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16. Abstract

Traffic engineers are often faced with operational and safety challenges at rural, high-speed signalized intersections. Vehicle-actuated control, combined with multiple advance detectors, is often used to improve operations and safety. However, this type of detection and control has not always resulted in a significant number of crashes. Crashes sometimes continue to occur at high-speed intersections, and delays to traffic movements can be unnecessarily long. An innovative detection-control system was developed for the Texas Department of Transportation to minimize both delay and crash frequency at rural intersections. This system was subsequently implemented at several intersections in Texas and its safety and operational benefits were evaluated.

This report documents the findings and conclusions reached as a result of a three-year implementation project. The Detection-Control System was installed at each of eight intersections in Texas during the three-year period. Five of the intersections were suitable for a before-after study of safety and operational data. An evaluation of the before-after data indicated that the Detection-Control System was able to reduce delay by 14 percent, stop frequency by 9 percent, red-light violations by 58 percent, heavy-vehicle red-light violations by 80 percent, and severe crash frequency by 39 percent.

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IN-SERVICE EVALUATION OF A DETECTION-CONTROL SYSTEM FOR HIGH-SPEED SIGNALIZED INTERSECTIONS

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DISCLAIMER

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NOTICE

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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- Mr. Doug Vanover, project director
- Mr. Jerry Keisler
- Mr. David Mitchell
- Mr. Roy Parikh
- Mr. Steve Walker

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CHAPTER 1. INTRODUCTION

High-speed signalized intersections sometimes present unique challenges to efforts intended to improve safety, efficiency, or both. Techniques for achieving safety often have an adverse effect on efficiency and those 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 section of roadway wherein 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, the compromise between safety and efficiency has been resolved on the side of safety. Intersection control systems that include an actuated controller and multiple advance detectors have been used to provide safe phase termination. Research has shown that systems with advance detection can reduce crashes, relative to intersections with pretimed control (*1*). However, advance detection typically requires a large gap in traffic to end the phase. During high-volume conditions, it is often not possible to find a large gap and 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 decline rapidly as volumes increase.

Bonneson et al. (*2*) developed an alternative detection and control system for providing dilemma zone protection for the Texas Department of Transportation. The system overcomes the limitations of the traditional, multiple advance detector system. This system (referred to as the Detection-Control System [D-CS]) uses external computer processing to intelligently forecast the best time to end the signal phase and then, in real time, instruct the signal controller to end the phase at the appropriate time. D-CS has been implemented at each of eight signalized intersections in Texas.

The objective of this report is to document an in-service evaluation of D-CS. The evaluation addresses both the operational and safety performance of the systems that were installed at several intersections in Texas. A brief description of D-CS is provided in Chapter 2, as is a status report on its implementation at Texas intersections is also described. Chapter 3 describes the evaluation of D-CS performance in terms of intersection operation, red-light violation frequency, and traffic safety. Each of these evaluations is discussed in a separate part of the chapter. Chapter 4 summarizes the main findings from the evaluation and the conclusions reached regarding D-CS performance.

CHAPTER 2. DETECTION-CONTROL SYSTEM

OVERVIEW

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 employs an external computer to process vehicle speed and length information to predict the best time to end the major-road through phase. This prediction is continuously evaluated and updated in real time. It is based on the number of vehicles in the dilemma zone in the immediate future as well as the number of minor movements waiting for service. D-CS attempts to identify when: (1) the fewest passenger cars will be in the dilemma zone, and (2) no heavy vehicles will be in the dilemma zone. It weighs these considerations against the delay incurred by vehicles in conflicting phases. D-CS uses two detectors in each major-road traffic lane (in a speed trap configuration). These detectors are located 800 to 1000 ft upstream of the intersection on both of the high-speed approaches.

Figure 1 shows D-CS and its relationship to the vehicle detection and traffic control systems at an intersection. D-CS consists of a speed trap monitored by a detector amplifier that is, in turn, monitored by an industrial computer. This computer uses the detector output to compute vehicle speed and length. It then uses these data to determine the best time to end the phase based on consideration of 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 identified, D-CS communicates its decision to the signal controller using its external Ring Force Off and Phase Hold inputs.

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

A key feature of D-CS is that it can determine, in real-time, when each vehicle will arrive to 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 (i.e., the zone is defined to begin 5.5 s travel time from the stop line and end 2.5 s from the stop line). D-CS measures each arriving vehicle's speed, forecasts its dilemma zone arrival and departure times, and holds the green interval when a vehicle is in its dilemma zone.

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.

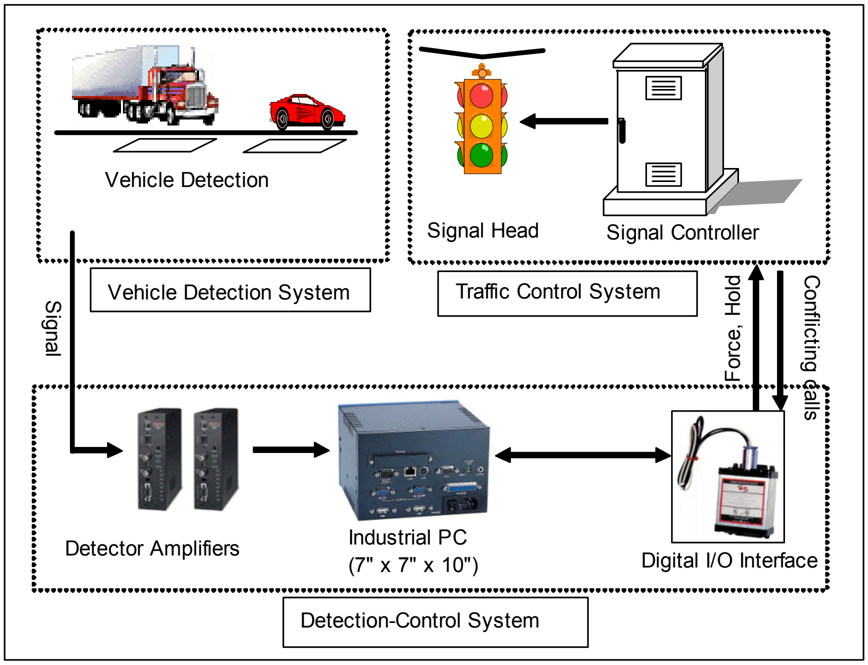

Figure 1. Detection-Control System Components.

To illustrate the implications of D-CS's dynamic dilemma-zone monitoring process, consider the following example. A vehicle traveling at 70 mph is at point A in Figure 2, and a vehicle traveling at 25 mph is at point B. Neither of these vehicles is in their respective dilemma zones, 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. It allows D-CS to consistently end the phase sooner than the traditional system. Over the course of 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.

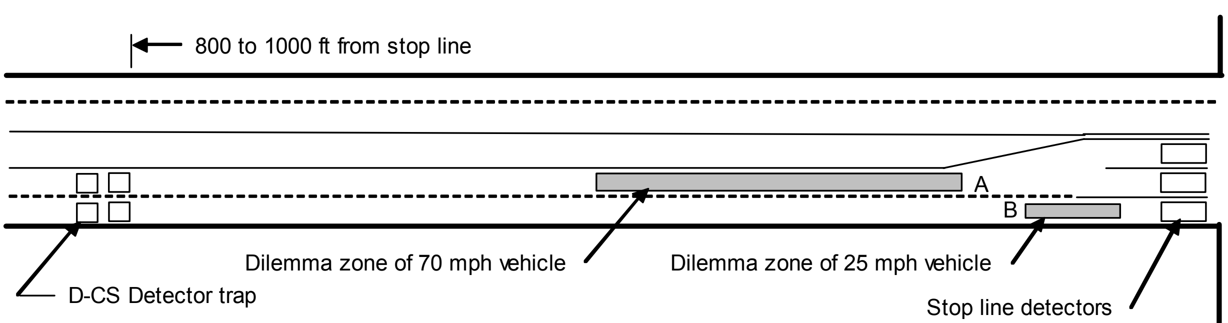

Figure 2. Detection-Control System Detection Design.

