Texas A&M Transportation Institute

Guidelines for the Implementation of a Statewide ATSPM System

Technical Report 0-7009-R1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

sponsored by the
Federal Highway Administration and the
Texas Department of Transportation
https://tti.tamu.edu/documents/0-7009-R1.pdf

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-23/0-7009-R1		
4. Title and Subtitle GUIDELINES FOR THE IMPLEMENTATION OF A STATEWIDE ATSPM SYSTEM		5. Report Date Published: December 2023 6. Performing Organization Code
7. Author(s) Srinivasa R. Sunkari and Nadeem Chaudhary		8. Performing Organization Report No. Report 0-7009-R1
9. Performing Organization Name and Address Texas A&M Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-7009
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office 125 E. 11th Street Austin, Texas 78701-2483		13. Type of Report and Period Covered Technical Report: August 2019–August 2022 14. Sponsoring Agency Code

15. Supplementary Notes

Project sponsored by the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Implementation of Automated Traffic Signal Performance Measures
URL: https://tti.tamu.edu/documents/0-7009-R1.pdf

16. Abstract

Agencies that operate traffic signals now have an emerging tool to help them succeed in their day-to-day operations. The availability of high-resolution traffic signal data along with analysis tools has enabled these agencies to troubleshoot problems very quickly before they escalate into bigger issues and to maintain and update signal timings in a proactive manner. This methodology is achieved by using tools called automated traffic signal performance measures (ATSPMs) or signal performance metrics. Currently, signal maintenance and operational issues are reactively identified through public feedback, and there could be a significant lag between problem occurrence, troubleshooting, and implementation of a corrective measure, causing public dissatisfaction. Agencies wanting to implement ATSPM systems need to have a good understanding of the requirements of the system. This report also provides detailed functional and technical requirements to support the development of formal specifications to procure an ATSPM system. These requirements are then coupled with guidelines for the local agencies. These guidelines start with identifying champions in the agency that will encourage the use of the system, assess the available resources, which include infrastructure, personnel, and financial resources, suggest prioritization of available resources to maximize the benefits of an ATSPM system, and finally recommend a step-by-step strategy to implement and operate the system.

17. Key Words	18. Distribution Statement
ATSPM, Iteris SPM, Miovision, Centracs, SPM, INRIX, Wejo	No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia https://www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	116	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

GUIDELINES FOR THE IMPLEMENTATION OF A STATEWIDE ATSPM SYSTEM

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Report 0-7009-R1
Project 0-7009
Project Title: Implementation of Automated Traffic Signal Performance Measures

Sponsored by the
Texas Department of Transportation
and the
Federal Highway Administration

Published: December 2023

TEXAS A&M TRANSPORTATION INSTITUTE
College Station, Texas 77843-3135

DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer (researcher) in charge of the project was Srinivasa Sunkari, P.E. #87591.

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.

ACKNOWLEDGMENTS

This project was sponsored by TxDOT and FHWA. The authors thank project director Wade Odell and members of the Project Monitoring Committee: America Garza, Barbara Russell, Jeremy Dearing, Jianming Ma, Kelli Williams, Mathew McCarty, Robert Guydosh, and Steve Chiu; and the state and federal sponsors.

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INTRODUCTION

Agencies that operate traffic signals now have an emerging tool to help them succeed in their day-to-day operations. The availability of high-resolution traffic signal data along with analysis tools has enabled these agencies to troubleshoot problems very quickly before they escalate into bigger issues and to maintain and update signal timings in a proactive manner. This methodology is achieved by using tools called automated traffic signal performance measures (ATSPMs) or signal performance metrics (SPMs). Currently, signal maintenance and operational issues are reactively identified through public feedback, and there could be a significant lag between problem occurrence, troubleshooting, and implementation of a corrective measure, causing public dissatisfaction. Agencies wanting to implement ATSPM systems need to have a good understanding of the requirements of the system. These requirements start with identifying champions in the agency that will encourage the use of the system, assess the available resources, which include infrastructure, personnel, and financial resources, and finally recommend a step-by-step strategy to implement and operate the system.

PROJECT BACKGROUND

Signal performance measures provide means for an operating agency to assess the success or failures of the initiatives to improve traffic signal operations. The traditional approach, based on field studies and manual calculation, for measuring signal performance is both time-consuming and costly. The Texas Department of Transportation (TxDOT) led the development of numerous intersection monitoring systems that could provide some performance measures to the system operators. Technological developments during the last decade, however, are enabling automatic generation of metrics to provide for a lower-cost solution to signal performance measurement. These developments include traffic signal controllers' ability to generate and log high-resolution controller event data as well as controller-independent devices to obtain and save such data. Various public and private entities have developed ATSPMs that use these high-resolution data to generate a whole host of performance metrics that can be used for assessing signal performance and identify faults. However, the architecture and costs of these ATSPMs vary significantly and impact their implementation based on available assets. This project is focused on providing guidelines to TxDOT as well as cities in Texas to identify, select, and implement the most suitable ATSPM platform for the operating agency.

PROJECT OBJECTIVES

The primary objective of this project is to:

- Develop draft specifications of an ATSPM system for statewide deployment.
- Conduct a workshop for the stakeholders about the draft specifications.
- Provide guidance to TxDOT districts about prioritizing the resources needed to implement an ATSPM system.

RESEARCH APPROACH

In this project, the Texas A&M Transportation Institute (TTI) conducted a review of the state of practice related to the implementation and use of ATSPMs to enhance traffic signal performance. TTI then compared the implementation requirements and other aspects of three ATSPM software suites commonly available in Texas. TTI also solicited the input from TxDOT engineers across the state about the use cases as well as their constraints to implement and use an ATSPM system. Based on this assessment, TTI developed draft specifications that TxDOT can use to procure an ATSPM system for statewide deployment to assess and improve traffic signal performance and operations.

LITERATURE AND STATE OF PRACTICE REVIEW

HISTORY OF SIGNAL PERFORMANCE MEASURES

TxDOT Funded Research

During the last 20 years, TxDOT has made significant investments in the development of ATSPMs to provide for a proactive approach to traffic signal maintenance and operations. Below is a summary of these efforts and resulting outcomes.

TxDOT Project 0-4422, entitled Measuring Performance of Traffic Signal Systems Using Existing Detector Technology, was the first project in this area (*1*). In the first year of this 2-year project, researchers:

- Assessed how TxDOT staff identified maintenance/operations issues.
- Identified common measures used by TxDOT staff to evaluate performance of traffic signals, and discussed how these measures could be measure automatically.
- Reviewed controller and detection technologies.
- Developed a list of potential performance measures along with their definitions, and evaluated how these measures could be derived from controller events (i.e., phase on, phase off, detector on, detector off).

Table 1 categorizes identified measures.

Table 1. Categories of Performance Measures.

Performance Category	Measures in Category
Reliability	Average number of phase activations, average number of vehicles served per cycle, average number of vehicles stopped per cycle, proportion of vehicles having to stop on an approach, percent of failed cycles
Measures of Efficacy	Average cycle time, average phase duration, average time to service, average proportion of green used to service queue
Safety	Average number of vehicles entering on yellow per cycle, average number of vehicles entering on red clearance interval per cycle, percentage of cycles experiencing a red clearance violation

In the second year of this project (*2*), researchers first used a hardware-in-the-loop simulation testbed to test the efficacy of performance measures generated by the EPAC 300 controller. The simulation scenario for this testbed consisted of a fully instrumented intersection with advance detectors, stop-bar detectors, and detectors downstream of stop bar. Next, researchers developed a real system and field-tested it at two intersections located in Milano and Huntsville, Texas. System architecture used a digital input-output card for interfacing with a TS-1 cabinet and enhanced bus interface unit (BIU) for TS-2 cabinets. The system also included a custom software module for recording traffic events and another software module for generating performance measurement reports. Key findings of this project included:

- Built-in performance measurement capabilities of controllers at the time were not adequate.
- Effectiveness and accuracy of performance measurement is highly dependent on the design of detection system.
- Traditional measures of effectiveness (i.e., control delay) cannot be computed without additional tracking of individual vehicles.
- There is a need to reassess how to gauge performance at isolated signals, including the uses of measures suggested in this project as surrogates for traditional measures.

Using the results of the above project as a foundation, TxDOT Project 0-6177 developed a complete toolbox for evaluating signal performance at signalized intersections and diamond interchanges (*3*). The toolbox was designed for use at locations using TS-2 cabinets and used a special type of BIU to collect controller event data. Then, it combined real-time controller event data with signal timing parameters to produce additional performance measures. These measures included: number of minimum and maximum greens per hour, average phase time, queue service time, occupancy on red, time to service, and phase utilization. Toolbox-used guidelines included pointers on how to use these measures for diagnostics. One limitation of this toolbox was the need for the user to manually enter signal timing parameters into the toolbox database and to ensure that entered data matched with the controller database. Another limitation of this toolbox was that any changes to timing data identified through the diagnostics process had to be manually programmed in the controller.

TxDOT Project 0-6775 (*4*) eliminated limitations of the above product by using National Transportation Communication for ITS (Intelligent Transportation Systems) Protocol (NTCIP) messages for communicating with traffic controllers. This project developed a new portable toolbox that consists of the following modules:

- A real-time monitoring module that automatically downloads all signal-timing data (i.e., basic timing, phase sequences, and coordination plan data) prior to beginning the recording of controller event data. It collects all or a user-selected sub-set of controller event data and saves them on the computer hard-disk for offline processing.
- An offline analysis module that reads the recorded data and converts them to charts/graphs useful for troubleshooting and operational analysis.
- A module with the capability to read signal timing data from a universal traffic data format file and download these (and any desired manually adjusted/entered) timings to the controller via NTCIP messages.

Testing showed that some traffic controllers did not have adequate communications speeds to collect all controller events in real-time. Testing also found that direct Ethernet-based connection was the most reliable means for recording data in real time (i.e., every 100 ms or faster). Testing also showed that remote communications can add significant latency in getting data. In such cases, smaller subsets of real-time events could be reliably collected.

Analysis of data collected at a diamond interchange located in Bryan, Texas, identified that one of the frontage road phases was consistently maxing out during late night and early morning hours. This site used video detection. Upon further investigation, TxDOT staff found that the brightness of the newly installed led-based signal heads were activating detection zones on this approach. TxDOT staff subsequently corrected this issue, which would have most likely gone undetected until some user complained.

Automated Traffic Signal Performance Measurement System Development

Starting in 2002, researchers at Purdue University, in cooperation with the Indiana Department of Transportation (INDOT), began work that led to the development of the first ATSPM system. The initial work involved full instrumentation (i.e., lane-by-lane detection at stop bar, main signal approaches, and downstream of stop bar) at a single intersection and detailed study of data obtained from this real testbed. In the following years, these researchers, in cooperation with the Utah Department of Transportation (UDOT), Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), other state agencies, and traffic controller manufactures, pushed forward along the path of implementing controller and detector event logging inside traffic controllers and using this logged data for offline development of performance measurement. This section contains a brief overview of key research and development.

A 2008 research study funded by INDOT evaluated the usefulness of controller event data to measure cycle-by-cycle performance of traffic signals at two intersections (*5*). Each intersection had inductive-loop-based lane-by-lane detection at the stop bar on all approaches and advance detection 400 ft upstream of the stop bar on arterial approaches. The study also recorded video data using multiple video cameras per approach. The study used an Autoscope Solo Pro video detection system to tap into 24-volt digital signals inside the signal cabinet to collect high-resolution detector and phase status data, which were processed later to generate signal performance measures. These performance measures included:

- Basic data: cycle length, green duration, and volume.
- Derived measures: service flow rate, estimated capacity, observed capacity, volume-to-capacity ratio, and number of cycle failures.
- Quantification of intersection performance: percent of arrivals on green, arrival type, and platoon profile.

In 2012, Purdue University researchers, in cooperation with some controller manufacturers, published a document that defined enumerations for encoding all possible controller events (*6*). These include cabinet events, detector events, phase events, overlap events, coordination events, barrier-ring events, and preemption events. This document also contains unassigned event codes for future expansion. High-resolution data-enabled controllers logged event code, event parameter, and time (at 100 ms resolution) event occurred. Table 2 illustrates snapshots of event data collected in the lab using computer simulation.

Table 2. Example of Controller Event Data.

Row #	Time Stamp	Event Code	Parameter	Description
1	12:34:01.2	0	8	Phase On
2	12:34:01.2	2	8	Phase Check
3	12:34:01.2	1	8	Phase Begin Green
4	12:34:01.2	21	4	Pedestrian Begin Walk
5	12:34:01.2	21	8	Pedestrian Begin Walk
6	12:34:05.2	22	4	Pedestrian Begin Clearance
7	12:34:05.2	22	8	Pedestrian Begin Clearance
8	12:34:17.2	7	8	Phase Green Termination
9	12:34:17.2	3	8	Phase Min Complete
10	12:34:17.2	8	8	Phase Begin Yellow Clearance
11	12:34:17.2	23	4	Pedestrian Begin Solid Don't Walk
12	12:34:17.2	23	8	Pedestrian Begin Solid Don't Walk
13	12:34:18.9	82	8	Detector On

In Table 2, Column 1 contains row numbers of the table and Column 2 contains the time stamps of the recorded event. Column 3 contains event code, and Column 4 provides the parameter that the event pertains to. Column 5 provides descriptions of events that do not need to be logged by the controller. As an example, the first highlighted row (Row 3) in this table shows that there was a begin green event (Code 1) for Phase 8 at time 12:34:01.2. The pair of highlighted rows (Rows 6 and 7) shows that pedestrian clearance for Phases 4 and 8 began at time 12:34:05.2. The last pair of highlighted rows (Rows 8 and 9) shows that at time 12:34:17.2, Phase 8 terminated after serving minimum green time. Using the time stamp of Phase Begin Green for this phase, it can be determined that Phase 8 was green for 16 seconds. The last row (Row 13) in this table shows that Phase 8 had a detector call 1.7 seconds after the onset of yellow clearance interval.

In 2012, UDOT started in-house development of the first ATSPM system that used high-resolution data logged by controllers to graphically display traffic signal performance measures (*7*). During the next five years, UDOT spent thousands of hours of staff time on system development, deployment, and enhancements. UDOT distributed the initial versions of software through USDOT's JPO Open-Source Application Development Portal (https://its.dot.gov/code/). For this reason, UDOT ATSPM is often referred to as open-source ATSPM. From the beginning, UDOT openly provided access to their ATSPM webpage to anyone interested in the system. This webpage also contains documentation and information about the software.

A 2015 Pooled Fund Study TPF-5(258) led by INDOT (and supported by numerous transportation agencies, including TxDOT) evaluated the uses of and requirements for performance measures in traffic signal systems facilitated by high-resolution controller event data (*8*). The study also looked at uses of external travel time measurements. The final report of this project provides a high-level synthesis of the systems engineering concepts for traffic signal control, followed by a presentation of the requirements for implementing data collection and processing of the data into signal performance measures. Examples are used to show a variety of uses of performance measures for communication and detector system health, quality of local control (i.e., capacity allocation, safety, pedestrian performance, preemption, and advanced control analysis), and quality of progression (i.e., evaluation and optimization). By the time this report was published, most major controller manufacturers had already implemented capabilities to record and report high fidelity controller event data using Purdue enumerations. In addition, UDOT already had extensive implementation of ATSPMs. Since then, many other departments of transportation (DOTs) (e.g., Florida, Nevada, Georgia, Arizona, Alabama, and New Jersey) have adopted the UDOT ATSPM (https://udottraffic.utah.gov/atspm/). Of these agencies, Georgia Department of Transportation (GDOT) has the largest ATSPM deployment (https://traffic.dot.ga.gov/ATSPM/).

GDOT has also made significant contributions to the development and enhancement of the open-source ATSPM system. These enhancements include additional performance measures and improved packaging of the executable to simplify system installation and updates. Separately, GDOT has also developed dashboards to make the system easier to use by technicians, engineers, and upper management. In addition, GDOT has developed improved documentation of the system. UDOT has already rolled in many of these enhancements into the currently released version of the software. While other features, including dashboards, are expected to be made available in the upcoming release. The most recent version (Version 4.2) of the UDOT ATSPM software is available at GitHub (*9*). Both UDOT and GDOT ATSPM sites provide extensive details about the capabilities of open-source system.

Commercial ATSPM Systems

The UDOT open-source ATSPM is available free of cost. In addition, documentation providing detailed descriptions of system components, hardware, and software requirements and how to install and configure the system are also freely available. Nevertheless, it requires significant in-house resources to install, configure, maintain, and use the system. Many agencies interested in an ATSPM do not have these required resources.

Taking advantage of this opportunity, numerous commercial enterprises have developed their own products. These developers include controller manufactures, established consulting firms, and several new companies solely established to capture a portion of the potential market. At the core level, most of them provide the same performance measures as the open-source ATSPM, which are described in a following section. With one exception, all these vendors primarily use customers' infrastructure (i.e., traffic controllers and communication backbone) but provide a turnkey solution. Features of these solutions include:

- Cloud-based data hosted on a cloud.
- Efficient storage and retrieval of the vast amount of raw and processed data generated by each connected signal.
- Improved graphic displays of standard performance measures with dynamic information access.
- New performance measures using external data (i.e., travel time).
- Graphical identification of intersections identified as having operational and maintenance issues.
- Dashboards to display summary information for consumption by different stakeholders, including technicians, engineers, decision makers, and the public.

Other Performance Measurement Solutions

The focus of this project is an ATSPM system that primarily uses controller event data to derive traffic signal performance measures. However, it should be noted that recent years have seen an emergence of performance measurements using probe vehicle and other crowd-sourced data. With a sufficiently large sample size, these systems can provide performance measures that can be used by agencies by themselves or in conjunction with controller-based performance measures. The advantage of these systems is that they do not need any agency infrastructure. As such, they can be quickly deployed through a subscription service.

PERFORMANCE MEASURES

A recent report commissioned by UDOT, in cooperation with Pennsylvania DOT, provides definitions of, and methods for calculating, performance measures produced by the UDOT ATSPM (*10*). The following subsections provide basic information about the performance measures currently available in the UDOT ATSPM. Readers interested in details of calculation procedures should refer to the cited reference.

Approach Volume

Approach volumes can be determined using either lane-by-lane count detectors at the stop bar or advanced count detectors upstream of the intersection. If both sensor types are present at an approach, the approach volume is computed for each sensor group. Opposing directions are calculated and presented on one graph, as shown in Figure 1. Volume data, normalized as flow rates, may be aggregated into custom-sized bins. The default value is 15 minutes. These data are used to calculate peak-hour factor, K factor, and D factor and can be used for planning purpose and/or for troubleshooting detector issues.

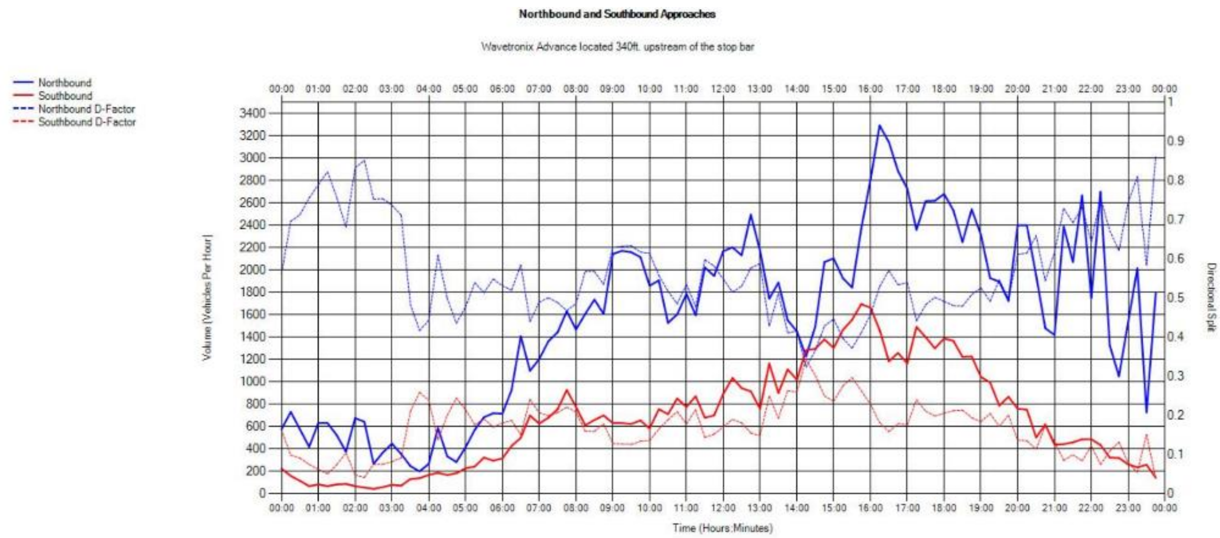


Figure 1. Chart of Approach Volumes.

