturers earlier when they contacted Naztec, but at that time, the other manufacturers decided against D-CS. With new evidence that D-CS improves safety at high-speed intersections, the manufacturers might now respond differently.

To integrate the D-CS algorithm, other controller manufacturers must have a significant incentive to do so, and they will probably need support from programmers who are familiar with the D-CS algorithm. A positive response from the controller manufacturers today might also occur simply because of above-ground detectors that are either available today or will be available soon to provide dilemma-zone protection. The current dilemma zone detectors do not have all the same features as D-CS (e.g., the emphasis on trucks and speed and length measurement accuracy), and the only way to know how well they work is to test them scientifically in a side-by-side comparison with D-CS.

Application Considerations

D-CS is intended for use at isolated, full-actuated intersections on high-speed roadways where the major road approach has an 85th-percentile speed (or posted speed limit) of 45 mi/h or higher. A left-turn bay is required for each major road approach, and a right-turn bay (or full-width shoulder) is desirable. For existing intersections with multiple advance detectors, decisionmakers should consider replacing the existing system with D-CS when the existing system's design life is finished.

Simulation and field study have shown that the system's performance degrades with frequent turning activity from the major road approaches. Performance has been acceptable when the turn percentage is less than 40 percent. The following conditions make D-CS even more desirable:

- Higher than normal truck traffic.
- Locations where approach speeds vary significantly.
- Locations with high crash rates (e.g., angle plus RE crashes).

APPENDIX A: PARTIAL FULL-DAY RESULTS

FULL DAY RESULTS

Table 49, table 50, table 51, and table 52 provide partial summaries of red-light runners and vehicles caught in the dilemma zone prior to converting to the regression analysis approach. These data are not corrected for exposure or other factors as the regression results are. Shaded cells indicate days not evaluated at the point that the procedure changed. Only the two Illinois sites have full days of dilemma zone results for phases 2 and 6, whereas all four sites show most of the red-light running results.

Table 49. Full-day data results for U.S. 24/Cummings Ln.

Condition	Date	Day of Week	RLR Final		Trucks—DZ		Cars—DZ	
			Trucks	Cars	Phase 2	Phase 6	Phase 2	Phase 6
Before D-CS	April 21	Tuesday	7	22				
	April 22	Wednesday	2	42	1	4	70	39
	April 23	Thursday	6	33				
	April 24	Friday	6	37				
	April 25	Saturday	1	31				
	April 26	Sunday	3	28				
	April 27	Monday	5	23				
With D-CS	May 2	Saturday	1	4				
	May 3	Sunday	0	6				
	May 4	Monday	1	1				
	May 5	Tuesday	1	5				
	May 6	Wednesday	1	4	4	1	64	8

DZ = dilemma zone.
Note: Blank cells represent days not evaluated at the point that the procedure changed.

Table 50. Full-day data results for U.S. 24/Main St.

Condition	Date	Day of Week	RLR Final		Trucks—DZ		Cars—DZ	
			Trucks	Cars	Phase 2	Phase 6	Phase 2	Phase 6
Before D-CS	April 21	Tuesday	4	14				
	April 22	Wednesday	10	24	1	0	58	10
	April 23	Thursday	11	21				
	April 24	Friday	6	25				
	April 25	Saturday	4	21				
	April 26	Sunday	1	27				
	April 27	Monday	3	26				
With D-CS	May 2	Saturday	2	4				
	May 3	Sunday	0	4				
	May 4	Monday	1	6				
	May 5	Tuesday	0	4				
	May 6	Wednesday	0	2	3	0	18	5

DZ = dilemma zone.
Note: Blank cells represent days not evaluated at the point that the procedure changed.

Table 51. Full-day data results for LA 3162/LA 3235.

Condition	Date	Day of Week	RLR Final		Trucks—DZ		Cars—DZ	
			Trucks	Cars	Phase 2	Phase 6	Phase 2	Phase 6
Before D-CS	June 5	Friday	7	7				
	June 6	Saturday	7	8				
	June 7	Sunday	3	10				
	June 8	Monday	10	6				
	June 9	Tuesday	13	6				
	June 10	Wednesday	4	4				
	June 11	Thursday	9	16				
With D-CS	June 13	Saturday	3	3				
	June 14	Sunday	7	5				
	June 15	Monday	11	8				
	June 16	Tuesday	7	8				
	June 17	Wednesday	5	0				
	June 18	Thursday	7	6				
	June 19	Friday	1	6				

DZ = dilemma zone.
Note: Blank cells represent days not evaluated at the point that the procedure changed.