IMPLEMENTATION STATUS AND SITE CHARACTERISTICS

D-CS has been installed at eight intersections in Texas as part of TxDOT Implementation Project 5-4022. All implementation sites are isolated, high-speed signalized intersections that have 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. The sites, and their characteristics, are listed in Table 1.

Table 1. Implementation Site Characteristics.

Implementation Site [1]	Nearest City	Major-Road Characteristics			Years With Signal	D-CS Installation Date
		Name	Through Lanes	Advance Detection [2]		
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.	Bulverde	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

Notes:

1 - Sites identified by underline were evaluated in a before-after study. The findings are described in Chapter 3.

2 - Advance detection used prior to the installation of D-CS. Loop: inductive loop detectors. VIVDS: video image vehicle detection system. Detection is provided via multiple advance detection zones.

The U.S. 84 & Williams Road site was unsignalized prior to D-CS installation. It was rationalized that the operational and safety benefits of D-CS could not be separated from those attributed to the addition of signalization. For this reason, this site was excluded from the before-after study described in Chapter 3. Also excluded from the evaluation were the two sites at which D-CS was most recently installed (i.e., U.S. 84 & F.M. 2837 and U.S. 59 & F.M. 3129). These sites were excluded because sufficient time had not lapsed by the date of this report to assess the crash history at these sites during the "after" period.

A before-after study was conducted for each of the five sites identified by underline in Table 1. Of these five sites, 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 VIVDS) as well as the number and location of advance detection zones. The site at Loop 340 & F.M. 3400 did not have advance detection prior to the installation of D-CS. It should also be noted that this site was deactivated on February 27, 2004, because of nearby construction activity.

The characteristics of the major-road approaches to the five intersections evaluated in the before-after study are listed in Table 2. The data in this table indicate that most intersections had backplates on the signal heads, two through lanes on each approach, and a 4.0 to 4.5-s yellow interval duration. The speed limit varied from 45 to 65 mph among the sites.

Table 2. Major-Road Approach Traffic Control and Geometry Characteristics.

Site	Approach	Signal Head Backplates	Speed Limit, mph	Clearance Path Length,[1] ft	Through Lanes (each approach)	Yellow Duration, s
Loop 340 & F.M. 3400	Northbound	Yes	60	80	1	4.0
	Southbound	Yes	60	80	1	4.0
U.S. 82 & F.M. 3092	Eastbound	Yes	55	100	2	4.5
	Westbound	Yes	55	100	2	4.5
U.S. 82 & Weber Dr.	Eastbound	Yes	55	90	2	4.5
	Westbound	Yes	55	90	2	4.5
U.S. 59 & F.M. 819	Northbound	No	45	90	2	4.0
	Southbound	No	55	90	2	4.0
U.S. 281 & Borgfeld Rd.	Northbound	No	65	80	2	4.0
	Southbound	No	65	80	2	4.0

Note:
1 - Clearance path length is measured from the stop line of the subject approach to the furthest edge of the last conflicting lane crossed.

CHAPTER 3. EVALUATION OF D-CS PERFORMANCE

This chapter describes an in-service evaluation of D-CS performance. This evaluation is based on a before-after study that was conducted at each of the five implementation sites identified in Table 1. The evaluation consists of an examination of intersection operation, red-light violations, and traffic safety. Details of the evaluation of each performance category are described in a separate part of the chapter. The first part describes the evaluation of intersection operation. Subsequent parts describe the evaluation of red-light violations and crash frequency.

EVALUATION OF INTERSECTION OPERATION

This part of the chapter describes an evaluation of the effect of D-CS on intersection operation. The measures of performance considered include control delay and stop frequency. In the first section, the data collection plan is discussed. It describes the types of data used to evaluate D-CS performance as well as the methods used to collect it. In the second section, the data collected before and after D-CS installation are used to quantify the change in intersection operation.

Data Collection Plan

This section describes the data collection plan for the evaluation of D-CS impact on intersection operation. The first subsection describes the composition of the evaluation database. The subsection that follows describes the data collection approach.

Database Composition

The measures of effectiveness used to evaluate D-CS operation include:

- control delay; and
- stop frequency.

These two measures were quantified for the traffic movements served by D-CS (i.e., the major-road through movements). The control delay data were collected using the field survey methods described in Chapter 16 of the *Highway Capacity Manual* (*3*). Both measures provide some indication of the operational efficiency of the intersection before and after D-CS was installed. A decrease in either (or both) of these measures is an indication of improved operating conditions.

Several signalization and traffic characteristics were measured during the "before" and the "after" studies. These characteristics include the green interval duration, cycle length, traffic volume, and heavy-vehicle percentage. They were used to help in the interpretation of any observed changes in delay or stop frequency.

Data Collection Approach

Data were collected at each of the five study sites before and after the installation of D-CS. For the "before" study, data were collected on each major-road approach for a period of four hours during one day. Similarly, data were collected for four additional hours on each approach following the installation of D-CS. All total, 80 hours of data were collected during 10 days of study at the five intersections. The data were collected between the hours of 8:00 a.m. and 6:00 p.m. Data were not collected during inclement weather or during unusual traffic conditions.

Two video camcorders were used to record traffic events during each field study. Each camcorder was strategically positioned to monitor the traffic stream on both major-road approaches. The camera field of view also included the signal indications on one approach. Figure 3 shows the camcorder locations for a typical intersection. Local conditions often dictated slight adjustments to camcorder placement at each site.

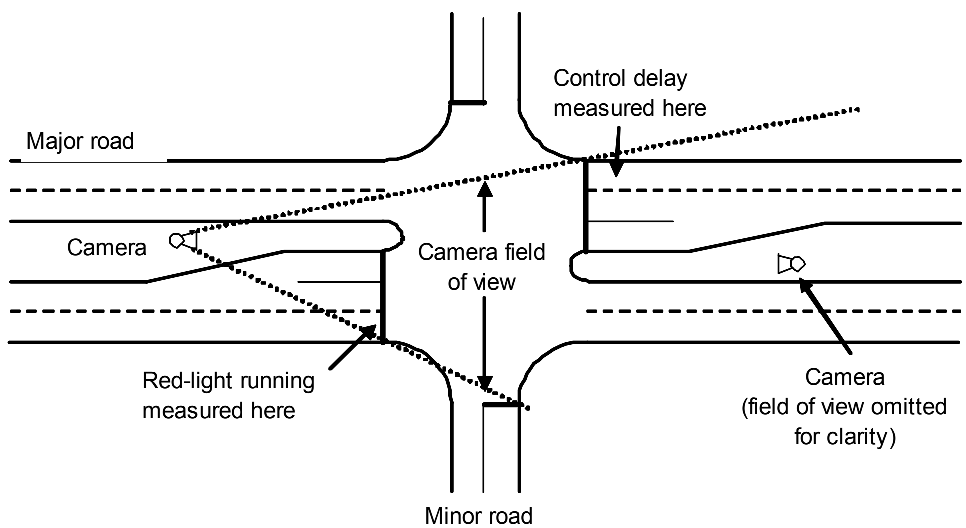

Figure 3. Camera Placement for the Before-After Study.

The operational performance measures at each intersection were extracted from the videotape recordings during their replay in the laboratory. As suggested by Figure 3, traffic events on the major-road approach that was opposing the camera (i.e., the approach with traffic moving toward the camcorder) were used to measure both delay and stop frequency. Signal indications for the adjacent approach were used to measure the green phase duration and cycle length.

Red-light violation frequency was also recorded for both major-road approaches for each videotape recording. The extraction and analysis of this data is described in the next part of this chapter.

Data Analysis

This section describes the findings from an evaluation of intersection operation before and after D-CS installation. The first subsection summarizes the delay and stop frequency data extracted from the videotape recordings. The summary includes average values for each performance measure. The second section reviews the methodology used to evaluate the before-after data. The last section describes the findings from the evaluation.