Phase Termination

Actuated phases may skip or terminate after serving the minimum time because of lack of demand or because a phase has reached its maximum programmed time. Figure 2 reports the reasons for phase terminations at an intersection (i.e., skip, gap-out, max-out, or force-off). This information can be useful in identifying phases that are consistently using all the allocated green time either due to high demands (normal operation) or due to detector faults.

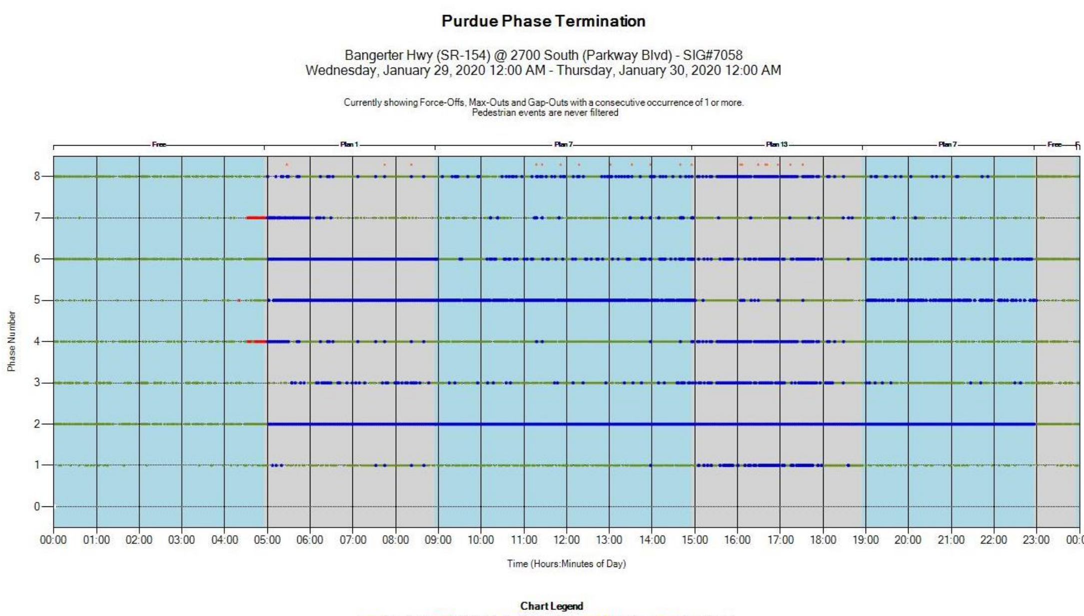


Figure 2. Purdue Phase Termination Chart.

Split Monitor

The measure provides detailed information about the performance of individual phases by providing phase duration, termination type, pedestrian phase service, and programmed splits. This measure is useful for assessing whether signal timing parameters have been programmed correctly, how much of the programmed split is being used, and evaluation of the impact of any signal timing adjustments. The pattern change information can also be used to infer events such as interruption of a pattern by preemption or priority control. Figure 3 illustrates this plot.

Purdue Split Failure

Split or phase failure occurs when there are unserved vehicles at the end of a phase. A phase experiencing an excessive number of consecutive failures is likely experiencing an operational problem that could be fixed by increasing split or max time or by adjusting detector setting. Phase-failure determination uses detector occupancy information during the phase time (i.e., sum of green, yellow, and all red intervals) and detector occupancy during the first five seconds of red interval. Figure 4 shows an example of this chart. This chart plots occupancy ratios during green and first five seconds of red and their trend lines. Vertical yellow lines identify phase failures.

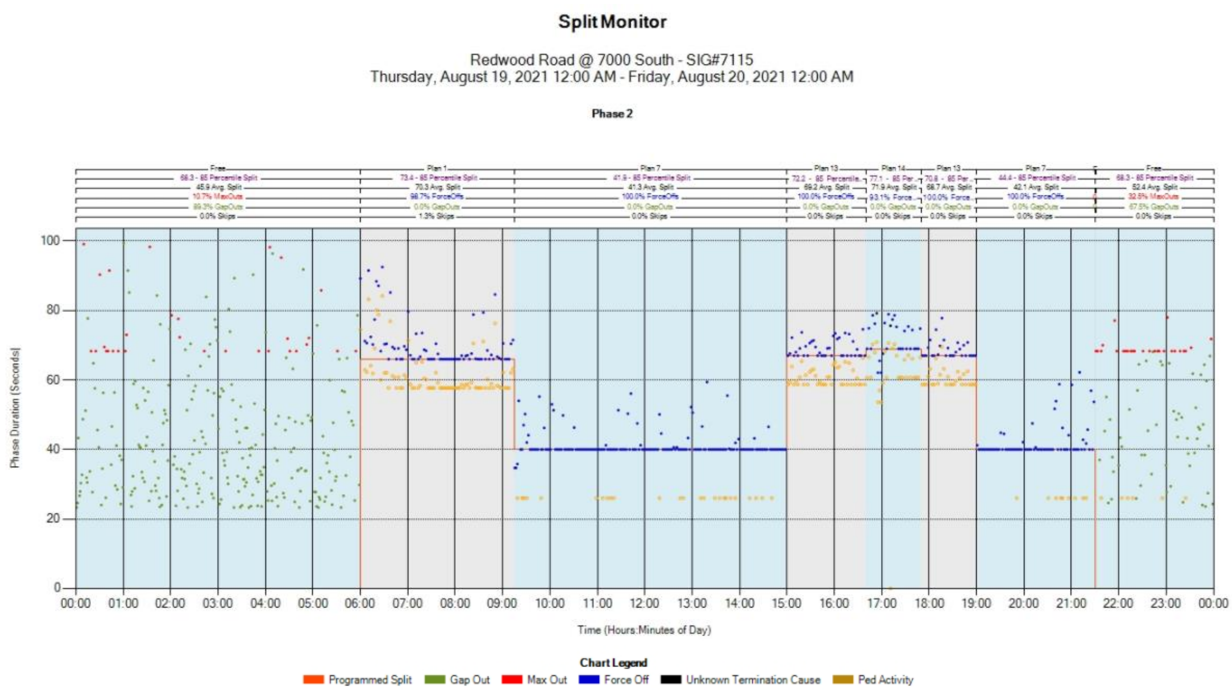


Figure 3. Split Monitor Chart.

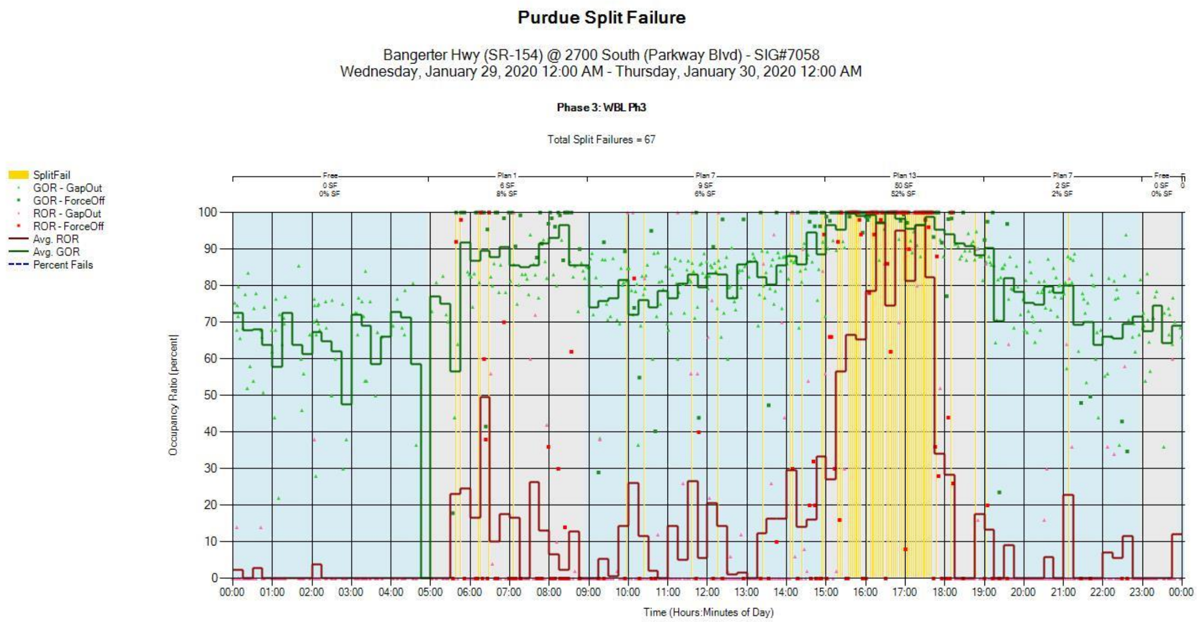


Figure 4. Purdue Split Failure Chart.

Approach Delay

This measure uses time difference between the onset of green interval and detector activation during the previous red interval to identify individual vehicle delay. Average and total delay are then calculated. This simplified delay calculation does not take into consideration vehicle deceleration, startup delay, or any queue length exceeding the detection zone. This measure is useful for identifying timing adjustments at uncongested intersections. Figure 5 illustrates a plot of this measure, which contains approach delay (in hours) and vehicle delay (in seconds) for the subject phase.

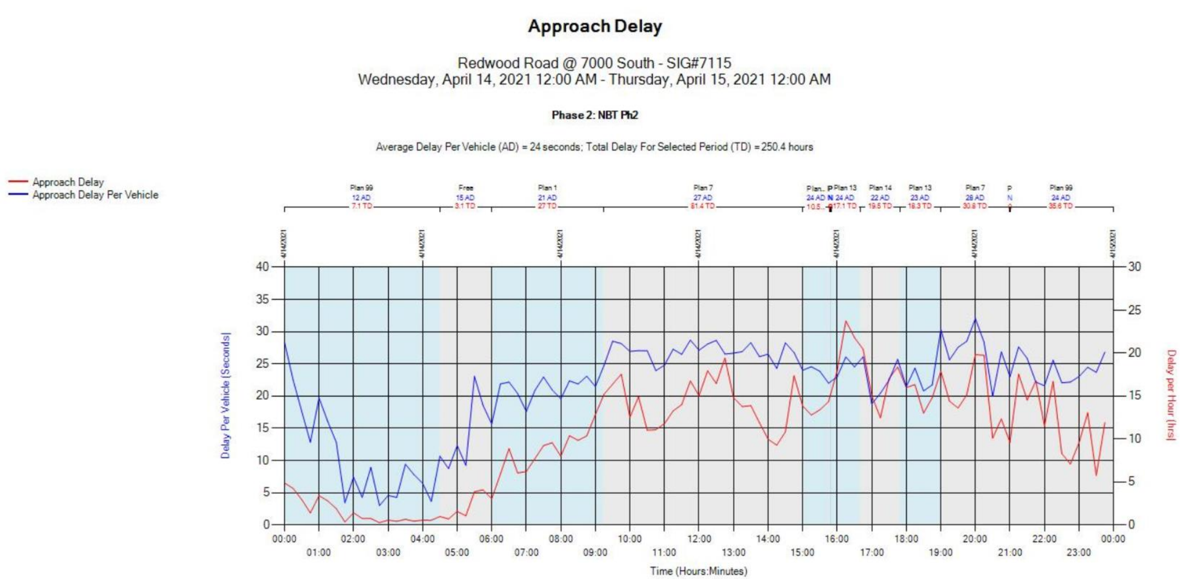


Figure 5. Approach Delay Chart.

Pedestrian Delay

This measure is based on the maximum pedestrian delay per cycle calculated as the time between the first push-button activation and the next walk interval. Calculations ignore multiple consecutive activations within a short period of time. Figure 6 illustrates a graph of pedestrian delays (vertical blue lines) for a single phase during a 24-hour period. The graph also shows times during which the signal is running free and any coordinated plans.

Yellow and Red Actuations

This measure reports actuations of detectors located (upstream or downstream) near the stop bar during yellow clearance, red clearance, and red times. These actuations (violations) can be used as a surrogate safety measure to flag unsafe or potentially unsafe intersections. Figure 7 shows a plot of these actuations for a protected left-turn phase. There is a significant increase in the number of actuations during red clearance time starting at 4 p.m. (16-hour mark). Here, the duration of yellow is 4 seconds, and the duration of red clearance time is 3 seconds.

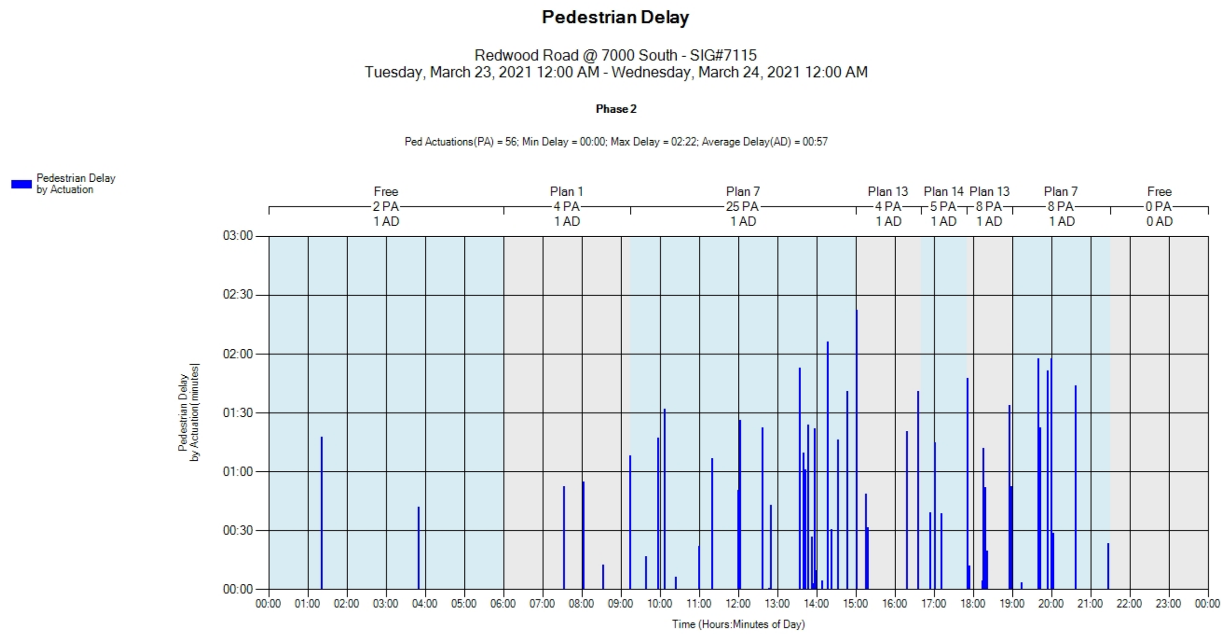


Figure 6. Pedestrian Delay Chart.

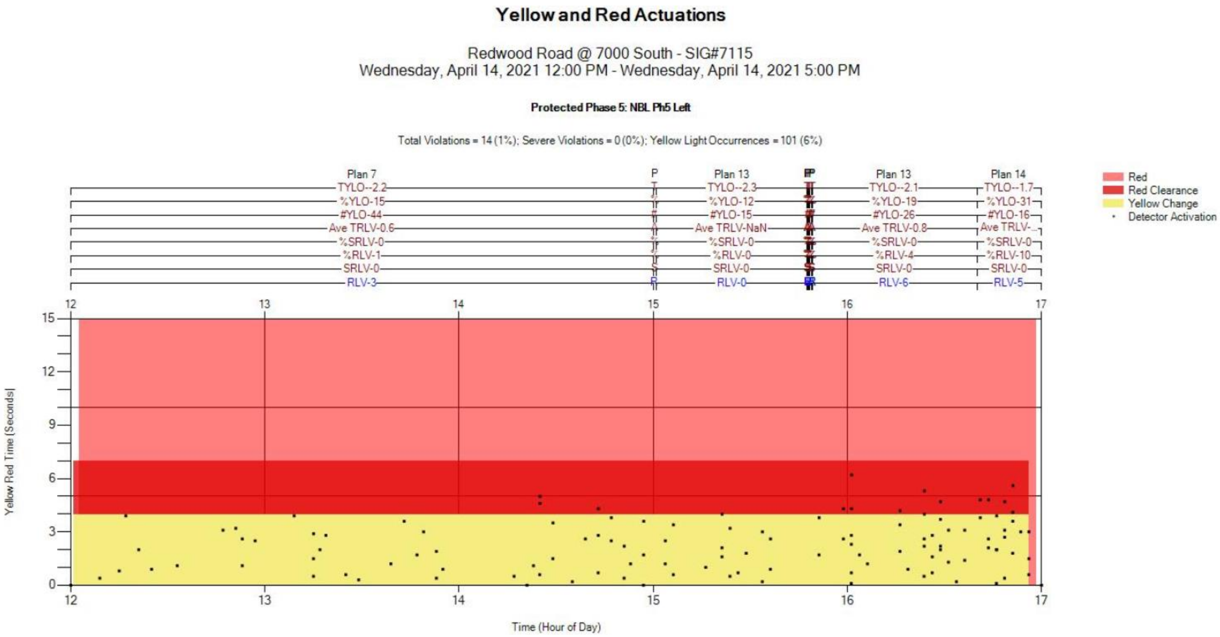


Figure 7. Chart of Actuations during Yellow and Red.

Purdue Coordination Diagram

This diagram plots arrival times of individual vehicles at the stop bar during a signal cycle together with the beginning of red and green intervals for a single through phase. This measure requires advance detection (i.e., located 400 ft upstream of stop bar). The computation process uses the time a vehicle actuated the advance detector and projects its arrival time at the stop bar using an assumed approach speed. The Purdue Coordination Diagram (PCD) assumes the cycle to be the time between two consecutive red phases. Figure 8 illustrates a sample PCD for a through phase. Here, dots below the green plot identify vehicles arriving on red, and dots above the green line identify vehicles arriving after the beginning of the green phase and before the next red phase. For additional information, the graph also includes a plot (black line) of vehicle demand. PCD is useful in visually identifying quality of progression.

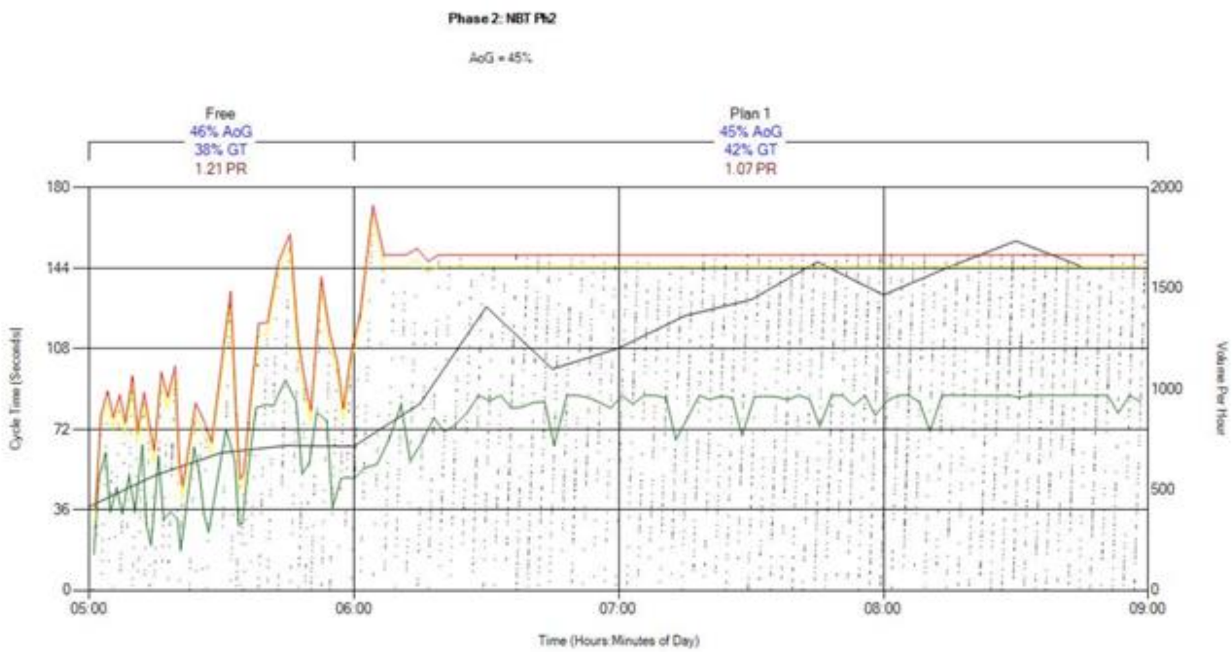


Figure 8. Purdue Coordination Diagram.

Preemption Details

This measure provides details about all preemption events occurring during a user-specified time. Information includes graphical information about preempt service requests receipt and preempt service times and other detailed information about each preempt. Detailed information depends on the type of preempt. Figure 9 illustrates a chart for Preempt 1 and contains information about time to service, dwell time, and time of “Input Off” for all preempts requests during a 24-hour period.

