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16. Abstract

The purpose of this research was to examine the type of performance measures that could be collected at an intersection and develop a system for automatically collecting these performance measures in the field. We began the research by conducting an assessment of the needs of the Texas Department of Transportation (TxDOT) practitioners for an automated system to collect intersection and traffic signal performance measures. We then examined capabilities of some of the existing traffic signal controllers and detection systems to produce the desired performance measures. Based on the findings of the needs assessments and an evaluation of the limitation of the existing detection system, we developed a series of innovative performance measures that practitioners could use to assess traffic operations and the effectiveness of the signal timing at intersections. We then developed a prototype system for automatically collecting these data in the field. We installed the prototype system in two different locations that exhibited different operating characteristics and assessed the ability of the system to collect meaningful and appropriate performance measures.

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DEVELOPMENT OF A TRAFFIC SIGNAL PERFORMANCE MEASUREMENT SYSTEM (TSPMS)

by

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DISCLAIMER

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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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- Henry Wickes – Project Director, Traffic Operations Division
- David Danz – Traffic Operations Division
- David Mitchell – Traffic Operations Division
- Don Baker – Traffic Operations Division
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

INTRODUCTION

FHWA defines a performance measurement as the "use of statistical evidence to determine progress toward specific defined organizational objectives" (*1*). This evidence can be factual information directly related to the performance of the system. For example, the number of vehicles using a roadway in a given time period is a classic performance measure used in traffic operations to assess the traffic-carrying ability of the roadway. Performance measures can also measure customer satisfaction for a facility or service. In traffic engineering, level-of-service, a qualitative indicator of how well traffic flows on a facility, is a classic example of a performance measure that is directed at gauging customer satisfaction. Regardless of the actual type of measure used to assess performance, the overall objectives and benefit of developing and using performance measures is to assess how closely a system performs toward its intended goal or purpose.

Many tools exist that can be used to assess the effectiveness of timing. For example, the *Highway Capacity Manual* provides a procedure for estimating control delay and assessing the Level-of-Service at an intersection (*2*). Computer simulation and optimization tools can estimate performance measures such as delay, stops, vehicle emission, fuel consumption, etc., based on traffic flow theory. These tools, however, generally provide an off-line assessment of intersection performance and require data to be collected in the field and returned to the office for further processing. Although field studies can directly assess the performance of traffic signal timing strategies, they are labor intensive and expensive and, as such, are generally used only to assess the effectiveness of operations during a specified period or at a particular intersection reported to operate poorly. There is a need to develop a tool that can be installed directly in a traffic signal cabinet in the field to measure traffic operations and the effectiveness of signal timing strategies at intersections.

This is the final report of a two-year study that we performed to investigate the development and use of real-time performance measures for traffic signals. This project set out to answer the following questions:

- What information about traffic signal performance can and should be measured directly at the field level?
- How do we collect this information from the detection and control equipment that already exists in the traffic signal cabinet?
- How do we use this information to improve operations?

OBJECTIVES

The overall goal of this project was to examine current and innovative methods of collecting measures that TxDOT can use to assess traffic operations at intersections and the performance of their traffic signals. The project was a two-year project; the first year focused on (1) analyzing the capabilities of existing technology and (2) assessing TxDOT's needs for measures related to the performance of traffic signals. The objectives of the first year of this project were as follows:

- Through interviews, identify how TxDOT engineers and traffic signal technicians assess performance of traffic operations and signals in the field.
- Assess the capabilities of the existing detection and traffic signal controller technology to provide these measures.
- If necessary, propose new and innovative measures for evaluating traffic operations and signals.

The completion of these objectives is documented in Report 0-4422-1 *(3)*.

The objectives of the second year of this project, the primary focus of this report, were as follows:

- Develop a system for collecting signal timing and traffic operations performance measures directly from the inputs of the traffic signal controller and the vehicle detection system inside the traffic signal cabinet.
- Install the system at several field locations as a proof-of-concept of the system.
- Collect information to assess the effectiveness of the system to produce effective and meaningful performance measures.

This report documents the completion of these objectives.

SUMMARY OF YEAR 1 ACTIVITIES

The first year of the project focused on identifying and developing measures that could be used to assess, in the field, the operations and effectiveness of traffic signal timing plans at an intersection. We first conducted a series of on-site interviews to determine TxDOT needs and requirements for a system to collect traffic signal performance information. We then conducted an assessment of the capabilities of existing traffic signal control and detection technologies to collect and monitor traffic operations and signal performance at intersections. Finally, we developed several innovative measures that might be useful to include in a system for monitoring the performance of traffic signals at intersections. The results of these studies are summarized in Report 0-4422-1 *Potential Measures of Assessing Signal Timing Performance Using Existing Technologies* (*3*). A summary of the key results is provided below:

- The primary way that most districts learn about operational problems at intersections is through citizen complaints. Because of staffing limitations, most districts do not have regular programs for evaluating and assessing intersection or signal timing performance.
- Most districts are supportive of a system that can be installed in the cabinet that collects information on intersection performance. Most districts cited the need for volume and turning movement counts as one of the prime desirable features of this system.
- Most traffic signal controllers support the collection of some traffic operations measures (such as speed, volume, and occupancy) primarily from system detectors. The accuracy of these measures is highly dependent upon the design and location of the detection system. Very few controllers support the collection of signal timing performance measures.
- Most districts are transitioning to video imaging vehicle detection (VIVD) systems to replace embedded loop detectors. The vehicle detection capabilities of these VIVD systems have been shown to be at least as effective as embedded loops. While some VIVD systems provide special detection features (such as detector switching and queue detection), TxDOT does not generally use these features. Furthermore, some of these features, such as queue detection, have been designed primarily for freeway applications.
- Some embedded loop manufacturers offer special features (such as vehicle classification and secondary vehicle detection), but these can be accessed only in a limited form.

- A number of measures can potentially measure intersection performance. These include the following:
  - the average time between activations of the same phase (i.e., the cycle time),
  - the Time to Service a vehicle once a call has been received by the controller,
  - the time required to clear the queue,
  - the average duration of the each interval (green, yellow, all-red, and red) for a phase,
  - the average number of vehicles entering on each interval,
  - the number of cycles and rate at which vehicles were entering the intersection on yellow and/or all-red interval, and
  - the rate at which the signal timing fails to clear all the demand at an intersection.

ORGANIZATION OF REPORT

The organization of the report is as follows. In Chapter 2, we present the results of several simulation studies that examined the capabilities of the built-in performance monitoring system of the Eagle® EPAC actuated controller. The results of this study provided valuable insight into the design of the detection system needed to provide adequate performance monitoring capabilities. In Chapter 3, we detail the development of the Traffic Signal Performance Monitoring System (TSPMS). This system uses the existing capabilities of the traffic signal controller and the detection system to generate performance measures that traffic signal engineers and technicians can use to monitor and assess the operation of the traffic signal in real time. In Chapter 4, we highlight some of the lessons learned as part of this research activity.

CHAPTER 2. EVALUATION OF EAGLE'S® MEASURE-OF-EFFECTIVENESS (MOE) TABLES

INTRODUCTION

In the last few years, FHWA has begun to place increased emphasis on measuring and monitoring performance of traffic management systems. This increased emphasis has led to a need to develop systems that can accurately collect and assess the effectiveness of traffic management strategies. Several traffic signal controller manufacturers, such as Eagle® Signal, provide performance measurement and monitoring capabilities as standard features in their traffic signal controllers. The purpose of this simulation study was as follows:

- using hardware-in-the-loop simulation, assess the accuracy and effectiveness of the built-in performance monitoring capabilities of the Eagle® EPAC 300 Actuated Traffic Signal Controller, given TxDOT's traditional surveillance and control design at a typical intersection, and
- provide guidelines and recommendations for setting up the controller and designing the detection system for utilizing this built-in feature.

BACKGROUND

The Eagle® EPAC 300 (*4*) can produce two reports that can be used to evaluate the effectiveness of traffic signal timing plans: the MOE Report and the Cycle MOE Report. The MOE Report produces performance measures that are intended to assess the effectiveness of the signal timing parameters of a controller operating in the coordination mode. It uses data collected by the intersection detectors to produce estimates of volume, stops, delay, and green phase utilization during the periods that a specific coordination plan is in effect in the controller. Table 1 provides the operational definition and method of calculating of each these measurements of effectiveness. Each of these calculations are made every sequence cycle and then averaged over the duration that the coordination plan is in effect in the controller. The MOE Report is produced ONLY when the controller is operating in coordinated mode. The controller has the capacity to store up to 24 MOE Reports before it begins overwriting the previously collected information. Furthermore, the measures are produced only for Phases 1 through 8. While this is generally sufficient for most intersections, it may not be adequate for intersections that use more than eight phases.

Table 1. Operational Definitions and Method of Calculating Signal Timing Performance Measures in Eagle® MOE Report.

Measurement of Effectiveness	Operational Definition	Method of Calculation
Volume	The average number of actuations during the sequence cycle for the duration of the pattern.	Accumulates the vehicle actuations sum for each phase per sequence cycle and averages for the duration of the pattern
Stops	The average number of vehicles that must stop at an intersection during the cycle of the duration of the pattern.	Accumulates the vehicle actuations sum for each phase per sequence cycle during non-green times and averages for the duration of the pattern.
Delays	The average time in seconds that vehicles are stopped during the sequence cycle for the duration of the pattern.	Accumulates the waiting time (number of cars waiting multiplied by time) for each phase per sequence cycle and averages for the duration of the pattern.
Utilization	The average seconds of green time used by each phase during the sequence cycle for the duration of the pattern.	Accumulates the green time used for each phase per sequence cycle and averages for the duration of the pattern.

Source: *(4)*.

The Cycle Report is similar to the MOE Report, but it reports specifically on the green interval utilization on a cycle-by-cycle basis. This report provides a history of how much time each phase was over- or under-utilized each cycle. It denotes how the controller adjusted the duration of each phase when it transitioned into coordination or changed to another coordination plan. The controller has the capacity to store up to 60 Cycle Reports before it begins writing over previously stored information.

STUDY METHODOLOGY

We used hardware-in-the-loop simulation to assess the accuracy and effectiveness of the Eagle® MOE reporting features. Figure 1 illustrates the concept of the hardware-in-the-loop simulation used in this study. With hardware-in-the-loop, a microscopic traffic simulation model is tied to a real traffic signal controller through a controller interface device (5). The traffic simulation model generates vehicle arrivals at the intersection. Detectors in the simulation model provide detector inputs to the controller through a controller interface device. The traffic signal controller reacts to the detector inputs according the timing parameters programmed into the controller, just as if it was implemented in a traffic signal cabinet in the field. The status of the pin outputs from the controller are sent back to the simulation model through the controller interface device and are used to change the signal indications in the simulation model. Simulated vehicles arriving at the intersection then react to the signal indications, either progressing through the intersection on a green signal indication or stopping at the intersection on a red signal indication. Because the controller operates just as it would if it was located in the field, it automatically produces an MOE Report. The performance measures collected by the simulation model are then compared to the performance measures produced by the controller.

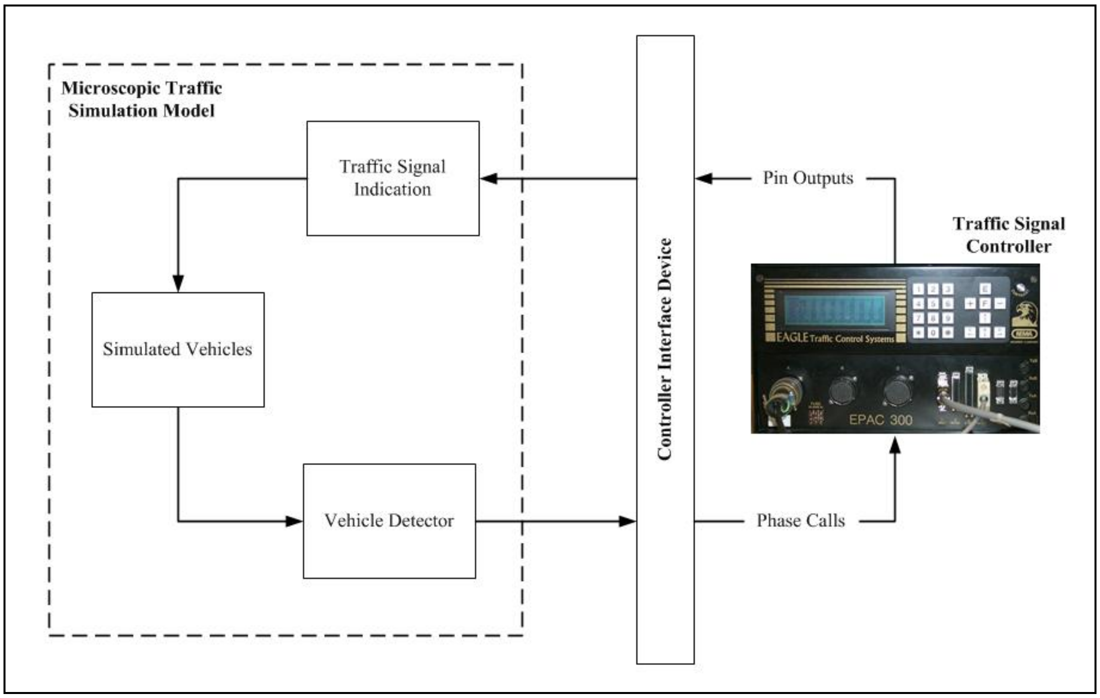


Figure 1. Concept of Hardware-in-the-Loop Simulation (5).

Test Intersection

We used the intersection of Wellborn Road and Rock Prairie Road in College Station, Texas, as our test intersection for this study. We selected this intersection because of our in-depth historical knowledge of the operations of this intersection and because the detection system and signal timing plans represent the typical way that TxDOT designs their intersections. Wellborn Road (FM 2154) is a high-speed arterial designed to rural standards and is located on the fringe of College Station. It is located in a high growth area that is transitioning from rural to suburban land development. Wellborn Road is a three-lane roadway (one 12-ft lane in each direction separated by a two-way, left-turn lane) with narrow (approximately 4 ft) shoulders in the vicinity of the intersection. At the intersection itself, the two-way, left-turn lane transitions to left-turn bays. The posted speed limit on Wellborn Road is 55 mph in the vicinity of the study intersection.

Rock Prairie Road is a major east-west arterial in the College Station area. To the east of the study intersection, Rock Prairie Road is designed to typical urban arterial standards, with two 12-ft lanes in each direction separated by a raised median island. A left-turn bay is provided for westbound left-turning traffic at the intersection. To the west of the intersection, Rock Prairie Road has two approach lanes (a left-turn lane with one through lane) and one departure lane. The approach lanes are separated from the departure lane by a small dividing island. Immediately to the west of the intersection (approximately 75 ft), Rock Prairie Road crosses a railroad track. The grade crossing is double gated, and the signal is controlled by a preemption sequence; however, for the purposes of this study, the railroad grade crossing was ignored.

The design of the detection system and the phases to which each detector was assigned is shown in Figure 2.

Signal Timing Plan

A real Eagle® EPAC 300 Actuated Controller controlled the signal indications in the simulation model. The actual timing plan that was implemented in the field was entered into the traffic signal controller used in the simulation study. The basic signal timing parameters used in the controller are shown in Table 2. The controller was set to provide coordination in the Permissive Mode, and the Dwell Method was selected for providing offset corrections.

Data Collection Procedures

The process of collecting the data used in this study required careful coordination between the traffic signal controller and the simulation model. Figure 3 illustrates the process used to ensure that the performance measures collected by the traffic signal controller and the simulation model represented similar conditions.

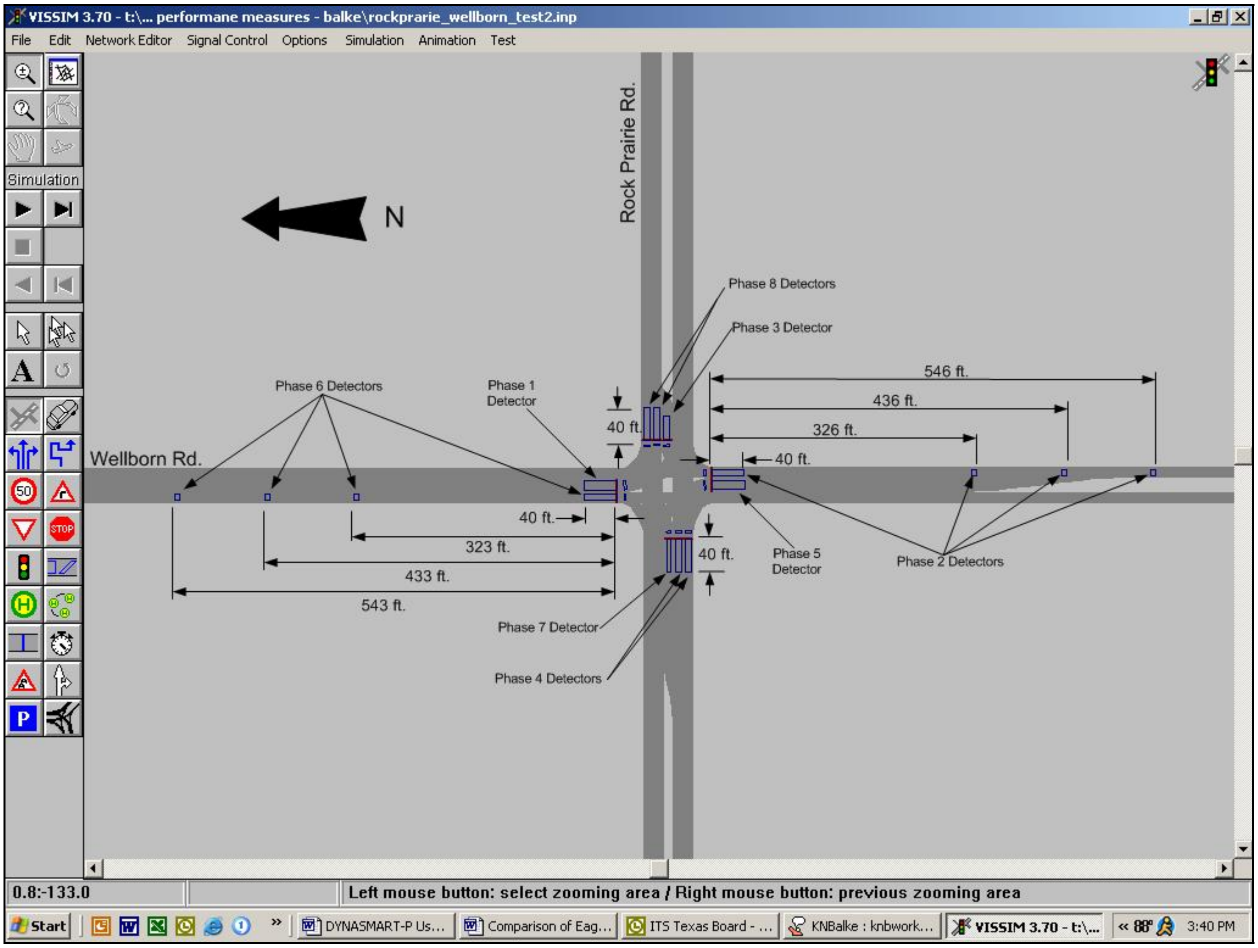


Figure 2. Detector Configuration Used to Evaluate Eagle® MOE Report Feature.

Table 2. Basic Signal Timing Parameters Used to Evaluate Eagle® MOE Report Feature.

Timing Parameter	Phase Number							
	1	2	3	4	5	6	7	8
Minimum Green (sec)	3	4	4	4	4	4	4	4
Passage Time (sec)	2.0	1.2	2.0	2.0	2.0	1.2	2.0	2.0
Max #1 Green (sec)	20	45	20	25	20	45	20	25
Yellow (sec)	4.0	5.0	4.0	4.0	4.0	5.0	4.0	4.0
All-Red (sec)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Phase Split (sec)	12	30	24	14	12	30	24	14
Mode Type	Actuated	Coordinated	Actuated	Actuated	Actuated	Coordinated	Actuated	Actuated

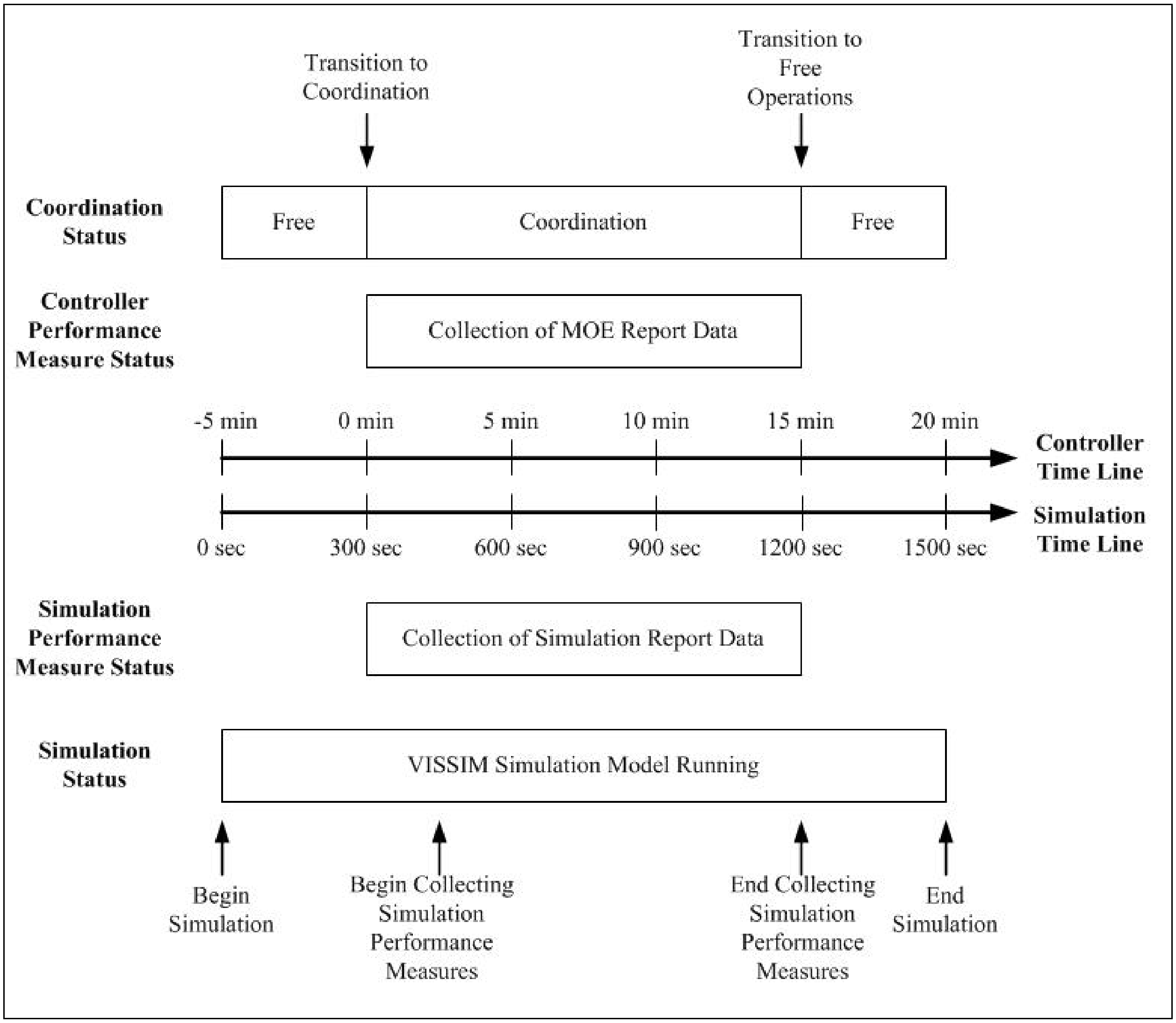


Figure 3. Process for Coordinating Collection of Traffic Signal Controller and Simulation Performance Measures.