Database Summary

The average green interval duration and cycle length for the study sites are listed in Table 3. These averages indicate that the major-road green duration increased at four sites (i.e., those on U.S. 82, U.S. 59, and U.S. 281). It decreased slightly at the one site with no prior advance detection. An analysis of intersection turn movements and overall operation indicated that the increase in green and cycle length was likely due to an increase in dwell time during the major-road green phase (primarily at the U.S. 82 & Weber Drive site). This dwell time occurred because the major road frequently retained the green indication due to a lack of conflicting calls.

Table 3. Major-Road Approach Signalization and Traffic Characteristics During Study.

Site	Approach	Ave. Green Duration, s		Ave. Cycle Length, s		Flow Rate, veh/h	
		Before	After	Before	After	Before	After
Loop 340 & F.M. 3400	Northbound	49	47	74	71	376	295
	Southbound	48	46	74	71	353	301
U.S. 82 & F.M. 3092	Eastbound	49	52	85	92	733	616
	Westbound	45	60	81	98	611	654
U.S. 82 & Weber Dr.	Eastbound	77	181	99	200	353	382
	Westbound	66	133	89	153	463	303
U.S. 59 & F.M. 819	Northbound	48	53	109	106	766	818
	Southbound	45	55	109	106	723	744
U.S. 281 & Borgfeld Rd.	Northbound	74	89	94	110	818	1427
	Southbound	33	38	58	69	1072	887
	Average:	**53**	**75**	**87**	**108**	**627**	**643**

The average major-road approach flow rate is shown in the last two columns. The flow rate decreased on some intersection approaches and increased on others between the "before" and "after" study periods. The change on individual approaches ranged from a 35 percent decrease to a 74 percent increase. Overall, flow rates during the "after" period were about 3 percent higher than those during the "before" period.

Statistical Analysis Methodology

The variations in flow rate and dwell time complicated the evaluation of the performance data because they tended to influence the delay and stop frequency on both major-road approaches. To remove these influences, the expected delay and stop frequency was computed using the procedures described in Chapter 16 of the *Highway Capacity Manual* (*3*). These expected values were then used to estimate the delay and stop frequency that would have occurred in the "after" period had D-CS not been installed. Any difference between this estimate and the observed delay and/or stop frequency was attributed to the D-CS operation. The statistical analysis of the delay and stop frequency data is summarized in the Appendix.

Evaluation

The delay and stop frequency data for the "before" and "after" periods at each site are listed in Table 4. The data in column 5 indicate that total control delay decreased at eight of the 10 intersection approaches. Delay increased slightly at two approaches. As indicated by the last row of the table, the overall major-road delay was reduced by 14 percent. This reduction is statistically significant. The delay reduction in the "after" period is likely due to the D-CS's more efficient operation, relative to the existing detection and control strategy.

Table 4. Before-After Delay and Stop Frequency Comparison.

Site	Approach	Total Control Delay			Total Vehicles Stopping		
		Expected in "After" Period, hours	Observed in "After" Period, hours	Relative Change, [1, 2] %	Expected in "After" Period, veh	Observed in "After" Period, veh	Relative Change, [1, 2] %
Loop 340 & F.M. 3400	Northbound	2.0	1.6	-20	289	217	<u>-25</u>
	Southbound	1.4	1.5	7	230	190	-17
U.S. 82 & F.M. 3092	Eastbound	6.8	6.4	-7	748	654	-13
	Westbound	7.3	6.4	-12	802	711	<u>-11</u>
U.S. 82 & Weber Dr.	Eastbound	0.4	0.3	<u>-42</u>	73	51	<u>-30</u>
	Westbound	0.4	0.2	<u>-44</u>	75	46	<u>-38</u>
U.S. 59 & F.M. 819	Northbound	15.7	13.2	<u>-16</u>	1324	1221	-8
	Southbound	14.2	11.5	<u>-19</u>	1315	1237	-6
U.S. 281 & Borgfeld Rd.	Northbound	3.2	1.6	<u>-49</u>	484	283	<u>-42</u>
	Southbound	6.5	7.4	13	753	953	<u>26</u>
	Overall:	**58.0**	**50.0**	**<u>-14</u>**	**6093**	**5563**	**<u>-9</u>**

Notes:
1 - Relative change = (After/Before − 1)× 100.
2 - Negative values denote a reduction. <u>Underlined</u> values are statistically significant at 95 percent level of confidence.

The data in column 8 of Table 4 indicate that stop frequency decreased at nine of the 10 intersection approaches. The increase at the southbound approach of U.S. 281 & Borgfeld Road is likely due to the increase in delay at this approach, and is likely associated with a larger minor-movement volume in the "after" period. If the minor-movement volume had not increased, it is likely that delay and stop frequency would have decreased at this intersection approach.

As indicated by the last row of Table 4, the overall average reduction in stop frequency is 9 percent. This reduction is statistically significant. The apparent reduction in stop frequency in the "after" period is likely due to the D-CS's more efficient operation, relative to the detection-control strategy in place during the "before" study.

EVALUATION OF RED-LIGHT VIOLATIONS

This part of the chapter describes an evaluation of the effect of D-CS on red-light violations. In the first section, the data collection plan is discussed. It describes the types of data used to evaluate D-CS performance as well as the methods used to collect it. In the second section, the data collected before and after D-CS installation are used to quantify the change in violation frequency.

Data Collection Plan

This section describes the data collection plan for the evaluation of D-CS impact on red-light violations on both major-road approaches to the intersection. The first subsection describes the composition of the violation database. The subsection that follows describes the data collection approach.

Database Composition

The database assembled for the red-light violation analysis included the frequency of red-light violations by both passenger car and heavy-vehicle drivers. Several other types of data were also included in the database to help in the interpretation of observed trends in violation frequency. Geometric data that were collected included the number of through traffic lanes and the clearance path length (i.e., distance from the stop line to the far side of the last conflicting travel path). Traffic control data collected included approach speed limit and the use of signal head backplates. Signalization and traffic characteristics collected included the yellow interval duration, green interval duration, cycle length, advance detection design, traffic volume, and heavy-vehicle percentage. These data were collected because they have been found to be correlated with red-light violation frequency (*4*).

Data Collection Approach

The data identified in the previous section were collected during a before-after study conducted at each of the five D-CS implementation sites. For the "before" study, data were collected on both major-road intersection approaches for a period of four hours during one day. Similarly, data were collected for four additional hours on each approach following the installation of D-CS. All total, 80 hours of data were collected during 10 days of study at the five intersections. Details of the data collection approach were described in a previous part of this chapter.

The frequency of red-light violations was extracted from a videotape recorded during the field studies. The tapes were replayed in the laboratory for this purpose. A vehicle was identified as having violated the red indication when it entered the intersection (as defined by the stop line) after the change in signal indication from yellow to red. The type of vehicle involved in the violation was recorded as either a passenger car or a heavy vehicle.

Data Analysis

This section describes the findings from an evaluation of red-light violation frequency before and after D-CS installation. The first subsection summarizes the traffic characteristics and the violation frequency extracted from the videotape recordings. The second section reviews the methodology used to evaluate the before-after data. The last section describes the findings from the evaluation.

Database Summary

Table 5 summarizes the traffic characteristics of each site during the study of red-light violations. The total number of vehicles observed during these studies are listed in columns 3 and 4. A total of 24,401 vehicles were observed during the "before" periods; a similar number was observed during the "after" periods. The data in columns 5 and 6 indicate that study durations were slightly less than four hours for each site. This deviation reflects the elimination of "partial" signal cycles at the start and end of each one-hour videotape, the occasional blockage of the camera field of view by large vehicles, and the occasional interruption of normal traffic flow (e.g., by emergency vehicles).

Tables 2, 3, and 5 summarize the geometry, traffic control, traffic volume, and signalization characteristics associated with each of the study sites. Table 6 summarizes the red-light violation frequency observed at each of the major-road approaches during both the "before" and "after" periods. Column 5 of this table indicates the relative change in red-light violation frequency from the "before" to the "after" period. Overall, violations were reduced 58 percent. Violations by heavy-vehicle drivers were reduced by 84 percent.