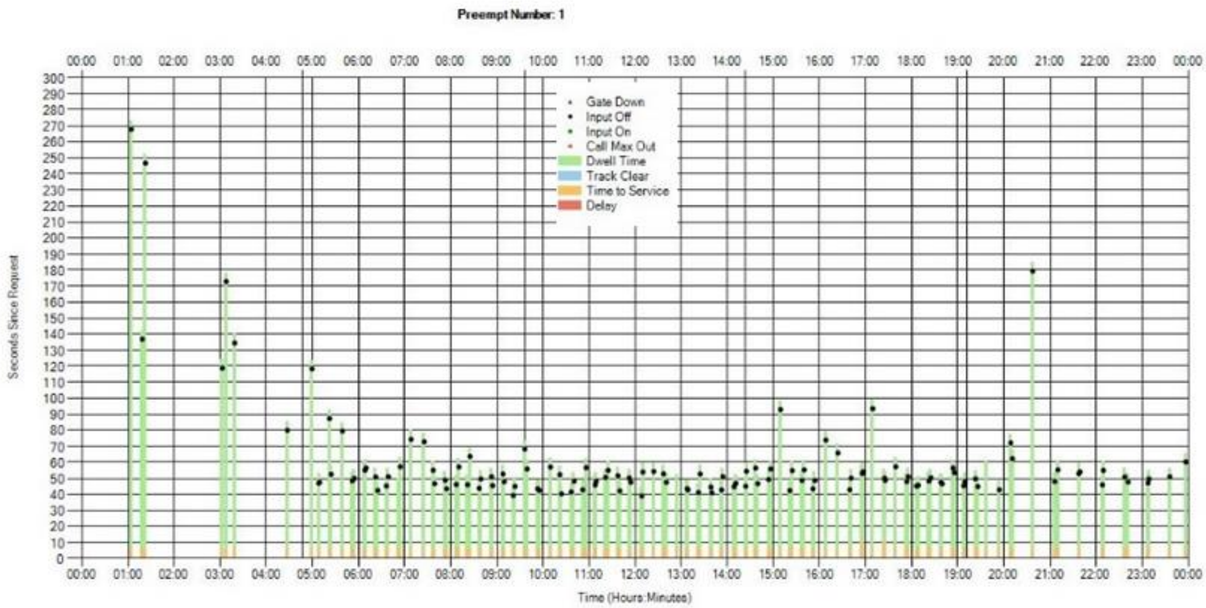


Figure 9. Preemption Detail Chart.

Approach Speed

This performance measure uses speed data obtained directly from setback (advance) detectors. Speeds of only those vehicles that are traveling over 5 mph and are detected 15 seconds after the start of green to the start of yellow are used. From this data, average speed, 15th percentile speed, and 85th percentile speed is calculated and reported together with the posted speed. Figure 10 illustrates an approach speed graph.

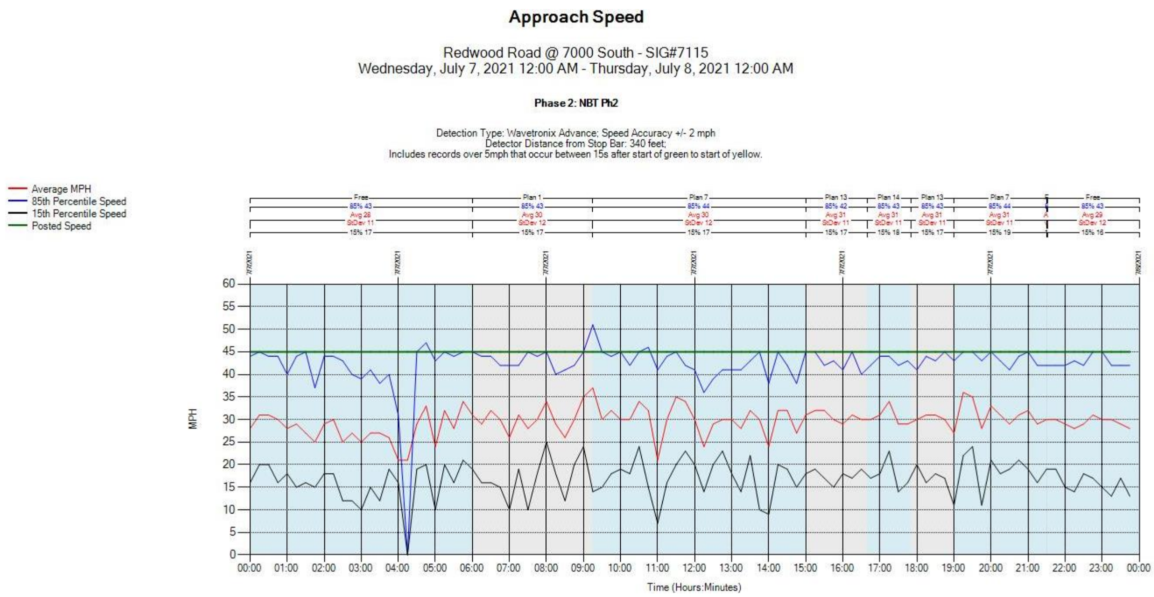


Figure 10. Approach Speed Chart.

Arrivals on Red

This performance measure applies to through phases, uses data from setback detectors to calculate vehicles arriving during red, and can help evaluate quality of progression. As illustrated in Figure 11, performance measures reported are the number of vehicles arriving on red, total number of vehicles, and percent of vehicles arriving on red.

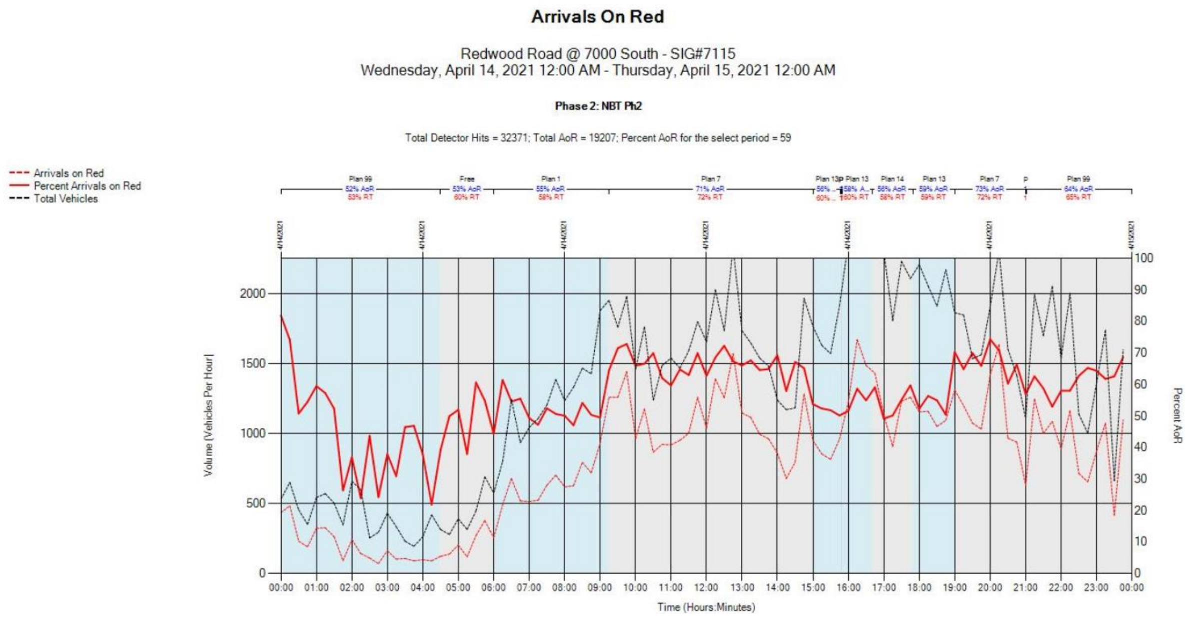


Figure 11. Arrivals on Red Chart.

Turning Movement Counts

This measure requires lane-by-lane detection capability and provides total counts and per lane counts for all lanes at an approach. Figure 12 illustrates turning movement count graph for an approach with three through lanes.

Timing and Actuation

As illustrated in Figure 13, the timing and actuation chart provides microscopic level detail about a selected phase. This information includes a plot of phase intervals (i.e., minimum green, green, yellow, red clearance, and red intervals) together with detector actuation information for all associated detectors. This information can be used for advanced analysis including troubleshooting of signal phasing and timing problems, identification of red-light runners, and analysis and reconstruction of crash data.

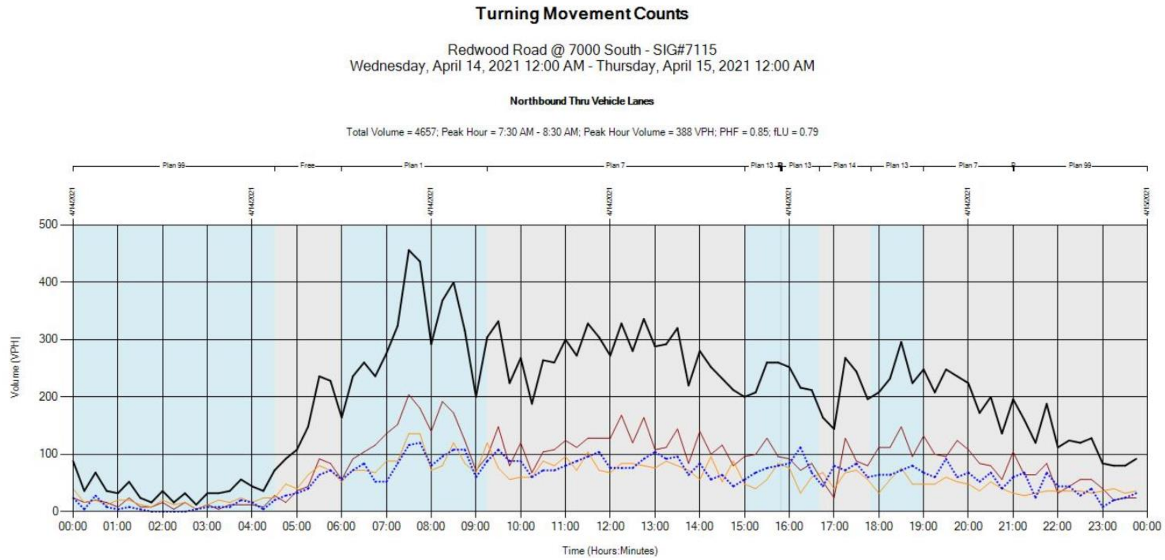


Figure 12. Chart of Turning Movement Counts.

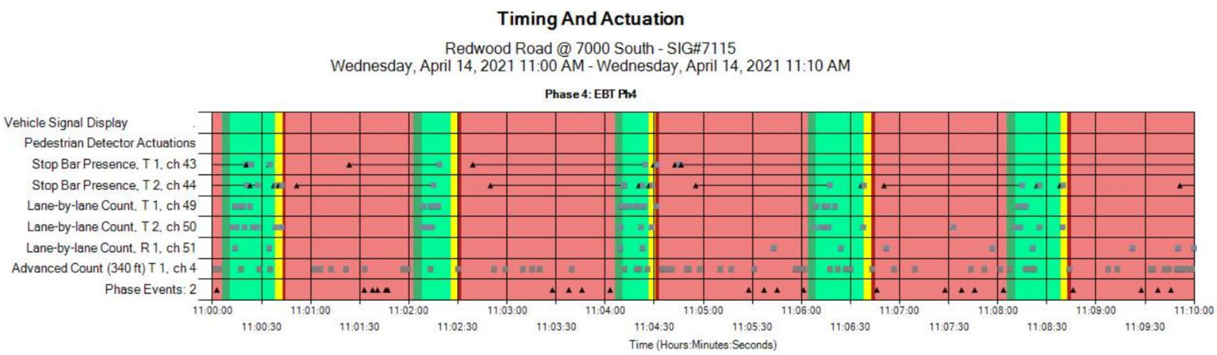


Figure 13. Timing and Actuation Chart.

Left-Turn Gap Analysis

Safe movement of left-turning vehicles during a permissive phase requires the availability of a sufficient number of large gaps in conflicting through traffic. This performance measure quantifies the number of gaps by size and graphs them over time to assist in determining locations and times during which permissive left-turn movements should be allowed. Figure 14 shows the gap analysis chart for one through phase at an intersection during a 24-hour period. Here, red color identifies the number of gaps between 1 and 3.3 seconds, and the light blue color shows the number of gaps larger than 7.4 seconds. Last, the blue line on the graph displays the percent gaps greater than or equal to the threshold of 7.4 seconds.

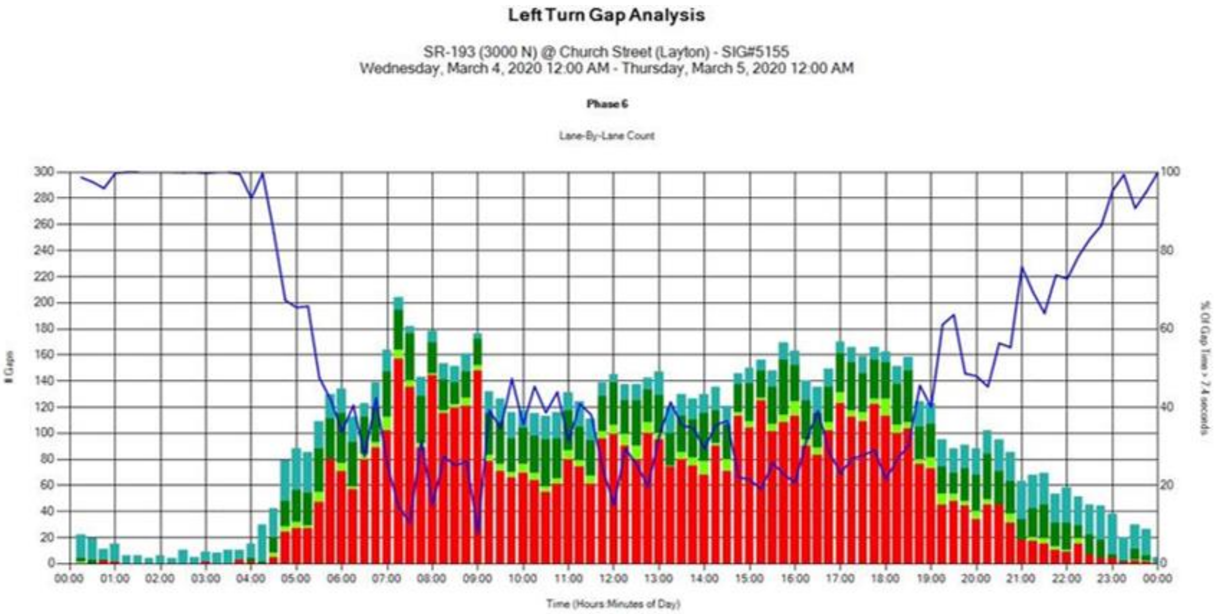


Figure 14. Left-Turn Gap Analysis Chart.

Purdue Link Pivot Analysis

In addition to the signal-based performance measures described above, UDOT ATSPM provides a feature that uses Purdue Link Pivot Algorithm (*11*) to optimize offsets. This algorithm determines offset that maximize arrivals on green along a predefined arterial route consisting of multiple adjacent intersections. Figure 15 provides an illustration of analysis for a four-intersection arterial. In this figure, the red rectangle at the top-right corner shows suggested offset adjustments, and the other red rectangles show the resulting impacts of these adjustments on individual and corridor level arrivals on green (AOG). The analysis predicts 3 percent increase in AOG if suggested offsets are implemented.

Detection Requirements

The set of performance measures an ATSPM system produces depends on the level of detectorization at the intersection. Figure 16 identifies the detectors required for producing different groups of performance measures.

Link	Signal	Location	Link Delta	Edit Link Delta	Offset(+ to Offset)	Existing Offset	New Offset
1	6432	6432 - 700 East 300 South	63	63	12	0	12
2	6431	6431 - 900 East State Street.	43	43	39	0	39
3	6429	6429 - 1320 South State St. (Provo)	86	86	86	0	86
4	6430	6430 - State Street 1860 South	0	0	0	0	0

Adjustments

Link	Approaches		Upstream AOG			Downstream AOG			Total Link AOG			Delta	AOG Chart
	Upstream	Downstream	Existing	Predicted	Change	Existing	Predicted	Change	Existing	Predicted	Change		
1	6432 Southbound	6431 Northbound	0	0		2159	2203		**2159**	**2203**		63	PCD Options
	6432 - 700 East 300 South	6431 - 900 East State Street.	NaN%	NaN%		66%	67%		**66%**	**67%**			
2	6431 Southbound	6429 Northbound	689	852		852	849		**1541**	**1701**		43	PCD Options
	6431 - 900 East State Street.	6429 - 1320 South State St. (Provo)	57%	71%		84%	84%		**70%**	**77%**			
3	6429 Southbound	6430 Northbound	439	416		1253	1323		**1692**	**1739**		86	PCD Options
	6429 - 1320 South State St. (Provo)	6430 - State Street 1860 South	89%	84%		59%	62%		**64%**	**66%**			
Corridor Summary			**1128**	**1268**		**4264**	**4375**		**5392**	**5643**			
			66 %	**75 %**		**66 %**	**68 %**		**66 %**	**69 %**			

Figure 15. Link Pivot Optimization of Offsets.

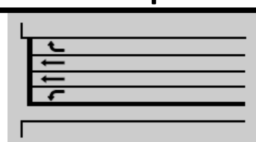
Vehicle Detection Required		Metric
None		**Purdue Phase Termination** (Maxouts/Forceoffs, Gapouts) **Split Monitor** **Preemption Details** (Days/times of service, delay, duration, etc) **Pedestrian Delay** (Requires pedestrian detection) **Timing and Actuation** (No actuation data without detection)
Lane-by-lane or Lane Group Presence		**Purdue Split Failure** **Left-Turn Gap Analysis**
Lane-by-lane Stop Bar Count		**Turning Movement Counts** **Yellow and Red Actuations** (Requires detectors downstream of stop-bar or stop-bar detectors with speed measurement
Advance Count		**Approach Delay** **Approach Volume** **Arrivals on Red** **Approach Speed** (Requires ability to measure speeds) **Purdue Coordination Diagram** **Purdue Offset Optimization**

Figure 16. Vehicle Detectors Required to Produce Different Performance Measures.

CONTROLLER EVENT DATA BASED ATSPM SYSTEMS

This section provides a brief overview of a few selected ATSPM systems.

Utah DOT ATSPM

Benefiting from its partnership with Purdue University, FHWA, and the Transportation Pooled Fund Program, UDOT implemented the ATSPM system as a cost-effective way to manage its signals (*12*). ATSPM enables UDOT to proactively manage traffic signals by quickly identifying maintenance issues and operational problems affecting traffic flow. UDOT utilizes visualization reports that can be used to evaluate the quality of traffic progression along corridors and identify unused green time for allocation to other intersection movements. System reports of vehicle delay, volumes, and speeds can be used to evaluate the effectiveness of signal timing adjustments. ATSPM visualizations can also be used to inform UDOT staff of vehicle and pedestrian detector malfunctions, saving staff time during maintenance operations. ATSPM tools speed up decision-making and help UDOT staff prioritize operation and maintenance efforts. UDOT's ATSPM also features a public-facing website (Figure 17) that allows users to quickly generate any one of the previously described charts and other reports.