Table 52. Full-Day Data Results for U.S. 27/Griffin Rd.

Condition	Date	Day of Week	RLR Final		Trucks—DZ		Cars—DZ	
			Trucks	Cars	Phase 2	Phase 6	Phase 2	Phase 6
Before D-CS	March 9	Monday	85	60				
	March 10	Tuesday	94	51				
	March 11	Wednesday						
	March 12	Thursday						
	March 13	Friday						
	March 14	Saturday						
	March 15	Sunday						
With D-CS	March 23	Monday	23	14				
	March 24	Tuesday	29	16				
	March 25	Wednesday	Missing	Missing				
	March 26	Thursday	28	22		2		18
	March 27	Friday	37	25				
	March 28	Saturday	8	23				
	March 29	Sunday	13	17				

DZ = dilemma zone.
Note: Blank cells represent days not evaluated at the point that the procedure changed.

APPENDIX B: EXPLANATION OF DATA TABLE HEADERS

INTRODUCTION

The following tables and text explain the format of the data tables. The sections included are as follows:

- Red-Light-Running Data File with .RLR Extension.
- Phase Status Data File with .PHS Extension.
- WSSA (.WAS) Files.
- Detector Status .SBD Files (On and Off).

Red-Light-Running Data File with .RLR Extension

The following definitions are for column headers listed in table 53:

- **RLR Detector**: Red-light-running detector number. RLR(1) is placed in front of the stop line of phase 2 left lane, RLR(2) in the right lane of phase 2, RLR(3) in the left lane of phase 6, and RLR(4) in the right lane of phase 6.

- **Duration of Off/On**: When a detector is occupied by a vehicle and turns on, this field provides the duration of the Off status for the detector before it turned On. However, when a vehicle clears the detector and it turns Off, the field provides the duration of presence call on the detector.

- **Detector Daily Count**: The RLR detectors were placed in front of the stop line for each lane on main street phases. The RLR detectors are used to count red-light runners on main street phases during red phase. They are also used to count through vehicles on main street phases during green, yellow, and red phases. The detector daily count provides the total number of activations on a RLR detector during the green, yellow, and red phases.

- **RLR Detector Phase Status**: Indicates the current status of the main street phase that the RLR detector corresponds to.

- **Phase Duration**: The phase duration in milliseconds provides the duration of the red phase when the RLR events happened.

The header of the .RLR data file includes information in the first few lines about the location of the intersection (state, city, and name of intersection), and the mapping of red-light detectors to phases. Table 53 is an example.

Table 53. Red-light-running (.RLR) files.

Hour	Minute	Second	Millisecond	Phase Number	RLR Detector*	RLR Detector Status	Duration of Off/ON*	RLR Hourly Count	RLR Daily Count	Detector Daily Count*	RLR Detector Phase Status*	Phase Duration*
10	32	57	783	2	RLR(1)	On	5178	1	8	3,711	Red	1,372
10	32	57	783	2	RLR(2)	On	20870	1	6	2,851	Red	1,372
10	32	59	135	2	RLR(1)	Off	1352	1	8	3,711	Red	2,724
10	32	59	345	2	RLR(2)	Off	1562	1	6	2,851	Red	2,934
10	52	27	355	6	RLR(3)	On	4877	1	3	1,709	Red	531
10	52	27	495	6	RLR(4)	On	2864	1	3	1,999	Red	671
10	52	27	875	6	RLR(3)	Off	520	1	4	1,709	Red	1,051
10	52	27	945	6	RLR(4)	Off	450	1	4	1,999	Red	1,121

*Explanation/definition of this column head is provided immediately before this table.

Phase Status Data File with .PHS Extension

The following definitions are for column headers listed in table 54:

- **Phase Status**: Indicates the onset or change of phase status. SOG indicates the start of green phase, SOY is the start of yellow phase, and SOR is the start of red phase.
- **Duration of Green**: Indicates the duration of the last green phase before the current change in phase status.
- **Duration of Red**: Indicates the duration of the last red phase before the current change in phase status.
- **Duration of Yellow**: Indicates the duration of the last yellow phase before the current change in phase status.
- **Duration of Max-Out Timer**: Indicates the time a vehicle waited on a conflicting phase on the main street before being serviced. If the max-out value equals the Max1 setting for the main street phase, this implies that the main street phase was terminated due to a max-out. Only rows that indicate the start of yellow phase (i.e., SOY) might have values in the max-out column that are greater than zero. The other two record types (SOG and SOR) will always have a zero in the max-out column.