The violation data are separately tabulated in Table 6 for the intersection at Loop 340 & F.M. 3400 and for the other four sites. As noted previously in the discussion associated with Table 1, the site at Loop 340 & F.M. 3400 did not have advance detection for green extension prior to the installation of D-CS. Hence, a more significant reduction in violations was expected at this site.

Table 5. Major-Road Approach Traffic Characteristics During Violation Study.

Site	Approach	Total Vehicles[1], veh		Study Duration, hours		Flow Rate[2], veh/h		Heavy-Vehicle[3] Percentage, %	
		Before	After	Before	After	Before	After	Before	After
Loop 340 & F.M. 3400	Northbound	1503	1152	3.99	3.90	377	295	24	24
	Southbound	1411	898	3.99	2.98	354	301	23	23
U.S. 82 & F.M. 3092	Eastbound	2743	2272	3.74	3.69	733	616	14	16
	Westbound	2376	2475	3.89	3.78	611	655	17	16
U.S. 82 & Weber Dr.	Eastbound	1321	1312	3.74	3.44	353	381	12	15
	Westbound	1813	1040	3.92	3.44	463	302	12	21
U.S. 59 & F.M. 819	Northbound	3026	3180	3.95	3.89	766	817	23	21
	Southbound	2789	2910	3.86	3.91	723	744	21	21
U.S. 281 & Borgfeld Rd.	Northbound	3187	5382	3.89	3.77	819	1428	13	5
	Southbound	4232	3462	3.95	3.90	1071	888	9	9
Overall:[4]		**24,401**	**24,083**	**38.92**	**36.70**	**627**	**643**	**17**	**17**

Notes:
1 - Count of vehicles observed during the study, the duration of which is listed in columns 5 and 6.
2 - Flow rate = total vehicles/study duration.
3 - A "heavy vehicle" is defined as any vehicle with more than four tires on the pavement, with the exception of a 1-ton pickup truck with dual tires on the rear axle (this vehicle was considered to be a "passenger car").
4 - A grand total is provided in columns 3 through 6. An overall average is provided in columns 7 through 10.

Table 6. Observed Red-Light Violation Frequency.

Site	Approach	Red-Light Violations (all vehicles)[1, 3]			Red-Light Violations (heavy vehicles)[1]		
		Observed Before, veh	Observed After, veh	Relative Change,[2] %	Observed Before, veh	Observed After, veh	Relative Change,[2] %
Loop 340 & F.M. 3400	Northbound	14	1	-93	5	0	-100
	Southbound	6	1	-83	2	1	-50
U.S. 82 & F.M. 3092	Eastbound	7	9	29	2	1	-50
	Westbound	14	6	-57	5	1	-80
U.S. 82 & Weber Dr.	Eastbound	13	2	-85	4	1	-75
	Westbound	11	2	-82	2	1	-50
U.S. 59 & F.M. 819	Northbound	15	7	-53	3	1	-67
	Southbound	23	5	-78	9	0	-100
U.S. 281 & Borgfeld Rd.	Northbound	14	19	36	2	0	-100
	Southbound	33	11	-67	3	0	-100
Overall:		**150**	**63**	**-58**	**37**	**6**	**-84**
Loop 340:		**20**	**2**	**-90**	**7**	**1**	**-86**
All sites but Loop 340:		**130**	**61**	**-53**	**30**	**5**	**-83**

Notes:
1 - Frequency of red-light violations during study (study duration for each approach is listed in Table 5).
2 - Relative change = (Obs. After/Obs. Before − 1) × 100. Negative values indicate a reduction in violation frequency.
3 - "All Vehicles" include both passenger cars and heavy vehicles.

Statistical Analysis Method

After reviewing the site characteristics shown in Tables 2, 3, and 5, there was some question as to whether the relative changes in violation frequency, noted in Table 6, were due to D-CS operation or other events (e.g., a change in volume or cycle length). Therefore, the data listed in Table 6 were more formally evaluated using a statistical analysis method that controls for changes in extraneous factors. This method follows that developed by Hauer *(5)* for the analysis of crash data. Specifically, it uses a multivariate regression model to estimate the expected frequency of red-light violations at a "typical" intersection approach. Empirical Bayes methods are then used to refine the estimate of expected violation frequency using the observed violation frequency in the "before" period. Finally, this estimate is extrapolated to the "after" period and compared with the observed violation frequency in the "after" period.

The change in violations due to the change in detection system is compared using the ratio of observed violations in the "after" period to expected violations in the "after" period. Persaud *(6)* describes an equation for estimating the standard deviation of this statistic. The multivariate regression model developed by Bonneson and Zimmerman *(4)* was used to estimate the expected red-light violation frequency for each intersection approach. The statistical analysis of the violation data is summarized in the Appendix.

Evaluation

The findings from the statistical analysis of the red-light violation data are summarized in Table 7. The relative-change values in columns 5 and 8 are different from those in Table 6 because of differences in their method of calculation. The values in Table 7 are considered to be a more accurate indication of relative change due to D-CS installation; their method of computation is documented in the Appendix.

The relative-change values listed in column 5 of Table 7 indicate that violations were reduced at nine of the 10 approaches. The increase in violations at one approach was not statistically significant. Overall, violations in the "before" period were reduced by 58 percent in the "after" period. This overall average is equivalent to that computed using the observed violation frequency and reported in Table 6. However, this equivalence is coincidental because of the significant differences in their method of calculation.

The one site that did not have advance detection (i.e., Loop 340 & F.M. 3400) experienced a 90 percent reduction in red-light violations. This reduction is likely due to the installation of D-CS at this location. It can be compared to the 65 percent reduction typically obtained from a traditional advance detector system (*1*). Because the violation reduction potential of D-CS (i.e., 90 percent) exceeds that for multiple advance detector systems (i.e., 65 percent), it is logical to infer that D-CS would be able to reduce violations when installed at an intersection that currently has a multiple advance detector system. In fact, the last row in Table 7 indicates that D-CS does have this capability. Specifically, the installation of D-CS at four sites with multiple advance detectors resulted in a 53 percent reduction in violations.

Table 7. Before-After Red-Light Violation Comparison.

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

Notes:
1 - Frequency of red-light violations during study (study duration for each approach is listed in Table 3).
2 - Relative change = (Obs. After/Exp. After − 1) × 100. Negative values of relative change indicate a reduction in violation frequency. <u>Underlined</u> values are statistically significant at 95 percent level of confidence.

If the 65 percent reduction for the multiple advance detection system is pooled with the additional observed 53 percent reduction for D-CS, the expected reduction can be computed as 84 percent (=100 − [100 − 65] × [100 − 53]/100). This result is similar to the 90 percent reduction found at the Loop 340 & F.M. 3400 site. It confirms that D-CS is able to reduce red-light violations at an intersection approach with no previous detection by 84 to 90 percent. This reduction is about twice that reported for camera enforcement of red-light violations *(7)*.

Data in the last column of Table 7 indicate the ability of D-CS to reduce red-light violations by heavy-vehicle drivers. D-CS has a special feature that monitors heavy vehicles on the intersection approach and gives them priority green extension *(2)*. Evidence of the benefit of this feature is the 80 percent reduction in violations by heavy vehicles, relative to 58 percent reduction for the combined traffic stream. The 80 percent reduction is extended to the four sites with multiple advance detectors because these systems are *not* able to provide priority extension to heavy vehicles.

EVALUATION OF TRAFFIC SAFETY

This part of the chapter describes an evaluation of the effect of D-CS on crash frequency. In the first section, the data collection plan is discussed. It describes the types of data used to evaluate D-CS performance as well as the methods used to collect it. In the second section, the data collected before and after D-CS installation are used to quantify the change in crash frequency.

Data Collection Plan

This section describes the data collection plan for the evaluation of D-CS impact on crashes on the major-road approaches to the intersection. The database assembled for the evaluation of intersection safety included: crash frequency, daily traffic demand, and period of time for which representative crash data were available. Crash data for the "before" period were obtained from the Texas Department of Public Safety (DPS) crash database. All crashes within ±0.1 miles of the intersection were considered for this analysis. Only those crashes that occurred on the highway equipped with D-CS were considered in the evaluation. Also, only crashes that were confirmed to be "intersection-related" were included.