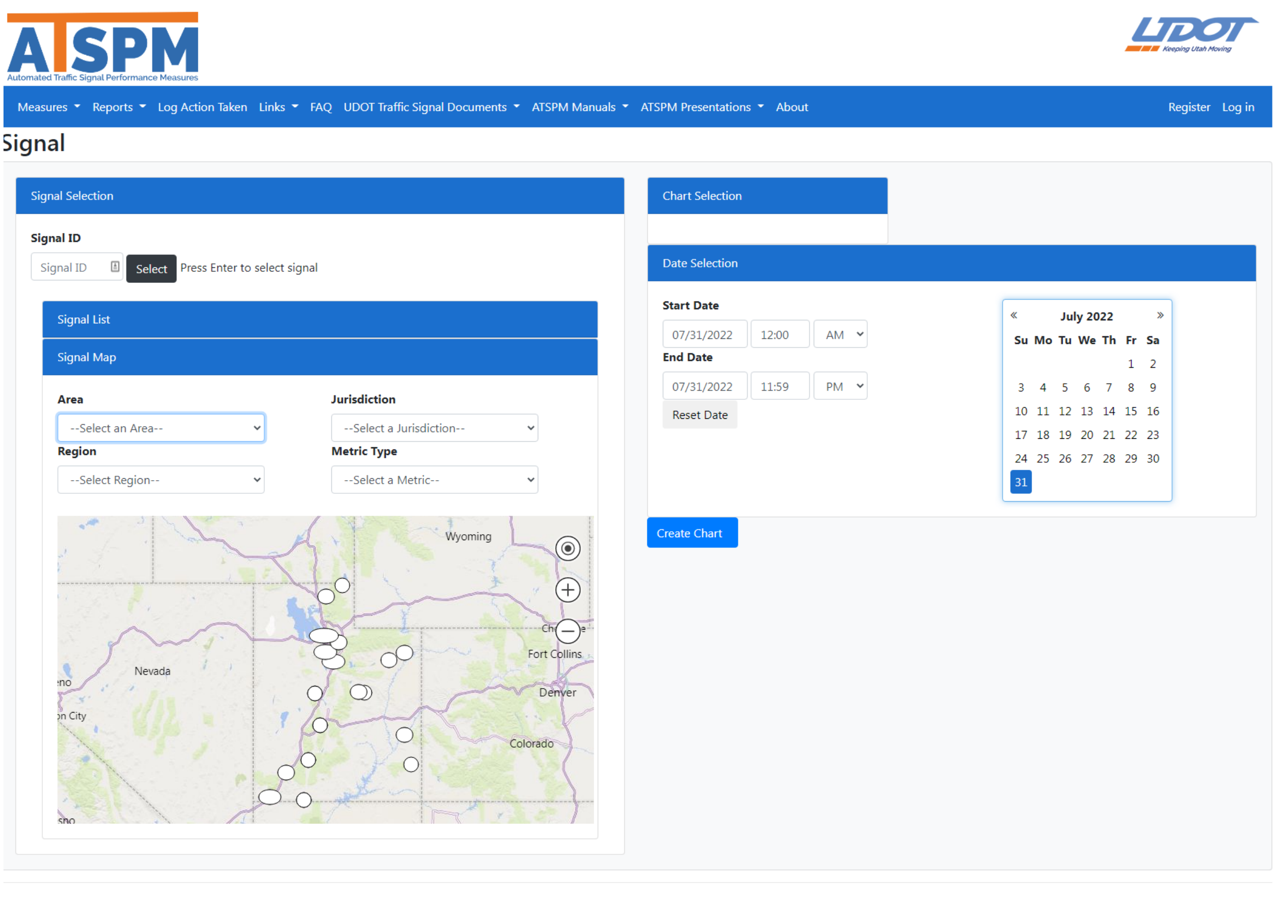


Figure 17. UDOT's ATSPM System.

Since implementing its ATSPM program, UDOT has noted a significant drop in public complaints and requests for traffic signal retiming. The ATSPM system quickly identifies problems such as failed detectors and emails notification to selected staff. These alerts allow UDOT to respond to issues before they become public nuisances and prolonged threats to mobility.

UDOT is collecting ATSPM at 96 percent of its 1,223 traffic signals. Partner agencies have connected 79 percent of their 852 signals and report data through the same centralized operation. Utah's end goal is to have all signals statewide connected and contributing data to its existing ATSPM system.

Budget

From November 2012 to February 2018, UDOT invested approximately 8,000 hours to the implementation and improvement of ATSPM. UDOT's 2017 annual maintenance budget was approximately $3,500 per signal. The agency's Traffic and Safety Division commits approximately $7 million annually for new traffic signals. UDOT estimates implementation costs for small ATSPM systems (about 50 signals) would be approximately $20,000. Large systems (on the order of 1,000 signals) would be approximately $230,000.

The ATSPM program was developed with high return on investment in mind. Resources invested in the program provide high-value benefits including the ability to assess and improve traffic flow, detect system malfunctions, and quantify multiple measures of performance. This reduces congestion and emissions and improves safety and operation and maintenance efficiency. UDOT's ATSPM implementation is designed to be cost-effective and not reliant on costly proprietary applications or a centralized traffic management system. Nevertheless, resource investments are needed to connect new signals and repair existing signal ATSPM hardware, as well as monitor and manage the system.

ATSPM Implementation

The UDOT ATSPM system operates independently of its central traffic signal system and is based around the following architecture (illustrated in Figure 18). High-resolution traffic signal controllers are used to store detailed signal phase and timing information as well as detector data associated with each equipped intersection. An Ethernet network and file transfer protocol connections are used to transfer high-resolution controller data from each intersection to the ATSPM central server every 15 minutes. ATSPM central servers provide data warehouse and web server functions. UDOT's ATSPM software was developed in-house by UDOT's Department of Technology Services. Data loggers are equipped with nonproprietary firmware to collect high-resolution data. UDOT's ATSPM allows for the interoperable use of controllers from different manufacturers and is publicly available under an open-source license at https://github.com/udotdevelopment/ATSPM/releases.

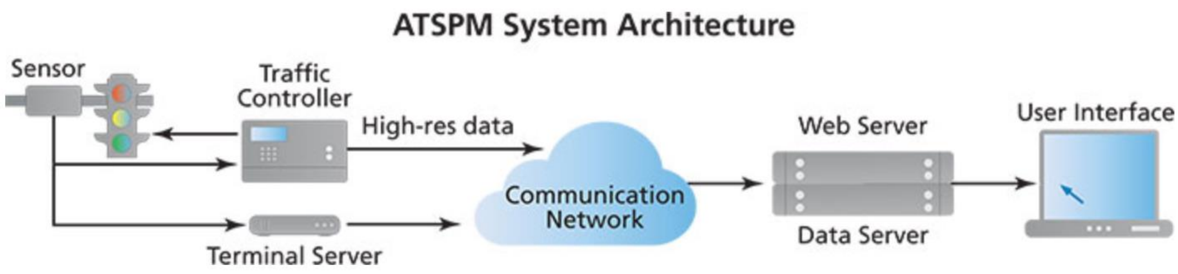


Figure 18. UDOT's ATSPM System Architecture.

Georgia Department of Transportation

As mentioned earlier, GDOT adapted the UDOT ATSPM platform and customized the platform to meet its needs. GDOT also added different dashboards for use by different types of users (i.e., decisions makers, engineers, and technicians). As shown in Figure 19, these dashboards are available through the modified main menu in the GDOT implementation.

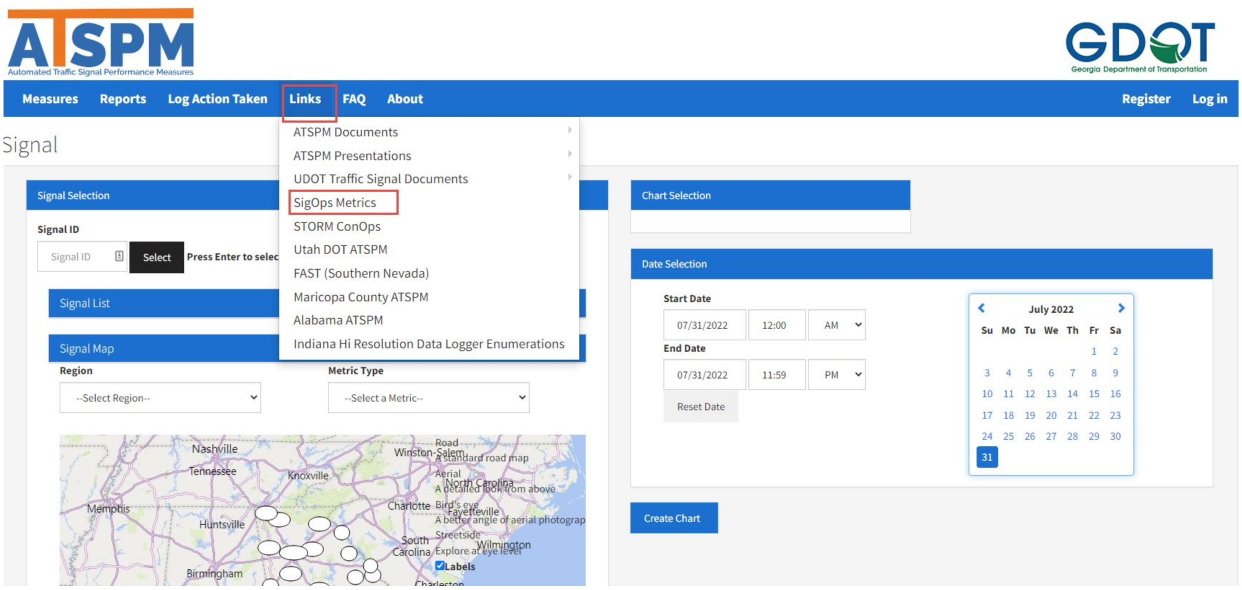


Figure 19. Link to Dashboards in the GDOT Implementation.

Figure 20 illustrates the one-month summary dashboard, which shows percent change in three categories of performance measures since last month. These categories include arterial performance, corridor volumes, and device and communications uptime. Reported arterial performance measures include throughput, arrivals on green, progression ratio, spillback rate, peak and off-peak period split failures, and travel time index. Definitions of these measures are provided under the "About" menu. Corridor volume measures include total volume, AM- and PM-peak volumes, and pedestrian actuations. Equipment measures calculated as percent values include vehicle detector availability, pedestrian push availability, and communications uptime. Another dashboard provides quarterly summaries of the same measures.

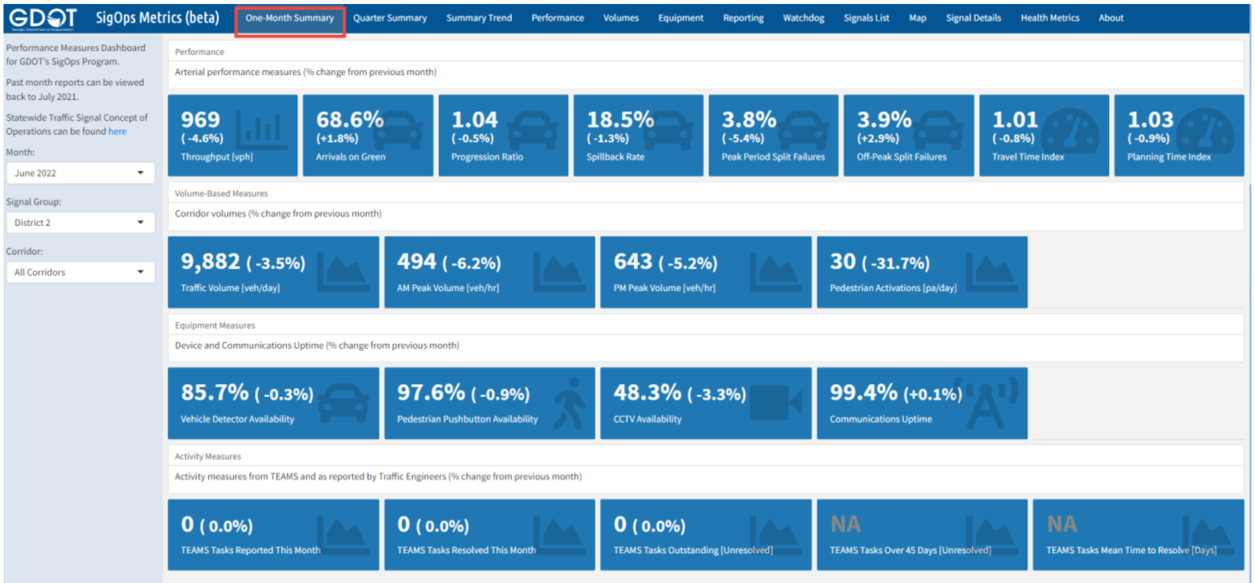


Figure 20. One-Month Summary Dashboard.

As illustrated in Figure 21, the summary trend dashboard provides the six-month trend information about the above performance measures (i.e., arterial performance, volume, and equipment) in the previous figure.

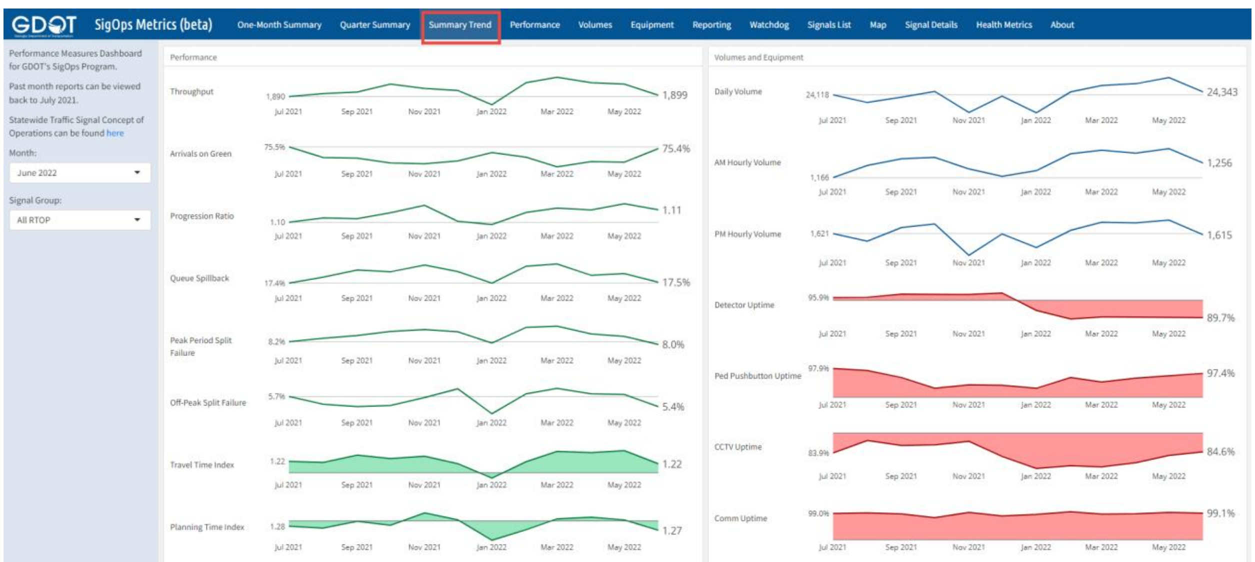


Figure 21. Summary Trend Dashboard.

Other dashboards provide further details. As show in Figure 22, the equipment dashboard provides detailed information about equipment issues. Summary information about the four categories is displayed at the top followed by detailed information about the selected category. In this illustration, details about detector uptime are displayed. Figure 23 illustrates the signal detail dashboard, which shows the daily adjusted count for detectors at the selected intersection for the selected month. Readers interested in additional information can access this information from the

GDOT website using the following link: https://sigopsmetrics.com/main/#section-one-month-summary.

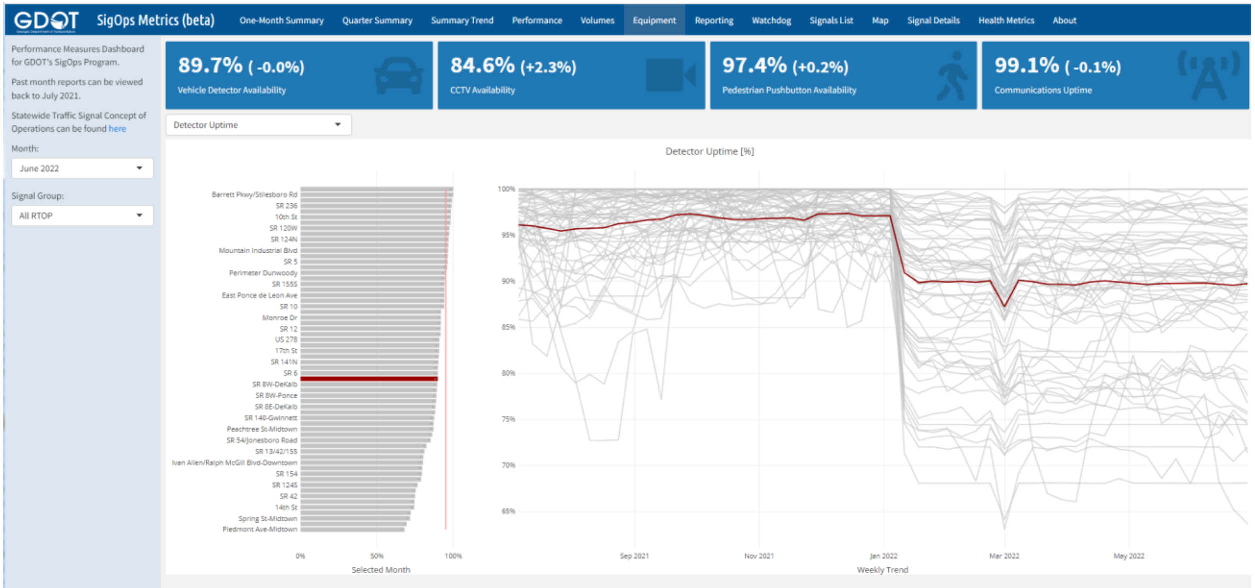


Figure 22. Equipment Dashboard.

Figure 23. Signal Detail Dashboard.

Iteris SPM

Iteris SPM is an example of a third-party (non-controller vendor) cloud-based solution. The Iteris installation package includes full implementation and phase setup and includes ongoing maintenance and system reviews. This system does not require special cabinet hardware but does require traffic signal controllers with high-resolution data logging capabilities. At least one firmware version of every TxDOT-approved controller provides this feature. The Iteris SPM system leverages the client (i.e., a city or DOT) agency's communications and detection infrastructure. The system uses a File Transfer Protocol (FTP) application installed on the agency server to grab high-resolution data from controllers configured in the system using their IP addresses. The data is then uploaded to the cloud and processed into alerts and reports. A web-based application provides access to these processed data. According to information provided by Iteris staff, the upfront cost of system installation and configuration ranges from $500 to $700 per intersection depending on the level of staff effort required. In addition, the average yearly cost of maintenance is around $400 per intersection. Groups of intersections (called regions) can be configured to allow for better management of intersections owned by the client. The system can be set up to provide alerts for different regions to different people.

Figure 24 shows the dashboard for Iteris SPM. This is the first screen a user sees after logging in. The main part of this screen is divided into two parts. The left side provides information about current operational (pink circle with an exclamation symbol) and maintenance (black circle with a wrench symbol) alerts. This information includes the number of alerts in each category followed by a listing of each alert with a description of that alert and a suggested performance measure to look at. The right side shows a map highlighting intersections meeting the selected criterion (in this case all intersections with at least zero alerts) using the slider bar at the top. Small circles with magenta color identify signals with zero alerts, small circles with any other color identify intersections with one alert, and larger circles identify intersections with multiple alerts. Pink circles identify intersections with operational alerts, black circles identify intersections with maintenance alerts, and pink plus black circles identify intersections with both types of alerts. Below is an example of each type of alert:

- Operational: An excessive percent of time, timing plan gaps out with vehicles left over to be serviced.
- Maintenance: Low count on an advance detector.

The “Reports” menu item at the top of the screen allows the user to see different performance measures for a selected intersection. Figure 25 shows a sample screen under this menu item. This screen also has two sections. The left side lets the user select an intersection (by clicking on the map), a performance measure, and a time frame (limited to a maximum of 48 hours). The “Draw Chart” button generates graphs on the right side of the screen. By default, it draws charts for all available phases, but users can click the phase number on the top to unselect a phase (or select an unselected phase). In Figure 25, Phase 4 is unselected. In this case, the charts show programmed splits (black squares), actual phase time, and reason for phase termination (here mainly force off and force off with presence) for Phases 2 and 6 on November 4, 2019, from 6 a.m. through 9 p.m.

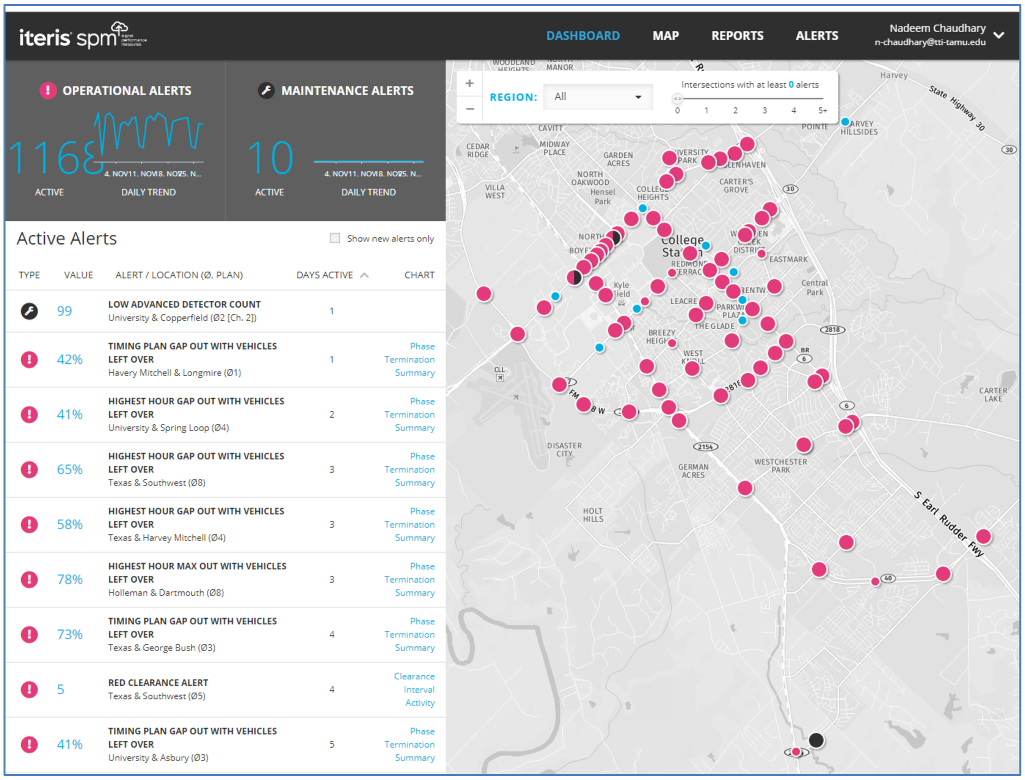


Figure 24. Iteris SPM Dashboard.