Because the Eagle® controller produces an MOE Report when the controller changes timing plans, we set up the simulations to cause the controller to first transition into and then out of coordination. At the start of the study, we set the controller to operate in the uncoordinated (or FREE) mode. We then used the Traffic Event feature of the controller to call the controller into coordination at a specific time of day. Another traffic event was set 15 minutes after the first event to cause the controller to transition from coordinated operation back to uncoordinated operation (thus producing an MOE Report). We started the simulation 5 minutes and 2 seconds before the controller was scheduled to go into coordination to allow the VISSIM® model to activate and allow traffic demands to reach the desired level before beginning the data collection process. The simulation model was programmed to begin collecting performance measures for a 15-minute duration. The data collection was scheduled to occur 5 minutes after beginning the simulation. This process allowed collection of the simulation performance measures and synchronization of the controller MOEs.

After the simulation was complete, we accessed the MOE Report through the front panel of the controller and recorded the values listed in the MOE Report. We then compared the results of the values recorded in the MOE Report with the results recorded by the simulation model.

RESULTS OF SIMULATION STUDIES

We conducted two simulation studies using the detector configuration and test procedures discussed above. In the first test, we used the traffic volumes and traffic patterns that currently exist at the intersection. Because these volumes were relatively light and did not result in any queuing, we doubled the traffic volumes in the second study. The purpose of these studies was to assess how well the detector configuration would allow the EPAC controller to capture the actual performance of traffic at the intersection.

Test 1 – Existing Volume

Results from this simulation study are shown in Tables 3 through 7. Table 3 shows the volume levels that currently exist at the intersection and that were programmed into the simulation model. Table 4 shows the MOE Report recorded in the Eagle® Controller for the duration of the evaluation. Table 5 shows the total number of vehicles, equivalent flow rate, total number of stops, total delay, and average delay recorded by the simulation model for the study inputs. Table 6 shows the duration of the green interval displayed for each phase by the controller given the simulation input parameters. Table 7 shows the average volume, flow, stops, and delay produced per cycle in the simulation model.

Table 3. Volume Levels Used in the Initial Comparison of Eagle® MOE Report.

Approach Name	Approach Direction	Turning Movement Volume (veh/hr)			Total Approach Volume (veh/hr)
		Left	Through	Right	
Rock Prairie	Eastbound	77	97	24	198
	Westbound	48	67	152	267
Wellborn	Northbound	22	223	27	272
	Southbound	144	246	74	464

Table 4. Eagle® MOE Report Produced for Initial Set of Traffic Volumes.

Performance Measure	Phase Number							
	1	2	3	4	5	6	7	8
Volume (veh/cycle)	0	13	1	2	1	12	1	1
Stops (stops/cycle)	0	4	1	2	1	4	0	1
Delay *10 (sec/cycle)	2	13	4	5	5	15	2	5
Utilization (sec/cycle)	2	47	6	8	5	41	5	8

Table 5. Performance Measures from VISSIM® with Initial Traffic Volumes.

Performance Measure	Phase Number							
	1	2	3	4	5	6	7	8
Volume (veh/15-minutes)	6	64	13	7	26	56	12	14
Equivalent Flow Rate (veh/hr)	24	256	52	28	104	224	48	56
Total Number of Stops	7	44	15	103	24	24	12	23
Total Delay (sec)	239	541	568	319	865	569	379	594
Avg. Delay (sec/veh)	39.8	8.5	43.6	45.6	33.3	10.2	31.6	42.4

Table 6. Observed Phase Durations from VISSIM®.

Cycle No.	Duration of Green Interval for Each Phase per Cycle (sec)							
	1	2	3	4	5	6	7	8
1	-	28	5	8	-	23	-	8
2*	-	102	8	8	-	102	7	8
3	-	45	-	8	6	33	-	8
4	5	48	-	8	5	48	15	8
5	-	38	5	7	6	26	-	7
6	-	49	9	8	6	37	9	8
7	6	32	7	8	6	32	-	8
8	-	46	8	8	6	34	8	8
9	5	34	5	8	6	33	5	8
10	-	48	10	8	5	37	10	8
11	6	31	-	7	6	31	-	7
Total	22	501	57	86	52	436	54	86
Average	2.0	45.5	5.2	7.8	4.7	39.6	4.9	7.8

*Signal in transition via Dwell Method

Table 7. Results from VISSIM® on a Per Cycle Basis.

Performance Measure	Phase Number							
	1	2	3	4	5	6	7	8
Volume (veh/cycle)	0.5	5.8	1.2	0.6	2.4	5.1	1.1	1.3
Stops (stops/cycle)	0.6	4.0	1.4	9.4	2.2	2.2	1.1	2.1
Total Delay (sec/cycle)	21.2	49.2	51.6	29.0	78.6	51.7	34.5	54.0
Average Delay (sec/veh/cycle)	3.6	0.77	4.0	4.1	3.0	0.9	2.9	3.9
Average Utilization (sec/cycle)	2.0	45.5	5.2	7.8	4.7	39.6	4.9	7.8

Table 8 compares the output of the MOE Report to the same performance measures collected in the VISSIM® model. This table shows that the performance measures produced by the controller in the MOE Report correspond relatively well with the actual measures, with two exceptions.

Table 8. Comparison of Eagle® MOE Report and Observed Performance Measures for Low Volume (Test 1) Simulation Inputs.

Performance Measure		Phase Number							
		1	2	3	4	5	6	7	8
Volume (veh/cycle)	Eagle®	0	13	1	2	1	12	1	1
	VISSIM®	0.5	5.8	1.2	0.6	2.4	5.1	1.1	1.3
Stops (stops/cycle)	Eagle®	0	4	1	2	1	4	0	1
	VISSIM®	0.6	4.0	1.4	9.4	2.2	2.2	1.1	2.1
Total Delay (sec/cycle)	Eagle®	20	130	40	50	50	150	20	50
	VISSIM®	21.2	49.2	51.6	29.0	78.6	51.7	34.5	54.0
Utilization (sec/cycle)	Eagle®	2	47	6	8	5	41	5	8
	VISSIM®	2.0	45.5	5.2	7.8	4.7	39.6	4.9	7.8

The first exception where the performance measures did not compare well was in the volume measure for Phases 2 and 6. For these measures, the Eagle® controller dramatically overestimated the number of vehicles using these approaches. This overestimation is a result of the design of the detection system on these approaches. Both of these approaches are high-speed approaches that use TxDOT's standard multi-detector layout for dilemma zone protections as well as a long-loop detector located at the stop bar. In this case, all the upstream detectors and the stop bar detectors are tied to the same phase call detector; therefore, the same vehicle can place multiple calls to the controller. There is a high probability that many of the vehicles placed multiple calls to the controller and were duplicated in the volume count.

The other approach where the performance measures did not agree well was the Phase 4 approach. This approach has a very unbalanced flow with a substantial right-turn volume. In this approach, the detection zone extends across multiple lanes, even though each lane has its own detector. By tying the detectors together, the controller cannot distinguish between right-turning and through traffic. As a result, the controller overestimates the delay experienced by traffic on this approach.

Substantial differences existed between the actual measured delay and the total delay recorded by the controller. For example, on Phase 2 and Phase 6, the Eagle® substantially overestimated the amount of delay experienced by traffic on these approaches. The reason for this is, again, the fact that multiple detectors call the same phase. These practices cause the same vehicles to be counted multiple times by the controller. Likewise, delays are substantially underestimated on Phase 4, where multiple lane detectors are tied together to provide a single detection zone for an approach. This practice causes the controller to miss some vehicles because the detection zone is already occupied. Also, note that the total measures produced by the controller delay for Phases 1, 3, 5, and 7 (all left-turn phases) are lower than the observed values. This is primarily caused by vehicle queues extending beyond the detection zones.

Double Existing Volumes

In this test, we kept the detector configuration and the traffic signal timing parameters the same, but doubled the entering volumes. Table 9 shows the traffic volumes used in the second comparison of the Eagle® MOE Report performance measures. These traffic volume levels were significant enough to produce a substantial queue on several of the major approaches, specifically in the southbound left-turn lane. Toward the end of the simulation runs, we observed queues from the southbound left-turn lanes spilling back into the through lanes, preventing through vehicles from passing through the intersection during their green indication.

Table 10 shows the MOE Report recorded in the Eagle® Controller for the duration of the evaluation. Table 11 shows the total number of vehicles, equivalent flow rate, total number of stops, total delay, and average delay recorded by the simulation model for the study inputs. Table 12 shows the duration of the green interval displayed for each phase by the controller given the simulation input parameters, and Table 13 shows the average volume, flow, stops, and delay produced per cycle in the simulation model. Table 14 shows the results of the comparison of the volumes, stops, delay, and utilization performance measures produced by the Eagle® controller and those same measures generated using the data from the VISSIM® run.

Table 9. Volume Levels Used in Second Comparison of Eagle® MOE Report.

Approach Name	Approach Direction	Turning Movement Volume (veh/hr)			Total Approach Volume (veh/hr)
		Left	Through	Right	
Rock Prairie	Eastbound	154	194	48	396
	Westbound	96	134	304	534
Wellborn	Northbound	44	446	54	544
	Southbound	288	492	148	928

Table 10. Eagle® MOE Report Produced for Test 2 Traffic Volumes.

Performance Measure	Phase Number							
	1	2	3	4	5	6	7	8
Volume (veh/cycle)	1	12	2	1	1	12	1	1
Stops (stops/cycle)	1	4	1	1	1	5	1	1
Delay *10 (sec/cycle)	3	19	5	6	8	24	3	6
Utilization (sec/cycle)	5	34	12	8	6	31	10	8

Table 11. Performance Measures from VISSIM® with Initial Traffic Volumes Doubled.

Performance Measure	Phase Number							
	1	2	3	4	5	6	7	8
Volume (veh/15-minutes)	12	126	38	42	36	106	24	51
Hourly Flow Rate (veh/hr)	48	504	152	168	144	424	96	204
Average Stops (stops/veh)	0.83	1.72	2.47	1.40	8.47	0.85	0.83	2.20
Total Number of Stops	10	217	94	59	305	90	20	112
Avg. Delay (sec/veh)	31.8	18.4	33.0	39.6	198.0	13.5	31.8	35.1
Total Delay (sec)	382	2318	1254	1663	7128	1431	763	1790

Table 12. Observed Phase Durations from VISSIM® with Double the Initial Traffic Volumes.

Cycle No.	Duration of Green Interval for Each Phase per Cycle (sec)							
	1	2	3	4	5	6	7	8
1	-	-	-	25	-	-	-	25
2	-	23	8	8	-	23	8	8
3*	5	56	15	8	6	55	15	8
4	-	38	11	8	6	26	11	8
5	5	31	5	8	6	30	-	8
6	6	36	14	8	6	36	14	8
7	6	27	16	8	6	27	16	8
8	5	26	15	7	6	25	-	7
9	6	27	9	8	6	27	9	8
10	5	33	15	8	6	32	15	8
11	6	26	11	8	6	26	11	8
12	-	41		8	5	30		8
Total	44	364	119	112	59	337	179	112
Total After Coordination	39	285	96	71	53	259	76	71
Number of Cycles After Coordination	7	9	8	9	9	9	6	9
Average	5.6	31.7	12.0	7.9	5.9	28.8	12.7	7.9

Table 13. Results from VISSIM® on a Per Cycle Basis with Double the Initial Traffic Volumes.

Performance Measure	Phase Number							
	1	2	3	4	5	6	7	8
Volume (veh/cycle)	1.1	11.5	3.5	3.8	3.3	9.6	2.2	4.6
Stops (stops/cycle)	0.9	19.7	8.5	5.4	27.7	8.2	1.8	10.2
Total Delay (sec/cycle)	34.7	210.7	114.0	151.2	648.0	130.1	69.4	162.7
Average Delay (sec/veh/cycle)	2.9	1.5	3.0	3.6	18.0	1.2	2.9	3.2
Average Utilization (sec/cycle)	4.0	33.1	10.8	10.2	5.4	30.6	16.3	10.2

Table 14. Comparison of Eagle® MOE Report and Observed Performance Measures for Test 2 Simulation Input Parameters.

Performance Measure		Phase Number							
		1	2	3	4	5	6	7	8
Volume (veh/cycle)	Eagle®	1	12	2	1	1	12	1	1
	VISSIM®	1.1	11.5	3.5	3.8	3.3	9.6	2.2	4.6
Stops (stops/cycle)	Eagle®	1	4	1	1	1	5	1	1
	VISSIM®	0.9	19.7	8.5	5.4	27.7	8.2	1.8	10.2
Total Delay (sec/cycle)	Eagle®	30	190	50	60	80	240	30	60
	VISSIM®	34.7	210.7	114.0	151.2	648.0	130.1	69.4	162.7
Utilization (sec/cycle)	Eagle®	5	34	12	8	6	31	10	8
	VISSIM®	4.0	33.1	10.8	10.2	5.4	30.6	16.3	10.2

These tables show that the detector configuration used with these higher traffic conditions at this intersection did a reasonable job of measuring traffic volumes; however, it did not accurately measure stops and total delays on many of the approaches. The system dramatically underestimated the amount of stops per cycle and the total delay experienced on these approaches. The particular detector configuration did relatively well at measuring the phase utilization per cycle.

Interpretation Of Results

For the left-turn phases (Phases 1, 3, 5, and 7), the reason traffic volumes, stops, and delays were underestimated with this detector configuration was that the queues on these approaches, along with the length of the detectors themselves, caused a uniform arrival pattern of traffic over the detectors. In other words, because there was stored demand on the approach and because the detectors were long enough to hold more than one vehicle, traffic constantly occupied the detection zone, placing calls to the controller on these phases. While this is ideal for traffic signal operation, in order to measure traffic volumes, the detector must be able to detect separate vehicles. In order for this to occur, the controller has to be able to detect gaps in the traffic stream.

The system also underestimated traffic volumes and stops on Phases 4 and 8 but for different reasons than those discussed above. The underestimation of volume and stops was due to essentially only one detection zone that covered both lanes. Even though each lane had its own detector, the detectors were tied together to provide one input into the traffic signal controller. (This is a common practice in traffic signal design.) As with the approaches that experience substantial queuing, the practice of using a signal detection zone to cover multiple lanes of traffic does not always allow the controller to distinguish between vehicles. If the spacing between vehicles in adjacent lanes is just right, multiple vehicles passing through the detection zone will look like a single vehicle to the controller because the detection zone is constantly occupied by vehicles. This phenomenon will cause the controller to underestimate the volume and delay on an approach.

As in the lighter volume scenario, the system dramatically overestimated traffic volumes and underestimated stops on Phases 2 and 6. As is typical for many intersections in Texas with high-speed approaches, a multiple-loop detector arrangement designed to provide dilemma zone protection is used on the approaches governed by the phases. With a multi-loop design, each detector provides a call to the controller; therefore, it is possible that on these approaches, one vehicle can place two to three calls per phase, depending upon the speed of the vehicle. We suspect that this is what occurred on the approaches governed by these phases. With this particular multi-loop detector configuration, the same vehicle was counted more than one time by the system. To improve the accuracy of these counts, agencies should consider decoupling the detectors from each other (which would have a negative impact on operations and safety) or implement a different arrangement of detectors.

GUIDELINES FOR USING THE EAGLE® EPAC PERFORMANCE MEASURING CAPABILITIES

While the Eagle® EPAC controller is capable of collecting signal performance information, it exhibits the following limitations:

- The controller can only generate signal performance information when it is operating in coordinated mode.
- The user is limited to collecting information on eight phases only.

Because of these limitations, we recommend using the performance monitoring system embedded in the Eagle® controller only in the simplest situations (i.e., single-lane approaches with no more than eight total phases). The following guidelines are provided if the user wishes to use the automatic performance measure report-generating features of the Eagle® EPAC controller.

- The Eagle® EPAC controller will only produce an MOE Report when (1) the controller is operating in the coordinated mode and (2) only when a change in the coordination plans occurs. Therefore, to use the internal performance monitoring system, the user must first devise a timing plan that permits the intersection to operate in coordinated operation. To begin collecting the performance measures produced in this report, the user can set a time-of-day event that calls in a particular timing plan (i.e., dial-split-offset combination in the coordinator) at a given time-of-day. The controller then automatically collects the volume, stop, delay, and utilization performance measures for as long as the particular timing plan is active. To end the data collection, the user can use another time-of-day event to cause the controller to change timing plans or to force the controller to go back to operating in the FREE mode or another coordination timing plan.

- To collect hourly or sub-hourly performance measures, the user has to call different coordination plans that correspond to the desired data collection interval. For example, if the user desires to collect performance measures in 1-hour intervals, the user must implement a new coordination plan every hour. This, however, does not mean the user has to change the timing parameters every hour. The same splits, cycle length, and offset can be used in multiple coordination plans so that the timing parameters remain constant for the duration. As long as the cycle length, splits, and offset remain the same, the controller should not go through a transition phase that affects the operation of traffic on the street. Also, the effects of the transition phase on the calculation of the performance measures should be minimal.
- To use the MOE reporting capabilities at an isolated intersection (i.e., one in which coordination is not normally required), the user can set the controller to operate in the full-actuated coordination mode. While this mode most closely replicates how the controller would work in the FREE mode, it is not exactly the same as the controller operating in the FREE mode. In the full-actuated coordinated mode, any used time in the controller is then assigned back to the coordinated phase. This may make the selected coordinated modes operate longer than desirable for isolated intersections.
- The user should exercise care in setting up the detection zones on each of the approaches to the intersection. At a minimum, each lane should have its own separate detection zone. Grouping multiple lanes in a single detection zone reduces the accuracy of the volume and stop accounts. Each detection zone then has to call separate phases, and overlaps would need to tie phases together to prevent conflicting indications on an approach.
- If multi-loop detection is required to provide dilemma zone protection, we recommend that inputs from only one detector in each lane, preferably a detector located close to the stop line, be used to provide inputs into the performance measuring system. Again, each detection zone would have to call a phase, and overlaps would need to tie phases together to prevent conflicting indications on an approach.

CHAPTER 3. DEVELOPMENT OF TRAFFIC SIGNAL PERFORMANCE MEASURING SYSTEM

INTRODUCTION

Because of the limitation of existing technology to collect accurate signal timing performance measures, we developed a system to directly measure the intersection and traffic signal performance using the existing traffic signal and detection system. The system, called the Traffic Signal Performance Monitoring System (or TSPMS for short) was developed to obtain information from the traffic signal system and from the detection system to generate performance measures in real time. We set up the system to record the status of the phase indication, phase calls, and detector inputs to assess the effectiveness of the signal timing. The system capitalizes on both the detection system installed to operate the system and special detectors installed upstream of the stop bar to measure the volume of traffic entering the intersection as well as produce safety-related measures. The following sections describe, in detail, the hardware and software components of the TSPMS and the two prototype data collection systems deployed at intersections in Milano and Huntsville, Texas.

THE TRAFFIC SIGNAL PERFORMANCE MONITORING SYSTEM

System Architecture

The basic system architecture of the TSPMS is shown in Figure 4. The TSPMS consists of three primary components: a Traffic Controller Interface Device (CID), a Traffic Signal Event Recorder (TSER), and a Performance Measure Report Generator (PMRG). The CID is a piece of hardware that provides a physical connection between the TSPMS and the Traffic Signal System. The TSER is a software program that runs on an industrial computer installed in the traffic signal cabinet to capture and store (in daily log files) changes in the status of the traffic signal controller and the traffic detectors. This program monitors the status of select outputs from the traffic signal controller and the vehicle detector, and stores the time at which the status of these outputs changed (i.e., changed from an "ON" state to an "OFF" state and vice versa). The PMRG is a separate software program that analyzes the log files and generates measures that can be used to assess the performance of the intersection and the traffic signal system. This program can be loaded on a laptop for immediate analysis in the field or located on a personal computer (PC) in the office so that off-line analysis of the data can be performed. Each component is described in more detailed description below.

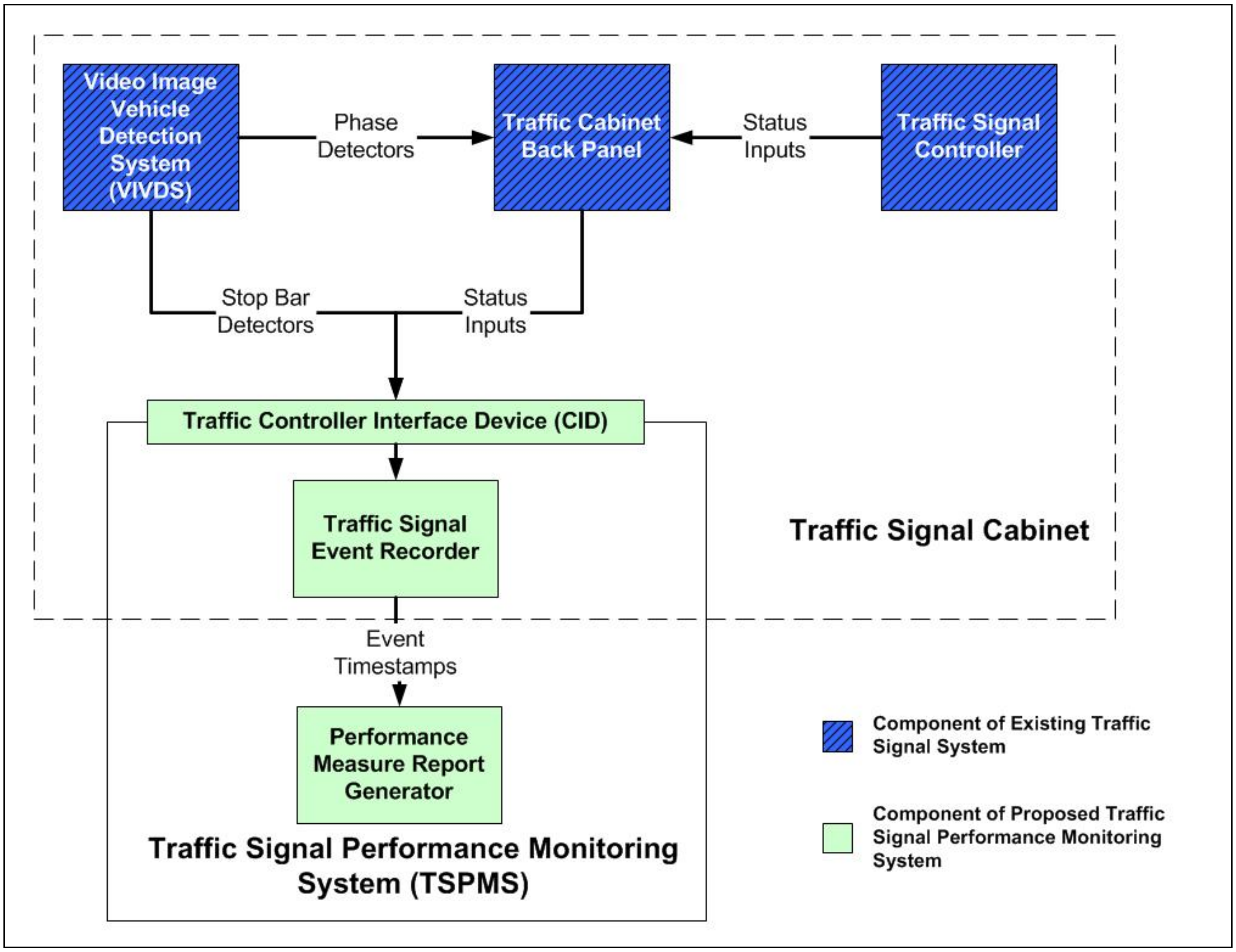


Figure 4. System Architecture of the Traffic Signal Performance Monitoring System (TSPMS).

Traffic Controller Interface Device

The traffic CID hardware interfaces the TSPMS with the low-voltage outputs from the traffic signal cabinet. It provides a means to tie the TSPMS into the traffic signal controller and the vehicle detection system so that changes in the status of various outputs of these systems can be recorded.