A preliminary examination of the crash data indicated that the frequency of property-damage-only crashes is highly variable due to differences in the reporting threshold used by law enforcement in the local jurisdictions. Therefore, the analysis described in this section is based only on severe crashes (i.e., those crashes designated as injury or fatal).

Crash types that are more likely to be influenced by D-CS (e.g., rear-end, left-turn opposed, sideswipe, etc.) were specifically identified to ensure that the safety effect, if any, would be accurately quantified. A separate analysis of severe "influenced" crashes was also conducted. The findings from this separate analysis are summarized at the end of this section.

Average annual daily traffic demands (AADTs) were obtained for the highway equipped with D-CS, in the vicinity of the intersection. These AADTs were extracted from the Texas Reference Marker System database for the years 1994 to 2003. AADTs for years 2004 and 2005 were estimated by projecting a best-fit trend line through the available AADT data.

One of the five sites (i.e., U.S. 281 & Borgfeld Road) had operated under signal control for only 18 months prior to D-CS installation. Hence, "before" period crash data at this site were limited to 18 months. All other sites operated under signal control for three or more years prior to D-CS installation. For each of these sites, crash data for three recent years were obtained from the DPS database.

Data Analysis

This section describes the findings from an evaluation of crash frequency before and after D-CS installation. The first subsection summarizes the traffic volume and crash data for each of the study sites. The last section describes the findings from the evaluation of these data.

Database Summary

Table 8 summarizes the traffic volume and crash characteristics associated with each of the five study sites. The data in columns 5 and 6 of this table indicate that there were 61 severe crashes at the five sites during the 13.5-year "before" period. Data in the last column indicate that there were 14 crashes at the same sites during the 5.33-year "after" period. The AADTs shown represent an average of the AADTs associated with each year of the "before" and the "after" periods.

Table 8. Observed Severe Crash Frequency.

Site	Approach	"Before" Study Period				"After" Study Period			
		Dates	AADT [1]	Years	Crashes	Dates	AADT [1]	Years	Crashes
Loop 340 & F.M. 3400	North and Southbound	1/00 - 12/02	10,900	3.0	10	3/03 - 12/03	15,000	0.83	3
U.S. 82 & F.M. 3092	East and Westbound	1/99 - 12/01	21,300	3.0	7	7/03 - 2/05	23,300	1.67	4
U.S. 82 & Weber Dr.	East and Westbound	1/99 - 12/01	12,100	3.0	8	8/03 - 2/05	12,400	1.58	2
U.S. 59 & F.M. 819	North and Southbound	7/01- 6/04	42,200	3.0	23	7/04 - 2/05	43,300	0.67	3
U.S. 281& Borgfeld Rd.	North and Southbound	2/03- 7/04	31,300	1.5	13	8/04 - 2/05	33,800	0.58	2
			Overall:	**13.5**	**61**	**--**	**--**	**5.33**	**14**

Note:
1 - AADTs listed are representative of the "before" and "after" study dates shown.

Evaluation

It is possible that some of the sites at which D-CS was installed were selected by TxDOT because they were identified as "high-crash" locations based on recent crash trends (however, it was not requested by the researchers that the sites have this distinction). During one or two consecutive years, an intersection can be identified as a high-crash location when, in fact, its crash frequency is above average simply because of random events, rather than a degradation in intersection safety. In subsequent years, the crash frequency at the high-crash location typically declines due to the natural tendency for crash trends to return to the mean (i.e., average) value. When a high-crash location has a safety treatment (e.g., D-CS) applied, the "regression-to-the-mean" phenomena can result in treatment effectiveness being overestimated because the observed reduction in crashes between the "before" and "after" periods may be partially explained by the intersection's natural tendency to have its crash frequency regress back to the mean frequency.

The empirical Bayes method (used for the violation analysis) is the appropriate technique for minimizing the effect of regression-to-the-mean when quantifying treatment effectiveness. However, this method was not used for the safety evaluation because the multivariate crash prediction model required for the Bayes method was not available. The implications of this limitation are discussed in a subsequent paragraph.

Given that a multivariate crash prediction model was not available, a crash rate was computed and used to estimate crash frequency during the "after" period. Specifically, the "before" data listed in Table 8 were used to compute a crash rate for the "before" period. This rate was then combined with the traffic volume in the "after" period and with the duration of the "after" period to estimate the expected number of crashes that would have occurred in the "after" period had D-CS not been installed. This expected number is shown in column 3 of Table 9; its calculation is documented in Table A-9 in the Appendix.

Table 9. Before-After Severe Crash Frequency Comparison.

Site	Approach	Expected Crashes in "After" Period	Observed Crashes in "After" Period	Relative Change,[1] %
Loop 340 & F.M. 3400	North and Southbound	3.8	3	-21
U.S. 82 & F.M. 3092	East and Westbound	4.2	4	-6
U.S. 82 & Weber Dr.	East and Westbound	4.3	2	-53
U.S. 59 & F.M. 819	North and Southbound	5.2	3	-42
U.S. 281& Borgfeld Rd.	North and Southbound	5.5	2	<u>-64</u>
	Overall:	**23.0**	**14**	**<u>-39</u>**

Note:
1 - Relative change = (Obs. After/Exp. After − 1) × 100. Negative values of relative change indicate a reduction in crash frequency. <u>Underlined</u> values are statistically significant at 95 percent level of confidence.

The last column of Table 9 compares the expected number of crashes in the "after" period with the observed number of crashes. The resulting relative-change values vary; however, all sites indicate a decrease in crashes. Overall, there is a 39 percent reduction in severe crashes. This reduction is statistically significant.

It is possible that some of the estimated 39 percent reduction could have occurred due to regression-to-the-mean and is not a consequence of installing D-CS. However, experience in quantifying this effect for other sites and the researchers' understanding that crash history was not a consideration in the selection of some sites, suggests that the severe crash reduction potential associated with D-CS is at least 35 percent.

The crash data analysis was repeated using only crashes that were likely to be influenced by D-CS operation. These crash were characterized as one of the following types: rear-end, left-turn opposed, or sideswipe. The results of the analysis indicated that "influenced" crashes were reduced by 50 percent. This result is statistically significant at a 95 percent level of confidence.

CHAPTER 4. FINDINGS AND CONCLUSIONS

This chapter summarizes the findings and offers conclusions reached from an in-service evaluation of the operational and safety performance of the D-CS. This system has been installed at eight intersections in Texas. The measures of effectiveness used to evaluate its performance include:

- control delay;
- stop frequency;
- red-light violation frequency; and
- crash frequency.

The first two measures listed provide some indication of the operational efficiency provided by the system. The latter two provide some 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. A before-after study method was used for the evaluation.

This chapter consists of two parts. The first part summarizes the findings from the analysis of the before-after study data. The second part lists the conclusions reached based on a review of the findings and experiences with D-CS.

FINDINGS

The results of the before-after evaluations described in Chapter 3 are summarized in Table 10. As indicated by the data in columns 3 and 4 of Table 10, intersection operation improved at almost every approach controlled by D-CS. Overall, control delay was reduced by 14 percent and stop frequency was reduced by 9 percent. These reductions are likely due to the D-CS's more efficient operation, relative to the detection and control strategy that was in operation prior to the installation of D-CS.

The data in columns 5 and 6 of Table 10 indicate that the frequency of red-light violations was reduced on almost every approach controlled by D-Cs. Overall, violations were reduced by 58 percent. More notably, violations by heavy-vehicle drivers were reduced by about 80 percent. When D-CS is used to replace an existing multiple advance loop detection system, violations are reduced by 53 percent. When D-CS is used at an intersection that does not have advance detection, then violations are reduced by about 90 percent.

The data in the last column of Table 10 indicate that the frequency of crashes was reduced 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. This reduction equates to about nine severe crashes prevented in the years that D-CS has been in operation (and probably about 18 property-damage-only crashes prevented). 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 appears to account for a 50 percent reduction in severe "influenced" crashes.