The Iteris SPM menu includes the following choices, but the menu only provides access to the measures applicable to a selected intersection:

- Coordination Diagram.
- Phase Termination Summary.
- Phase Termination Detail.
- Turning Movement Counts.
- Preempt/Transition.
- Clearance Interval Activity.
- Wait Time.

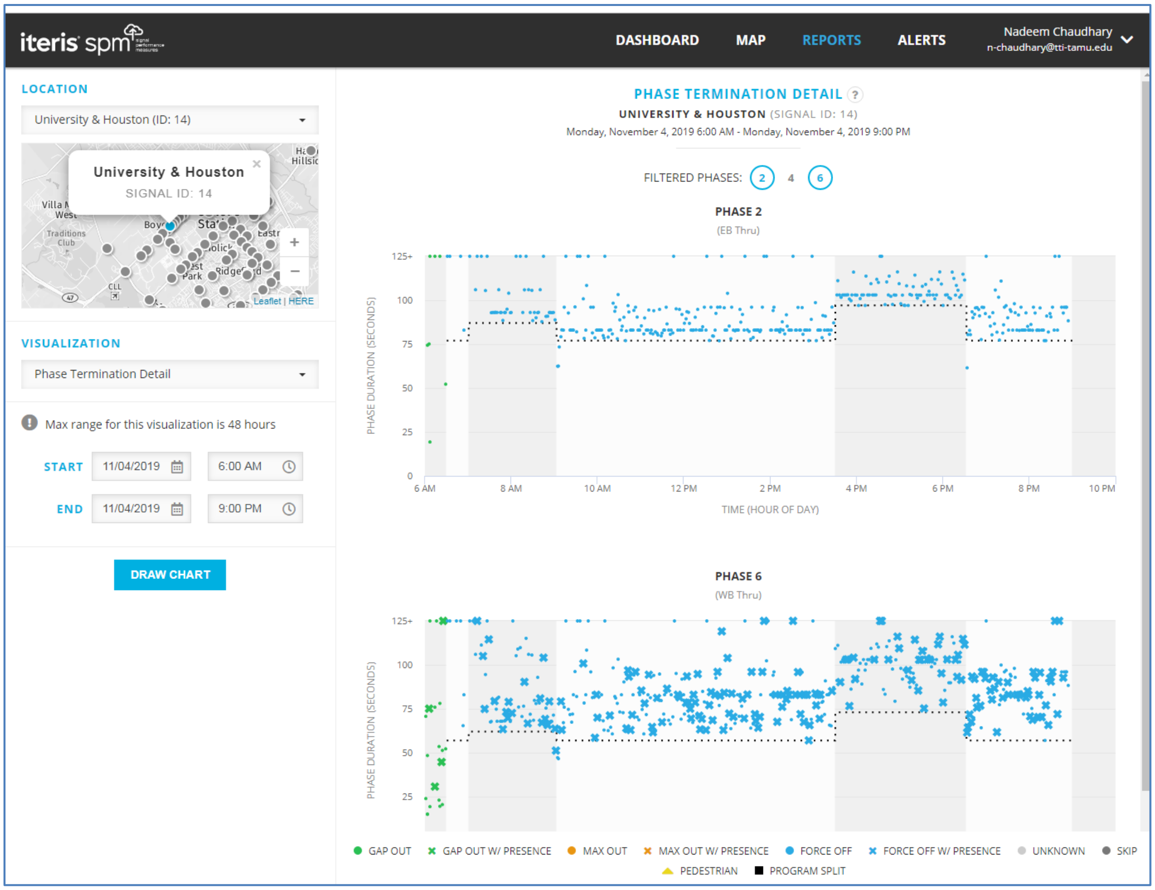


Figure 25. Iteris SPM Phase Termination.

Figure 26 illustrates the coordination diagram for Phases 2 and 6 for a selected intersection and selected plan. This diagram shows vehicle detections during green, yellow, and red intervals. It also displays percent of vehicles arriving on green (57.8 percent and 47.8 percent for Phases 2 and 6, respectively), percent of cycle the phase is green, and platoon ratio (an indicator of quality of progression). Hovering the mouse cursor on different parts of the screen (a data filed or graph) provides additional information (i.e., definition of a data item, or data value).

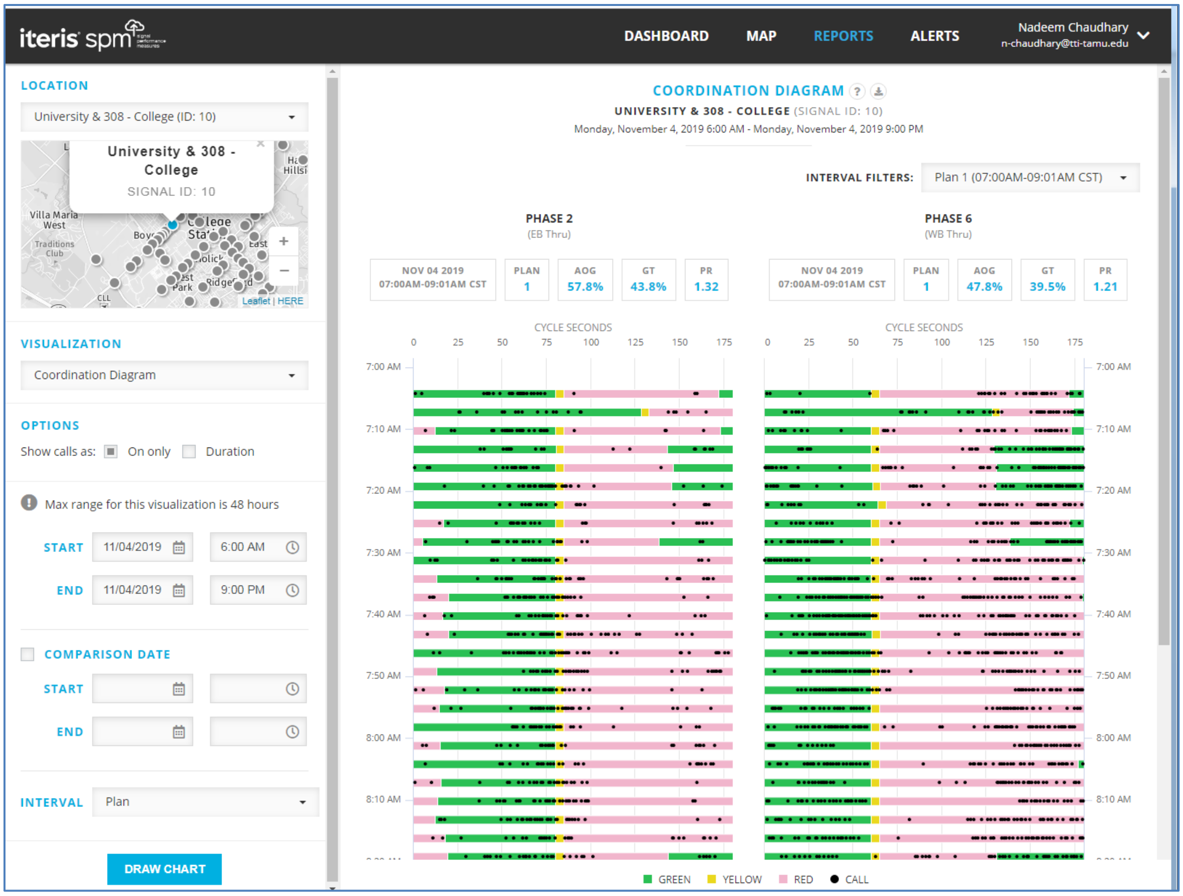


Figure 26. Iteris SPM Coordination Diagram.

Miovision ATSPM

The Miovision ATSPM system uses a proprietary hardware device—called TrafficLink—to collect controller event data (*13*). It sends collected controller event data to a cloud via a cellular connection using a secure virtual private network channel. TrafficLink can be installed in any existing cabinet, eliminating the need for upgrading the controller or cabinet. Wireless communication allows the system to be installed in remote locations. TrafficLink also supports Wi-Fi and uses snooping techniques to grab media access control (MAC) addresses of devices to assess their travel time between multiple points. Even though a MAC address does not contain any personally identifiable information, Miovision uses encryption techniques to ensure that a single driver's commute cannot be correlated over time (*14*). TrafficLink connectivity is provided via a single wireless antenna capable of both Wi-Fi and cellular communication. For locations lacking detection, Miovision also offers a single camera-based solution (Smartview 360) to provide vehicle and pedestrian detection at all approaches at an intersection.

Miovision ATSPM accompanies a web-based portal that automatically generates alerts and performance measures. Automatic alerts are provided via configurable SMS and email messages when any of the following conditions are detected at any intersections (*13*):

- Signal in flash.
- Power loss.
- Uninterrupted Power Supply (UPS) activity.
- Faulty detector.
- Loss of connection.

Depending on available detection infrastructure, TrafficLink performance measures include (*15*):

- No detectors.
    - Red/Green Allocation: The proportion of green time allocated to each approach and movement.
    - Preemption Summary: Reports of preemption events, durations, and triggers, including railroad crossings or emergency vehicle preempts.
- Stop-bar detection.
    - Red and Green Occupancy Ratio: Gauges the demand for the various phases based on the ratio of time that vehicles are present in the associated movements. This allows for tuning of split times between phases.
    - Purdue Split Failure: Industry-standard metric that charts the frequency of split failure occurrences, an incident where green signal time fails to meet the vehicle volume demand.
    - Simple Delay: Simplified approach delay measures the time between detector activation during red signals and movement service at start of green signals. Simple delay approximates the overall delay experienced by intersection users.
- With advanced upstream detection.
    - Arrival Volumes: Counts of total vehicle traffic through an intersection from each approach.
    - Arrivals-on-Red versus Arrival-on-Green: Counts of total vehicle volume arriving during red or green, giving a rough sign of progression quality for the given movement.
    - Purdue Coordination Diagram: A graphical representation of individual vehicle arrivals relative to cycle time (red, yellow, and green), highlighting arrival characteristics, and platoon progression quality.
    - Average Delay: The length of time vehicles are delayed at a congested intersection.

According to a January 2019 memorandum (*16*), it cost Pima County, Arizona, $11,400 per intersection to install the Miovision system at 103 intersections. This system also includes camera-based volume data collection capability as well as Wi-Fi sniffer. The yearly data maintenance fee of $998/intersection provides the full data analytics capability to this agency.

USE CASES OF ATSPM SYSTEMS

This section reproduces selected ATSPM use cases reported in a recent report prepared for UDOT (*17*).

System Health Monitoring

For an ATSPM system to perform as intended/designed, system health should be good. In other words:

- Al controllers must have power and are producing data logs.
- There are no failed detectors.
- All communication links are up and running.

However, since the above subsystems can and do fail, an ATSPM system must have the capability to monitor and report conditions pointing to potential malfunctions. The open-source ATSPM labels this feature as the "Watch Dog" function. ATSPM Watch Dog sends email alerts to designated individuals when it detects conditions that can be caused by above events.

Too Few Records during a Specified Time Period

In the UDOT implementation, the Watch Dog function sends email alerts whenever there are less than a specified number of (i.e., 500) records within a 24-hour time widow starting at 12 a.m. Figure 27 illustrates this action using the Phase Termination Chart.

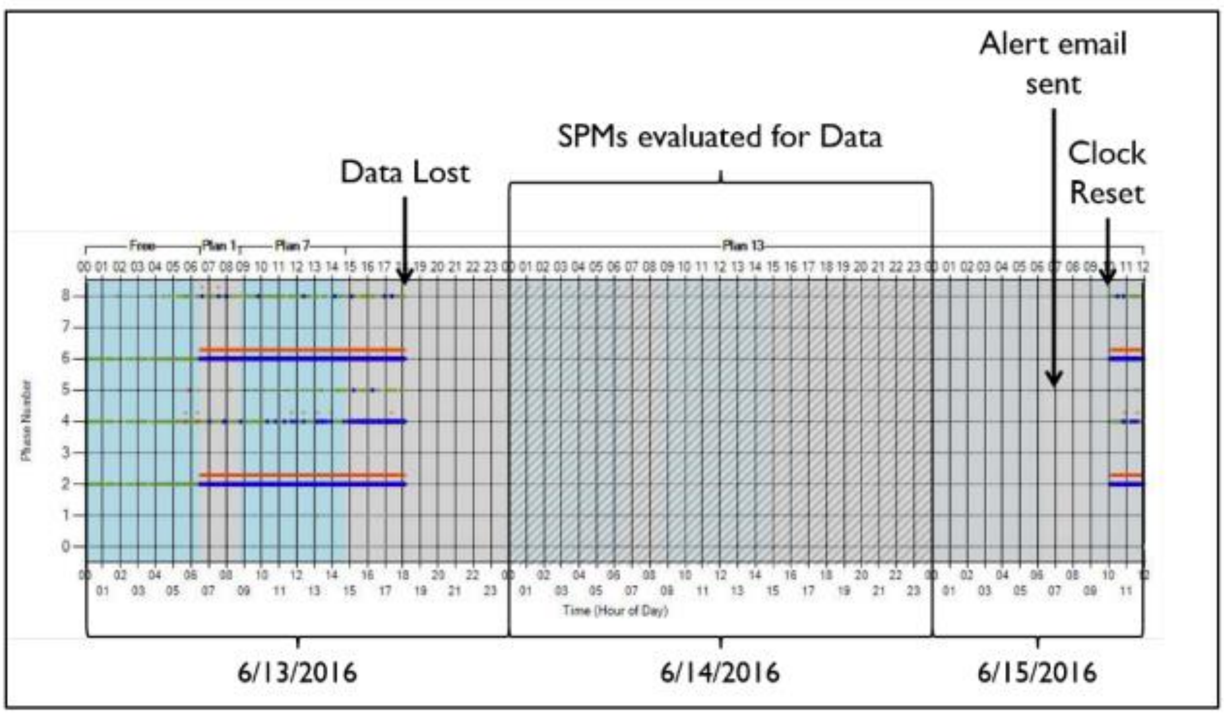


Figure 27. Phase Termination Chart Showing Missing Data.

Upon receipt of an alert, it is the user's responsibility to investigate the exact cause of missing data. The problem could be as simple as a failed communication link. However, it could be a case where the traffic controller was replaced, but the new controller either did not have appropriate firmware or was not configured properly.

Too Many Force-Off Occurrences

The Watch Dog sends an email alert if a signal phase experienced more than 90 percent force-offs in at least 50 activations between 1 a.m. and 5 a.m. the same day. Force-off only applies during coordinated operation. Figure 28 illustrates the application of this check using the Phase Termination Chart. This condition could be due to a bad detector input or a stuck pedestrian detector.

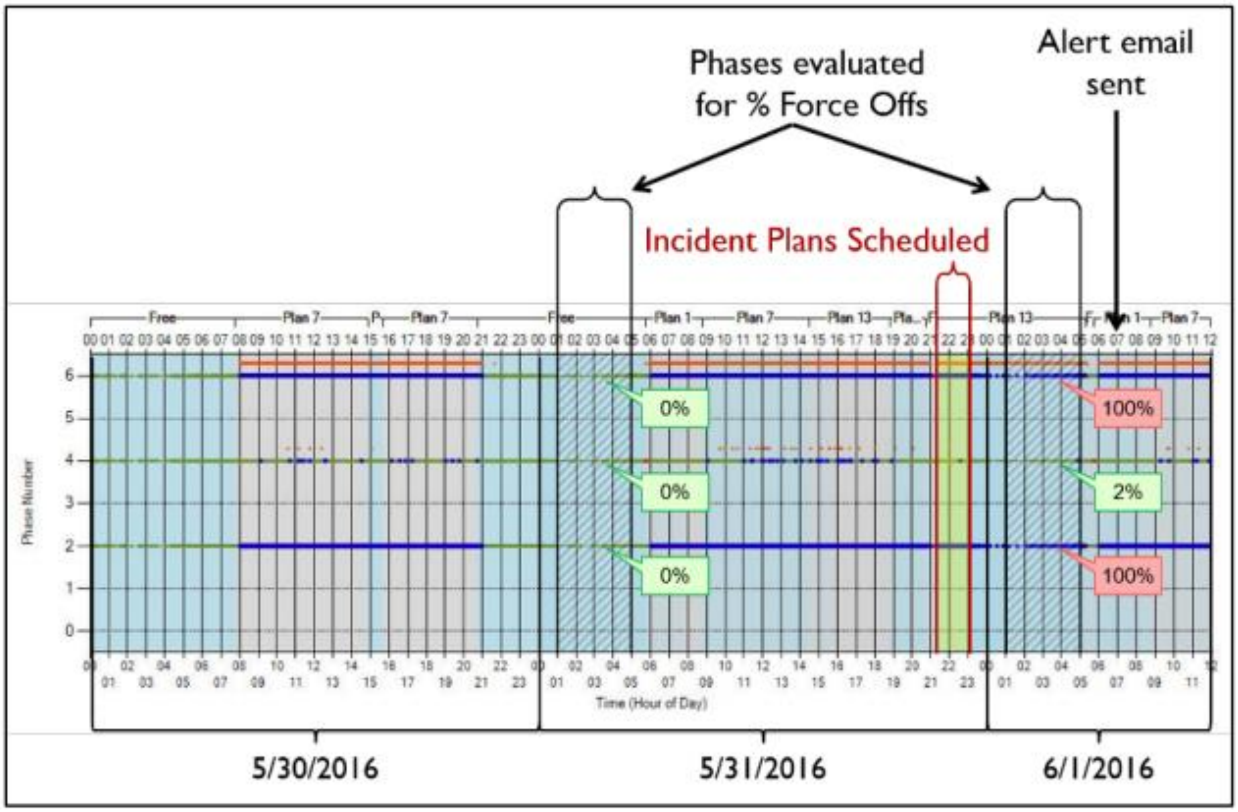


Figure 28. Alert Generated When Too Many Force-Offs Detected.

Too Many Max-Out Occurrences

The Watch Dog reports the signal ID if a phase has 90 percent max-outs in 50 activations between 1 a.m. and 5 a.m. the same day. This information can help identify faulty detectors, as illustrated in Figure 29.