The CID's hardware architecture depends on the type of cabinet and controller used at the intersection. For a TS-1 type cabinet and controller, the CID consists of a digital input/output (I/O) card and a terminal strip to interface the direct current (DC) system with a cabinet's back panel at an intersection. For our implementations, we used a National Instruments PCI 6527 digital I/O card. The I/O card was installed in an industrial computer and connected to the back panel of the traffic signal cabinet using a terminal strip. (These devices are shown in Figure 5). Jumper wires run to the Phase On, Ring 1 Status Bit, Ring 2 Status Bit, and the Vehicle Call Detector terminal strips on the back panel of the cabinet. Figure 6 shows the physical implementation of the TSPMS within a TS-1 controller cabinet.

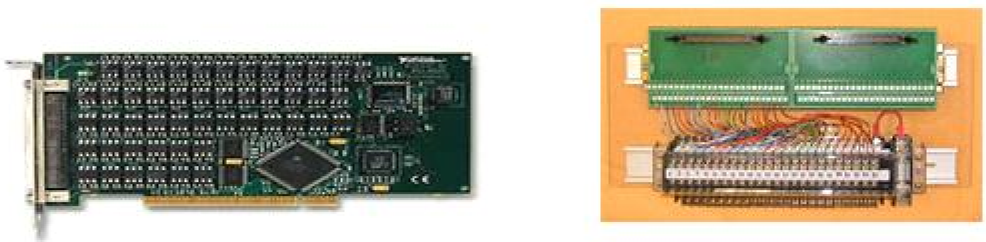


Figure 5. National Instruments PCI 6527 Digital I/O Card and a Terminal Strip Used with TS-1 Implementations of TSPMS.

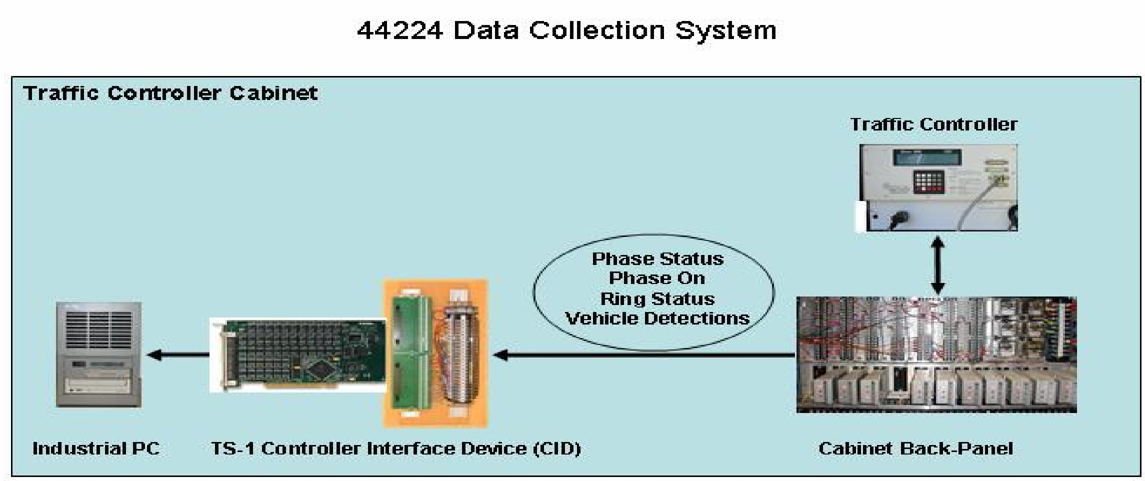


Figure 6.   Physical Implementation of TSPMS with a TS-1 CID.

To use the system with a TS-2 controller and cabinet, the system requires an enhanced Bus Interface Unit (BIU) to capture the required traffic events at an intersection. Figure 7 shows an example of the enhanced BIU used with the system. The BIU “plugs” into a slot in the TS-2 cabinet and ties into the serial communication system within the cabinet. A serial cable transfers the Phase On, Ring Status Bits, and Vehicle Call detections to the TSER via the RS-232 port. Figure 8 illustrates a DC system with a TS-2 CID.

Figure 7. Enhanced Bus Interface Unit (BIU) Used with TS-2 Implementations of TSPMS.

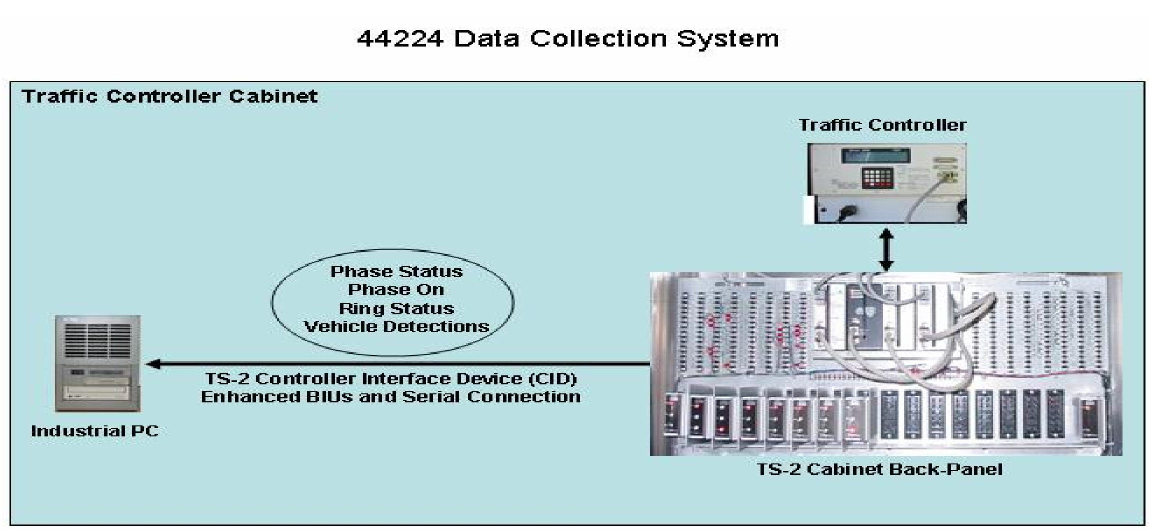


Figure 8. Physical Implementation of TSPMS with a TS-2 CID.

Traffic Signal Event Recorder

The TSER software program monitors and stores phase and detector status outputs from the traffic signal controller. Developed using the Microsoft® Visual Basic® programming language, the TSER software interfaces with a Traffic Signal System (TSS) through a CID and checks the status of the Phase On, the Ring Status Bits, and the Vehicle Detectors every 15-20 milliseconds. As shown in Table 15, the Ring Status Bits provide information as to the current status of the signal indications. The system logs changes in the status of these inputs together with a time stamp in a daily file.

Figure 9 shows a sample of daily log data produced by the system. The daily log file names include the date of the file and consist of month, day, and year. An example of a daily log file name is "08042004," which is the daily log file for August 8, 2004. Events logged into daily log files consist of comma-delimited fields. Each logged event (raw or deduced) starts with a time stamp that includes the hour, minute, second, and millisecond when the event was recorded based on the industrial PC system time. Table 16 shows the types of raw and deduced events logged into the daily log file and the fields logged for each event. A description of the fields included in the event follows each event line.

The TSER runs on an industrial-grade PC installed in the cabinet and interfaces with the traffic signal system through the CID. In field implementations of the system, we used an industrial PC manufactured by Kontron America. This computer had a 1GHz Intel Pentium 3 central processing unit (CPU), a 40 GB hard drive, and 256 MB of Random Access Memory (RAM). For TS-1 cabinets and controllers, the industrial PC should contain one or two National Instruments PCI 6527 digital I/O cards to interface with TS-1 cabinets and controllers. If the implementation is in a TS-2 type cabinet, the system requires a four-port RS-232 serial card to interface with the enhanced BIU.

Table 15. Information Provided by Coded Status Bits (3 per ring).

Bit A	Bit B	Bit C	Ring State Name
OFF	OFF	OFF	Min Green
ON	OFF	OFF	Extension
OFF	ON	OFF	Maximum
ON	ON	OFF	Green Rest
OFF	OFF	ON	Yellow Change
ON	OFF	ON	Red Clearance
OFF	ON	ON	Red Rest
ON	ON	ON	Undefined

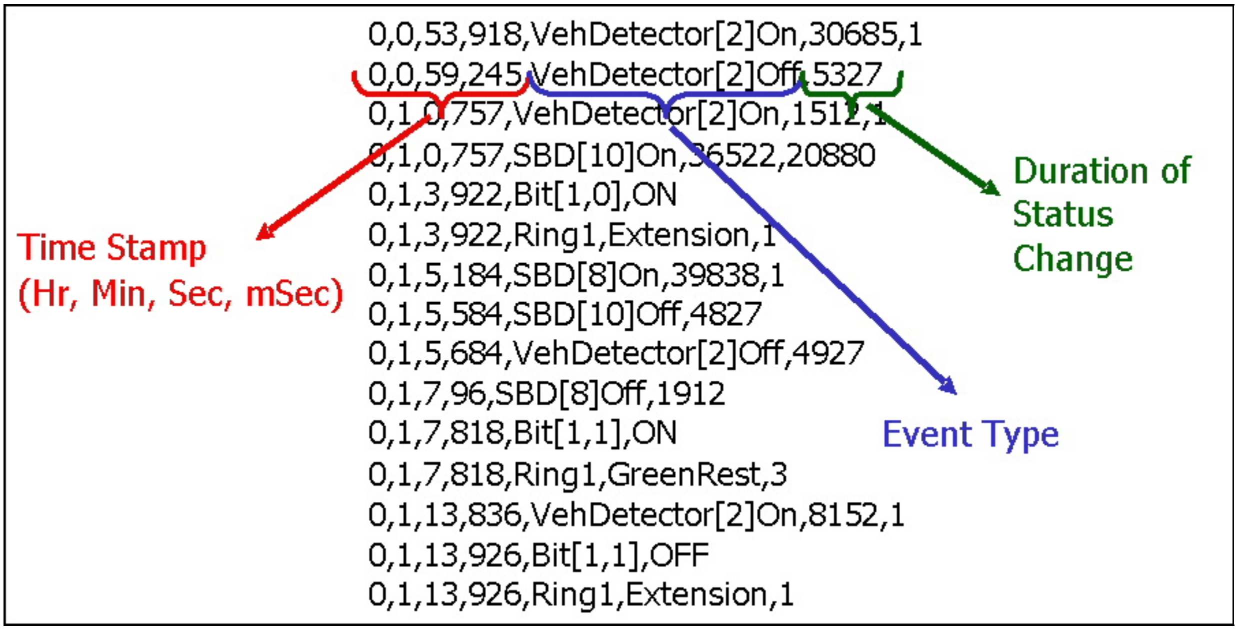


Figure 9. Sample of Data Produced by Traffic Event Logger.

Table 16. Types of Raw and Deduced Events Logged into the Daily Log File.

Event	Example of Event Log	Description of Event Log	Event Type
Ring Status Bit Event	0,0,0,727,Bit[2,1],ON	Hour, Minute, Second, Millisecond, Bit[Ring Number, Bit(1-A, 2-B, 3-C], Status(ON/OFF)	Raw
Phase ON/OFF Status	0,0,10,732,2,Phase-OFF	Hour, Minute, Second, Millisecond, Phase Number, Phase-Off/Phase-On	Raw
Stop Bar Detector Status Off	0,0,1,208,SBD[11]Off,2213	Hour, Minute, Second, Millisecond, SBD[Detector Number]Off, Time detector was occupied in milliseconds	Raw
Stop Bar Detector Status Off	0,0,2,820,SBD[4]On,9053,1	Hour, Minute, Second, Millisecond, SBD[Detector Number]On, Time detector was Off in milliseconds, Number of vehicles detected during the current phase (green, yellow, red clearance, red)	Raw
TxDOT Detector Off Event	0,0,16,400,VehDetector[6]Off,3926	Hour, Minute, Second, Millisecond, SBD[Detector Number]Off, Time detector was occupied in milliseconds	Raw
TxDOT Detector On Event	0,0,12,474,VehDetector[6]On,13880,1	Hour, Minute, Second, Millisecond, SBD[Detector Number]On, Time detector was Off in milliseconds, Number of vehicles detected during the current phase (green, yellow, red clearance, red)	Raw
Ring Status Event	0,0,4,733,Ring1,YellowChange,4	Hour, Minute, Second, Millisecond, Ring Number, Ring Status (Table 1)	Deduced
Phase Status Duration	0,0,4,733,2,SOY,107946,10	Hour, Minute, Second, Millisecond, Phase Number, SOG(Green), SOY(Yellow), SOAR(Red Clearance), SOR(Red), Duration of the previous phase in milliseconds, Vehicles detected during previous phase	Deduced

Performance Measure Report Generator

The PMRG is a log file analysis software utility. Through a graphical interface, the user selects the daily log files, and the program processes and displays performance measures generated from the log. The raw events contained in the log files include Phase Status, Phase On, Ring Status, and Vehicle Detections. The performance measures produced by the program include the following:

- cycle time,
- time to service,
- queue service time,
- duration of the green, yellow, all-red and red interval for each phase,
- number of vehicle entering the intersection during each interval,
- yellow and all-red violation rates, and
- phase failure rate.

Table 17 details the operational definitions used to compute the above-listed performance measures. Each of these performance measures are discussed in detail below.

Cycle Time

Cycle time is the time that elapses between each successive time that a phase is activated. As shown in Figure 10, cycle time is the difference in time between the start of green of the current cycle and the start of green of the previous cycle for the same phase or movement.

For pre-timed signals, cycle time is equivalent to the cycle length. This is because with pre-timed signals, the start time of each phase occurs at the same point every cycle. With fully actuated signals, however, cycle time is not the same as cycle length. With fully actuated control, the duration (and, to some degree, the sequencing) of each phase can vary from cycle to cycle. Cycle time measures these potential fluctuations and provides operators with an idea of the relative length of time between servicing each phase. Approaches that have moderate to light demand and/or sporadic arrival patterns exhibit long cycle times. Approaches that experience very uniform or heavy demand would likely exhibit short cycle times. Long cycle time could also be an indication that the maximum (or MAX) timers in the controller may be set too long.

Table 17. Operational Definitions of Performance Measures Computed by TSPMS.

Performance Measure	Definition of Performance Measure	Formula for Calculating Performance Measure
Cycle Time	The time that elapses between subsequent activations of a particular phase. It is measured as the difference in time between the start of green for the current phase and the previous start of green for the same phase.	$CT_{\phi(i)} = t_{\phi(i)Green="On"} - t_{(\phi(i)Green="On")-1}$ where, $CT_{\Phi(i)}$ = Cycle time for phase (i), (sec) $t_{\Phi(i)Green=\text{"ON"}}$ = Timestamp of the start of the green interval of current phase (i), (sec) $t_{(\Phi(i)Green=\text{"ON"})-1}$ = Timestamp of the start of the green interval of previous phase (i), (sec)
Time to Service	The time interval from when a call was first placed for a phase to the start of green for that phase.	$TTS_{\phi(i)} = t_{\phi(i)Green="ON"} - t_{VehDetector\phi(i)="ON"}$ where, $TSS_{\Phi(i)}$ = Time to service for phase (i), (sec) $t_{\Phi(i)Green=\text{"ON"}}$ = Timestamp of the start of the green interval of phase (i), (sec) $t_{VehDetector\Phi(i)=\text{"ON"}}$ = Timestamp of the first call on vehicle detectors for phase (i), (sec)
Queue Service Time	The time required to clear the queue on a particular approach. It is measured as the difference in time between the start of the green for a particular phase and when a constant call on the phase detector is extinguished.	$QST_{\phi(i)} = t_{VehDetector\phi(i)="OFF"} - t_{\phi(i)Green="ON"}$ where, $QST_{\Phi(i)}$ = Queue service time for phase (i), (sec) $t_{\Phi(i)Green=\text{"ON"}}$ = Timestamp of the start of the green interval of phase (i), (sec) $t_{VehDetector\Phi(i)=\text{"OFF"}}$ = Timestamp of when call from vehicle detectors for phase (i) is dropped, (sec)
Duration of Green, Yellow, All-Red, and Red Intervals	The duration of the green, yellow, all-red, and red intervals during each phase. It is measured as the elapsed time between the beginning and end of each interval in the phase.	$DUR_{Int(x),\phi(i)} = t_{Int(x),\phi(i)="OFF"} - t_{Int(x),\phi(i)="ON"}$ where, $DUR_{Int(x),\Phi(i)}$ = Duration of the (x) interval of phase (i), (sec) $t_{Int(x),\Phi(i)=\text{"OFF"}}$ = Timestamp of the end of interval (x) of phase (i), (sec) $t_{Int(x),\Phi(i)=\text{"ON"}}$ = Timestamp of the start of interval (x) of phase (i), (sec) x = green, yellow, all-red, or red indication of the signal

Table 17. Operational Definitions of Performance Measures Computed by TSPMS (cont).

Performance Measure	Definition of Performance Measure	Formula for Calculating Performance Measure
Number of Vehicles Entering during Green, Yellow, All-Red, and Red Intervals	The number of vehicles that enter the intersection (measured at the stop bar) while each interval during a phase is active.	$n_{Int(x),\phi(i)} = \sum_{t_{Int(x),\phi(i)="ON"}}^{t_{Int(x),\phi(i)="OFF'}} SBD\phi(i) = "ON"$ where, $n_{Int(x),\Phi(i)}$ = Number of vehicle entering during the (x) interval of phase (i) SBD Φ(i) = "ON" = Activation of the stop bar detector for phase (i) $t_{Int(x),\Phi(i)=\text{"OFF"}}$ = Timestamp of the end of interval (x) of phase (i), (sec) $t_{Int(x),\Phi(i)=\text{"ON"}}$ = Timestamp of the start of interval (x) of phase (i), (sec) x = green, yellow, all-red, or red indication of the signal
Yellow and All-Red Violation Rates	The rate at which a vehicle was recorded entering the intersection during that yellow and all-red portion of the phase. It is computed by dividing the number of cycles in which one or more vehicles was observed entering the intersection during the yellow and all-red intervals by the total number of cycles observed during the evaluation period.	$vr_{yellow/all-red,\phi(i)} = \frac{n_{cycle\ yellow/all-red}}{N}$ where, $vr_{yellow/all-red,\phi(i)}$ = yellow or all-red violation rate for phase (i) n_{cycle} = number of cycles in which one or more vehicles was observed entering the intersection during the yellow and all-red intervals N = total number of cycles observed during evaluation period
Phase Failures	A flag set when the queue fails to clear during a specific phase. The queue is assumed not to have cleared the approach if the call on the vehicle detector for that phase never clears.	–

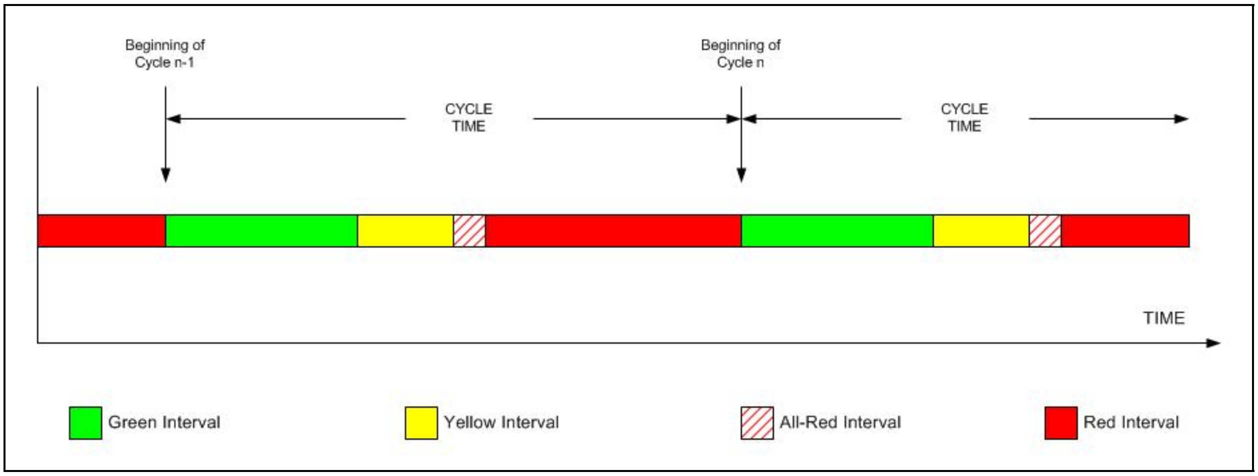


Figure 10. Illustration of Operational Definition of Cycle Time.

Time to Service

Time to Service is the time differential between when a call for a phase came in to the controller and when that call was serviced by activating the phase. Time to Service is determined by measuring the elapsed time from when the controller first receives a call for a phase to when the green indication is provided by the signal. It is the time differential between when the call for a phase first came into the controller to when the controller was about to service the phase (i.e., a green indication). Figure 11 illustrates the concept of Time to Service.

Time to Service is equivalent to the maximum amount of time that a motorist has to wait on an approach, and is a measure of the "snappiness" of the signal timing at an intersection. Intersections that are operating efficiently (or "snappy") tend to have lower Times to Service (i.e., less time between when a vehicle arrives at an intersection and when it is serviced by the signal [in the absence of demand on the opposing approaches]). Signals that experience long Times to Service increase driver frustration, particularly if there is little demand on the cross street.

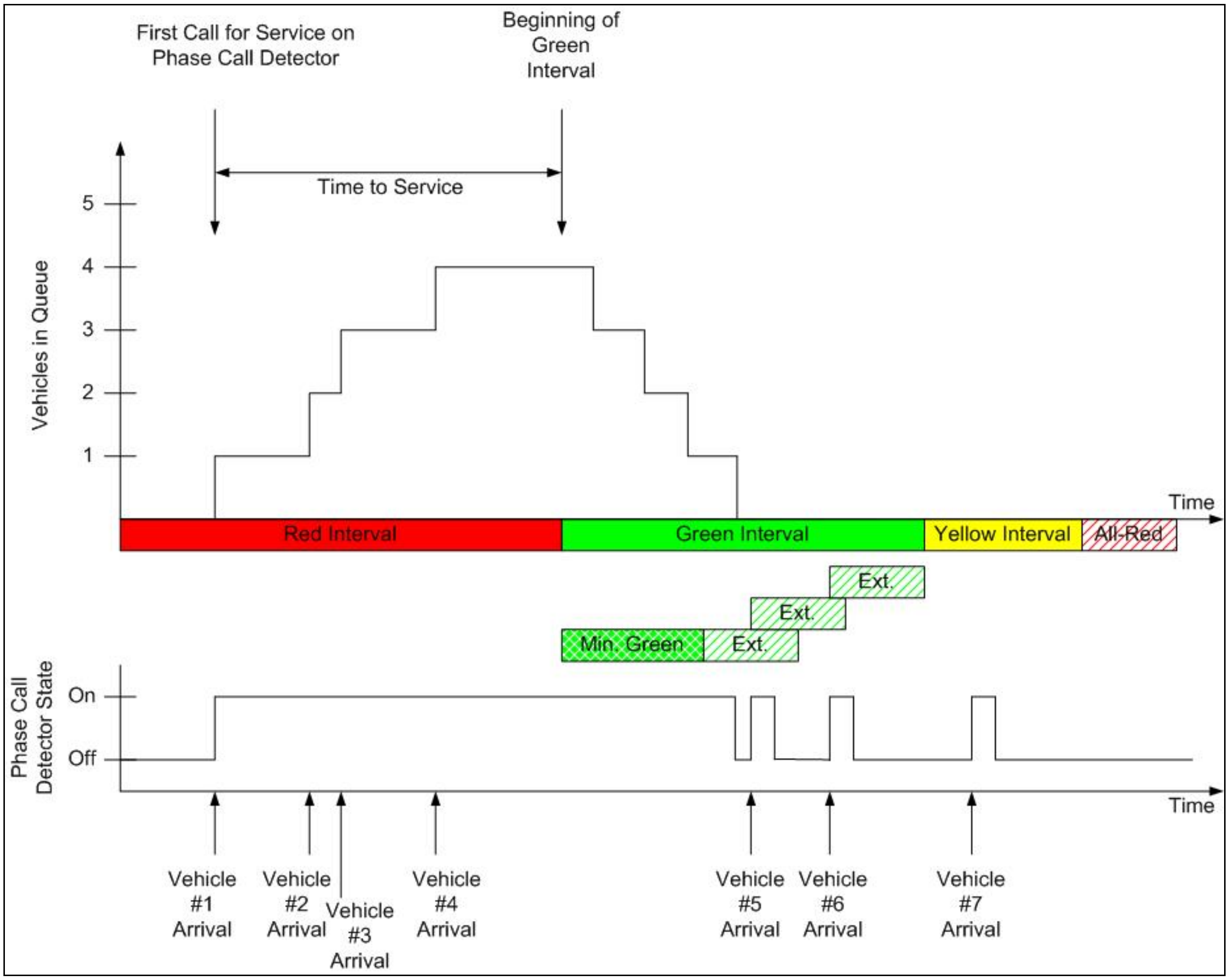


Figure 11. Illustration of the Time to Service Performance Measure.