The header of the .PHS data file includes information in the first few lines about the location of the intersection (state, city, and name of intersection), important phase settings (minimum green, passage time, Max1), and detector phase mapping. Table 54 is an example of a .PHS file.

Table 54. Phase status (.PHS) files.

Hour	Minute	Second	Millisecond	Phase Number	Phase Status*	Duration of Green*	Duration of Red*	Duration of Yellow*	Duration of Max-out Timer*
0	0	52	553	6	SOG	30,9284	16043	5,779	0
0	0	52	623	2	SOG	30,9204	16113	5,779	0
0	1	14	244	2	SOY	21,621	16113	5,779	3225
0	1	20	72	2	SOR	21,621	16113	5,828	0
0	1	21	985	1	SOG	6,019	531875	4,646	0
0	1	27	964	1	SOY	5,979	531875	4,646	0
0	1	32	690	1	SOR	5,979	531875	4,726	0
0	1	34	293	2	SOG	21,621	14221	5,828	0
0	8	24	673	2	SOY	410,380	14221	5,828	12,118
0	8	24	673	6	SOY	452,120	16043	5,779	12,118
0	8	30	451	2	SOR	410,380	14221	5,778	0
0	8	30	451	6	SOR	452,120	16043	5,778	0

*Explanation/definition of this column head is provided immediately before this table.
SOG = start of green phase.
SOY = start of yellow phase.
SOR = start of red phase.

WSSA (.WAS) Files

Two WSSAs were installed at each evaluated intersection, one on each main street phase. The WSSA sends a contact closure presence call to the controller every time it determines that a vehicle is within the dilemma zone boundaries specified by the user (2.0 to 6.0 seconds for all the evaluated sites). The WSSA drops the presence call whenever it detects that no vehicle is in its dilemma zone among the detected vehicles by the radar sensor. Both signals (On and Off) were monitored and captured by the data collection system and logged into the .WAS file. The WSSA presence call signal were used by the post-processing data analysis software to flag the main street phase cycles where a vehicle might have been caught in its dilemma zone. If the WSSA placed a presence call just before the yellow phase on either one of the main street phases and did not drop the call till after the onset of yellow phase, this was an indication that there might have been a vehicle in its dilemma zone at the start of yellow phase on the main street. The following list provides the subjects and definitions found in table 55:

- **WSSA Number**: WAS(1) On and Off signal are received from the WSSA that was installed on main street phase 2 at each evaluated intersection. Similarly WAS(2) On and Off signals were received from the SSA that was installed on main street phase 6.

- **WSSA Status**: Indicates the status of WSSA.

- **Duration of Off/On**: If the WSSA status is On, then the duration indicates how long the sensor has been off in milliseconds. Otherwise, if the sensor status is Off, then the duration indicates how long the presence call lasted in milliseconds.

- **Daily Count**: Indicates the number of event counts (On or Off) since midnight.

Table 55 is an example of files from the WSSA sensor.

Table 55. The WSSA (.WAS) files.

Hour	Minute	Second	Millisecond	Phase	WSSA Number*	WSSA Status*	Duration of Off/On*	Daily Count*	Phase Status	Phase Duration
6	55	8	223	2	WAS(1)	On	8,851	924	Red	2,554
6	55	10	65	6	WAS(2)	On	13,749	698	Green	90,630
6	55	11	587	2	WAS(1)	Off	3,249	924	Red	5,918
6	55	13	380	6	WAS(2)	Off	3,400	698	Green	93,945
6	55	21	301	2	WAS(1)	On	9,848	925	Green	1,442
6	55	22	423	2	WAS(1)	Off	1,100	925	Green	2,564
6	55	27	741	2	WAS(1)	On	5,302	926	Green	7,882
6	55	33	239	2	WAS(1)	Off	5,548	926	Green	13,380
6	55	33	599	2	WAS(1)	On	400	927	Green	13,740
6	55	35	962	2	WAS(1)	Off	2,250	927	Green	16,103

*Explanation/definition of this column head is provided immediately before this table.