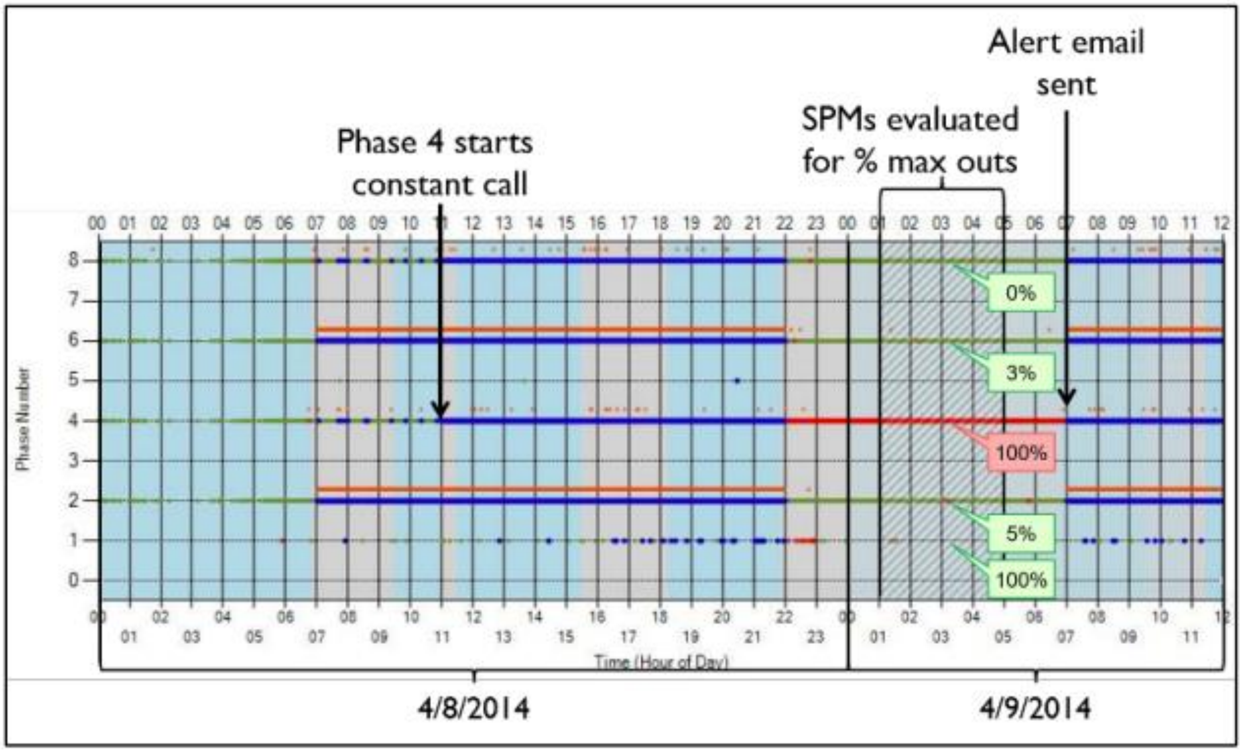


Figure 29. Alert Generated When Too Many Max-Outs Detected.

Low Advance Detection Counts

The Watch Dog reports intersections where a detector configured for PCD has a recorded count of less than 100 vehicles between 5 p.m. and 6 p.m. There could be several reasons for this, including:

- No data, as discussed earlier.
- Phase data present, but no or low count data. This case may arise due to a faulty detector or a detector configuration issue.

Figure 30 illustrates the chain of events using PCD. Here, the system stopped receiving detections during the early morning hours on December 11, 2016; detector volumes were evaluated using 5 p.m. to 6 p.m. data from that day, and the alert was sent the next day. The sensor was reset by noon the following day, and normal operation resumed.

High Pedestrian Activation Occurrences

The Watch Dog sends an email alert if a signal phase detects more than 200 pedestrian activations between 1 a.m. and 5 a.m. on a signal day. This is in indication of a stuck pedestrian button. Figure 31 illustrates the alert generated due to this condition.

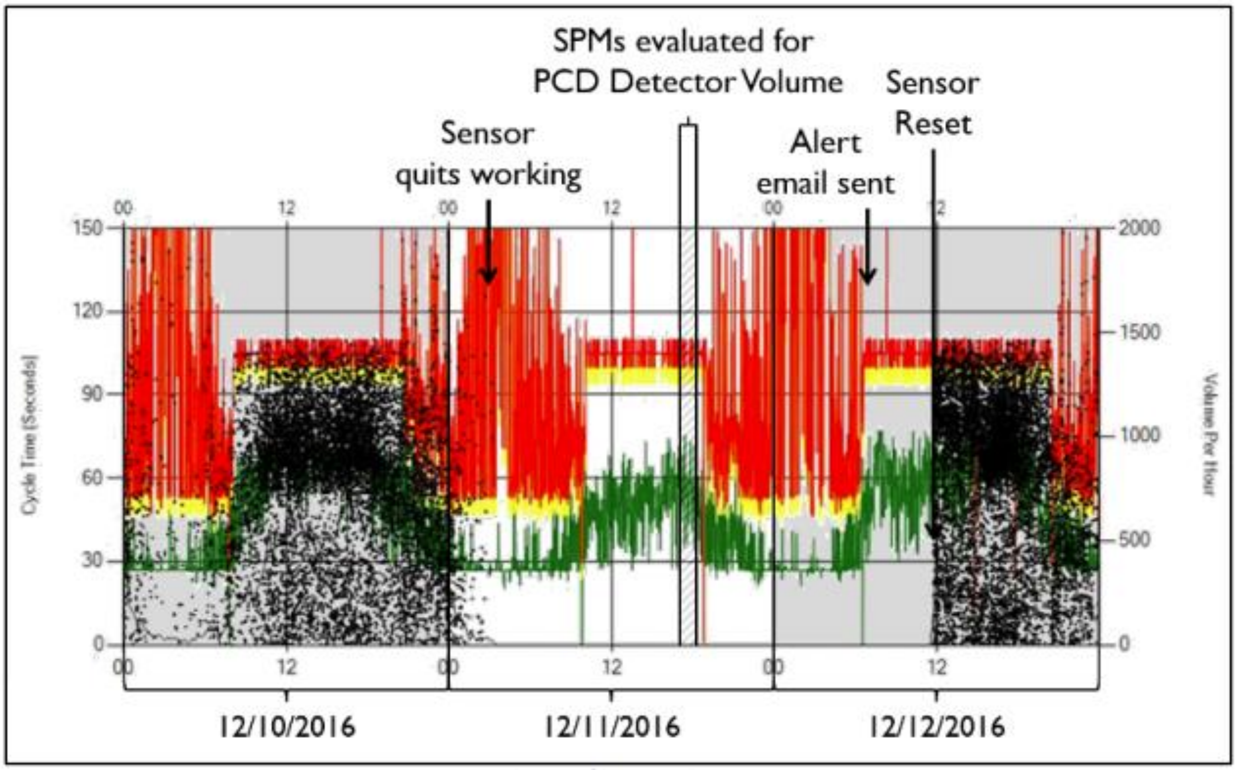


Figure 30. Detection of Low Counts.

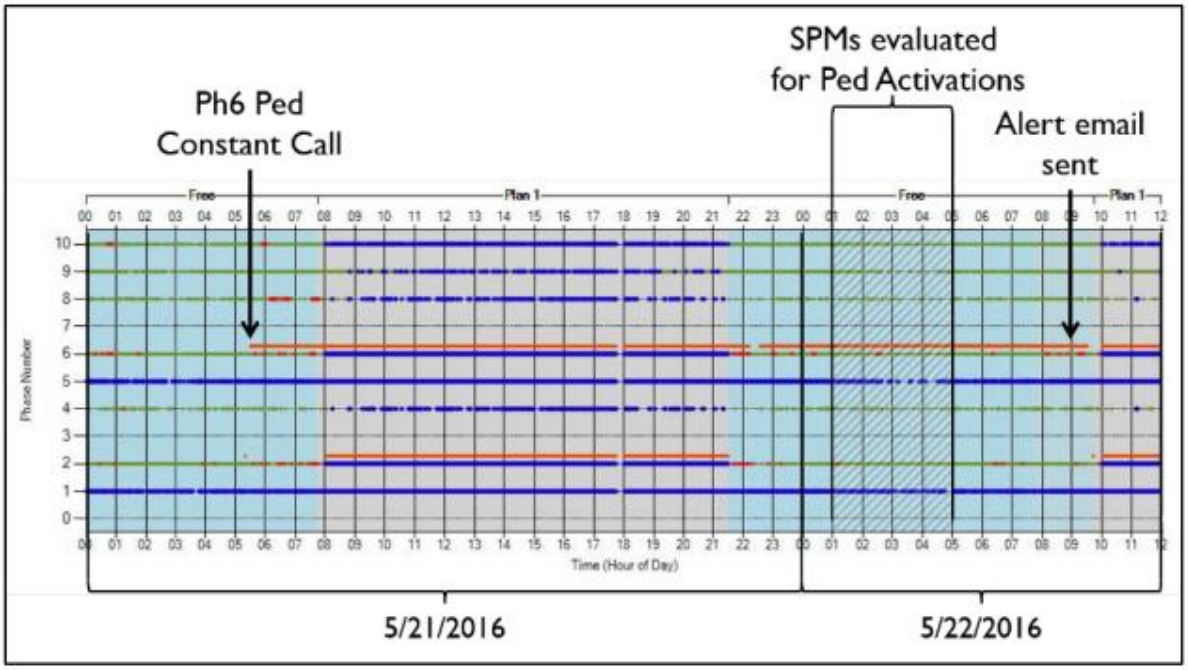


Figure 31. High Number of Pedestrian Detections.

Common Complaints

Frequently, operators receive complaints from motorists of various problems they encounter. Having access to an ATSPM-type system can support a quick diagnosis to minimize the response time to troubleshoot the problem at the intersection. Following are some examples of complaints received by the operators.

Not Enough Green Time

There could be several reasons for drivers experiencing this issue.

Case 1: A Bad Detector

Figure 32 shows a case where there were multiple reports that the eastbound left-turn phase did not have adequate green time. A review of the split monitor chart (left side of figure) for a.m. peak conditions, during which the phase has heavy demand, showed that the average phase time was 32.7 seconds with the phase gapping out 91.4 percent of the time. Troubleshooting revealed a bad sensor. After the sensor was replaced, average phase time increased to 50.4 seconds, and percentage of gap outs reduced to 60.3.

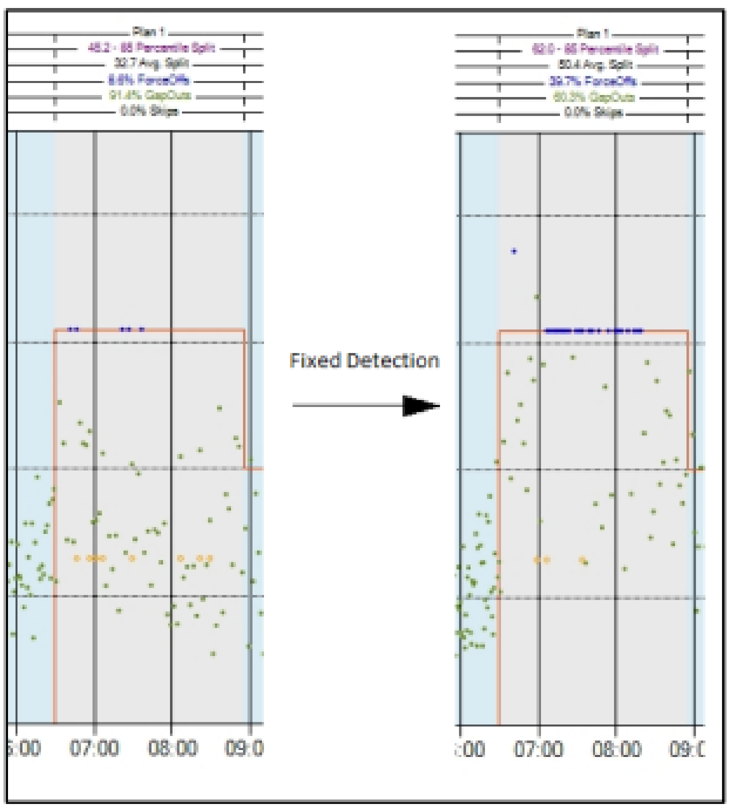


Figure 32. Use of Split Monitor Chart to Identify a Bad Detector.

Case 2: Split Failure

In another case illustrated in the top part of Figure 33, the westbound left-turn phase failed to clear numerous times during the day, as indicated by vertical yellow lines on the Split Failures chart. The signal was retimed, which resulted in a significant reduction in split failures as shown in the bottom part of this figure.

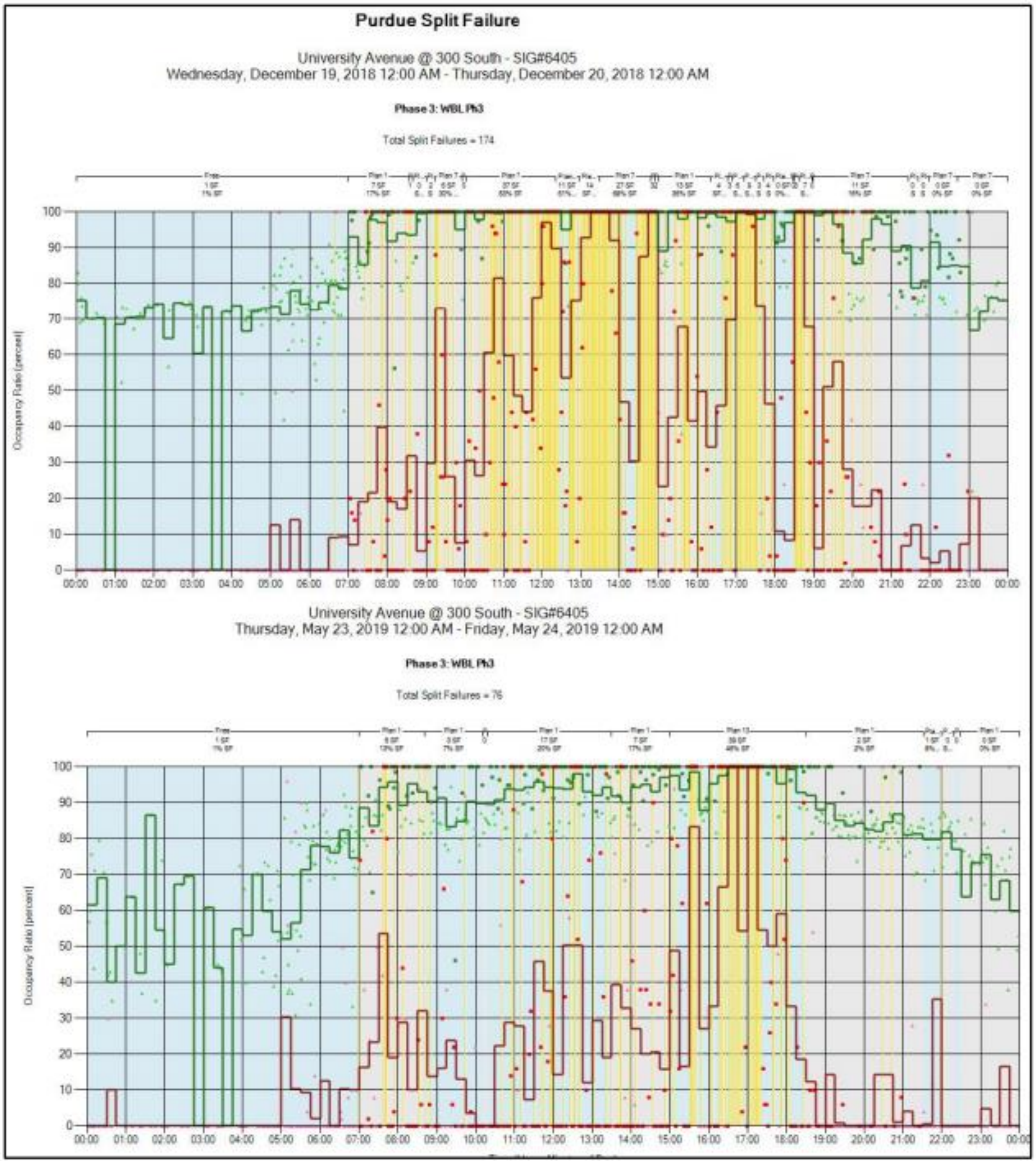


Figure 33. Detection of Split Failures and Correction through Signal Retiming.

Skipped Movement

This happens when a vehicle is present, but the phase is not served. It happens because of detection issues. In the Figure 34 illustration, a movement reported 12.2 percent skipping, which became 0 percent after detector adjustments.

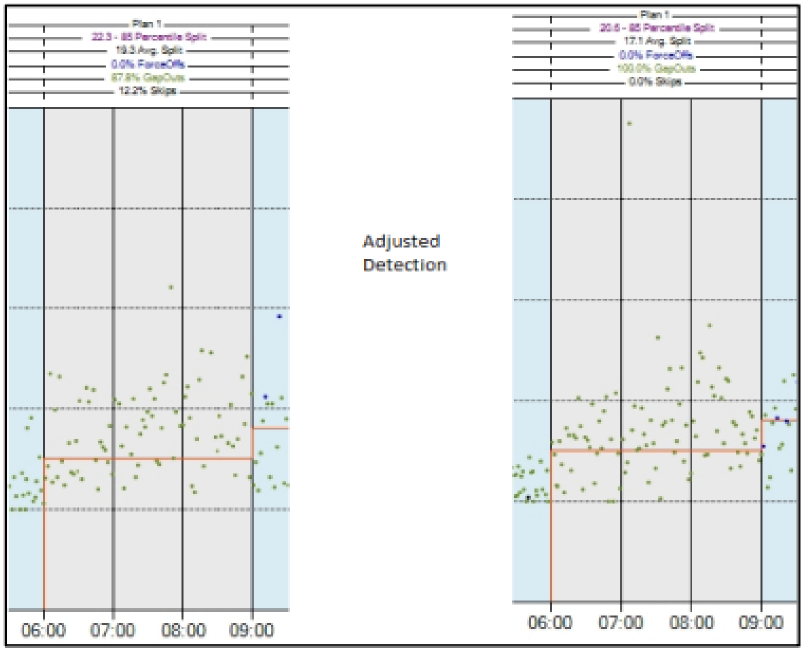


Figure 34. Bad Detector Causing Phase to Skip.

Phase Started to Max Out

Figure 35 shows the split monitor chart for a case where a utility contractor damaged a loop on the side street. As a result, the side street phase started maxing out during free operation. The chart helped in identifying the issue.

BIU Errors

The phase termination diagram in Figure 36 shows a case where all phases started to max-out (midnight to just before 10 a.m.). In this case, the cause was a bad detector BIU where all movements were connected to this one source. A review of controller status helped with the diagnosis, which required a filed visit for repairs.

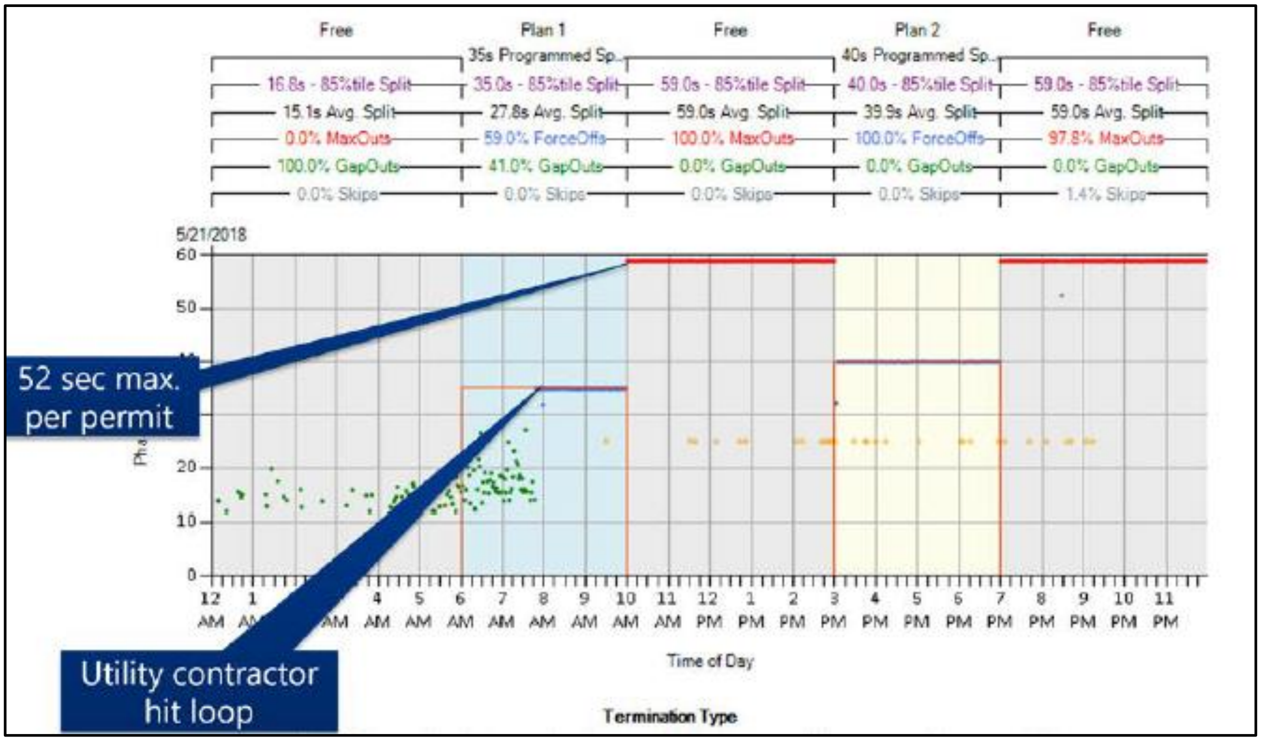


Figure 35. Split Monitor Chart Helps Identify a Damaged Detector.