Queue Service Time

As shown in Figure 12, we defined Queue Service Time as the time between when a phase becomes green and when the queued traffic clears the intersection. Measuring when the queue clears the intersection requires the use of a long-loop detector operating in the presence mode located at the stop bar. If the loop is long enough, a queue over the detector is likely to place a constant call (or remain in the "ON" state) to the controller until the queue has cleared the detector. Therefore, we attributed any subsequent change in the detector's state (i.e., from "ON" to "OFF") to vehicles arriving at the intersection after the queue has cleared. We assumed the queue to have cleared the intersection once the detection system ceases measuring a constant call on the associated phase call detector.

Interval Duration

The TSPMS computes the duration of each of the intervals displayed during a phase, including the green interval, the yellow interval, the all-red interval, and the red interval. We defined the duration of the green interval to be from the start of the green interval to the start of the yellow clearance interval. Likewise, we defined the duration of the yellow and all-red intervals to be from the beginning of the yellow interval to the beginning of the all-red interval and from the beginning of the all-red interval to the beginning of the red interval, respectively. We measured the duration of the red interval as the elapsed time between the start of the red interval for a phase to the start of the next green interval. The sum of the durations of the green, yellow, all-red, and red intervals is equal to the cycle time.

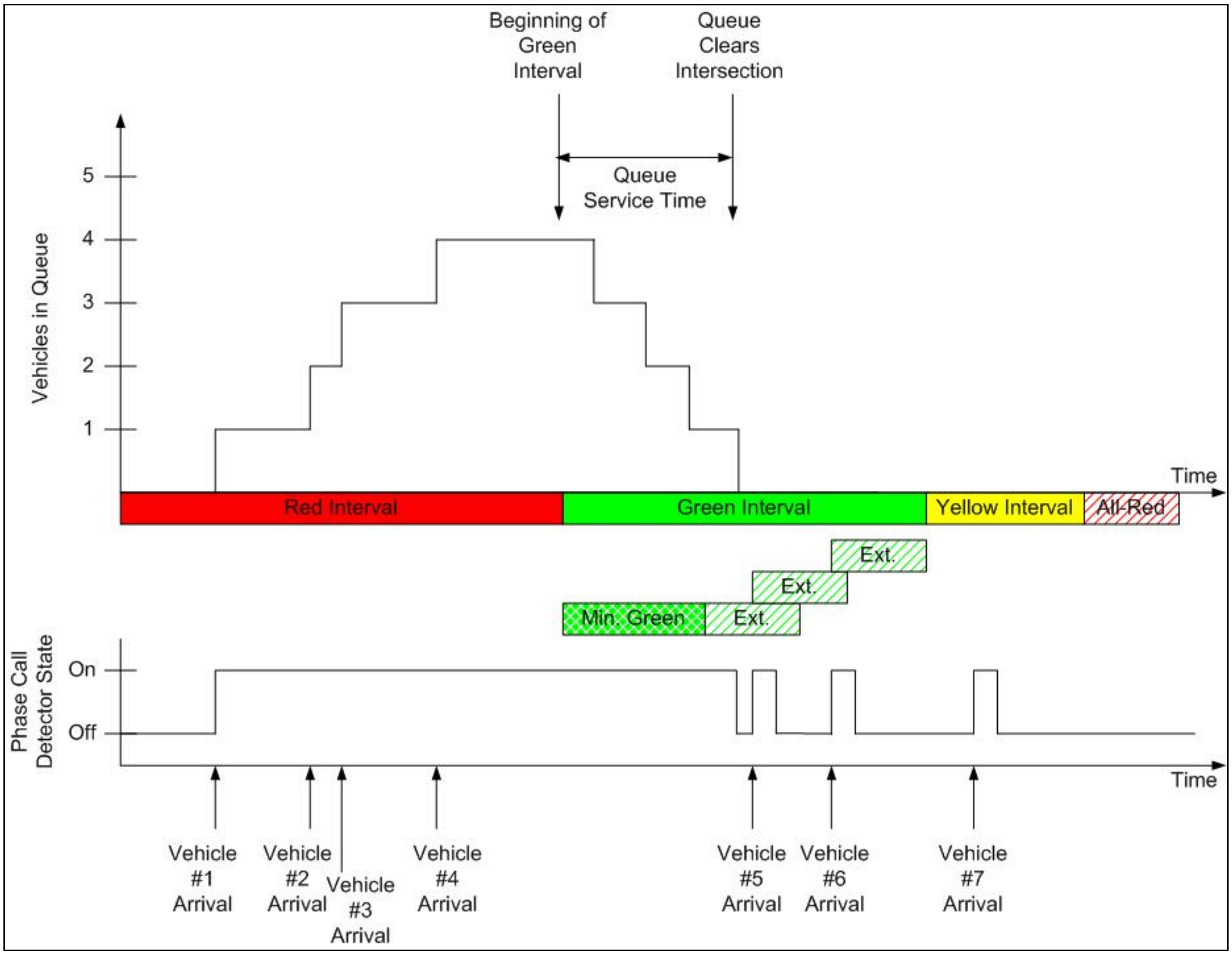


Figure 12. Illustration of Queue Service Time Performance Measure.

Number of Vehicles Entering Per Interval

The TSPMS allows operators to collect volume (or, more precisely, the number of vehicles serviced) during each interval during the phase. We monitor special detection zones downstream of the stop bar and count the number of vehicles that enter the intersection during each interval. The TSPMS records volume information on a per cycle basis. We use this information to compute the average and total number of vehicles entering the intersection during each interval in the phase.

Yellow and All-Red Violation Rates

The TSPMS computes the yellow and all-red violation rates. We used the special stop bar count detectors to determine if a phase during the cycle was one in which a yellow or all-red violation occurred. If a vehicle was detected entering the intersection during the yellow or all-red, we flagged that cycle as one in which a yellow or all-red violation occurred. We then computed the violation rates by comparing the number of cycles that a particular phase experienced a yellow or all-red violation to the total number of cycles that a particular phase experienced during the evaluation period.

Under ideal operating conditions, the violation rates should be close to zero. An all-red violation rate of 1.0 implies that at least one vehicle entered the intersection during the all-red clearance interval every time that phase activated. Because of the serious nature of red-light violations, agencies may consider some type of mitigation strategy (e.g., increased enforcement or improved signal timing operation) if the observed all-red violation rate exceeds 0.10.

Similarly, the yellow violation rate can be used to assess the effectiveness of the clearance interval. If the yellow-clearance violation rate is relatively high, agencies might consider corrective measures such as increased enforcement or modifications to the clearance intervals.

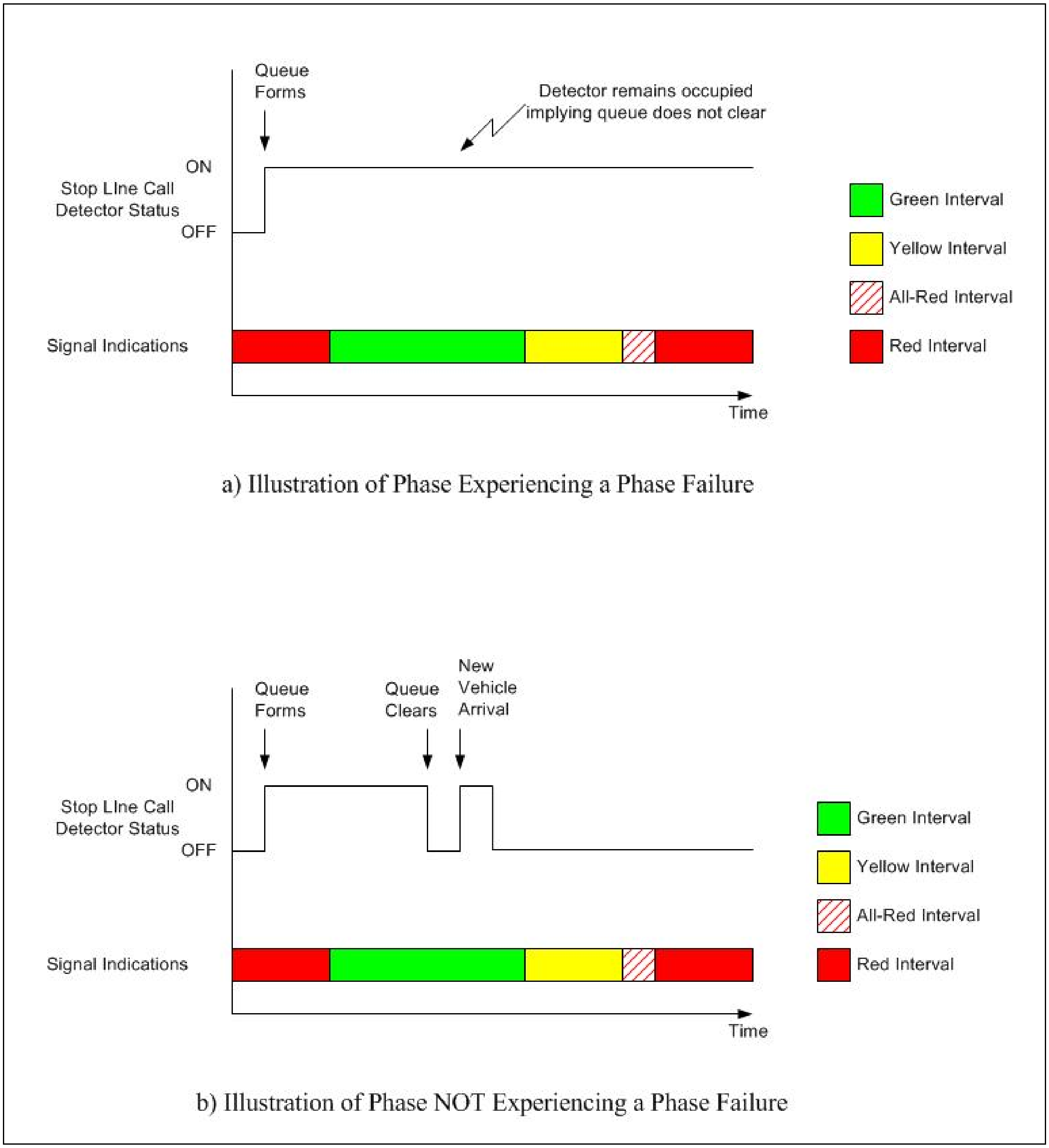
Phase Failure Rate

Phase Failure Rate is another performance measure computed by the TSPMS. Phase Failure Rate is the ratio of the number of cycles of a phase (or movement) where the queue failed to clear over the total number of cycles that phase (or movement) experienced during the evaluation period. We used the standard long stop line detectors to determine if the queue failed to clear on a cycle. We define a phase failure as a cycle where (1) the status of a stop line detector is "ON" at the beginning of the phase (i.e., beginning of the green interval) and (2) its status does not change (i.e., remains "ON") the entire time that the phase is active (i.e., until the red-clearance interval started for that particular phase). We assume that as long as vehicles occupy the stop line detectors, putting a constant call into the controller, a queue exists in that particular lane. If the stop line detector changes state (i.e., changes from "ON" to "OFF"), we assume that the queue has been serviced and any subsequent calls represent new arrivals. Figure 13 illustrates the operational definition of phase failure that we used in developing our system.

The Phase Failure Rate can be expected to range between 0.0 and 1.0. An approach that is operating efficiently would have a Phase Failure Rate approaching 0.0. A Phase Failure Rate of 0.0 implies that the queue is clearing the intersection every time the movement is serviced. A Phase Failure Rate approaching 1.0 indicates that the queue is not clearing the intersection every time the approach is serviced. Depending upon the level of traffic at an intersection, Phase Failure Rates of less than 0.2 are acceptable.

Detection System Setup

The TSPMS computes some performance measures by determining if vehicles are present over some of the detectors during specific portions of the system. Figure 14 shows the recommended detection scheme for the TSPMS. The TSPMS uses both the traditional detectors that call the phase as well as special count detectors installed specifically for collecting signal-related performance measures. For example, the system uses the status of the phase call detectors located near the stop line to compute the Time to Service, the Queue Service Time, and Phase Failure Rate performance measures. Other performance measures (such as the number of vehicles entering on specific intervals and the yellow and all-red violation rates) use the status of special detectors. These special detectors are directional detectors installed downstream of the stop line at an intersection. To prevent false detection, they are relatively small (no more the 3 feet in length) and need to be located far enough downstream from the stop line so that vehicles do not queue over them. These detection zones should also be set to operate in the presence mode and detect vehicles flowing only in the direction of the signal indication. These detectors are intended to count only vehicles entering the intersection and should call or extend traffic signal phases.



a) Illustration of Phase Experiencing a Phase Failure

b) Illustration of Phase NOT Experiencing a Phase Failure

Figure 13. Illustration of Operational Definition of Phase Failure.

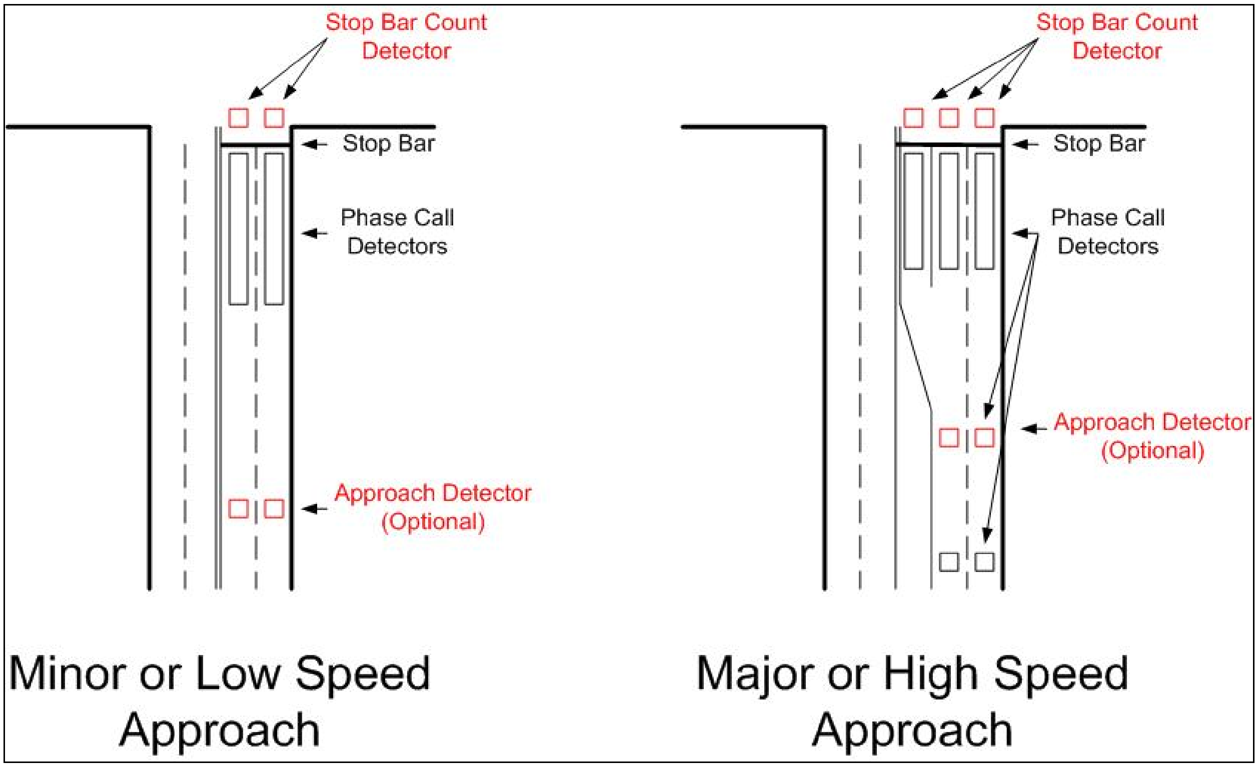


Figure 14. Recommended Detector Layout for TSPMS.

PROOF-OF-CONCEPT DEPLOYMENTS

The TSPMS was installed at two intersections in different locations in Texas: at the east intersection of US-70 and SH-36 in Milano, and at the intersection of FM 2871 and FM 247 in Huntsville. The following section discusses those field implementations.

Milano, Texas

A prototype of the TSPMS was installed at the east intersection of US-79 and SH-36 in Milano, Texas. The intersection is a T-intersection located in a primarily rural area. Traffic volumes are relatively light, but with a high percentage of truck traffic. Figure 15 shows the approximate location of the test intersection where we installed the TSPMS.

Detector Setup

Detection at the intersection is provided with a three-camera AutoScope VIVD system. This system has a total of 16 available detection outputs from the VIVD – four of those outputs provided phase call information to the controller. TTI researchers used the eight available detection zones and detection zones for the four omitted phases (4, 5, 7, and 8) to monitor movement of vehicles upstream of the intersection and movement of vehicles just ahead of the stop bar after green phase starts. Figure 16 illustrates the layout of the intersection in Milano and placement of TxDOT and TTI detectors.

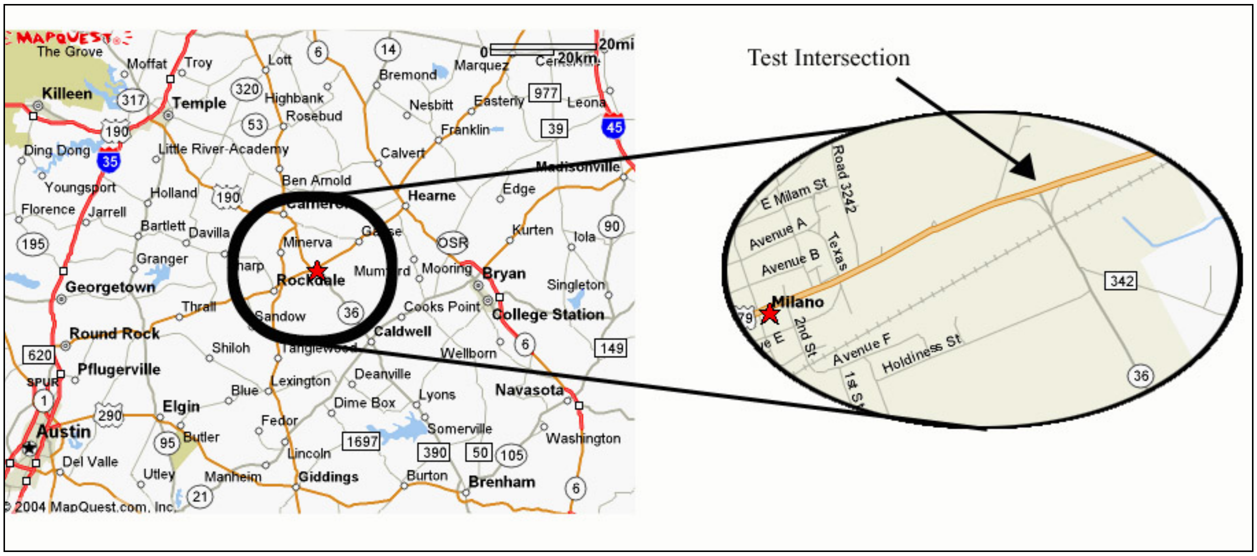


Figure 15. Location of Test Intersection in Milano, Texas.

Collected Performance Measures

After installation, the system collected performance measure data for approximately 2 weeks. We did not receive any reports that the system interfered with the operation of the traffic signal or the detection system. We also installed a digital video recorder at the intersection to record video images from the detection system. We used the video to verify the accuracy of the TSPMS.

The results of the proof-of-concept timing are shown in Tables 18 through 25. Table 18 shows the average cycle time for each phase for each hour from a typical day at the Milano intersection. Table 19 shows the average and 85th percentile of the Time to Service performance measures collected by the TSPMS at the Milano intersection. Recall the Time to Service is the amount of time that elapses from when a call comes in to a phase to when it is serviced by a green indication. Table 20 shows the average Queue Service Time recorded at the intersection.

Table 21 shows average duration of the intervals for each phase at the intersection. The average and total number of vehicles entering the Milano intersection during each interval for each phase are shown in Table 22 and Table 23, respectively. Finally, Table 24 and 25 show the number of vehicles observed and the cycle violation rate for vehicles entering the intersection during the yellow and all-red portions of the signal phase.

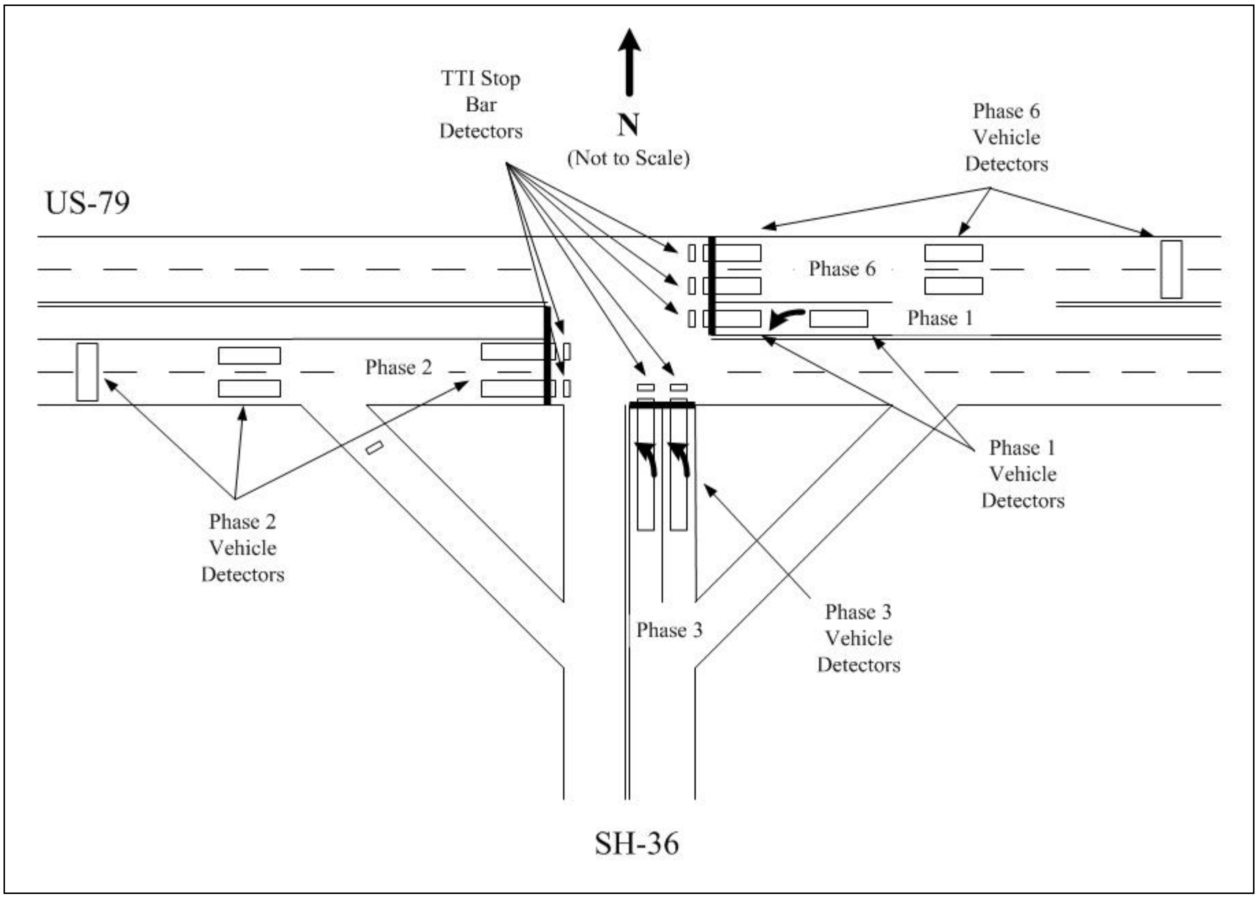


Figure 16. Placement of Detectors at the Intersection of US-79 and SR-36 in Milano, Texas.