Table 10. Before-After Operation and Safety Comparison.

Site	Approach	Relative Change,[1, 2] %				
		Control Delay	**Stop Frequency**	**Red-Light Violations (all vehicles)**	**Red-Light Violations (heavy veh.)**	**Crash Frequency**
Loop 340 & F.M. 3400	Northbound	-20	-25	-93	-100	-21
	Southbound	7	-17	-85	-46	
U.S. 82 & F.M. 3092	Eastbound	-7	-13	19	-46	-6
	Westbound	-12	-11	-49	-69	
U.S. 82 & Weber Dr.	Eastbound	-42	-30	-61	-37	-53
	Westbound	-44	-38	-57	-22	
U.S. 59 & F.M. 819	Northbound	-16	-8	-58	-69	-42
	Southbound	-19	-6	-79	-100	
U.S. 281 & Borgfeld Rd.	Northbound	-49	-42	-50	-100	-64
	Southbound	13	27	-52	-100	
Overall:		**-14**	**-9**	**-58**	**-80**	**-39**
Loop 340:		**-9**	**-22**	**-90**	**-84**	**-21**
All sites but Loop 340:		**-14**	**-8**	**-53**	**-79**	**-43**

Notes:
1 - Relative change = (After/Before − 1)× 100.
2- Negative values denote a reduction.

CONCLUSIONS

The objective of the Detection-Control System 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; and
- maintains or reduces overall intersection delay.

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 where 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, the Detection-Control System is a dynamic dilemma-zone monitoring process because it identifies the dilemma zone for *each* vehicle, in *real time*, and *prior* to when the information is needed. It differs from the operation of the multiple advance detector system because the latter system searches for a time when a segment of each approach is clear of vehicles.

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

The last two benefits identified in the previous list are realized in two ways. First, they are partly achieved by the detection-control algorithm's dynamic dilemma-zone monitoring process. This process is often able to find the "best time to end the phase" sooner than the multiple advance detector system. This capability translates into shorter phases and lower overall delay. Second, the Detection-Control System 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.

CHAPTER 5. REFERENCES

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APPENDIX: ANALYSIS WORKSHEETS

Table A-1. Estimated Delay in After Period.

Site	Approach	"Before" Study Period [1]			"After" Study Period [1]		
		Observed Total Delay (D_b), hours	Standard Deviation of D_b (S_{Db}), [2] hours	Expected Total Delay ($E[D]_b$),[3] hours	Expected Total Delay ($E[D]_a$),[3] hours	Standard Deviation of D_a (S_{Da}), [2] hours	Expected in "After" Period ($DLY*$), [4] hours
Loop 340 & F.M. 3400	Northbound	2.77	0.42	2.35	1.67	0.12	1.96
	Southbound	1.96	0.34	2.22	1.58	0.20	1.39
U.S. 82 & F.M. 3092	Eastbound	7.25	0.83	8.06	7.60	0.45	6.84
	Westbound	6.94	0.11	6.59	6.94	0.52	7.31
U.S. 82 & Weber Dr.	Eastbound	1.14	0.11	1.06	0.39	0.04	0.42
	Westbound	1.67	0.16	1.81	0.47	0.02	0.43
U.S. 59 & F.M. 819	Northbound	19.14	1.30	18.87	15.52	0.83	15.74
	Southbound	20.70	1.05	19.87	13.66	0.60	14.23
U.S. 281 & Borgfeld Rd.	Northbound	1.41	0.07	2.78	6.20	0.28	3.16
	Southbound	6.53	0.39	9.65	9.67	0.28	6.54
	Total:	**69.51**	**1.99**	**73.26**	**63.70**	**1.32**	**58.02**

Notes:

1 - Delay values listed represent total control delay incurred during a 4-hour period.

2 - S_{Db} = 4.0 times the mean square error of a "no-intercept" regression model relating the observed and expected total delay for each hour of the 4-hour "before" study period. S_{Da} is based on data in the "after" study period.

3 - Expected total control delay values for each hour were obtained by multiplying the approach flow rate (from Table 3) by 4.0 hours and then by the control delay (in s/veh) computed using the procedures in Chapter 16 of the *Highway Capacity Manual* (*3*).

4 - $DLY* = D_b \times E[D]_a / E[D]_b$

Table A-2. Delay Statistical Analysis.

Site	Approach	Total Delay, hours		Variance[1] of DLY^* ($V[DLY^*]$)	Ratio[2] (R)	Standard Deviation[3] of R (s_R)	t statistic[4]	p value[5]
		Expected in "After" Period (DLY^*)	Observed in "After" Period (D_a)					
Loop 340 & F.M. 3400	Northbound	1.96	1.57	0.09	0.80	0.14	-1.60	0.08
	Southbound	1.39	1.49	0.06	1.07	0.23	0.16	0.56
U.S. 82 & F.M. 3092	Eastbound	6.84	6.38	0.61	0.93	0.13	-0.62	0.28
	Westbound	7.31	6.41	0.01	0.88	0.07	-1.70	0.07
U.S. 82 & Weber Dr.	Eastbound	0.42	0.25	0.00	0.58	0.10	-4.03	0.00
	Westbound	0.43	0.24	0.00	0.56	0.08	-5.66	0.00
U.S. 59 & F.M. 819	Northbound	15.74	13.15	1.14	0.84	0.08	-2.17	0.04
	Southbound	14.23	11.50	0.52	0.81	0.06	-3.30	0.01
U.S. 281 & Borgfeld Rd.	Northbound	3.16	1.62	0.03	0.51	0.09	-5.30	0.00
	Southbound	6.54	7.42	0.15	1.13	0.08	1.61	0.92
	Overall:	**58.02**	**50.03**	**2.61**	**0.86**	**0.03**	**-4.12**	**0.00**

Notes:

1 - $V[DLY^*] = (E[D]_a / E[D]_a)^2 \times S_{Db}^2$

2 - $R = D_a / RLR^*$

3 - $s_R = 1/DLY^* \times [S_{Da}^2 + (D_a/D_b)^2 S_{Db}^2]^{0.5}$

4 - $t = (R - 1)/s_R$

5 - p value: probability of error in a claim that total delay is reduced (i.e., that R is less than 1.0) using the t-distribution and 6 degrees of freedom (= 8−2) for each approach; 78 degrees of freedom for the overall estimate.

Table A-3. Estimated Stop Frequency in After Period.

Site	Approach	"Before" Study Period[1]			"After" Study Period[1]		
		Observed Total Stops (S_b), veh	Standard Deviation of S_b (S_{Sb}),[2] veh	Expected Total Stops ($E[S]_b$),[3] veh	Expected Total Stops ($E[S]_a$),[3] veh	Standard Deviation of S_a (S_{Sa}),[2] veh	Expected in "After" Period ($STP*$),[4] veh
Loop 340 & F.M. 3400	Northbound	388	38	163	121	21	289
	Southbound	295	40	151	118	22	230
U.S. 82 & F.M. 3092	Eastbound	887	60	388	327	38	748
	Westbound	827	18	325	315	30	802
U.S. 82 & Weber Dr.	Eastbound	173	17	84	35	8	73
	Westbound	248	19	138	42	4	75
U.S. 59 & F.M. 819	Northbound	1401	90	542	512	60	1324
	Southbound	1533	53	547	469	21	1315
U.S. 281 & Borgfeld Rd.	Northbound	242	8	230	461	41	484
	Southbound	928	55	653	530	55	753
Total:		**6922**	**147**	**3221**	**2930**	**110**	**6093**

Notes:

1 - Stopped vehicle values listed represent total number of stopped vehicles during a 4-hour period.

2 - S_{Sb} = 4.0 times the mean square error of a "no-intercept" regression model relating the observed and expected stop frequency for each hour of the 4-hour "before" study period. S_{Sa} is based on data in the "after" study period.