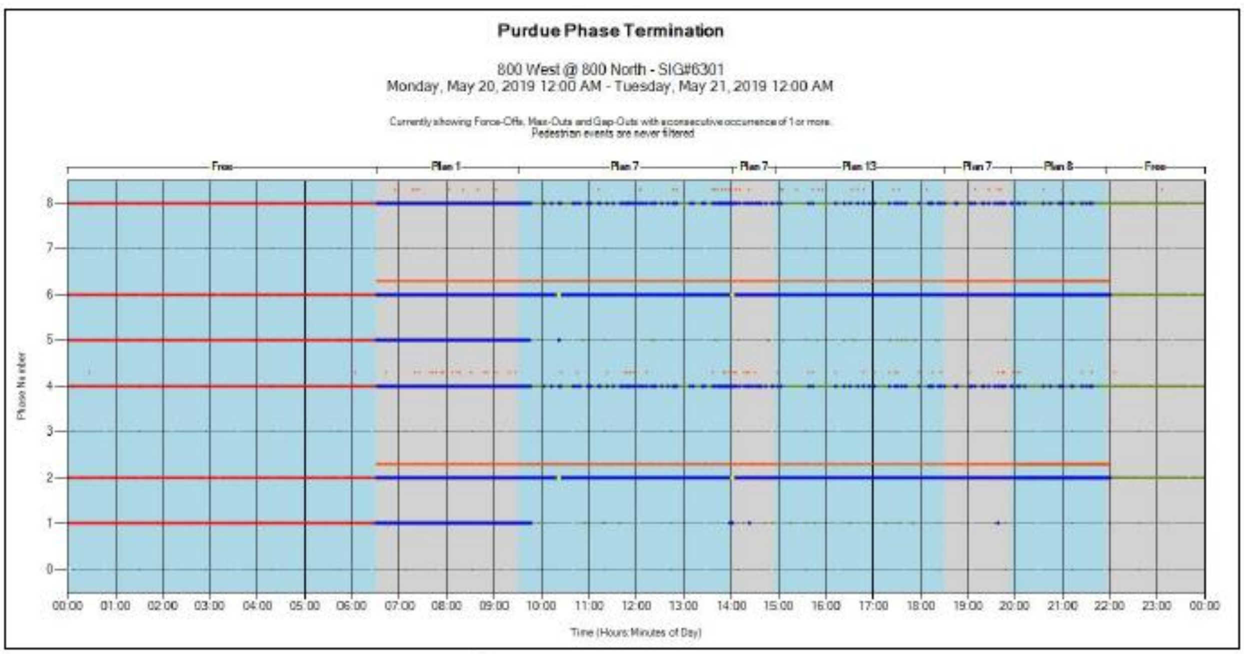


Figure 36. Phase Termination Chart Helps Identify a Bad BIU.

Signal Coordination Case Studies

Split Monitor

Figure 37 shows a case from Georgia where the average and 85th percentile splits for Phase 8 are 17.2 and 21 seconds, respectively, when the plan is running. For this plan, the programmed split for Phase 8 is 34 seconds. This data shows that the phase time could be significantly reduced (by up to 13 seconds) and remain adequate to serve traffic demand.

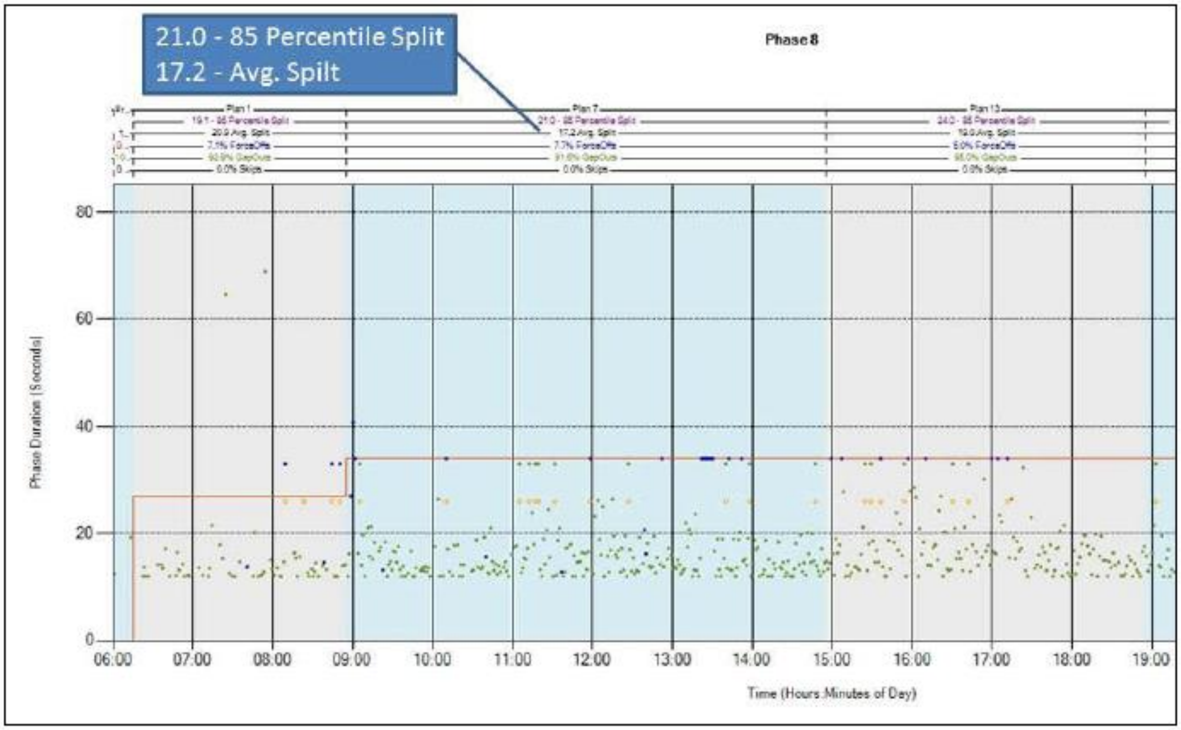


Figure 37. Use of Split Monitor Chart to Identify Split Adjustment Need.

Split Failure

Figure 38 illustrates a case where the split failure chart was used to identify an inadequate split. This figure shows that between 9 a.m. and 7 p.m., there were 97 split failures for this left-turn phase. The agency increased the splits for this phase in Plans 7 and 13 by 7 and 13 seconds, respectively. The split failure chart in Figure 39 verifies that these changes reduced split failures for the same time to 55, a 43 percent reduction.

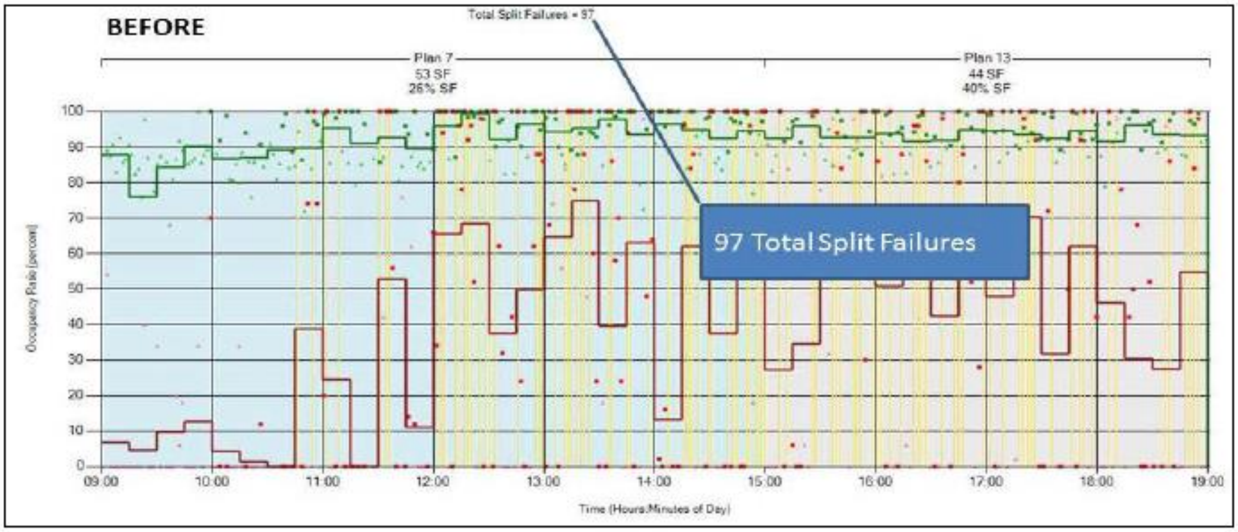


Figure 38. Split Failure Chart Used to Identify Need to Adjust a Split.

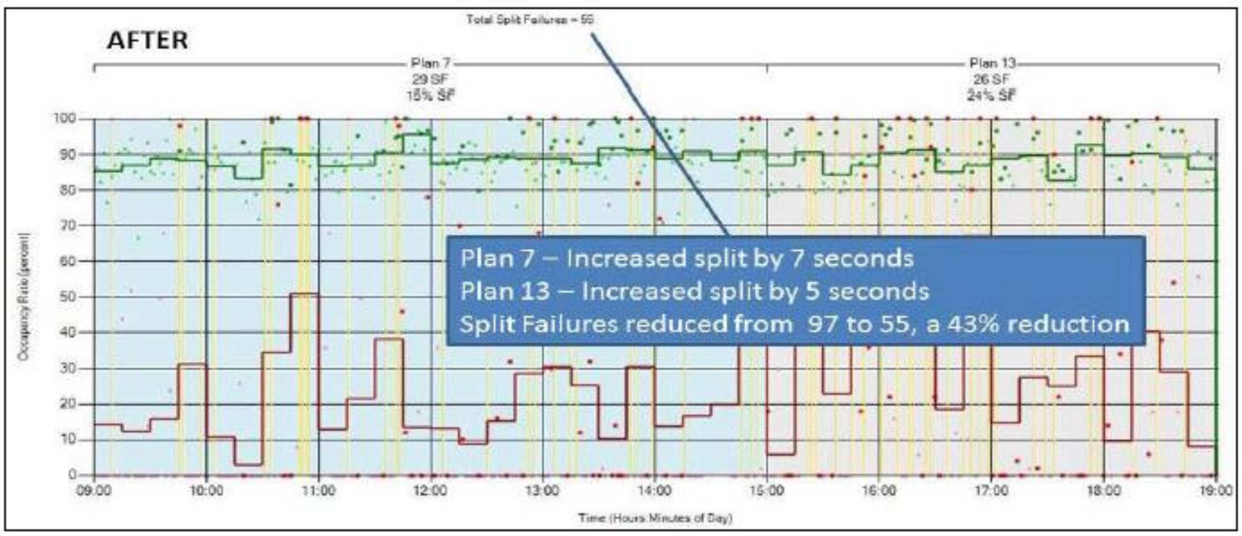


Figure 39. Split Failure Chart Verifies the Positive Effects of Increased Split.

Cycle Length Analysis

Case 1: Need to Increase the Cycle Length

Figure 40 illustrates a case where the phase termination chart showed a high number of force-offs for all phases, indicating that the cycle length needed to be increased.

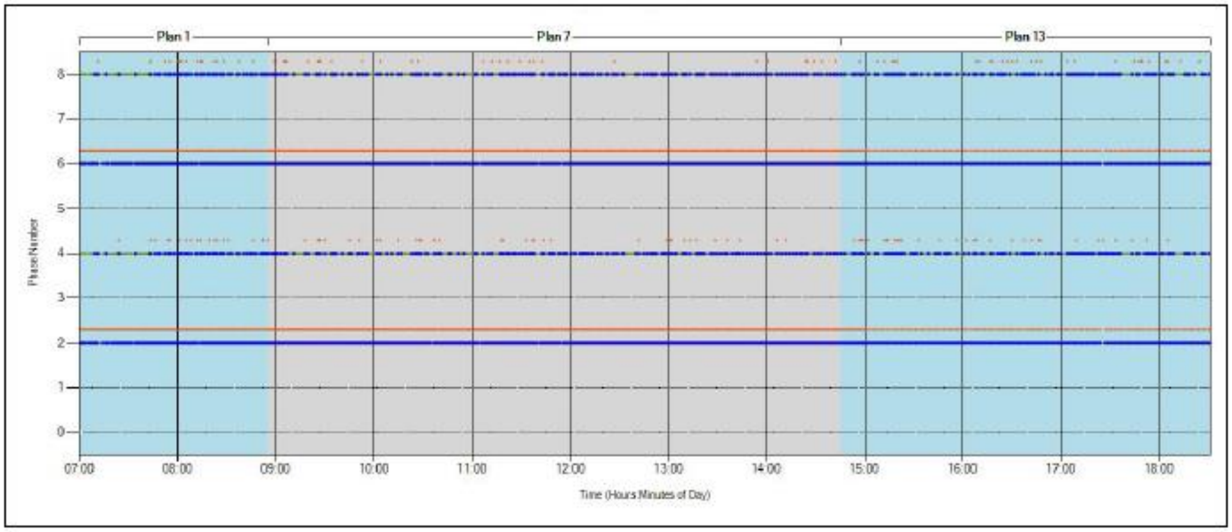


Figure 40. Phase Termination Chart Helps Identify the Need to Increase Cycle Length.

Case 2: The Cycle Length Could Be Reduced

The PCD in Figure 41 illustrates that the subject coordinated phase has around 30 seconds of extra time at the back end of the phase. As illustrated in this figure, most of the platoon from the upstream signal clears the intersection within 90 seconds of the plan cycle length of 110 seconds. This indicates that from the perspective of this phase, the cycle length can be shortened by 30 seconds. However, additional Measures of Effectiveness (MOEs) should be reviewed before any action is taken. These MOEs include PCD for the opposing coordinated phase, phase termination data for non-coordinated phases, and cycle failure data.

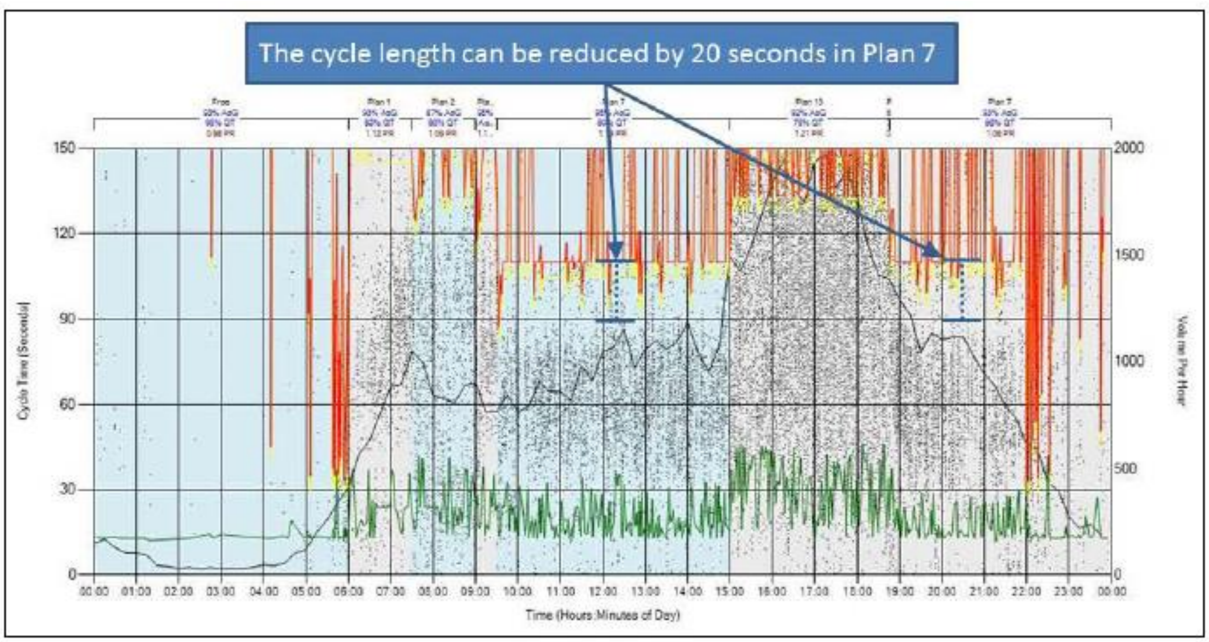


Figure 41. Use of PCD to Identify That Cycle Length Could Potentially Be Shortened.

Case 3: Identifying Programming Errors

Figure 42 illustrates a case of non-optimal coordination. In this case PCD showed that a significant number of vehicles were arriving during the red. Investigation revealed that this was caused by a programming error where the offset reference point was incorrectly set at the beginning of green instead of the beginning of yellow.

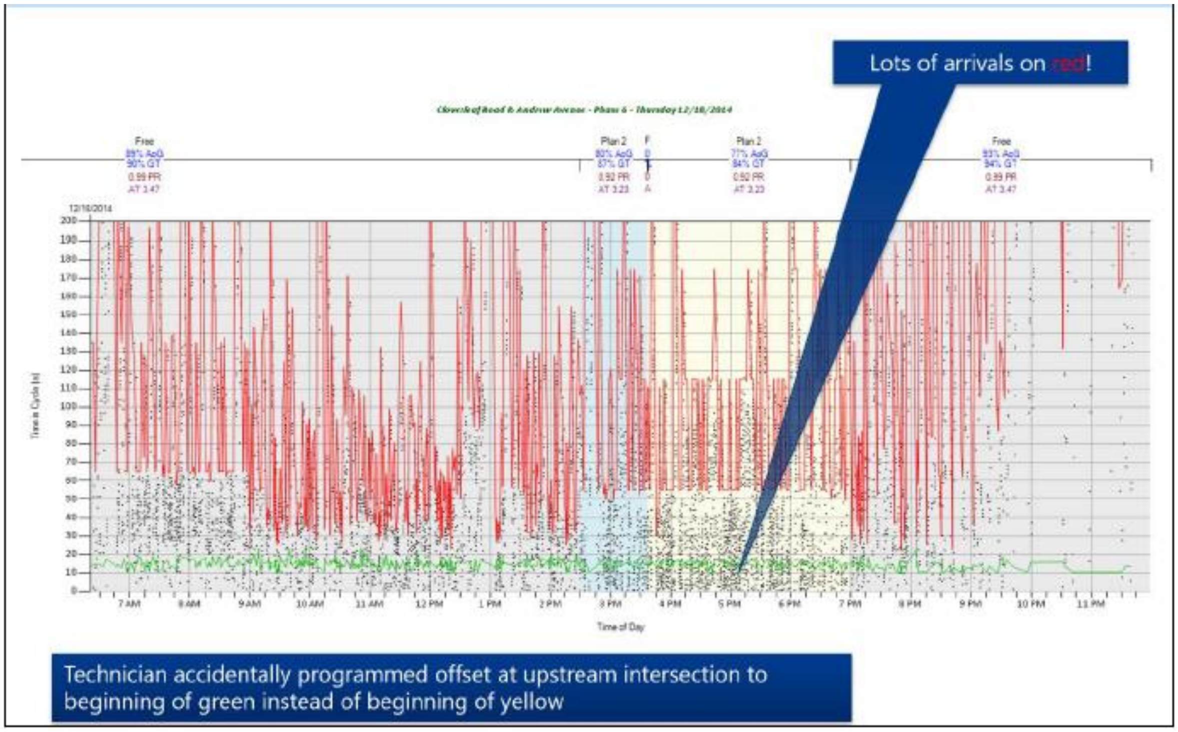


Figure 42. Use of PCD to Identify a Programming Error.

The programming error was corrected, which increased vehicles arriving on green from 77 percent to 95 percent, as shown in Figure 43.

Identifying the Need for Signal Retiming

It is a common DOT practice to evaluate corridor signal operations at preselected intervals (i.e., every three or five years) to identify which corridors need to be retimed. An ATSPM can do a better job by identifying corridors needing to be retimed based on degraded performance. Figure 44 illustrates a case where the tracking of arrivals on green along a corridor over a period of 1.5 years identified signal retiming need. If the agency had not tracked this performance measure, another 1.5 years would have gone by before this system would have been evaluated based on the department policy of considering retiming every three years. This data-supported decision-making provides for a more proactive approach where retiming is done only when needed. In addition, such data from all corridors can be compared to prioritize projects competing for limited yearly resources.