Table 18. Average Cycle Time (sec) per Phase by Time-of-Day for a Typical Day – Milano, Texas.

Time Period		Phase 1	Phase 2	Phase 3	Phase 6
Hour Beginning	Hour Ending				
0:00:00	0:59:59	578.3	129.8	134.4	134.4
1:00:00	1:59:59	1936.2	179.4	189.4	189.4
2:00:00	2:59:59	5813.1	200.2	212.0	212.0
3:00:00	3:59:59	4115.0	150.4	157.0	157.0
4:00:00	4:59:59	3342.1	152.4	159.0	159.0
5:00:00	5:59:59	-*	90.2	89.0	90.2
6:00:00	6:59:59	6106.7	61.4	62.7	62.4
7:00:00	7:59:59	-*	66.6	66.7	66.6
8:00:00	8:59:59	8219.1	71.3	70.9	71.3
9:00:00	9:59:59	537.3	67.6	69.3	68.9
10:00:00	10:59:59	-*	60.0	60.0	60.0
11:00:00	11:59:59	2957.0	60.4	62.4	62.4
12:00:00	12:59:59	489.4	66.2	71.4	71.5
13:00:00	13:59:59	2487.3	61.8	61.9	61.8
14:00:00	14:59:59	1262.0	61.2	62.1	62.2
15:00:00	15:59:59	-*	61.9	61.8	61.9
16:00:00	16:59:59	4018.0	65.6	67.1	66.8
17:00:00	17:59:59	1913.4	64.0	65.0	65.1
18:00:00	18:59:59	1812.4	60.2	61.2	61.2
19:00:00	19:59:59	1889.8	83.0	85.0	84.9
20:00:00	20:59:59	1903.1	88.6	90.9	90.7
21:00:00	21:59:59	1781.7	98.4	102.8	104.3
22:00:00	22:59:59	587.7	98.0	99.2	98.0
23:00:00	23:59:59	5224.1	114.8	123.1	123.3

* Note: There was no activation of this phase during the evaluation interval.

Note that for Phase 1, the Time to Service is zero in most of the periods throughout the day. Phase 1 is a lagging left-turn phase, and most vehicle calls can be serviced during the permissive period of this phase. Another observation from this table is that Times to Service on Phases 2 and 6 are substantially lower than the Time to Service performance measure for Phase 3. Phases 2 and 6 are the predominant movements at this intersection, and as such, the signal timing and the detector system favor minimizing wait time for motorists on these approaches. Phase 3 is a cross-street movement, and therefore its Time to Service is substantially higher. The average time that a motorist would have to wait for service on Phase 3 (or northbound) approach is approximately 13-14 seconds, while the average time a motorist would have to wait for service on Phases 2 and 6 is approximately 2.5 to 3.5 seconds.

Table 19. Average and 85th Percentile Time to Service (sec) per Phase by Time-of-Day for a Typical Day – Milano, Texas.

Time Period		Phase 1	Phase 2	Phase 3	Phase 6
Hour Beginning	Hour Ending				
0:00:00	0:59:59	0 (0)	0.3 (0.0)	8.4 (17.0)	0.15 (0.0)
1:00:00	1:59:59	0 (0)	0.1 (0.0)	7.3 (10.1)	0.06 (0.0)
2:00:00	2:59:59	0 (0)	0.0 (0.0)	8.5 (14.2)	0.14 (0.0)
3:00:00	3:59:59	0 (0)	0.3 (0.0)	6.3 (6.2)	0.02 (0.5)
4:00:00	4:59:59	0 (0)	0.5 (0.0)	10.1 (16.9)	0.61 (0.0)
5:00:00	5:59:59	-	0.8 (0.4)	10.5 (19.3)	0.20 (0.0)
6:00:00	6:59:59	0 (0)	1.3 (3.0)	12.1 (22.2)	1.12 (1.9)
7:00:00	7:59:59	-	1.7 (6.0)	13.0 (21.6)	2.31 (7.1)
8:00:00	8:59:59	0 (0)	1.8 (4.0)	13.4 (22.8)	1.51 (2.1)
9:00:00	9:59:59	9.3 (19.6)	2.9 (8.4)	14.5 (23.4)	2.12 (8.0)
10:00:00	10:59:59	-	2.0 (4.3)	12.7 (21.9)	1.75 (5.4)
11:00:00	11:59:59	5.8 (12.2)	2.3 (5.9)	14.3 (22.9)	2.47 (6.5)
12:00:00	12:59:59	0 (0)	3.7 (9.8)	11.9 (19.8)	2.77 (9.0)
13:00:00	13:59:59	0 (0)	2.9 (7.4)	14.2 (24.8)	1.71 (6.7)
14:00:00	14:59:59	0 (0)	2.1 (4.3)	14.0 (22.1)	2.58 (6.9)
15:00:00	15:59:59	-	2.9 (10.2)	12.6 (20.7)	2.26 (5.4)
16:00:00	16:59:59	3.1 (5.2)	2.5 (7.0)	14.9 (25.0)	3.50 (9.3)
17:00:00	17:59:59	6.3 (6.3)	1.1 (2.2)	13.3 (22.6)	1.83 (2.9)
18:00:00	18:59:59	4.0 (8.4)	2.8 (7.4)	14.5 (23.6)	1.86 (5.2)
19:00:00	19:59:59	0 (0)	0.7 (0.8)	11.2 (21.1)	0.97 (1.1)
20:00:00	20:59:59	0 (0)	0.6 (0.1)	11.5 (19.3)	1.12 (2.6)
21:00:00	21:59:59	0 (0)	0.6 (0.0)	12.8 (22.0)	0.73 (0.0)
22:00:00	22:59:59	0 (0)	0.5 (0.0)	8.5 (12.0)	0.04 (0.0)
23:00:00	23:59:59	0 (0)	0.1 (0.0)	8.3 (10.4)	0.74 (0.0)

*Average (85th Percentile)

Table 20 shows the average Queue Service Time recorded at the intersection. The table shows that the average Queue Service Time for Phases 2 and 6 is relatively small, on the order of 2.5 to 3.5 seconds. Queue Service Time is the time that elapses from the start of the green phase until the time the queue clears the detector. Note that the Queue Service Time is substantially higher on Phase 3 during the middle portion of the day (from 7:00 am to essentially 8:00 pm) when traffic on the main street (i.e., Phases 2 and 6) is heaviest, and the controller cannot respond as quickly to competing demands.

Table 20. Average and 85th Percentile Queue Service Time (sec) per Phase by Time-of-Day for a Typical Day – Milano, Texas.

Time Period		Phase 1	Phase 2	Phase 3	Phase 6
Hour Beginning	Hour Ending				
0:00:00	0:59:59	0.0 (0.0)	1.0 (0.0)	4.5 (7.4)	0.06 (0.0)
1:00:00	1:59:59	0.0 (0.0)	0.5 (0.0)	4.7 (6.7)	0.25 (0.0)
2:00:00	2:59:59	0.0 (0.0)	1.4 (0.0)	3.6 (5.5)	0.26 (0.0)
3:00:00	3:59:59	0.0 (0.0)	0.4 (0.0)	5.1 (8.9)	0.09 (0.0)
4:00:00	4:59:59	0.0 (0.0)	0.5 (0.0)	4.6 (6.6)	0.38 (0.0)
5:00:00	5:59:59	-	0.8 (0.9)	4.7 (7.4)	0.36 (0.0)
6:00:00	6:59:59	0.0 (0.0)	1.3 (3.0)	6.3 (9.6)	1.04 (3.5)
7:00:00	7:59:59	-	1.7 (6.0)	8.1 (11.2)	1.30 (4.1)
8:00:00	8:59:59	0.0 (0.0)	1.8 (4.0)	8.2 (12.2)	1.29 (4.6)
9:00:00	9:59:59	4.4 (9.1)	2.9 (8.4)	8.9 (14.3)	2.42 (5.7)
10:00:00	10:59:59	-	2.0 (4.3)	8.2 (12.2)	1.82 (5.8)
11:00:00	11:59:59	1.5 (3.1)	2.3 (5.9)	8.5 (13.5)	2.93 (7.8)
12:00:00	12:59:59	0.0 (0.0)	3.7 (9.8)	8.1 (11.1)	1.96 (6.7)
13:00:00	13:59:59	0.0 (0.0)	2.0 (5.6)	8.3 (12.5)	2.21 (4.8)
14:00:00	14:59:59	0.0 (0.0)	2.7 (6.8)	9.5 (14.3)	2.33 (6.5)
15:00:00	15:59:59	-	2.6 (8.2)	8.7 (14.7)	2.52 (6.5)
16:00:00	16:59:59	1.4 (2.3)	2.4 (6.1)	8.9 (14.1)	2.00 (5.7)
17:00:00	17:59:59	6.0 (6.0)	1.4 (4.6)	8.5 (13.3)	1.42 (4.9)
18:00:00	18:59:59	0.6	1.7 (7.4)	8.3 (13.0)	1.27 (4.4)
19:00:00	19:59:59	0.0 (0.0)	0.8 (0.9)	7.5 (10.7)	0.93 (3.0)
20:00:00	20:59:59	0.0 (0.0)	0.5 (0.1)	7.3 (11.7)	1.42 (4.8)
21:00:00	21:59:59	0.0 (0.0)	0.6 (0.0)	4.7 (6.9)	0.68 (0.0)
22:00:00	22:59:59	0.0 (0.0)	0.5 (0.0)	5.1 (8.7)	0.13 (0.0)
23:00:00	23:59:59	0.0 (0.0)	0.1 (0.0)	4.9 (8.2)	0.29 (0.0)

Table 21 shows the average duration of the green, yellow, all-red, and red intervals for each phase by time-of-day. Note that for Phase 1, the average duration of the green interval was 5 seconds while the average duration of the red interval was very large. This is because the green interval for this phase seldom displayed and when it did, it displayed only for its minimum requirement. This table also shows how the duration of the intervals change as the traffic volumes change throughout the day. During the late night and early morning hours, the average green durations are relatively long for Phases 2 and 6 (the main-street phases) and relatively short for Phase 3 (the cross-street phase). During the middle of the day, the average durations of the green intervals for Phases 2 and 6 decrease, while the average duration of the green interval for Phase 3 increases. An examination of Tables 22 and 23 shows that traffic demands on Phase 3 increase dramatically during these time periods.

Tables 22 and 23 show the average and total number of vehicles observed entering the intersection during each interval. One item to note from these tables is that there are a substantial number of vehicles entering the intersection during the red intervals for Phases 1, 2, and 3. For Phase 1, the high number of vehicles observed entering during the red interval is caused by the way the signal operates. Phase 1 controls the westbound left turn. This left turn operates in a protected-permissive mode with Phase 1 controlling the protected interval and Phase 6 governing the permissive interval. Many of the vehicles reported as entering on the red interval of Phase 1 actually entered the intersection on the permissive portion of the left-turn phase (i.e., with a green signal provided by Phase 6). A review of the TSPMS logic showed that we incorrectly tied the count detector associated with this movement to only Phase 1 and not both Phase 1 and Phase 6. We need to revise the logic in the TSPMS to account for permissive periods to get a better indication of the actual number of vehicles entering the intersection during the red interval for these types of left-turn situations.

The high numbers of vehicles entering the intersection on Phases 2 and 3 were caused by a high volume of right-turn-on-red movements at the intersection. Further modifications to the TSPMS software and detector configuration are needed to address the right-turn-on-red situation.

Table 21. Average Interval Duration (sec) Recorded by the TSPMS for Each Phase.

Time Period		Phase 1				Phase 2				Phase 3				Phase 6			
Hour Beginning	Hour Ending	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red
0:00:00	0:59:59	5.0	4.0	2.0	3850.4	109.6	4.0	2.0	14.1	8.7	3.5	2.0	120.2	114.1	4.0	2.0	14.3
1:00:00	1:59:59	5.0	4.0	2.0	4826.3	159.5	4.0	2.0	13.9	8.5	3.5	2.0	175.4	169.3	4.0	2.0	14.1
2:00:00	2:59:59	5.0	4.0	2.0	4104.0	181.1	4.0	2.0	13.1	7.7	3.5	2.0	198.8	192.7	4.0	2.0	13.3
3:00:00	3:59:59	5.0	4.0	2.0	3336.1	129.7	4.0	2.0	14.8	9.3	3.5	2.0	142.1	136.1	4.0	2.0	14.9
4:00:00	4:59:59	5.0	4.0	2.0	6015.7	132.9	4.0	2.0	13.5	8.0	3.5	2.0	145.5	139.4	4.0	2.0	13.6
5:00:00	5:59:59	-	-	-	-	69.6	4.0	2.0	14.6	8.9	3.5	2.0	74.6	69.6	4.0	2.0	14.6
6:00:00	6:59:59	5.0	4.0	2.0	8209.1	40.5	4.0	2.0	14.9	9.3	3.5	2.0	47.9	41.5	4.0	2.0	14.9
7:00:00	7:59:59	-	-	-	-	44.3	4.0	2.0	16.3	10.8	3.5	2.0	50.4	44.3	4.0	2.0	16.3
8:00:00	8:59:59	5.0	4.0	2.0	981.2	47.9	4.0	2.0	14.7	11.2	3.5	2.0	54.2	48.1	4.0	2.0	17.2
9:00:00	9:59:59	8.0	4.0	2.0	1836.9	43.6	4.0	2.0	18.1	12.1	3.5	2.0	51.7	45.6	4.0	2.0	17.3
10:00:00	10:59:59	-	-	-	-	37.3	4.0	2.0	16.7	11.1	3.5	2.0	43.3	37.3	4.0	2.0	16.7
11:00:00	11:59:59	5.0	4.0	2.0	1240.4	37.1	4.0	2.0	17.3	11.7	3.5	2.0	45.3	39.2	4.0	2.0	17.3
12:00:00	12:59:59	5.0	4.0	2.0	704.5	43.4	4.0	2.0	17.0	11.4	3.5	2.0	54.5	48.4	4.0	2.0	17.1
13:00:00	13:59:59	5.0	4.0	2.0	2078.7	38.0	4.0	2.0	17.8	12.1	3.5	2.0	44.3	38.2	4.0	2.0	17.6
14:00:00	14:59:59	5.0	4.0	2.0	3124.3	36.8	4.0	2.0	18.4	12.5	3.5	2.0	44.2	38.1	4.0	2.0	18.2
15:00:00	15:59:59	-	-	-	-	37.8	4.0	2.0	15.1	12.6	3.5	2.0	43.7	37.8	4.0	2.0	18.1
16:00:00	16:59:59	5.0	4.0	2.0	1108.6	42.2	4.0	2.0	17.5	11.9	3.5	2.0	19.8	43.5	4.0	2.0	17.4
17:00:00	17:59:59	8.1	4.0	2.0	2713.5	40.3	4.0	2.0	17.7	12.1	3.5	2.0	47.3	41.4	4.0	2.0	17.8
18:00:00	18:59:59	5.0	4.0	2.0	1929.3	37.2	4.0	2.0	17.1	11.1	3.5	2.0	44.6	38.4	4.0	2.0	16.8
19:00:00	19:59:59	5.0	4.0	2.0	1274.3	60.9	4.0	2.0	16.0	10.4	3.5	2.0	69.1	63.0	4.0	2.0	15.9
20:00:00	20:59:59	5.0	4.0	2.0	4341.8	66.8	4.0	2.0	15.8	10.5	3.5	2.0	74.9	68.8	4.0	2.0	15.9
21:00:00	21:59:59	5.0	4.0	2.0	515.7	77.7	4.0	2.0	14.7	8.6	3.5	2.0	88.6	84.0	4.0	2.0	14.3
22:00:00	22:59:59	5.0	4.0	2.0	5207..5	77.5	4.0	2.0	14.5	8.9	3.5	2.0	84.8	77.5	4.0	2.0	14.5
23:00:00	23:59:59	5.0	4.0	2.0	2695.9	94.3	4.0	2.0	14.4	9.0	3.5	2.0	108.6	102.6	4.0	2.0	14.4

Table 22. Average Number of Vehicles Entering the Milano Intersection During Each Interval for Each Phase.

Time Period		Phase 1				Phase 2				Phase 3				Phase 6			
Hour Beginning	Hour Ending	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red
0:00:00	0:59:59	0.0	0.0	0.0	3.0	1.17	0.00	0.03	0.03	1.57	0.04	0.11	0.57	0.93	0.00	0.00	0.00
1:00:00	1:59:59	4.2	0.0	0.0	0.0	1.00	0.05	0.00	0.00	1.83	0.11	0.00	0.17	0.89	0.00	0.00	0.00
2:00:00	2:59:59	0.0	0.0	0.0	3.0	0.67	0.00	0.00	0.20	1.71	0.12	0.00	0.24	0.71	0.00	0.00	0.00
3:00:00	3:59:59	0.0	0.0	0.0	8.0	0.75	0.00	0.04	0.00	2.09	0.22	0.04	0.30	0.57	0.04	0.00	0.00
4:00:00	4:59:59	0.0	0.0	0.0	20.0	1.08	0.04	0.00	0.04	1.57	0.09	0.04	0.17	0.87	0.04	0.00	0.09
5:00:00	5:59:59	-	-	-	-	1.56	0.00	0.00	0.10	2.23	0.08	0.08	0.25	1.28	0.00	0.00	0.00
6:00:00	6:59:59	0.0	0.0	0.0	53.0	1.33	0.00	0.02	0.08	1.71	0.03	0.00	0.12	1.03	0.03	0.00	0.02
7:00:00	7:59:59	-	-	-	-	2.09	0.04	0.02	0.17	2.40	0.04	0.00	0.08	1.53	0.08	0.04	0.04
8:00:00	8:59:59	0	0.0	0.0	2.0	2.10	0.04	0.02	0.14	2.49	0.10	0.00	0.25	1.90	0.04	0.00	0.06
9:00:00	9:59:59	1.3	0.0	0.0	17.8	3.11	0.04	0.04	0.15	3.06	0.15	0.06	0.17	1.92	0.12	0.04	0.08
10:00:00	10:59:59	-	-	-	-	2.55	0.03	0.05	0.30	2.35	0.10	0.03	0.20	2.15	0.07	0.07	0.07
11:00:00	11:59:59	0.3	0.0	0.0	15.0	2.83	0.07	0.05	0.30	2.47	0.05	0.00	0.32	2.07	0.07	0.02	0.09
12:00:00	12:59:59	0.0	0.0	0.0	6.7	3.07	0.10	0.04	0.20	2.54	0.08	0.02	0.46	2.40	0.10	0.04	0.08
13:00:00	13:59:59	1.0	0.0	0.0	18.0	2.69	0.05	0.14	0.24	2.52	0.12	0.05	0.22	2.22	0.02	0.03	0.05
14:00:00	14:59:59	0.0	0.0	0.0	35.3	2.81	0.02	0.03	0.17	2.66	0.07	0.05	0.17	2.69	0.07	0.03	0.02
15:00:00	15:59:59	-	-	-	-	3.03	0.02	0.03	0.38	2.76	0.07	0.07	0.29	2.40	0.05	0.03	0.02
16:00:00	16:59:59	1.4	0.0	0.0	14.0	3.20	0.05	0.04	0.42	2.94	0.04	0.06	0.25	2.13	0.02	0.04	0.04
17:00:00	17:59:59	1.0	0.0	0.0	29.0	2.57	0.04	0.04	0.45	2.75	0.02	0.00	0.25	2.15	0.07	0.00	0.04
18:00:00	18:59:59	0.0	0.0	0.0	17.7	1.89	0.05	0.02	0.30	2.29	0.02	0.02	0.15	1.52	0.03	0.00	0.02
19:00:00	19:59:59	0.0	0.0	0.0	8.5	2.05	0.02	0.02	0.09	1.95	0.05	0.00	0.12	1.43	0.00	0.02	0.05
20:00:00	20:59:59	0.0	0.0	0.0	10.0	2.12	0.02	0.02	0.07	2.02	0.07	0.05	0.19	1.31	0.05	0.02	0.00
21:00:00	21:59:59	0.0	0.0	0.0	2.3	1.46	0.00	0.00	0.09	1.71	0.09	0.09	0.53	1.48	0.00	0.00	0.00
22:00:00	22:59:59	0.0	0.0	0.0	23.0	1.45	0.00	0.03	0.03	1.92	0.05	0.05	0.27	1.13	0.05	0.00	0.00
23:00:00	23:59:59	0.5	0.0	0.0	0.5	0.97	0.00	0.00	0.17	1.67	0.07	0.11	0.22	1.26	0.00	0.00	0.00

Table 23. Total Number of Vehicles Entering the Milano Intersection During Each Interval for Each Phase.

Time Period		Phase 1				Phase 2				Phase 3				Phase 6			
Hour Beginning	Hour Ending	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red
0:00:00	0:59:59	0	0	0	3	34	0	1	1	44	1	3	16	26	0	0	0
1:00:00	1:59:59	6	0	0	0	19	1	0	0	33	2	0	3	16	0	0	0
2:00:00	2:59:59	0	0	0	3	12	0	0	4	29	2	0	35	12	0	0	0
3:00:00	3:59:59	0	0	0	8	18	0	1	0	48	5	1	7	13	1	0	0
4:00:00	4:59:59	0	0	0	20	26	1	0	1	36	2	1	4	20	1	0	2
5:00:00	5:59:59	-	-	-	-	27	0	0	3	89	3	3	10	50	0	0	0
6:00:00	6:59:59	0	0	0	53	80	0	1	5	99	2	0	2	61	2	0	1
7:00:00	7:59:59	-	-	-	-	111	2	1	9	127	2	0	4	81	4	2	2
8:00:00	8:59:59	0	0	0	2	107	2	1	7	127	5	0	13	97	2	0	3
9:00:00	9:59:59	5	0	0	71	165	2	2	8	159	8	2	9	100	6	2	4
10:00:00	10:59:59	-	-	-	-	153	2	3	18	141	6	2	12	129	4	4	4
11:00:00	11:59:59	1	0	0	46	54	4	3	18	143	3	0	19	120	4	1	5
12:00:00	12:59:59	0	0	0	40	166	5	2	11	127	4	1	23	120	5	2	4
13:00:00	13:59:59	1	0	0	18	156	3	8	14	146	7	3	13	129	1	2	3
14:00:00	14:59:59	0	0	0	106	166	1	2	10	154	4	3	10	156	4	2	1
15:00:00	15:59:59	-	-	-	-	176	1	2	22	163	4	4	17	139	3	2	2
16:00:00	16:59:59	2	0	0	28	176	3	2	23	156	2	3	13	115	1	2	2
17:00:00	17:59:59	1	0	0	29	144	2	2	25	154	1	0	14	118	4	0	2
18:00:00	18:59:59	0	0	0	53	115	3	1	18	135	1	1	9	91	2	0	1
19:00:00	19:59:59	0	0	0	17	88	1	1	4	82	2	0	5	60	0	1	2
20:00:00	20:59:59	0	0	0	10	91	1	1	3	85	3	2	8	55	2	1	0
21:00:00	21:59:59	0	0	0	7	51	0	0	3	58	3	3	18	49	0	0	0
22:00:00	22:59:59	0	0	0	23	55	0	1	1	34	2	2	10	43	2	0	0
23:00:00	23:59:59	1	0	0	1	28	0	0	5	45	2	3	6	34	0	0	0

Table 24. Number of Cycles and Violation Rate of Vehicles Entering on Yellow Interval for Each Phase at the Milano Intersection.