3 - Expected stops for each hour were obtained by multiplying the approach flow rate (from Table 3) by 4.0 hours and then by the value (1-g/C)/(1-v/s), where g is the average phase duration, C is the average cycle length, v is the flow rate per lane, and s is the saturation flow rate (assumed to be 1800 veh/h/ln).

4 - $STP* = S_b \times E[S]_a / E[S]_b$

Table A-4. Stop Frequency Statistical Analysis.

Site	Approach	Total Stops, veh		Variance [1] of *STP** (*V[STP*]*)	Ratio [2] (*R*)	Standard Deviation [3] of *R* (s_R)	*t* statistic [4]	*p* value [5]
		Expected in "After" Period (*STP**)	Observed in "After" Period (S_a)					
Loop 340 & F.M. 3400	Northbound	289	217	823	0.75	0.10	-2.49	0.02
	Southbound	230	190	977	0.83	0.15	-1.26	0.13
U.S. 82 & F.M. 3092	Eastbound	748	654	2565	0.87	0.08	-1.67	0.07
	Westbound	802	711	307	0.89	0.04	-2.70	0.02
U.S. 82 & Weber Dr.	Eastbound	73	51	52	0.70	0.13	-2.41	0.03
	Westbound	75	46	32	0.62	0.07	-5.39	0.00
U.S. 59 & F.M. 819	Northbound	1324	1221	7266	0.92	0.07	-1.09	0.16
	Southbound	1315	1237	2069	0.94	0.04	-1.68	0.07
U.S. 281 & Borgfeld Rd.	Northbound	484	283	260	0.58	0.09	-4.77	0.00
	Southbound	753	953	2012	1.26	0.10	2.49	0.98
Overall:		**6093**	**5563**	**16,363**	**0.91**	**0.03**	**-3.30**	**0.00**

Notes:
1 - $V[STP^*] = (E[S]_a / E[S]_a)^2 \times S_{Sb}^2$
2 - $R = S_a / RLR^*$
3 - $s_R = 1/STP^* \times [S_{Sa}^2 + (S_a/S_b)^2 \, S_{Sb}^2]^{0.5}$
4 - $t = (R - 1)/s_R$
5 - *p* value: probability of error in a claim that stop frequency is reduced (i.e., that *R* is less than 1.0) using the *t*-distribution and 6 degrees of freedom (= 8 − 2) for each approach; 78 degrees of freedom for the overall estimate.

Table A-5. Estimated Red-Light Violations in After Period - All Vehicles.

Site	Approach	"Before" Study Period[1]				"After" Study Period[1]	
		Observed Red-Light Violations (X_b)	Expected Red-Light Violations[2] ($E[R]_b$), veh/h	*weight*[3]	Expected Violations given X_b[4] ($E[R\|X]_b$), veh/h	Expected Red-Light Violations[2] ($E[R]_a$), veh/h	Expected in "After" Period[5] ($RLR*$)
Loop 340 & F.M. 3400	Northbd.	14	8.7	0.15	4.3	7.0	13.5
	Southbd.	6	7.6	0.17	2.5	6.7	6.6
U.S. 82 & F.M. 3092	Eastbd.	7	4.1	0.29	2.5	3.3	7.6
	Westbd.	14	4.1	0.28	3.7	3.4	11.8
U.S. 82 & Weber Dr.	Eastbd.	13	1.5	0.51	2.5	0.9	5.2
	Westbd.	11	2.3	0.40	2.6	1.2	4.7
U.S. 59 & F.M. 819	Northbd.	15	5.5	0.22	4.2	5.7	16.7
	Southbd.	23	6.1	0.21	6.0	6.3	24.2
U.S. 281 & Borgfeld Rd.	Northbd.	14	7.7	0.17	4.3	18.3	38.3
	Southbd.	33	15.3	0.09	9.0	9.9	22.7
Total:		**150**	**62.9**	**--**	**41.6**	**62.7**	**151.2**
Loop 340:		**20**	**16.3**	**--**	**6.8**	**13.7**	**20.1**
All sites but Loop 340:		**130**	**46.6**	**--**	**34.8**	**49.0**	**131.2**

Notes:

1 - Frequency of red-light violations during study (study duration for each approach is listed in Table 5).

2 - Expected red-light violations before $E[R]_b$ and after $E[R]_a$ were computed using the multivariate regression model described in Reference (*4*).

3 - *weight* = $1/(1 + E[R]_b\, H_b /6.1)$ where, H_b is the duration of the "before" study period, in hours (from Table 5).

4 - $E[R|X]_b = E[R]_b \times weight + (1 - weight)\, X_b / H_b$.

5 - $RLR* = H_a \times E[R|X]_b \times E[R]_a / E[R]_b$ where, H_a is the duration of the "after" study period, in hours (from Table 5).

Table A-6. Red-Light Violation Statistical Analysis - All Vehicles.

Site	Approach	Violation Freq., veh		Variance [1] of *RLR**, (*V[RLR*]*)	Ratio [2] (*R*)	Standard Deviation [3] of *R* (s_R)	*z* statistic [4]	*p* value [5]
		Expected in "After" Period (*RLR**)	Observed in "After" Period (X_a)					
Loop 340 & F.M. 3400	Northbd.	13.5	1	9.0	0.07	0.07	-13.4	0.00
	Southbd.	6.6	1	3.6	0.15	0.13	-6.4	0.00
U.S. 82 & F.M. 3092	Eastbd.	7.6	9	4.4	1.19	0.45	0.2	0.60
	Westbd.	11.8	6	6.9	0.51	0.22	-2.4	0.01
U.S. 82 & Weber Dr.	Eastbd.	5.2	2	1.4	0.39	0.26	-2.4	0.01
	Westbd.	4.7	2	1.3	0.43	0.28	-2.1	0.02
U.S. 59 & F.M. 819	Northbd.	16.7	7	13.3	0.42	0.17	-3.6	0.00
	Southbd.	24.2	5	20.2	0.21	0.09	-8.6	0.00
U.S. 281 & Borgfeld Rd.	Northbd.	38.3	19	72.8	0.50	0.14	-3.7	0.00
	Southbd.	22.7	11	13.2	0.48	0.16	-3.4	0.00
Overall:		**151.2**	**63**	**146.0**	**0.42**	**0.06**	**-9.6**	**0.00**
Loop 340:		**20.1**	**2**	**12.6**	**0.10**	**0.07**	**-13.2**	**0.00**
All sites but Loop 340:		**131.2**	**61**	**133.4**	**0.47**	**0.07**	**-7.6**	**0.00**

Notes:
1 - $V[RLR^*] = RLR^* \times E[R]_a \times H_a / (6.1 + E[R]_b\, H_b)$
2 - $R = X_a / RLR^*$
3 - $s_R = R \times [1/X_a + V[RLR^*]/(RLR^*)^2\ ]^{0.5} / [1 + V[RLR^*]/(RLR^*)^2\ ]$
4 - $z = (R - 1)/s_R$
5 - *p* value: probability of error in a claim that violations are reduced (i.e., that *R* is less than 1.0).

Table A-7. Estimated Red-Light Violations in After Period - Heavy Vehicles.

Site	Approach	"Before" Study Period [1]				"After" Study Period [1]	
		Observed Red-Light Violations (X_{bh})	Expected Red-Light Violations [2] ($E[R]_{bh}$), veh/h	*weight* [3]	Expected Violations given X_{bh} [4] ($E[R\|X]_{bh}$), veh/h	Expected Red-Light Violations [2] ($E[R]_{ah}$), veh/h	Expected in "After" Period [5] (RLR_h*)
Loop 340 & F.M. 3400	Northbd.	5	2.1	0.15	1.4	1.7	4.4
	Southbd.	2	1.7	0.17	0.7	1.5	1.9
U.S. 82 & F.M. 3092	Eastbd.	2	0.6	0.29	0.5	0.5	1.9
	Westbd.	5	0.7	0.28	1.1	0.5	3.3
U.S. 82 & Weber Dr.	Eastbd.	4	0.2	0.51	0.6	0.1	1.6
	Westbd.	2	0.3	0.40	0.4	0.3	1.3
U.S. 59 & F.M. 819	Northbd.	3	1.3	0.22	0.9	1.2	3.3
	Southbd.	9	1.3	0.21	2.1	1.3	8.6
U.S. 281 & Borgfeld Rd.	Northbd.	2	1.0	0.17	0.6	0.8	1.9
	Southbd.	3	1.4	0.09	0.8	0.9	2.1
Total:		**37**	**10.6**	**--**	**9.2**	**8.8**	**30.0**
Loop 340:		**7**	**3.8**	**--**	**2.1**	**3.2**	**6.2**
All sites but Loop 340:		**30**	**6.8**	**--**	**7.1**	**5.6**	**23.8**

Notes:

1 - Frequency of red-light violations during study (study duration for each approach is listed in Table 5).