Detector .SBD File (Detector On Events)

- **Total On Time**: Provides the total time in milliseconds that a detector was occupied during the current cycle.

- **Total Off Time**: Provides the total time in milliseconds that a detector was not occupied during the current cycle.

- **Occupancy On Green**: Provides the total time in milliseconds that a detector was occupied during the corresponding main street phase green phase.

- **Occupancy on Red**: Provides the total time in milliseconds that a detector was occupied during the corresponding main street phase red phase.

- **Daily Count**: Provides the total number of detector actuations since midnight.

Table 56 is an example of the .SBD files. Other files had detector “OFF” events as shown in table 57.

Table 56. Detector Status .SBD files.

Hour	Minute	Second	Millisecond	Phase Number	Detector Number	Status	Duration of Previous On	Total On Time*	Occupancy On Green*	Occupancy On Red*	Phase Status	Phase Duration
10	27	42	743	2	SBD(1)	Off	216	4,545	0	761,081	Green	69,290
10	27	42	913	2	SBD(2)	Off	211	4,583	4,748	250	Green	69,460
10	27	42	913	2	SBD(10)	Off	197	21,804	22,830	0	Green	69,460
10	27	43	394	2	SBD(10)	Off	232	22,036	22,991	0	Green	69,941

*Explanation/definition of this column head is provided immediately before this table.

Table 57. Detector .SBD file (detector off events).

Hour	Minute	Second	Millisecond	Phase Number	Detector Number	Detector Status	Duration of Previous Off	Total Off Time*	Daily Count*	Occupancy On Green*	Occupancy On Red*	Phase Status	Phase Duration
10	27	42	532	2	SBD(1)	On	1,928	74,687	3,142	0	681,586	Green	69,079
10	27	42	743	2	SBD(2)	On	1,918	74,569	3,153	4,578	250	Green	69,290
10	27	42	743	2	SBD(10)	On	493	66,736	10,504	22,660	0	Green	69,290
10	27	43	233	2	SBD(10)	On	286	67,022	10,505	22,830	0	Green	69,780
10	27	43	313	6	SBD(5)	On	33,808	68,786	2,028	0	154,857	Green	69,940

*Explanation/definition of this column head is provided immediately before this table.

D-CS Advance Detector Trap .SPD Files

The .Spd files contain information about the D-CS advance detector trap actuations and the per vehicle speed calculations after a vehicle clears the trailing detector in each trap. The algorithm calculates the On speed and Off speed for every detected vehicle once the trailing detector in a trap is cleared. The On speed is based on the time difference between a vehicle’s actuations on the leading and trailing detectors in each trap, while the Off speed is calculated using the time difference between the two time stamps when the vehicle cleared both leading and trailing detectors in each trap. The occupancy on both leading and trailing detectors was also calculated and used to calculate the length of the vehicle using the vehicle speed that has just been calculated.

Advance Trap Detector No: A detector trap is installed upstream of the intersection in each lane on the main street phase approaches. All the intersections where D-CS was evaluated had two lanes per approach on main street approaches. The leading and trailing detectors in each trap were named according to the following scheme:

- A1 is the leading trap detector in the left lane of main street phase 2.
- B1 is the trailing trap detector in the left lane of main street phase 2.

- A2 is the leading trap detector in the right lane of main street phase 2.
- B2 is the trailing trap detector in the right lane of main street phase 2.
- A3 is the leading trap detector in the left lane of main street phase 6.
- B3 is the trailing trap detector in the left lane of main street phase 6.
- A4 is the leading trap detector in the right lane of main street phase 6.
- B4 is the trailing trap detector in the right lane of main street phase 6.

Table 58 shows an example of the Advance Detector .SPD files.

Table 58. D-CS advance detector trap .SPD files.

Hour	Minute	Second	Millisecond	Phase	Advance Trap Detector Number*	Detector Status	Duration Off/On	Phase Status	Phase Duration
0	41	56	335	6	A3	On	14,330	Green	38,496
0	41	56	545	6	A3	Off	197	Green	38,706
0	41	56	545	6	B3	On	14,329	Green	387,060
0	41	56	765	6	B3	Off	197	Green	38,926

*Explanation/definition of this column head is provided immediately before this table.

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