Time Period		Phase 1			Phase 2			Phase 3			Phase 6		
Hour Beginning	Hour Ending	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate
0:00:00	0:59:59	0	0	0	29	0	0.00	28	1	0.04	28	0	0.00
1:00:00	1:59:59	0	0	0	19	1	0.05	18	2	0.11	18	0	0.00
2:00:00	2:59:59	0	0	0	18	0	0.00	17	2	0.12	17	2	0.12
3:00:00	3:59:59	0	0	0	24	0	0.00	23	4	0.17	23	0	0.00
4:00:00	4:59:59	0	0	0	24	1	0.04	23	2	0.09	23	2	0.09
5:00:00	5:59:59	0	0	0	39	0	0.00	40	3	0.08	39	2	0.05
6:00:00	6:59:59	0	0	0	60	0	0.00	58	1	0.02	59	10	0.17
7:00:00	7:59:59	0	0	0	53	2	0.04	53	2	0.04	53	11	0.21
8:00:00	8:59:59	0	0	0	51	1	0.02	51	5	0.10	51	9	0.18
9:00:00	9:59:59	0	0	0	53	2	0.04	52	6	0.12	52	12	0.23
10:00:00	10:59:59	0	0	0	60	2	0.03	60	6	0.10	60	15	0.25
11:00:00	11:59:59	0	0	0	60	4	0.07	58	3	0.05	58	9	0.16
12:00:00	12:59:59	0	0	0	54	4	0.07	50	4	0.08	50	11	0.22
13:00:00	13:59:59	0	0	0	58	3	0.05	58	6	0.10	58	9	0.16
14:00:00	14:59:59	0	0	0	59	1	0.02	58	4	0.07	58	15	0.26
15:00:00	15:59:59	0	0	0	58	1	0.02	59	4	0.07	58	11	0.19
16:00:00	16:59:59	0	0	0	55	3	0.05	53	2	0.04	54	12	0.22
17:00:00	17:59:59	0	0	0	56	2	0.04	56	1	0.02	55	9	0.16
18:00:00	18:59:59	0	0	0	61	3	0.05	59	1	0.02	60	8	0.13
19:00:00	19:59:59	0	0	0	43	1	0.02	42	2	0.05	42	3	0.07
20:00:00	20:59:59	0	0	0	43	1	0.02	42	3	0.07	42	5	0.12
21:00:00	21:59:59	0	0	0	35	0	0.00	34	2	0.06	33	2	0.06
22:00:00	22:59:59	0	0	0	38	0	0.00	37	2	0.05	38	3	0.08
23:00:00	23:59:59	0	0	0	29	0	0.00	27	2	0.07	27	1	0.04

Table 25. Number of Cycles and Violation Rate of Vehicles Entering on All-Red Interval of Each Phase at the Milano Intersection.

Time Period		Phase 1			Phase 2			Phase 3			Phase 6		
Hour Beginning	Hour Ending	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate
0:00:00	0:59:59	0	0	0	29	1	0.03	28	3	0.11	28	0	0.00
1:00:00	1:59:59	0	0	0	19	0	0.00	18	0	0.00	18	0	0.00
2:00:00	2:59:59	0	0	0	18	0	0.00	17	0	0.00	17	0	0.00
3:00:00	3:59:59	0	0	0	24	1	0.04	23	1	0.04	23	0	0.00
4:00:00	4:59:59	0	0	0	24	0	0.00	23	1	0.04	23	0	0.00
5:00:00	5:59:59	0	0	0	39	0	0.00	40	3	0.08	39	0	0.00
6:00:00	6:59:59	0	0	0	60	2	0.03	58	0	0.00	59	0	0.00
7:00:00	7:59:59	0	0	0	53	1	0.02	53	0	0.00	53	3	0.06
8:00:00	8:59:59	0	0	0	51	1	0.02	51	0	0.00	51	0	0.00
9:00:00	9:59:59	0	0	0	53	2	0.04	52	3	0.06	52	1	0.02
10:00:00	10:59:59	0	0	0	60	2	0.03	60	2	0.03	60	2	0.03
11:00:00	11:59:59	0	0	0	60	3	0.05	58	0	0.00	58	0	0.00
12:00:00	12:59:59	0	0	0	54	2	0.04	50	1	0.02	50	3	0.06
13:00:00	13:59:59	0	0	0	58	5	0.09	58	3	0.03	58	1	0.02
14:00:00	14:59:59	0	0	0	59	2	0.03	58	3	0.05	58	0	0.00
15:00:00	15:59:59	0	0	0	58	2	0.03	59	4	0.07	58	0	0.00
16:00:00	16:59:59	0	0	0	55	2	0.04	53	3	0.06	54	4	0.07
17:00:00	17:59:59	0	0	0	56	2	0.04	56	0	0.00	55	0	0.00
18:00:00	18:59:59	0	0	0	61	1	0.02	59	1	0.02	60	1	0.02
19:00:00	19:59:59	0	0	0	43	1	0.02	42	0	0.00	42	1	0.02
20:00:00	20:59:59	0	0	0	43	1	0.02	42	2	0.05	42	1	0.02
21:00:00	21:59:59	0	0	0	35	0	0.00	34	3	0.09	33	0	0.00
22:00:00	22:59:59	0	0	0	38	1	0.03	37	2	0.05	38	0	0.00
23:00:00	23:59:59	0	0	0	29	0	0.00	27	2	0.07	27	0	0.00

Accuracy of Performance Measures

We conducted a comparison of the performance measures produced by the TSPMS versus those produced from manual observations. We randomly selected one hour of the day for one phase. We then used the recorded video from the intersection to produce the performance measures for that time period. The results of this comparison are summarized in Table 26. This table shows that the performance measures produced by the TSPMS correlated relatively closely to the actual measures. The one measure that did not correlate well was the red-light violation rate. The TSPMS system measured approximately 6 percent of the cycles exhibit a red-light violation, while observation reveals that this rate was closer to 2 percent of the cycle. We suspect that this large difference was a result of a high number of right-turn-on-red movements that occurred during this time period.

Table 26. Comparison of Select Performance Measures.

Selected Performance Measures	Measured by TSPMS	Observed from Video	Percent Difference
Avg. Time to Service (sec)	13.9	16.8	17
Avg. Queue Service Time (sec)	8.2	8.1	1
Avg. Green Time (sec)	11.0	11.0	0
Avg. # of Vehicles Entering on Green (sec)	129	116	11
Tot. # of Vehicles Entering	135	120	13
% Cycles- Red Violation	5.7	1.9	200

Huntsville, Texas

The TSPMS system was also installed and tested at the intersection of FM 247 and FM 2821 in Huntsville, Texas (Figure 17). This location is a four-legged intersection operating with an eight-phase intersection. Located close to Huntsville High School, the traffic volumes through this intersection were substantially higher than those through the test intersection in Milano, Texas.

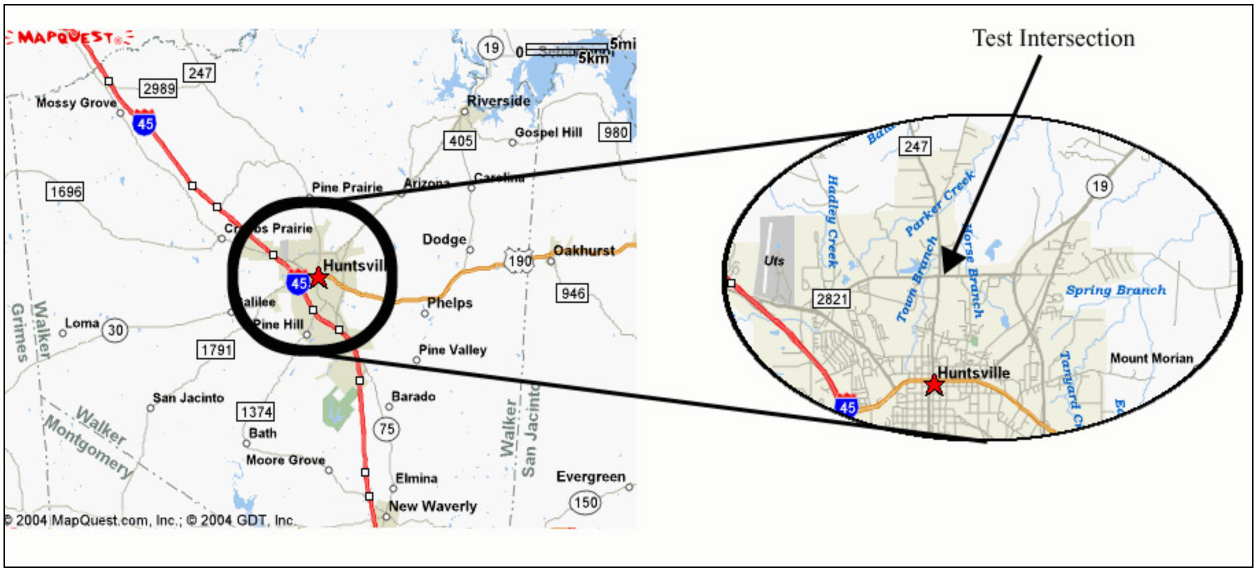


Figure 17. Location of Test Intersection in Huntsville, Texas.

Detector Setup

The existing four-camera Iteris® VIVD system installed at the intersection in Huntsville did not have any available or unused detection zones other than the TxDOT detection zones controlling the intersection. TTI researchers split the four camera feeds and used an AutoScope VIVD system to place the extra detection zones the algorithm needed to collect the required traffic data. Figure 18 illustrates the layout of the intersection in Huntsville and placement of TxDOT and TTI detectors. Again, a TS-1 CID interfaced with the TSS at the site because the cabinet and controller are of TS-1 type.

Collected Performance Measures

The results of the proof-of-concept timing are shown in Table 27 through Table 39. Table 27 shows the average cycle time for each phase for each hour from a typical day at the intersection in Huntsville. Table 28 shows the average and 85th percentile of the Time to Service performance measure collected by the TSPMS for Phases 1 through 4 and Phases 5 through 8, respectively. Table 29 shows the average Queue Service Time recorded at the intersection. The average duration of the intervals for each phase at the intersection are shown in Table 30 and Table 31, while the average and total number of vehicles entering the intersection during each interval for each phase are shown in Table 32 through Table 35. Finally, the number of vehicles observed and the cycle violation rate for vehicles entering the intersection during the yellow and all-red portions of each signal phase are shown in Table 36 through Table 39.

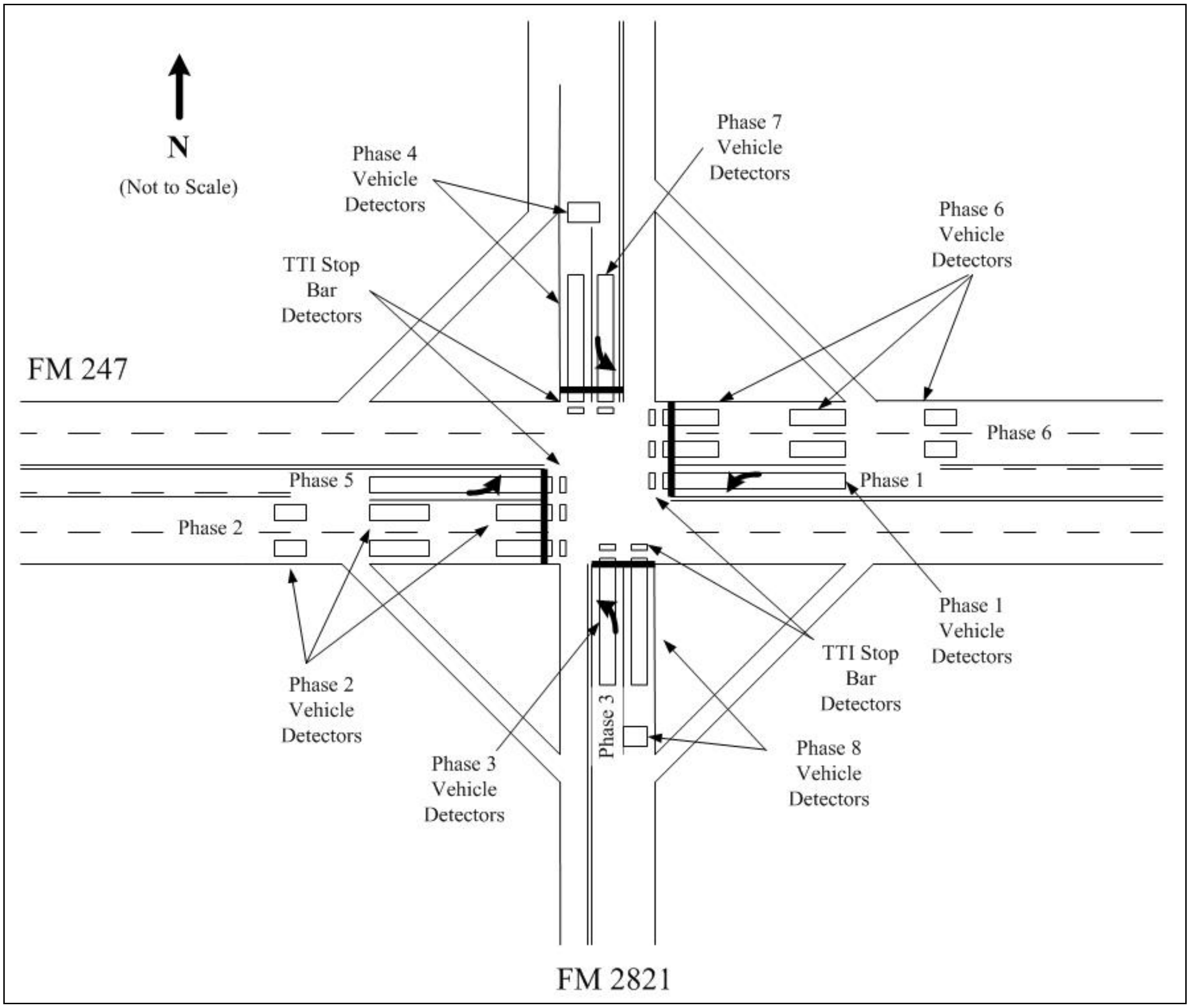


Figure 18. Placement of Detectors at the Intersection FM 247 and FM 2821 in Huntsville, TX.

Accuracy of Performance Measures

As in the previous study, we recorded the video feeds from the VIVD system to evaluate the accuracy of the performance measures. Using the recorded vehicles, we manually produced selected performance measures, such as the Time to Service, Queue Service Time, etc., for an hour-long period selected at random. We then compared observed performance measures to those produced by the TSPMS.

Due to problems with the video feed we were not able to clearly see all of the intersection approaches. Therefore, we could not perform a valid statistical comparison of the performance measures. However, for those phases that we were able to see clearly, the performance measures computed by the TSPMS matched closely with those produced manually. The results of that comparison are shown in Table 40.

Table 27. Average Cycle Time (sec) per Phase by Time of Day for a Typical Day – Huntsville, Texas.

Time Period		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
Hour Beginning	Hour Ending								
0:00:00	0:59:59	1008.5	43.4	NA	42.4	1495.9	42.9	-	43.4
1:00:00	1:59:59	3372.6	42.3	-	42.8	694.8	42.3	698.5	42.8
2:00:00	2:59:59	1090.2	42.4	-	42.9	1818.4	41.5	-	42.4
3:00:00	3:59:59	1204.8	48.1	949.7	48.1	1016.4	48.1	6228.3	18.1
4:00:00	4:59:59	625.2	48.6	1634.5	46.6	314.7	46.6	809.8	46.6
5:00:00	5:59:59	371.5	49.5	924.4	49.0	263.8	49.4	521.6	49.0
6:00:00	6:59:59	136.4	64.8	304.3	66.3	164.1	65.7	145.9	65.1
7:00:00	7:59:59	128.2	84.5	188.2	85.2	134.3	85.4	169.8	85.2
8:00:00	8:59:59	167.83	61.1	295.4	59.9	130.5	60.8	200.2	59.9
9:00:00	9:59:59	170.24	59.1	327.2	59.2	147.0	59.2	267.3	57.3
10:00:00	10:59:59	175.6	55.4	299.1	55.7	190.1	54.7	317.6	55.7
11:00:00	11:59:59	190.9	62.7	234.8	62.4	136.9	62.4	225.8	61.3
12:00:00	12:59:59	174.1	61.8	244.4	61.9	122.0	60.9	244.7	61.9
13:00:00	13:59:59	138.7	66.0	218.6	65.8	120.7	64.6	261.2	65.8
14:00:00	14:59:59	177.0	65.4	225.8	65.6	137.4	65.1	200.4	65.6
15:00:00	15:59:59	98.6	84.0	218.9	84.5	112.5	84.7	136.5	82.6
16:00:00	16:59:59	167.7	73.9	248.1	76.4	102.8	76.8	119.5	74.8
17:00:00	17:59:59	146.5	76.4	294.6	73.7	112.4	73.4	133.6	73.7
18:00:00	18:59:59	223.5	57.0	679.4	56.1	135.6	56.5	264.2	56.1
19:00:00	19:59:59	337.9	55.8	430.8	55.6	150.0	55.6	312.0	55.6
20:00:00	20:59:59	586.7	57.6	357.9	57.7	118.3	58.0	269.5	57.7
21:00:00	21:59:59	418.2	48.2	907.6	48.0	266.9	48.2	395.4	47.4
22:00:00	22:59:59	845.6	15.9	621.9	46.6	297.3	46.3	395.2	46.6
23:00:00	23:59:59	NA	43.2	3419.7	43.2	1611.8	42.2	NA	43.2

Table 28. Average and 85th Percentile Time to Service (sec) per Phase by Time-of-Day for a Typical Day – Huntsville, Texas.

Time Period		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
Hour Beginning	Hour Ending								
0:00:00	0:59:59	0.0 (0.0)	0.02 (0.02)	0.0 (0.0)	0.6 (0.0)	7.8 (13.8)	0.4 (0.0)	0.0 (0.0)	1.5 (0.0)
1:00:00	1:59:59	10.7 (10.7)	0.1 (0.0)	-	0.2 (0.0)	12.0 (14.5)	0.2 (0.0)	0.0 (0.0)	1.0 (0.0)
2:00:00	2:59:59	7.3 (11.4)	0.1 (0.0)	-	0.5 (0.0)	7.2 (7.8)	0.2 (0.0)	-	0.7 (0.0)
3:00:00	3:59:59	11.2 (12.8)	0.8 (0.0)	0.0 (0.0)	0.7 (0.0)	11.6 (15.6)	0.7 (0.0)	6.4 (6.4)	1.3 (0.0)
4:00:00	4:59:59	11.8 (19.8)	0.3 (0.0)	0.0 (0.0)	2.2 (0.0)	21.1 (28.9)	2.3 (2.9)	0.0 (0.0)	2.9 (0.5)
5:00:00	5:59:59	16.6 (27.1)	2.3 (2.6)	2.7 (6.0)	5.2 (15.2)	13.5 (17.4)	4.1 (11.0)	6.5 (15.4)	6.4(22.0)
6:00:00	6:59:59	25.7 (33.4)	13.8 (31.7)	3.9 (6.2)	22.5 (39.0)	23.3 (38.5)	17.3 (32.4)	14.1 (45.3)	18.7 (40.2)
7:00:00	7:59:59	43.7 (79.2)	28.3 (72.6)	34.3 (87.7)	16.1 (49.6)	33.3 (59.4)	31.6 (64.3)	29.7 (74.3)	30.4 (56.8)
8:00:00	8:59:59	20.4 (36.0)	9.4 (23.3)	4.3 (5.7)	16.7 (34.6)	24.2 (33.2)	14.8 (34.4)	6.0 (17.4)	16.4 (32.1)
9:00:00	9:59:59	18.5 (26.7)	8.5 (24.3)	9.4 (26.1)	15.7 (30.6)	21.2 (34.3)	10.4 (24.2)	13.7 (45.0)	12.0 (25.8)
10:00:00	10:59:59	15.4 (19.0)	9.2 (21.5)	4.3 (4.3)	18.0 (35.8)	18.1 (27.1)	7.1 (17.2)	6.6 (9.6)	11.3 (28.4)
11:00:00	11:59:59	23.4 (33.4)	12.1 (30.1)	6.3 (8.8)	15.1 (33.9)	18.6 (27.0)	14.3 (29.1)	13.8 (42.8)	21.1 (40.5)
12:00:00	12:59:59	24.9 (42.9)	11.2 (24.1)	9.8 (27.4)	17.8 (37.7)	21.8 (32.1)	14.7 (31.8)	11.6 (28.6)	17.3 (34.2)
13:00:00	13:59:59	17.9 (27.6)	16.3 (33.2)	2.7 (8.0)	22.1 (40.9)	22.4 (34.9)	15.6 (33.5)	23.9 (59.7)	20.8 (40.8)
14:00:00	14:59:59	25.5 (40.0)	16.9 (36.4)	10.2 (26.7)	16.8 (35.9)	17.0 (32.0)	16.7 (34.0)	15.6 (51.8)	19.8 (43.6)
15:00:00	15:59:59	31.0 (50.9)	33.3 (52.9)	13.1 (34.6)	25.9 (50.2)	33.9 (51.6)	35.6 (54.6)	21.4 (57.9)	31.2 (56.5)
16:00:00	16:59:59	35.7 (73.5)	27.1 (52.3)	4.1 (8.8)	22.4 (41.5)	30.5 (49.7)	25.4 (45.5)	21.0 (55.0)	27.7 (50.4)
17:00:00	17:59:59	27.0 (40.6)	22.5 (45.9)	7.7 (11.1)	19.6 (43.1)	24.5 (44.9)	23.0 (43.7)	19.4 (57.8)	32.1 (45.5)
18:00:00	18:59:59	13.0 (19.9)	9.7 (22.8)	0.0 (0.0)	12.0 (29.7)	18.3 (30.1)	9.8 (19.5)	8.3 (14.3)	14.5 (31.6)
19:00:00	19:59:59	17.9 (24.7)	6.5 (18.6)	0.0 (0.0)	11.6 (31.1)	15.5 (26.8)	7.6 (20.5)	5.3 (3.5)	14.1 (31.2)
20:00:00	20:59:59	14.8 (25.4)	3.8 (11.2)	7.3 (4.9)	7.8 (23.6)	14.7 (23.3)	6.1 (16.0)	3.1 (4.1)	12.8 (30.0)
21:00:00	21:59:59	18.5 (23.9)	2.2 (4.2)	8.9 (19.5)	3.2 (6.3)	14.1 (20.5)	3.1 (12.3)	6.9 (19.9)	5.0 (14.7)
22:00:00	22:59:59	13.1 (13.9)	0.8 (0.0)	0.0 (0.0)	4.7 (14.7)	17.2 (21.1)	1.0 (0.1)	0.8 (0.0)	4.6 (12.4)
23:00:00	23:59:59	NA	0.7 (0.0)	0.0 (0.0)	1.5 (0.0)	6.3 (6.3)	0.4 (0.0)	NA	2.8 (0.0)

Table 29. Average and 85th Percentile Queue Service Time (sec) per Phase by Time-of-Day for a Typical Day – Huntsville, Texas.