2 - Expected red-light violations before $E[R]_{bh} = p_{bh} \times E[R]_b /100$ and after $E[R]_{ah} = p_{ah} \times E[R]_a /100$ where, $E[R]_b$ and after $E[R]_a$ are obtained from Table A-5, p_{bh} = percent of heavy vehicles in the "before" period, and p_{ah} = percent of heavy vehicles in the "after" period.

3 - $weight = 1/(1 + E[R]_b\, H_b /6.1)$ where, H_b is the duration of the "before" study period, in hours (from Table 5).

4 - $E[R|X]_{bh} = E[R]_{bh} \times weight + (1 - weight)\, X_{bh} /H_b$.

5 - $RLR_h^* = H_a \times E[R|X]_{bh} \times E[R]_{ah} /E[R]_{bh}$ where, H_a is the duration of the "after" study period, in hours (from Table 5).

Table A-8. Red-Light Violation Statistical Analysis - Heavy Vehicles.

Site	Approach	Violation Freq., veh		Variance[1] of RLR_h* ($V[RLR_h*]$)	Ratio[2] (R_h)	Standard Deviation[3] of R_h (s_{Rh})	z statistic[4]	p value[5]
		Expected in "After" Period (RLR_h*)	Observed in "After" Period (X_{ah})					
Loop 340 & F.M. 3400	Northbd.	4.4	0	2.9	0.00	0.00	--	--
	Southbd.	1.9	1	1.0	0.54	0.37	-1.6	0.06
U.S. 82 & F.M. 3092	Eastbd.	1.9	1	1.2	0.54	0.34	-1.8	0.04
	Westbd.	3.3	1	1.8	0.31	0.24	-3.0	0.00
U.S. 82 & Weber Dr.	Eastbd.	1.6	1	0.5	0.63	0.47	-1.0	0.15
	Westbd.	1.3	1	0.6	0.78	0.49	-0.9	0.19
U.S. 59 & F.M. 819	Northbd.	3.3	1	2.4	0.31	0.23	-3.3	0.00
	Southbd.	8.6	0	7.1	0.00	0.00	--	--
U.S. 281 & Borgfeld Rd.	Northbd.	1.9	0	1.2	0.00	0.00	--	--
	Southbd.	2.1	0	1.2	0.00	0.00	--	--
Overall:		**30.0**	**6**	**20.1**	**0.20**	**0.08**	**-9.7**	**0.00**
Loop 340:		**6.2**	**1**	**3.9**	**0.16**	**0.14**	**6.1**	**0.00**
All sites but Loop 340:		**23.8**	**5**	**16.1**	**0.21**	**0.10**	**8.4**	**0.00**

Notes:

1 - $V[RLR_h*] = RLR_h* \times E[R]_{ah} \times H_a / (p_{bh} \times 6.1 + E[R]_{bh} H_b)$

2 - $R_h = X_{ah}/RLR_h*$

3 - $s_{Rh} = R_h \times [1/X_{ah} + V[RLR_h*]/(RLR_h*)^2]^{0.5} / [1 + V[RLR_h*]/(RLR_h*)^2]$

4 - $z = (R_h - 1)/s_{Rh}$

5 - p value: probability of error in a claim that violations are reduced (i.e., that R is less than 1.0).

Table A-9. Estimated Severe Crash Frequency in After Period.

Site	Time Period			AADT, veh/d (V_a, V_b)	"Before" Study Period		"After" Study Period	
	Before or After	Duration, years (y_a, y_b)	Year		Crash Freq., crash/period (C_b)	Crash Rate,[1] crashes/veh (cr_b)	Expected Crash Freq.,[2] crash/period (c_a)	Variance of c_a[3] ($V[c_a]$)
Loop 340 & F.M. 3400	Before	1.00	2000	10,300	4	0.000305		
		1.00	2001	11,500	1			
		1.00	2002	11,000	5			
	After	0.83	2003	15,000			3.81	1.45
						Total:	3.81	1.45
U.S. 82 & F.M. 3092	Before	1.00	1999	21,000	3	0.000109		
		1.00	2000	22,000	3			
		1.00	2001	21,000	1			
	After	0.50	2003	23,000			1.26	0.23
		1.00	2004	23,300			2.55	0.93
		0.17	2005	23,800			0.43	0.03
						Total:	4.24	1.18
U.S. 82 & Weber Dr.	Before	1.00	1999	11,600	2	0.000220		
		1.00	2000	12,700	3			
		1.00	2001	12,000	3			
	After	0.42	2003	12,100			1.11	0.15
		1.00	2004	12,500			2.75	0.95
		0.17	2005	12,600			0.46	0.03
						Total:	4.33	1.13
U.S. 59 & F.M. 819	Before	0.50	2001	42,000	1	0.000182		
		1.00	2002	42,000	7			
		1.00	2003	42,000	10			
		0.50	2004	43,200	5			
	After	0.50	2004	43,200			3.92	0.67
		0.17	2005	43,400			1.31	0.08
						Total:	5.24	0.74
U.S. 281 & Borgfeld Rd.	Before	0.92	2003	30,000	8	0.000277		
		0.58	2004	33,300	5			
	After	0.42	2004	33,300			3.84	1.14
		0.17	2005	34,900			1.61	0.20
						Total:	5.46	1.34
						Grand Total:	23.1	5.84

Notes:
1 - $cr_b = \Sigma C_{b,i} / \Sigma(y_{b,i} \times V_{b,i})$; where, $y_{b,i}$ = duration for "before" year i, $V_{b,i}$ = AADT for "before" year i.
2 - $c_{a,i} = cr_b \times [y_{a,i} \times V_{a,i}]$; where, $y_{a,i}$ = duration for "after" year i, $V_{a,i}$ = AADT for "after" year i.
3 - $V[c_{a,i}] = c_{a,i} \times [y_{a,i} \times V_{a,i}] / \Sigma(y_{b,i} \times V_{b,i})$.

Table A-10. Crash Frequency Statistical Analysis.

Site	Approach	Crash Frequency: Expected in "After" Period (c_a)	Crash Frequency: Observed in "After" Period (C_a)	Variance of c_a ($V[c_a]$)	Ratio[1] (R)	Standard Deviation of R (s_R)[2]	z statistic[3]	p value[4]
Loop 340 & F.M. 3400	North and Southbound	3.8	3	1.45	0.79	0.47	-0.28	0.39
U.S. 82 & F.M. 3092	East and Westbound	4.2	4	1.18	0.94	0.50	0.01	0.50
U.S. 82 & Weber Dr.	East and Westbound	4.3	2	1.13	0.46	0.33	-1.54	0.06
U.S. 59 & F.M. 819	North and Southbound	5.2	3	0.74	0.57	0.33	-1.23	0.11
U.S. 281& Borgfeld Rd.	North and Southbound	5.5	2	1.34	0.37	0.26	-2.38	0.01
Overall:		**23.1**	**14**	**5.84**	**0.61**	**0.17**	**-2.24**	**0.01**

Notes:

1 - $R = C_a / c_a$

2 - $s_R = R \times [1/C_a + V[c_a]/c_a^2]^{0.5} / [1 + V[c_a]/c_a^2]$

3 - $z = (R - 1) / s_R$

4 - p value: probability of error in a claim that crashes are reduced.