Time Period		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
Hour Beginning	Hour Ending								
0:00:00	0:59:59	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.1 (0.0)	2.7 (4.1)	0.2 (0.0)	0.0 (0.0)	0.7 (0.0)
1:00:00	1:59:59	4.5 (4.5)	0.1 (0.0)	-	0.2 (0.0)	5.1 (5.9)	0.2 (0.0)	0.0 (0.0)	0.4 (0.0)
2:00:00	2:59:59	3.8 (6.0)	0.0 (0.0)	-	0.2 (0.0)	3.7 (4.2)	0.2 (0.0)	-	0.4 (0.0)
3:00:00	3:59:59	5.2 (6.1)	0.1 (0.1)	0.0 (0.0)	0.1 (0.0)	3.6 (4.4)	0.2 (0.0)	1.8 (1.8)	0.4 (0.0)
4:00:00	4:59:59	3.7 (5.0)	0.2 (0.0)	0.0 (0.0)	0.8 (0.0)	5.3 (7.1)	0.9 (3.1)	0.0 (0.0)	0.7 (0.3)
5:00:00	5:59:59	4.6 (5.7)	1.2 (3.6)	0.3 (0.6)	1.8 (4.6)	5.1 (6.1)	2.3 (5.3)	3.7 (12.1)	2.9 (6.2)
6:00:00	6:59:59	7.4 (11.2)	4.0 (9.2)	1.9 (4.9)	10.8 (19.3)	6.3 (8.8)	6.3 (10.3)	2.0 (5.2)	7.2 (13.9)
7:00:00	7:59:59	12.3 (24.0)	8.0 (16.0)	4.8 (10.2)	19.0 (38.3)	8.7 (12.4)	9.9 (15.3)	7.7 (17.4)	15.2 (27.3)
8:00:00	8:59:59	6.0 (7.5)	3.7 (7.0)	1.6 (4.2)	7.7 (12.8)	6.4 (7.0)	5.2 (9.5)	2.4 (6.6)	8.5 (16.1)
9:00:00	9:59:59	6.0 (8.7)	3.5 (6.6)	2.2 (5.4)	6.6 (13.0)	6.1 (9.2)	4.8 (8.6)	2.7 (8.0)	6.0 (11.5)
10:00:00	10:59:59	6.0 (9.5)	4.1 (8.0)	0.7 (0.6)	6.6 (10.6)	5.9 (8.2)	3.4 (6.7)	2.7 (6.7)	5.5 (11.1)
11:00:00	11:59:59	6.4 (7.5)	4.4 (8.9)	1.3 (3.4)	7.4 (13.8)	7.6 (10.7)	5.4 (9.9)	3.3 (8.5)	8.6 (14.3)
12:00:00	12:59:59	5.7 (7.7)	3.6 (7.6)	0.4 (0.4)	7.6 (11.5)	8.3 (12.0)	4.7 (8.8)	1.8 (4.3)	9.9 (17.1)
13:00:00	13:59:59	6.0 (7.9)	5.1 (10.5)	2.4 (3.7)	10.1 (18.5)	7.9 (11.0)	5.6 (9.5)	2.7 (4.9)	9.4 (13.7)
14:00:00	14:59:59	6.3 (8.4)	5.8 (10.5)	1.0 (3.6)	11.2 (18.5)	6.1 (8.5)	5.0 (10.0)	3.8 (6.2)	10.6 (18.1)
15:00:00	15:59:59	8.6 (12.1)	7.6 (11.8)	2.6 (6.1)	18.1 (30.5)	8.1 (12.4)	10.1 (14.3)	3.6 (7.0)	17.1 (25.4)
16:00:00	16:59:59	6.6 (9.5)	8.0 (13.3)	2.9 (6.8)	15.2 (24.5)	10.2 (14.0)	7.3 (12.5)	2.5 (5.0)	12.0 (20.0)
17:00:00	17:59:59	7.6 (12.3)	6.3 (10.0)	1.9 (5.3)	11.9 (22.7)	9.0 (13.5)	6.9 (12.1)	1.9 (5.0)	14.3 (21.1)
18:00:00	18:59:59	5.2 (7.5)	3.8 (6.8)	0.0 (0.0)	6.7 (12.6)	6.6 (8.8)	3.5 (6.5)	0.9 (0.2)	6.8 (12.6)
19:00:00	19:59:59	5.3 (7.7)	2.1 (4.7)	0.1 (0.0)	5.3 (11.7)	5.6 (8.0)	3.8 (5.5)	1.1 (1.9)	6.7 (14.2)
20:00:00	20:59:59	5.5 (7.5)	1.8 (4.1)	1.8 (5.6)	3.2 (7.5)	6.4 (9.8)	2.0 (4.4)	0.9 (2.4)	5.7 (10.7)
21:00:00	21:59:59	4.6 (5.4)	0.7 (3.1)	3.3 (7.3)	1.5 (5.0)	5.2 (6.6)	1.2 (3.8)	3.8 (5.0)	2.7 (7.2)
22:00:00	22:59:59	3.8 (4.3)	0.5 (0.0)	0.0 (0.0)	1.6 (4.8)	4.1 (5.1)	0.5 (0.7)	1.7 (0.0)	1.7 (4.9)
23:00:00	23:59:59	NA	0.3 (0.0)	0.0 (0.0)	0.7 (0.0)	4.5 (4.5)	0.2 (0.0)	NA	0.9 (3.6)

Table 30. Average Interval Duration (sec) for Phase 1 through Phase 4 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 1				Phase 2				Phase 3				Phase 4			
Hour Beginning	Hour Ending	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red
0:00:00	0:59:59	5.9	4.0	1.0	761.3	20.6	4.0	2.0	16.8	5.0	4.0	1.0	NA	10.4	4.0	2.0	27.0
1:00:00	1:59:59	6.5	4.0	1.0	3361.3	20.3	4.0	2.0	16.1	-	-	-	-	10.4	4.0	2.0	26.4
2:00:00	2:59:59	6.5	4.0	1.0	1078.7	20.4	4.0	2.0	16.2	-	-	-	-	10.0	4.0	2.0	26.9
3:00:00	3:59:59	7.2	4.0	1.0	1192.6	20.7	4.0	2.0	21.5	17.9	4.0	1.0	956.8	10.3	4.0	2.0	31.9
4:00:00	4:59:59	6.2	4.0	1.0	614.0	22.3	4.0	2.0	18.2	5.0	4.0	1.0	1624.5	11.0	4.0	2.0	29.7
5:00:00	5:59:59	6.9	4.0	1.0	359.7	23.0	4.0	2.0	20.4	10.2	4.0	1.0	909.2	12.0	4.0	2.0	31.4
6:00:00	6:59:59	9.7	4.0	1.0	121.8	25.7	4.0	2.0	34.3	8.0	4.0	1.0	291.3	18.9	4.0	2.0	41.6
7:00:00	7:59:59	13.6	4.0	1.0	109.5	28.5	4.0	2.0	49.7	12.4	4.0	1.0	170.8	25.6	4.0	2.0	52.9
8:00:00	8:59:59	8.2	4.0	1.0	154.7	24.7	4.0	2.0	30.2	9.6	4.0	1.0	280.8	16.3	4.0	2.0	1054.8
9:00:00	9:59:59	8.0	4.0	1.0	157.3	25.3	4.0	2.0	27.4	8.1	4.0	1.0	314.2	14.4	4.0	2.0	38.7
10:00:00	10:59:59	8.3	4.0	1.0	162.3	24.0	4.0	2.0	25.6	8.9	4.0	1.0	285.1	13.2	4.0	2.0	36.4
11:00:00	11:59:59	8.6	4.0	1.0	177.3	26.4	4.0	2.0	30.1	9.3	4.0	1.0	220.5	14.8	4.0	2.0	41.3
12:00:00	12:59:59	7.9	4.0	1.0	161.2	27.1	4.0	2.0	29.0	8.6	4.0	1.0	230.8	14.9	4.0	2.0	41.3
13:00:00	13:59:59	8.5	4.0	1.0	125.2	26.8	4.0	2.0	33.1	8.1	4.0	1.0	205.5	16.2	4.0	2.0	43.4
14:00:00	14:59:59	8.6	4.0	1.0	163.4	25.9	4.0	2.0	34.0	10.0	4.0	1.0	210.7	18.5	4.0	2.0	41.4
15:00:00	15:59:59	11.1	4.0	1.0	82.5	26.2	4.0	2.0	51.7	11.0	4.0	1.0	202.8	25.9	4.0	2.0	52.4
16:00:00	16:59:59	9.2	4.0	1.0	153.6	30.6	4.0	2.0	40.7	9.3	4.0	1.0	233.8	23.6	4.0	2.0	47.5
17:00:00	17:59:59	10.0	4.0	1.0	131.5	26.7	4.0	2.0	40.3	11.8	4.0	1.0	277.8	22.7	4.0	2.0	44.4
18:00:00	18:59:59	8.1	4.0	1.0	210.5	25.2	4.0	2.0	25.4	7.0	4.0	1.0	667.5	15.2	4.0	2.0	2039.8
19:00:00	19:59:59	7.3	4.0	1.0	325.6	26.4	4.0	2.0	23.5	7.3	4.0	1.0	418.6	13.9	4.0	2.0	35.9
20:00:00	20:59:59	8.3	4.0	1.0	573.4	26.8	4.0	2.0	24.4	6.4	4.0	1.0	346.5	15.2	4.0	2.0	35.9
21:00:00	21:59:59	6.5	4.0	1.0	406.4	22.3	4.0	2.0	20.2	7.6	4.0	1.0	895.0	12.0	4.0	2.0	30.3
22:00:00	22:59:59	5.9	4.0	1.0	731.8	21.7	4.0	2.0	18.1	6.2	4.0	1.0	910.7	12.0	4.0	2.0	28.3
23:00:00	23:59:59	0.0	0.0	0.0	NA	20.4	4.0	2.0	16.9	20.0	4.0	1.0	3394.7	10.3	4.0	2.0	26.9

Table 31. Average Interval Duration (sec) for Phase 5 through Phase 8 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 5				Phase 6				Phase 7				Phase 8			
Hour Beginning	Hour Ending	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red
0:00:00	0:59:59	6.1	4.0	1.0	1484.9	20.3	4.0	2.0	16.6	5.0	4.0	1.0	NA	10.4	4.0	2.0	27.0
1:00:00	1:59:59	7.1	4.0	1.0	682.8	20.0	4.0	2.0	16.3	5.0	4.0	1.0	688.3	10.0	4.0	2.0	26.8
2:00:00	2:59:59	5.7	4.0	1.0	1807.7	20.2	4.0	2.0	15.3	-	-	-	-	10.0	4.0	2.0	26.4
3:00:00	3:59:59	5.7	4.0	1.0	1005.6	20.7	4.0	2.0	21.3	5.0	4.0	1.0	6218.3	14.6	4.0	2.0	27.5
4:00:00	4:59:59	7.2	4.0	1.0	302.5	21.1	4.0	2.0	19.5	6.5	4.0	1.0	798.2	10.5	4.0	2.0	30.1
5:00:00	5:59:59	7.1	4.0	1.0	251.7	22.7	4.0	2.0	20.7	7.6	4.0	1.0	509.0	11.3	4.0	2.0	31.6
6:00:00	6:59:59	8.8	4.0	1.0	150.3	26.5	4.0	2.0	33.2	10.0	4.0	1.0	130.9	14.8	4.0	2.0	44.3
7:00:00	7:59:59	11.0	4.0	1.0	118.3	30.2	4.0	2.0	49.2	16.3	4.0	1.0	148.6	21.1	4.0	2.0	58.1
8:00:00	8:59:59	8.4	4.0	1.0	117.1	23.1	4.0	2.0	31.7	9.2	4.0	1.0	186.0	15.1	4.0	2.0	38.9
9:00:00	9:59:59	8.8	4.0	1.0	133.2	24.4	4.0	2.0	28.8	9.8	4.0	1.0	252.5	13.9	4.0	2.0	37.4
10:00:00	10:59:59	8.6	4.0	1.0	176.5	23.8	4.0	2.0	24.9	8.8	4.0	1.0	303.9	13.2	4.0	2.0	36.4
11:00:00	11:59:59	10.4	4.0	1.0	121.5	24.4	4.0	2.0	32.0	7.7	4.0	1.0	213.2	15.3	4.0	2.0	40.0
12:00:00	12:59:59	11.1	4.0	1.0	105.9	23.3	4.0	2.0	31.6	7.7	4.0	1.0	232.0	16.1	4.0	2.0	39.7
13:00:00	13:59:59	10.2	4.0	1.0	105.5	25.3	4.0	2.0	33.3	9.3	4.0	1.0	246.9	15.8	4.0	2.0	44.0
14:00:00	14:59:59	8.5	4.0	1.0	123.8	25.2	4.0	2.0	33.9	8.7	4.0	1.0	186.7	17.3	4.0	2.0	42.3
15:00:00	15:59:59	10.6	4.0	1.0	96.9	28.0	4.0	2.0	50.7	10.4	4.0	1.0	121.0	23.3	4.0	2.0	53.3
16:00:00	16:59:59	12.2	4.0	1.0	85.5	24.2	4.0	2.0	46.6	9.3	4.0	1.0	105.2	18.4	4.0	2.0	50.4
17:00:00	17:59:59	11.2	4.0	1.0	96.2	23.5	4.0	2.0	43.8	8.3	4.0	1.0	120.3	19.8	4.0	2.0	47.9
18:00:00	18:59:59	9.2	4.0	1.0	121.4	23.4	4.0	2.0	27.1	5.9	4.0	1.0	253.3	13.5	4.0	2.0	36.6
19:00:00	19:59:59	7.9	4.0	1.0	167.1	24.0	4.0	2.0	25.6	5.9	4.0	1.0	301.2	13.7	4.0	2.0	36.0
20:00:00	20:59:59	9.3	4.0	1.0	104.0	22.0	4.0	2.0	30.0	8.4	4.0	1.0	256.2	14.0	4.0	2.0	37.7
21:00:00	21:59:59	7.4	4.0	1.0	254.5	21.2	4.0	2.0	21.0	7.3	4.0	1.0	383.1	11.5	4.0	2.0	29.9
22:00:00	22:59:59	6.5	4.0	1.0	285.8	20.7	4.0	2.0	19.6	6.4	4.0	1.0	383.6	10.6	4.0	2.0	30.0
23:00:00	23:59:59	6.4	4.0	1.0	1600.4	20.0	4.0	2.0	16.2	-	-	-	-	10.7	4.0	2.0	26.5

Table 32. Average Number of Vehicles Entering per Phase for Phase 1 through Phase 4 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 1				Phase 2				Phase 3				Phase 4			
Hour Beginning	Hour Ending	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red
0:00:00	0:59:59	0.5	0.00	0.00	4.50	0.41	0.00	0.00	0.04	0.00	0.00	0.00	0.04	0.07	0.01	0.00	0.12
1:00:00	1:59:59	2.00	0.00	0.00	4.00	0.12	0.00	0.00	0.04	-	-	-	-	0.05	0.00	0.00	0.12
2:00:00	2:59:59	1.25	0.00	0.00	3.50	0.15	0.01	0.00	0.06	-	-	-	-	0.06	0.01	0.00	0.20
3:00:00	3:59:59	1.25	0.00	0.00	4.50	0.11	0.05	0.01	0.11	0.00	0.00	0.00	0.93	0.22	0.01	0.00	0.28
4:00:00	4:59:59	0.83	0.00	0.00	2.83	0.42	0.01	0.00	0.12	0.00	0.00	0.00	30.67	0.36	0.04	0.00	0.55
5:00:00	5:59:59	1.20	0.00	0.00	3.60	1.14	0.01	0.03	0.33	0.50	0.00	0.00	11.75	0.65	0.01	0.01	1.10
6:00:00	6:59:59	2.42	0.00	0.00	3.81	3.91	0.07	0.00	0.27	1.33	0.00	0.00	11.58	2.62	0.07	0.06	2.09
7:00:00	7:59:59	5.35	0.01	0.07	7.11	9.44	0.26	0.00	3.98	1.60	0.07	0.00	16.20	5.88	0.33	0.07	3.74
8:00:00	8:59:59	1.67	0.29	0.00	3.71	2.53	0.05	0.03	1.63	0.69	0.00	0.00	13.31	2.43	0.15	0.02	1.63
9:00:00	9:59:59	1.77	0.00	0.00	3.59	2.90	0.10	0.02	0.21	0.33	0.17	0.00	12.42	1.51	0.05	0.03	1.66
10:00:00	10:59:59	1.56	0.00	0.06	3.11	2.69	0.09	0.05	0.22	0.50	0.00	0.00	10.08	1.46	0.17	0.02	1.42
11:00:00	11:59:59	1.86	0.05	0.00	3.90	3.68	0.04	0.07	0.26	0.63	0.06	0.00	9.75	1.47	0.07	0.00	2.12
12:00:00	12:59:59	1.55	0.05	0.00	2.60	3.56	0.19	0.07	0.17	0.40	0.00	0.00	9.47	2.03	0.03	0.05	1.83
13:00:00	13:59:59	1.73	0.08	0.00	2.81	4.70	0.15	0.07	0.28	0.38	0.00	0.00	10.19	1.84	0.07	0.02	2.24
14:00:00	14:59:59	1.86	0.10	0.00	3.90	5.33	0.09	0.05	0.20	0.53	0.00	0.00	15.07	2.44	0.16	0.02	1.78
15:00:00	15:59:59	2.78	0.11	0.03	2.86	7.09	0.14	0.00	0.40	1.65	0.12	0.00	16.76	3.74	0.07	0.00	3.62
16:00:00	16:59:59	1.73	0.05	0.00	4.23	7.48	0.17	0.09	0.15	0.71	0.07	0.00	14.71	2.68	0.09	0.00	2.72
17:00:00	17:59:59	2.22	0.13	0.00	3.43	5.90	0.12	0.06	0.16	0.92	0.00	0.00	14.38	2.02	0.04	0.04	2.14
18:00:00	18:59:59	1.24	0.06	0.00	2.18	3.24	0.06	0.02	0.29	0.00	0.00	0.00	32.00	1.34	0.05	0.00	1.18
19:00:00	19:59:59	1.22	0.00	0.00	2.33	2.32	0.08	0.03	0.11	0.00	0.11	0.00	11.33	1.05	0.06	0.02	0.78
20:00:00	20:59:59	1.29	0.00	0.00	5.29	2.11	0.10	0.08	0.18	0.44	0.33	0.00	13.67	0.81	0.05	0.00	1.25
21:00:00	21:59:59	1.13	0.00	0.00	3.00	1.04	0.04	0.03	0.28	0.00	0.00	0.00	15.25	0.51	0.03	0.00	0.62
22:00:00	22:59:59	1.00	0.00	0.00	3.33	0.67	0.00	0.03	0.09	0.00	0.00	0.00	22.00	0.44	0.03	0.00	0.44
23:00:00	23:59:59	NA	NA	NA	-	0.48	0.00	0.02	0.09	0.00	0.00	0.00	9.00	0.19	0.01	0.01	0.20

Table 33. Average Number of Vehicles Entering per Phase for Phase 5 through Phase 6 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 5				Phase 6				Phase 7				Phase 8			
Hour Beginning	Hour Ending	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red
0:00:00	0:59:59	0.67	0.00	0.00	4.33	0.25	0.00	0.00	0.13	0.0	0.00	0.00	3.00	0.17	0.01	0.00	0.22
1:00:00	1:59:59	1.50	0.00	0.00	3.50	0.15	0.00	0.00	0.04	0.0	0.00	0.00	13.33	0.06	0.00	0.00	0.12
2:00:00	2:59:59	0.50	0.00	0.00	4.00	0.36	0.01	0.00	0.08	-	-	-	-	0.12	0.01	0.00	0.11
3:00:00	3:59:59	0.50	0.00	0.00	2.25	0.41	0.00	0.00	0.12	0.00	0.00	0.00	35.00	0.14	0.00	0.00	0.12
4:00:00	4:59:59	1.46	0.00	0.00	3.15	0.78	0.03	0.04	0.29	0.43	0.00	0.00	11.00	0.24	0.01	0.00	0.26
5:00:00	5:59:59	1.17	0.17	0.00	2.67	2.16	0.01	0.08	0.44	0.25	0.00	0.00	18.75	0.43	0.01	0.00	0.76
6:00:00	6:59:59	1.83	0.04	0.00	3.13	4.94	0.06	0.00	1.09	1.28	0.00	0.00	8.80	1.11	0.00	0.00	1.89
7:00:00	7:59:59	2.18	0.04	0.00	4.46	9.07	0.37	0.09	1.35	3.24	0.29	0.00	13.76	2.74	0.05	0.05	3.86
8:00:00	8:59:59	1.41	0.07	0.00	3.48	3.42	0.15	0.05	1.17	0.67	0.06	0.00	8.61	1.35	0.12	0.02	1.12
9:00:00	9:59:59	1.44	0.04	0.00	2.92	3.23	0.11	0.07	0.53	0.58	0.00	0.00	13.83	1.02	0.05	0.03	1.19
10:00:00	10:59:59	1.42	0.05	0.05	4.11	2.80	0.02	0.08	0.79	0.83	0.00	0.00	11.50	0.99	0.06	0.00	1.31
11:00:00	11:59:59	2.15	0.04	0.00	3.73	4.26	0.05	0.07	1.00	0.81	0.19	0.00	12.19	1.83	0.05	0.00	1.64
12:00:00	12:59:59	2.30	0.03	0.00	3.07	3.71	0.10	0.07	0.86	0.55	0.00	0.00	17.00	1.76	0.09	0.02	1.64
13:00:00	13:59:59	2.14	0.03	0.03	2.24	4.30	0.05	0.13	1.04	0.82	0.00	0.00	10.47	2.18	0.07	0.00	1.82
14:00:00	14:59:59	1.92	0.00	0.04	3.31	3.45	0.11	0.04	1.24	1.05	0.11	0.00	10.53	2.26	0.07	0.04	2.64
15:00:00	15:59:59	2.30	0.03	0.00	2.64	7.70	0.26	0.21	2.09	1.04	0.08	0.00	8.50	4.12	0.09	0.02	3.47
16:00:00	16:59:59	3.20	0.11	0.06	3.06	5.32	0.11	0.04	2.36	0.67	0.03	0.00	6.20	3.83	0.17	0.02	3.17
17:00:00	17:59:59	2.78	0.09	0.03	2.78	5.06	0.02	0.02	3.00	0.89	0.00	0.04	7.35	4.38	0.04	0.00	2.59
18:00:00	18:59:59	2.08	0.00	0.00	3.75	2.30	0.13	0.05	1.10	0.29	0.00	0.00	10.29	2.00	0.06	0.05	1.31
19:00:00	19:59:59	1.64	0.05	0.00	2.59	1.48	0.08	0.05	0.50	0.25	0.00	0.00	9.58	1.59	0.05	0.02	0.84
20:00:00	20:59:59	2.31	0.21	0.00	2.48	1.48	0.02	0.03	0.94	0.39	0.00	0.00	7.46	1.59	0.08	0.05	0.94
21:00:00	21:59:59	1.14	0.07	0.00	3.14	0.84	0.03	0.01	0.55	0.00	0.14	0.00	10.14	0.77	0.03	0.00	0.64
22:00:00	22:59:59	1.00	0.00	0.00	3.30	0.38	0.03	0.01	0.24	0.00	0.00	0.00	5.11	0.53	0.01	0.00	0.47
23:00:00	23:59:59	1.00	0.00	0.00	7.00	0.20	0.00	0.0	0.12	-	-	-	-	0.35	0.02	0.01	0.29

Table 34. Total Number of Vehicles Entering per Phase for Phase 1 through Phase 4 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 1				Phase 2				Phase 3				Phase 4			
Hour Beginning	**Hour Ending**	**Green**	**Yellow**	**All-Red**	**Red**	**Green**	**Yellow**	**All-Red**	**Red**	**Green**	**Yellow**	**All-Red**	**Red**	**Green**	**Yellow**	**All-Red**	**Red**
0:00:00	0:59:59	1	0	0	9	34	0	0	3	0	0	0	58	6	1	0	10
1:00:00	1:59:59	2	0	0	4	10	0	0	3	-	-	-	-	4	0	0	10
2:00:00	2:59:59	5	0	0	14	13	1	0	5	-	-	-	-	5	1	0	17
3:00:00	3:59:59	5	0	0	18	8	4	1	8	0	0	0	13	16	1	0	21
4:00:00	4:59:59	5	0	0	17	32	1	0	9	0	0	0	92	28	3	0	43
5:00:00	5:59:59	12	2	0	36	83	1	2	24	2	0	0	47	47	1	1	79
6:00:00	6:59:59	63	1	0	99	215	4	0	15	16	0	0	139	144	4	3	115
7:00:00	7:59:59	150	17	2	149	406	11	0	171	24	0	0	243	247	14	3	157
8:00:00	8:59:59	35	6	0	78	149	3	2	96	9	0	0	173	146	9	1	98
9:00:00	9:59:59	39	0	0	79	177	6	1	13	4	2	0	149	92	3	2	101
10:00:00	10:59:59	28	0	1	56	175	6	3	14	6	0	0	121	95	11	1	92
11:00:00	11:59:59	39	1	0	82	210	2	4	15	10	1	0	156	85	4	0	123
12:00:00	12:59:59	31	1	0	52	210	11	4	10	6	0	0	142	118	2	3	106
13:00:00	13:59:59	45	2	0	73	254	8	4	15	6	0	0	163	101	4	1	123
14:00:00	14:59:59	39	2	1	82	293	5	3	11	8	0	0	226	134	9	1	98
15:00:00	15:59:59	100	4	0	103	305	6	0	17	28	2	0	285	157	3	0	152
16:00:00	16:59:59	38	1	0	93	344	8	4	7	10	1	0	206	126	4	0	128
17:00:00	17:59:59	51	3	0	79	295	6	3	8	12	0	0	187	99	2	2	105
18:00:00	18:59:59	21	1	0	37	204	4	1	18	0	0	0	115	87	3	0	77
19:00:00	19:59:59	11	0	0	21	151	5	2	7	0	1	0	102	67	4	1	50
20:00:00	20:59:59	9	0	0	37	131	6	5	11	4	3	0	123	51	3	0	79
21:00:00	21:59:59	9	0	0	24	78	3	2	21	0	0	0	61	38	2	0	46
22:00:00	22:59:59	3	0	0	10	53	0	2	7	0	0	0	22	34	2	0	34
23:00:00	23:59:59	NA	NA	NA	NA	39	0	2	7	0	0	0	9	16	1	1	17

Table 35. Total Number of Vehicles Entering per Phase for Phase 5 through Phase 8 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 5				Phase 6				Phase 7				Phase 8			
Hour Beginning	Hour Ending	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red	Green	Yellow	All-Red	Red
0:00:00	0:59:59	2	0	0	13	21	0	0	11	0	0	0	3	14	1	0	18
1:00:00	1:59:59	3	0	0	7	13	0	0	3	0	0	0	40	5	0	0	10
2:00:00	2:59:59	1	0	0	8	31	1	0	7	-	-	-	-	10	1	0	9
3:00:00	3:59:59	2	0	0	9	31	0	0	9	0	0	0	35	10	0	0	9
4:00:00	4:59:59	19	0	0	41	60	2	3	22	3	0	0	77	19	1	0	20
5:00:00	5:59:59	14	2	0	32	158	1	6	32	2	0	0	150	31	1	0	55
6:00:00	6:59:59	44	1	0	75	267	3	0	59	32	0	0	220	62	0	0	106
7:00:00	7:59:59	61	1	0	125	390	16	4	58	68	6	6	289	115	2	2	162
8:00:00	8:59:59	38	2	0	94	202	9	3	69	12	1	1	155	81	7	1	67
9:00:00	9:59:59	36	1	0	73	197	7	4	32	7	0	0	166	64	3	2	75
10:00:00	10:59:59	27	1	1	78	185	1	5	52	10	0	0	138	64	4	0	85
11:00:00	11:59:59	56	1	0	97	243	3	4	57	13	3	3	195	108	3	0	97
12:00:00	12:59:59	69	1	0	92	219	6	4	51	6	0	0	187	102	5	1	95
13:00:00	13:59:59	62	1	1	65	241	3	7	58	14	0	0	178	120	4	0	100
14:00:00	14:59:59	50	0	1	86	190	6	2	68	20	2	2	200	124	4	2	145
15:00:00	15:59:59	76	1	0	87	331	11	9	90	27	2	2	221	177	4	1	149
16:00:00	16:59:59	112	4	2	107	250	5	2	111	20	1	1	186	184	8	1	152
17:00:00	17:59:59	89	3	1	89	248	1	1	147	23	0	0	191	214	2	0	127
18:00:00	18:59:59	50	0	0	90	145	8	3	69	4	0	0	144	130	4	3	85
19:00:00	19:59:59	36	1	0	57	95	5	3	32	3	0	0	115	102	3	1	54
20:00:00	20:59:59	67	6	0	72	93	1	2	59	5	0	0	97	100	5	3	59
21:00:00	21:59:59	16	1	0	44	63	2	1	41	0	1	1	71	40	2	0	36
22:00:00	22:59:59	10	0	0	33	30	2	1	19	0	0	0	46	41	1	0	37
23:00:00	23:59:59	1	0	0	7	17	0	0	10	-	-	-	-	29	2	1	20

Table 36. Number of Cycles and Violation Rate of Vehicles Entering on Yellow for Phases 1 through 4 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 1			Phase 2			Phase 3			Phase 4		
Hour Beginning	Hour Ending	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate
0:00:00	0:59:59	2	0	0.000	83	0	0.000	1	0	0.000	83	1	0.012
1:00:00	1:59:59	1	0	0.000	85	0	0.000	-	-	-	84	0	0.000
2:00:00	2:59:59	4	0	0.000	85	1	0.012	-	-	-	84	1	0.012
3:00:00	3:59:59	4	0	0.000	75	3	0.040	14	0	0.000	74	1	0.014
4:00:00	4:59:59	6	0	0.000	77	1	0.013	3	0	0.000	78	3	0.039
5:00:00	5:59:59	10	0	0.000	73	1	0.014	4	0	0.000	72	1	0.014
6:00:00	6:59:59	26	0	0.000	55	3	0.055	12	0	0.000	55	4	0.073
7:00:00	7:59:59	28	10	0.357	43	8	0.186	15	1	0.067	42	13	0.310
8:00:00	8:59:59	21	4	0.191	59	2	0.034	13	0	0.000	60	9	0.150
9:00:00	9:59:59	22	0	0.000	61	3	0.049	12	2	0.167	61	3	0.049
10:00:00	10:59:59	18	0	0.000	65	6	0.092	12	0	0.000	65	10	0.154
11:00:00	11:59:59	21	1	0.048	57	2	0.035	16	1	0.063	58	4	0.069
12:00:00	12:59:59	20	1	0.050	59	9	0.153	15	0	0.000	58	2	0.035
13:00:00	13:59:59	26	2	0.077	54	6	0.111	16	0	0.000	54	4	0.074
14:00:00	14:59:59	21	2	0.095	55	5	0.091	15	0	0.000	55	8	0.146
15:00:00	15:59:59	36	3	0.083	43	5	0.116	17	2	0.118	42	3	0.071
16:00:00	16:59:59	22	1	0.046	46	8	0.174	14	1	0.071	47	4	0.085
17:00:00	17:59:59	23	3	0.130	50	6	0.120	13	0	0.000	49	1	0.020
18:00:00	18:59:59	17	1	0.059	63	3	0.048	5	0	0.000	65	3	0.046
19:00:00	19:59:59	9	0	0.000	65	5	0.077	9	1	0.111	64	4	0.063
20:00:00	20:59:59	7	0	0.000	62	3	0.048	9	2	0.222	55	3	0.055
21:00:00	21:59:59	8	0	0.000	75	2	0.027	4	0	0.000	74	2	0.027
22:00:00	22:59:59	3	0	0.000	79	0	0.000	1	0	0.000	78	8	0.103
23:00:00	23:59:59	-	-	-	82	0	0.000	1	0	0.000	83	1	0.012

Table 37. Number of Cycles and Violation Rate of Vehicles Entering on Yellow for Phases 5 through 8 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 5			Phase 6			Phase 7			Phase 8		
Hour Beginning	Hour Ending	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate
0:00:00	0:59:59	3	0	0.000	84	0	0.000	1	0	0.000	83	1	0.012
1:00:00	1:59:59	2	0	0.000	85	0	0.000	3	0	0.000	84	0	0.000
2:00:00	2:59:59	2	0	0.000	87	1	0.012	-	-	-	85	1	0.012
3:00:00	3:59:59	4	0	0.000	75	0	0.000	1	0	0.000	74	0	0.000
4:00:00	4:59:59	13	0	0.000	77	2	0.026	7	0	0.000	78	1	0.013
5:00:00	5:59:59	12	2	0.167	73	1	0.014	8	0	0.000	72	1	0.014
6:00:00	6:59:59	24	1	0.042	54	3	0.056	25	0	0.000	56	0	0.000
7:00:00	7:59:59	28	1	0.036	43	14	0.326	21	4	0.191	42	1	0.024
8:00:00	8:59:59	27	2	0.074	59	8	0.136	18	1	0.056	60	5	0.083
9:00:00	9:59:59	25	1	0.040	61	7	0.115	12	0	0.000	63	3	0.048
10:00:00	10:59:59	19	1	0.053	66	1	0.015	12	0	0.000	65	4	0.062
11:00:00	11:59:59	26	1	0.039	57	3	0.053	16	3	0.188	59	3	0.051
12:00:00	12:59:59	30	1	0.033	59	4	0.068	11	0	0.000	58	5	0.086
13:00:00	13:59:59	29	1	0.035	56	3	0.054	17	0	0.000	55	4	0.073
14:00:00	14:59:59	26	0	0.000	55	6	0.109	19	2	0.105	55	3	0.055
15:00:00	15:59:59	33	1	0.030	43	8	0.186	26	2	0.077	43	4	0.093
16:00:00	16:59:59	35	4	0.114	47	5	0.106	30	1	0.033	48	6	0.125
17:00:00	17:59:59	32	2	0.063	49	1	0.020	26	0	0.000	49	2	0.041
18:00:00	18:59:59	24	0	0.000	63	8	0.127	14	0	0.000	65	4	0.062
19:00:00	19:59:59	22	1	0.046	64	5	0.078	12	0	0.000	64	3	0.047
20:00:00	20:59:59	29	5	0.172	63	1	0.016	13	0	0.000	63	4	0.064
21:00:00	21:59:59	14	1	0.071	75	2	0.027	7	1	0.143	75	2	0.027
22:00:00	22:59:59	10	0	0.000	78	2	0.026	9	0	0.000	78	1	0.013
23:00:00	23:59:59	1	0	0.000	84	0	0.000	-	-	-	83	2	0.024

Table 38. Number of Cycles and Violation Rate of Vehicles Entering on All-Red for Phases 1 through 4 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 1			Phase 2			Phase 3			Phase 4		
Hour Beginning	Hour Ending	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate
0:00:00	0:59:59	2	0	0.000	83	0	0.000	1	0	0.000	83	0	0.000
1:00:00	1:59:59	1	0	0.000	85	0	0.000	-	0	0.000	84	0	0.000
2:00:00	2:59:59	4	0	0.000	85	0	0.000	-	0	0.000	84	0	0.000
3:00:00	3:59:59	4	0	0.000	75	1	0.013	14	0	0.000	74	0	0.000
4:00:00	4:59:59	6	0	0.000	77	0	0.000	3	0	0.000	78	0	0.000
5:00:00	5:59:59	10	0	0.000	73	2	0.027	4	0	0.000	72	1	0.014
6:00:00	6:59:59	26	0	0.000	55	0	0.000	12	0	0.000	55	3	0.055
7:00:00	7:59:59	28	2	0.071	43	0	0.000	15	0	0.000	42	3	0.071
8:00:00	8:59:59	21	0	0.000	59	2	0.034	13	0	0.000	60	1	0.017
9:00:00	9:59:59	22	1	0.056	61	1	0.016	12	0	0.000	61	2	0.033
10:00:00	10:59:59	18	0	0.000	65	3	0.046	12	0	0.000	65	1	0.015
11:00:00	11:59:59	21	0	0.000	57	3	0.053	16	0	0.000	58	0	0.000
12:00:00	12:59:59	20	0	0.000	59	3	0.051	15	0	0.000	58	3	0.052
13:00:00	13:59:59	26	0	0.000	54	3	0.056	16	0	0.000	54	1	0.019
14:00:00	14:59:59	21	0	0.000	55	3	0.055	15	0	0.000	55	1	0.018
15:00:00	15:59:59	36	1	0.028	43	0	0.000	17	0	0.000	42	0	0.000
16:00:00	16:59:59	22	0	0.000	46	4	0.087	14	0	0.000	47	0	0.000
17:00:00	17:59:59	23	0	0.000	50	3	0.060	13	0	0.000	49	2	0.041
18:00:00	18:59:59	17	0	0.000	63	1	0.016	5	0	0.000	65	0	0.000
19:00:00	19:59:59	9	0	0.000	65	2	0.031	9	0	0.000	64	1	0.016
20:00:00	20:59:59	7	0	0.000	62	4	0.065	9	0	0.000	55	0	0.000
21:00:00	21:59:59	8	0	0.000	75	1	0.013	4	0	0.000	74	0	0.000
22:00:00	22:59:59	3	0	0.000	79	1	0.013	1	0	0.000	78	0	0.000
23:00:00	23:59:59	-	-	-	82	2	0.024	1	0	0.000	83	1	0.012

Table 39. Number of Cycles and Violation Rate of Vehicles Entering on All-Red for Phases 5 through 8 by Time-of-Day – Huntsville, Texas.

Time Period		Phase 5			Phase 6			Phase 7			Phase 8		
Hour Beginning	Hour Ending	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate	# of Total Cycles	# of Cycles	Violation Rate
0:00:00	0:59:59	2	0	0.000	84	0	0.000	1	0	0.000	83	0	0.000
1:00:00	1:59:59	1	0	0.000	85	0	0.000	3	0	0.000	84	0	0.000
2:00:00	2:59:59	4	0	0.000	87	0	0.000	-	-	-	85	0	0.000
3:00:00	3:59:59	4	0	0.000	75	0	0.000	1	0	0.000	74	0	0.000
4:00:00	4:59:59	6	0	0.000	77	3	0.039	7	0	0.000	78	0	0.000
5:00:00	5:59:59	10	0	0.000	73	3	0.041	8	0	0.000	72	0	0.000
6:00:00	6:59:59	26	0	0.000	54	0	0.000	25	0	0.000	56	0	0.000
7:00:00	7:59:59	28	0	0.000	43	4	0.093	21	0	0.000	42	2	0.048
8:00:00	8:59:59	21	0	0.000	59	3	0.051	18	0	0.000	60	1	0.017
9:00:00	9:59:59	22	0	0.000	61	3	0.049	12	0	0.000	63	2	0.032
10:00:00	10:59:59	18	1	0.053	66	5	0.076	12	0	0.000	65	0	0.000
11:00:00	11:59:59	21	0	0.000	57	2	0.035	16	0	0.000	59	0	0.000
12:00:00	12:59:59	20	0	0.000	59	2	0.034	11	0	0.000	58	1	0.017
13:00:00	13:59:59	26	1	0.035	56	5	0.089	17	0	0.000	55	0	0.000
14:00:00	14:59:59	21	1	0.039	55	2	0.036	19	0	0.000	55	2	0.036
15:00:00	15:59:59	36	0	0.000	43	8	0.186	26	0	0.000	43	1	0.023
16:00:00	16:59:59	22	2	0.057	47	2	0.043	30	0	0.000	48	1	0.021
17:00:00	17:59:59	23	1	0.031	49	1	0.020	26	1	0.038	49	0	0.000
18:00:00	18:59:59	17	0	0.000	63	3	0.048	14	0	0.000	65	3	0.046
19:00:00	19:59:59	9	0	0.000	64	3	0.047	12	0	0.000	64	1	0.016
20:00:00	20:59:59	7	0	0.000	63	2	0.032	13	0	0.000	63	3	0.047
21:00:00	21:59:59	8	0	0.000	75	1	0.013	7	0	0.000	75	0	0.000
22:00:00	22:59:59	3	0	0.000	78	1	0.013	9	0	0.000	78	0	0.000
23:00:00	23:59:59	-	-	-	84	0	0.000	-	-	-	83	1	0.012

CHAPTER 4. LESSONS LEARNED FROM RESEARCH

SUMMARY OF RESEARCH

The purpose of this research was to examine the type of performance measures that could be collected at an intersection and develop a system for automatically collecting these performance measures in the field. We began the research by conducting a needs assessment of practitioners to understand the type and level of information that they wanted from an automated system. We then examined the capabilities of some existing traffic signal controllers and detection capabilities to produce these measures. Based on the findings of the needs assessment and the limitations of the existing detection systems, we developed a series of innovative performance measures that practitioners could use to assess the effectiveness of signal timing at an intersection. We then developed a prototype system for automatically collecting these data in the field. We installed the prototype system in two different locations that exhibit different operating characteristics and assessed the ability of the system to collect meaningful and appropriate performance measures.

USE OF PERFORMANCE MEASURES

Performance measures and performance monitoring can be powerful tools available to agencies for gauging the effectiveness of their traffic control strategies and identifying potential operational problems as they are developing. As part of this research, we identified several performance measures that could potentially be used to assist TxDOT in measuring the effectiveness of their signal timing strategies. We then developed a system for automatically collecting these performance measures in real-time on a cycle-by-cycle basis directly from the traffic signal controller and cabinet. While the actual value of these performance measures depends upon what TxDOT is trying to accomplish with the signal timing at the intersection and the specific situation, the following is a discussion of how these innovative performance measures could be used for making improvements or conducting before and after studies.

- *Cycle time* is a measure of the elapsed time between each subsequent activation of a phase (i.e., from the start of green of one phase to the start of green of the same phase in a previous cycle). For pretimed cycles where the phases are not actuated, cycle time should be equivalent to cycle length. For actuated signals, the *Cycle time* can be used to assess how frequently a particular phase is activated. Long *Cycle times* generally mean that demands are relatively light and the phase is not activated very frequently. *Cycle time*, coupled with phase duration and the time to service value, could also be used to identify potential locations that might benefit from phase sequence changes, such as switching from protected only to protected permissive phase. Likewise the *Cycle time* measure could potentially be used to assess the effectiveness of converting from a leading to a lagging left-turn phasing. *Cycle time* could be used to alert technicians that a potential problem exists with the detection system on an approach. Long *cycle times* with high demand or queue service time could provide an indication that the detection system is not functioning correctly or that calls to the controller are being missed.

- Because it is difficult to accurately measure approach delay without being able to measure queue length, *Time to Service* is a surrogate measure for approach delay. It is measured as the time between when a vehicle first initiated a call to be issued for the phase and when that call is serviced. This measure can be used to assess the "snappiness" of controller settings used at an intersection. Long *Time to Service* values generally indicate that a motorist has to wait a long time before the controller provides the motorist with an indication, especially if all the other approaches had relatively short *Time to Service* values. Long *Time to Service* values can be potentially reduced by shortening the MAX and/or PASSAGE (Gap) timers to make the controller operate "more snappy." Long *Time to Service* values potentially could also be used to determine if the detection system is functioning properly.
- *Queue Service Time* is the portion of a phase that is needed to clear any stored vehicles that exist on an approach. By comparing the *phase duration* and the *queue service time*, the technician can determine what portion of the phase is used to service the built-up demand (i.e., queue) and what portion of the phase is used by random arrival. When these two values are relatively close, it means that most of the phase is being utilized to service the queue. A *Queue Service Time* that is relatively short (compared to the phase duration) implies that large portion of the phase is being used

to service random vehicle arrivals. Reducing the PASSAGE (or Gap) time would make the signal operate more "snappy" and bring the two values closer together.

- *Interval Duration* represents the amount of time that each interval (green, yellow, all-red, and red) during a phase was actually active during a given cycle. These values can be used to compare what the actual phase durations are compared to what they are programmed to be. For example, if the observed yellow and all-red durations are not what have been programmed into the controller, then the technician would know that there is a potential problem with the controller. A technician could use the duration of the green interval to determine if the controller was "maxing out" (i.e., terminating by reaching the maximum timer). The average duration of the green interval on a phase, especially with actuated signals, is also a very important input parameter of traffic signal timing evaluation tools.
- The *Number of Vehicles Entering Per Interval* is a measure that indicates the number of vehicles that are serviced during each interval of a phase. This measure "counts" the number of vehicles that enter the intersection during the green, yellow, all-red, and red intervals and can provide useful insight into the volume of traffic using an intersection. The sum of these values could potentially be used to provide volume counts for each movement serviced by each phase. A high number of vehicles entering during the yellow and/or all-red interval might indicate a problem with the clearance intervals or the need for increased enforcement. A high number of vehicles entering during a red interval, particularly for a through movement phase, might indicate a high right-turn-on-red demand. These values could also be used to provide input into signal timing optimization programs to develop different time-of-day or traffic responsive timing plans.
- The *Yellow and All-Red Violation Rates* can be used to identify potential safety-related problems that might occur at an intersection. These measures indicate the proportion of cycles in a given evaluation period where one or more vehicles entered the intersection during the yellow or all-red portion of a phase. A high value (i.e., a value approaching 1) indicates that there was a high number of cycles during the evaluation period that experienced at least one vehicle entering the intersection during the all-red or yellow clearance intervals. A high all-red violation rate can be used to

assess the need for increased yellow time or the need for increased red-light running enforcement. High violation rates during the yellow interval might indicate a need to provide increased dilemma zone protection or to reduce the overall cycle length, especially if the time to service is particularly long on the approach.

- The *Phase Failure Rate* is a measure of the congestion that exists on an approach. It can be used to assess whether or not there is enough green time provided on an approach to service the demand and it quantifies the number of cycles where a queue fails to clear during the allotted green time. A high *Phase Failure Rate* on only one approach might indicate a need to reallocate the green time at the intersection or a problem with the detection system. High *Phase Failure Rates* on more than one approach might indicate the need to increase the overall cycle length or physical capacity at an intersection.

LESSONS LEARNED

The following list some of the lessons we learned as part of conducting this research:

- Several detection and signal controller manufacturers offer built-in capabilities to collect some signal timing performance measures; however, these capabilities need to be greatly expanded in order to provide accurate measures of signal performance.
- The effectiveness and accuracy of these systems are highly dependent upon the design of the detection system and the placement of the detection zones. Care must be taken in designing and placing detection zones for traffic monitoring purposes to ensure that individual traffic streams are measured and monitored. TxDOT's current practice of combining detection zones limits the ability to collect accurate and meaningful performance measures. In order to produce accurate performance measures, traffic arrival patterns must be measured separately on a lane-by-lane basis. In addition, special detection zones, generally located downstream of the stop bar, are required to provide accurate count information on each approach.
- Some of the traditional measures used to assess performance, such as intersection control delay, are difficult to measure accurately in the field because the current state-of-the-practice of our detection systems does not permit tracking individual

vehicles. As the capabilities of detection technology continue to evolve, many of the refinements and new features of this technology can potentially be used to improve our performance monitoring capabilities.

- Given the current state-of-the-practice of vehicle detection capabilities, we need to reassess how we gauge performance at isolated intersections. Several non-traditional performance measures, such as Time to Service and Queue Service Time, represent new measures that can potentially be used to assess signal performance. These measures can often be used as surrogates for more traditional performance measures.

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