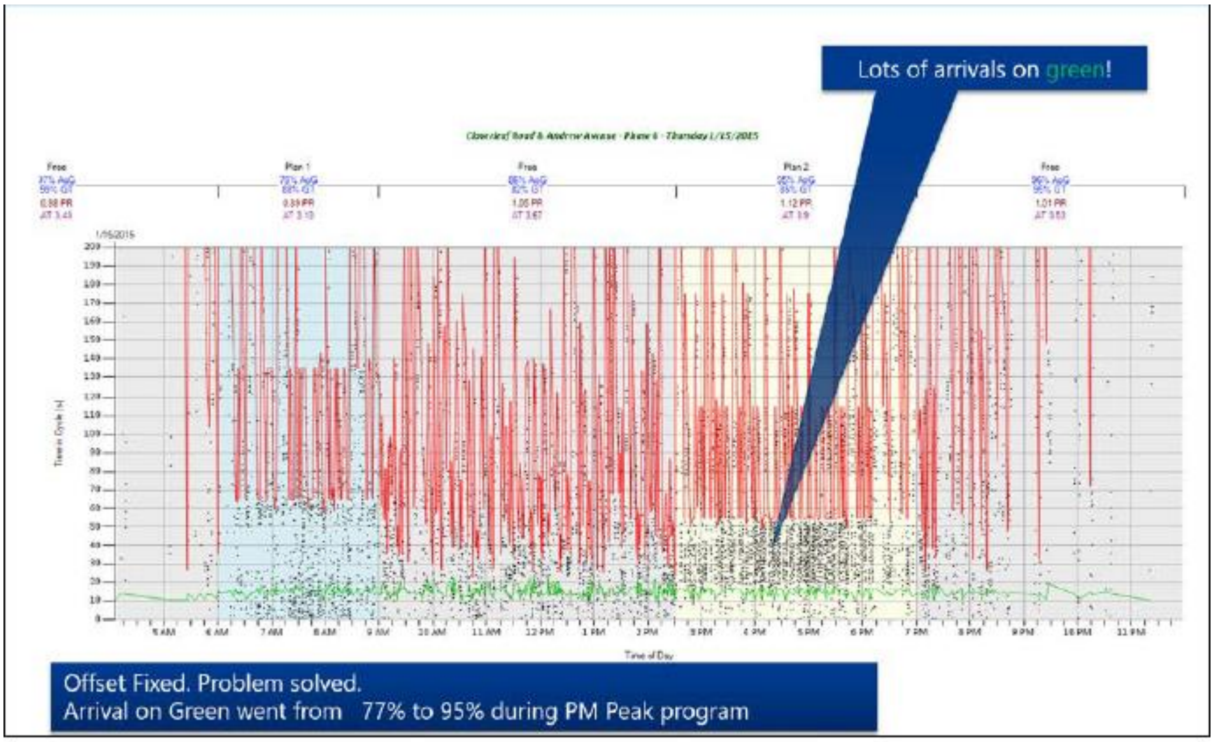


Figure 43. PCD Verifies the Positive Impact of Error Correction.

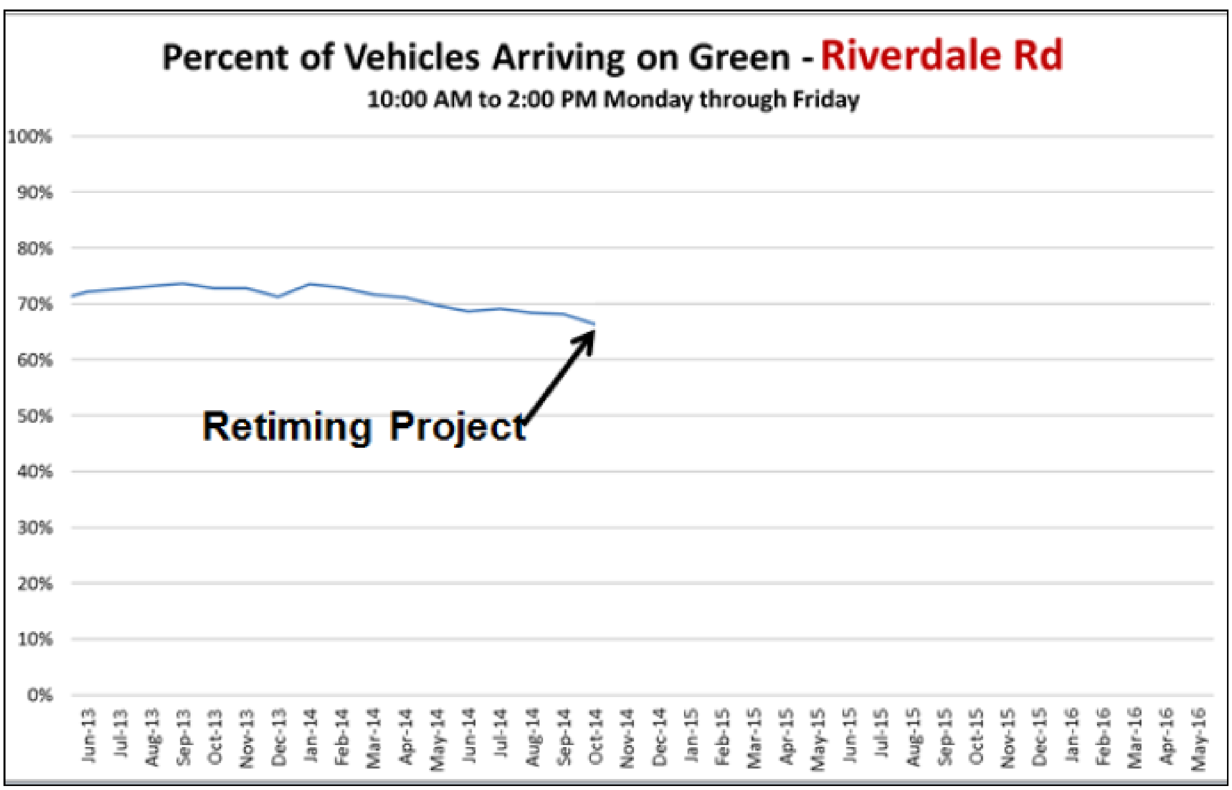


Figure 44. Identification of Signal Retiming Need Using Arrival on Green Trend.

TXDOT STATE OF PRACTICE AND USER NEEDS

TxDOT is a large agency with a central office responsible for statewide matters and 25 districts responsible for the operations and maintenance of transportation infrastructure. The characteristics of areas covered by these districts range from rural (with a few signalized intersections) to highly urbanized with many signalized intersections and diamond interchanges operating as coordinated systems. As such, there is a wide range in the traffic signal–related needs, available infrastructure, and available resources. Some of these districts rely heavily on the central Traffic Operations Division, while others mostly operate signals on their own.

During this project, researchers used various methods to gain an understanding of the needs of TxDOT staff as they relate to the maintenance and operation of a traffic signal system, their knowledge of and any experiences with ATSPM systems, and how an ATSPM system might help them do their jobs better. Key findings of these efforts are summarized below.

About five years ago, staff from the Traffic Operations Division implemented a pilot installation of the UDOT ATSPM system with the help of a consultant. They used the system to test the high-resolution data collection capabilities of TxDOT-approved controllers. The consultant also modified the open-source system to enable cellular modem–based communication. Traffic Operations Division staff worked with several districts to link/configure their signals to the ATSPM system. The San Antonio District, having eight signals in the system, was the largest contributor to this pilot deployment. However, San Antonio District staff found that the system was not easy to use in that it required regular monitoring, and the limited human resources did not permit that. Unfortunately, the champions of this pilot system, both in Austin and San Antonio, retired soon after that, and the other staff was reassigned to other projects. At the time this information was obtained in November of 2019:

- UDOT ATSPM was still running.
- Another consultant had been assigned to maintain the system, but many of the signals, including several signals from San Antonio, were offline. Four of the eight San Antonio signals went offline because the signal controller was upgraded but never reconfigured to work with the ATSPM system.

The result of TxDOT staff providing this information was that the pilot deployment has been effectively abandoned. Furthermore, based on this experience TxDOT staff believed that a path to move forward would be a commercial turnkey ATSPM solution with a reasonable per-intersection per-year subscription fee.

The TxDOT Houston District is the only district that has formally embarked on the deployment of an ATSPM system by purchasing around 30 licenses of the Econolite eAdaptive system, which also includes ATSPMs. One license is required for each supported signal. District staff decided to use this route because they do not have the resources required by the open-source

ATSPM solution. The primary objective is to use the system to proactively manage flow along arterial corridors without human intervention. So far, signals along three arterial corridors have been configured in the system. These corridors include SH 242, NASA Road 1, and a section of FM 1960. Econolite eAdaptive mode is based on the Purdue Link Pivot algorithm for offset optimization with proprietary enhancements. Along SH 242, TxDOT has installed 40-ft stop bar detection using a pair of two 6×20 loops, 6×6 loops for advance detectors, and post-stop bar detection. The system will be expanded to include additional corridors. District staff does not plan to add individual intersections for the purpose of obtaining just intersection performance measures.

In addition, the TxDOT Paris District now has several of their signalized intersections connected to Iteris SPM system, which provides a cloud-based solution.

With a few exceptions, most people who provided feedback believe that an ATSPM system can be beneficial if it can:

- Reduce time to troubleshoot.
- Reduce time to maintain with reduced staff.
- Automatically recommend timing changes.
- Automatically change timings via an adaptive feature.
- Provide timely and precise alerts because of a lack resources needed for monitoring.
- Provide measures in a form that provide for uses to prioritize allocation of limited resources.

Several participants believe that it would be nice to have the entire state on a common cloud-based standardized system. Furthermore, such a system should be able to keep track of who did what. However, some felt that one-size fits all may not fulfill their specific needs. A few participants from smaller districts indicated that they would prefer to be either supported by the Traffic Safety Division or the adjacent larger district. In addition, there was general agreement that districts will need adequate training in the use of such a system. Last, there were some concerns about requests for data under open records and related requirements to store data for long periods of time.

GUIDELINES FOR IMPLEMENTATION OF AN ATSPM SYSTEM

Once an agency has decided to implement an ATSPM-type system, the agency has the following eight stages to proceed (*18*):

- Select Performance Measures.
- Determine Implementation Scale.
- Conduct System Requirement Gap Assessment.
- Procure Resources.
- Configure System.
- Verify System.
- Apply Performance Measures.
- Integrate into Agency Practice.

The following sections describe these stages in more detail.

SELECT PERFORMANCE MEASURES

It is important for an operating agency to select performance measures that align with the agency objectives, since there are too many measures that can be monitored to assess implementation success.

Define Operating Environment

The selection of the performance measures starts with selecting/defining the operating environment. This selection provides a context for the type of performance measures that are applicable for the environment. Multi-jurisdictional impact is one of the environments that the agency needs to assess. Performance measures of some intersections and corridors in an area can be of use for multiple jurisdictions in the area. Such a dual-use situation can encourage sharing of costs for the implementation of a signal performance measure system. Roadway classifications and transportation networks can also define the environment. The agency assessing an arterial performance will have progression and throughput of vehicles as a performance measure, while the same agency when assessing a local street may prefer pedestrian delay. Traffic patterns also influence the selection of the environment. Locations that have a significant change in traffic patterns will require a different performance measure compared to locations that have a significant change in traffic patterns over time. Finally, goals selected by the agency to improve mobility, safety, and pedestrian access have an influence on the performance measures selected. This issue is critical to ensure that the agency is meeting its stated goals.

Identify Users

After the agency selects the operating environment, the agency then must identify users of the system. Users include pedestrians, bicyclists, light vehicles, heavy vehicles, emergency vehicles, transit vehicles, and rail. The effectiveness of serving each of these users requires different performance measures. Serving pedestrians may require pedestrian delay as a performance measure. However, if bicyclists are important at an intersection, bicycle delay and bicycle safety measure are more important. Throughput and progression are important performance measures for light vehicles. Time to service an emergency vehicle, number of preempts, and duration of preempts are a measure of service for emergency operators. Finally, transit vehicles may require special detection and controller firmware coupled with unique signal phasing. Hence, identification of users is critical to select the appropriate performance measures.

Establish Movement and User Priorities

Once users are identified, priorities must be determined for each user to determine the critical performance measures. An agency might have multiple users at an intersection. However, establishing a priority of the existing users will help in establishing a series of performance measures for the agency.

Select Objectives

The agency's objectives should reflect the operating environment, facility users, and their priorities and influence the selection of performance measures. However, performance measures for these objectives are primarily impacted by the infrastructure and the type of operations. These include communications, detection, uncoordinated timing, coordinated timing, and advance systems. Each performance measure can thus be categorized based on the above-mentioned factors.

Select Signal Performance Measures

Based on the factors identified earlier, the agency can select from a suite of performance measures. Currently, the ATSPM system being used by UDOT (*7*) has a total of 26 performance measures. More performance measures are likely to be developed by other users or developers of SPMs. These 26 performance measures are categorized by objectives and users. These objectives range from equipment health to progression, and users range from pedestrians to rail.

DETERMINE IMPLEMENTATION SCALE

Once signal performance measures are identified, a framework for implementation by an agency is developed. Typically, implementation will range from pilot studies to systematic upgrades to systemwide implementation. These choices are usually dictated by numerous factors including availability of champions or leadership, availability of funding, quality of existing infrastructure, or the size of jurisdiction. Each of these choices also have some advantages and challenges.

CONDUCT SYSTEM REQUIREMENT GAP ASSESSMENT

An agency must determine the additional resources required to implement a system to determine performance measures. The resources are generally in three categories. The agency should go through a checklist (illustrated in Figure 45) to assess the requirements in these three categories.

SYSTEM COMPONENTS	**Communication**	☐ Communication available? Communication Type: ____
	Detection	☐ Detection as-built drawings available? ☐ Detector channel mapping information available? Detector Wiring: ☐ Lane-by-Lane ☐ Series Detection on Major Street / Minor Street / Left-Turn Lanes: ☐ Stop Bar Presence ☐ Stop Bar Count ☐ Advance ☐ Count Past the Stop Bar ☐ Speed For Advance Detection, Distance from Stop Bar: ____
	Data Logging	Controller Vendor: ____ Model Number: ____ Onboard Cards (If Any): ____ ☐ High-resolution data logging available? Firmware Version: ____ ☐ Firmware upgrade required? External Hardware Vendor: ____ Model Number: ____
	Data Storage	☐ Server available for data storage? ☐ Cloud-based solution available for data storage? Available storage capacity: ____
	Software	☐ Database available? Database Type: ____ ☐ Central system available? Central System Type: ____
WORKFORCE	**Staffing Resources**	Signal Engineers/Technicians: ____ IT Staff (Available to Support Traffic Signal Network): ____ IT Staff Experience: ☐ Databases ☐ Programming ☐ Network ☐ Opportunities for ongoing training? Senior/Executive Managers: ____ Senior-Level Support: ☐ High - Committed ☐ Medium - Interested ☐ Low - Skeptical
BUSINESS PROCESSES	**Documentation**	☐ Traffic Signal Management Plan? ☐ Business process documented? ☐ ATSPM documented in agency policy? ☐ Design and maintenance standards? ☐ATSPM budget line item?
	Coordination	Partner Agencies: ____ Shared Staff Resources: ____ Shared Technology: ____

Figure 45. Checklist of Existing Resources for Gap Assessment (*18*).

System Components

System components comprise communication infrastructure, detection, data logging systems, data storage asset, and software to analyze the data. The agency needs take stock of the existing system components and assess the needs to implement a system to generate performance measures based on the system requirements. An example is communications infrastructure. If system components do not include communication infrastructure, implementation of an ATSPM system requires the operator to install communication infrastructure. If intersections do not have traffic signal controllers that can generate high-resolution data, either new signal controllers must be installed or external data loggers must be installed. The gap assessment process identifies the components to be added to the existing infrastructure based on the performance measures that are identified.

Workforce

Workforce primarily consist of personnel to use, operate, and maintain the system. Users and operators include engineers and senior technicians along with higher-level technical personnel. However, the agency also needs to ensure enough IT personnel are available to support in the configuration and the maintenance of the system.

Business Processes

Business processes consist of documentation and coordination requirements. Documentation includes a traffic signal management plan, business process, documentation of ATSPM in agency policy, design standards, and funding for ATSPM.

PROCURE RESOURCES

Once a gap assessment is complete, the agency must procure resources. Following are the resources needed for the implementation of a system to generate performance measures.

Data

There are two types of data that an agency needs to generate performance measures: (a) internal data, which comprise signal controller data; and (b) external data, which can assess some performance measures without using traffic signal controller data. Internal data consist of the following.

Controller High-Resolution Data

High-resolution data from the controller consist of the signal status and detector status 10 times a second. These data can provide a lot of information about the performance of the individual intersection. These data, however, require some data management and data processing to generate desired performance measures.

Central System Low-Resolution Data

An inexpensive way to get some controller data is to access the data received at the traffic management center (TMC) from the signal controllers in the field. These data obviously do not have the high resolution to get a good understanding of the state of the intersection. These data usually consist of the binned data (i.e., 15-minute count and occupancy) collected by the traffic signal controller that are transmitted to the TMC at some predetermined intervals.

External data can consist of the data listed below.

Automated Vehicle Identification (AVI) Data

Automated vehicle identification data are obtained from AVI toll tags that are installed on some vehicles. The agency may install some AVI tag readers at strategic locations to obtain data to support travel time studies and origin-destination studies.

Probe Vehicle Speed Data

These data are usually collected in an anonymized manner over segments of roadworks by a data provider. This information is also available by a Bluetooth low energy system that records the MAC addresses of Bluetooth devices at various locations, anonymizes the MAC addresses, and determines vehicle speed data. Agencies may use these data to assess the performance of the road network.

Automated Vehicle Location Data

An agency may instrument their fleet vehicles with GPS devices. The location of these vehicles is then available continuously in an automated manner. An agency can then use the continuously available probe data to assess the performance of a corridor or network.

System Components

System components consist of the following.

Communication

Communication is the most important element to generate signal performance measures. Based on the resources available many agencies prefer to install high quality and high broadband communication network like fiber. Where fiber is not available, wireless communication may be installed.

Detection

Proper detection is essential to generate performance measures. Detector design and configuration of the detectors depends on the type of performance measures selected.

Data Logging

Most of the applications that generate performance measures require high-resolution data from the traffic signal controller. However, some agencies may not have the budget to upgrade their controllers. In such cases, a data logger is installed in the cabinet that is connected to the signal controller.

Data Storage

The agency needs to prepare for central storing of the data being collected to generate these performance measures. Based on the IT capabilities of the agency as well as the financial resources available, the agency may select either to procure servers where the data are stored or purchase space in the cloud for storage.

Software

The final piece to generate the performance measures is the software to analyze the data. There are numerous software packages that have been developed. This software generates the performance measures in various formats. Some software uses the signal controller high-resolution data from a local server whereas some transfer the data to the cloud and process the data using their own resources. The agency needs to assess the business model that suites the agency before selecting a software.

CONFIGURE SYSTEM

The agency should develop a consistent procedure to configure the system at each of the intersections being integrated into the performance measures system. Consistency in configuration includes selecting the proper IP address of each device in the cabinet, a phase and detector numbering scheme, and the distance of the detectors from the stop bar both upstream and downstream if present.

VERIFY SYSTEM

Configuration Verification

Once the system is configured, verification of the data is conducted to ensure that the data being generated are as per the requirements of the software that is processing the data. Numerous tests can be conducted to verify if the various performance measures are accurate. Some of these tests include availability of data continuously, local time stamp shown accurately, intersection configuration, and detector configuration.

Data Validation and Verification

Data validation includes accuracy of turning movements counts based on personal knowledge of the intersections and verification of travel time and speed studies based on field studies.

APPLY PERFORMANCE MEASURES

Once the system verification is complete, the performance measures are applied and are available to be used by the agency. The selection of the performance measures earlier was done to meet the agency objectives. These performance measures provide the agency an opportunity to go to the next step to integrate into agency practice. This practice is an ongoing process, and the measures to be used depend on the user. A senior level engineer might use a different performance measure than a junior engineer or a senior technician.

INTEGRATE ATSPM INTO TXDOT DISTRICT OPERATIONS

By integrating signal performance measures into day-to-day practice, an agency will have continuous monitoring capabilities. Further, developing a record of performance will enable an agency to be better informed about the effectiveness of maintenance and operations practices and where to invest funding and staff resources. One way to move toward performance-based management is to weave signal performance measures into a traffic signal management plan (TSMP) (*19*). A TSMP can help an agency attract resources by demonstrating needs, prioritizing activities, and defining "basic service" as it relates to the traffic signal system. Once an agency has developed a definition, it can use signal performance measures to:

- Identify how well it is meeting expectations.
- Identify where it needs to invest in the traffic signal system.
- Communicate those messages to policymakers and elected officials.

Without a clear definition for basic service, it can be difficult for managers to communicate the value of their program and the impacts of resource allocation and budget cuts (*20*). This section builds off that idea and provides additional guidance for creating a TSMP.

Identify a Champion

A study entitled Evaluating the Benefits and Costs of Implementing Automated Traffic Signal Performance interviewed six early adopter agencies (*21*). This included three state agencies—UDOT, GDOT, and Pennsylvania Department of Transportation (PennDOT)—and three local agencies—Lake County Department of Transportation, Clark County (WA), and Maricopa County Department of Transportation. A common thread among the interviewed agencies was they all had strong executive support for making investments such as ATSPM implementation. This was particularly critical for UDOT because it took on considerable risk by investing thousands of in-house labor hours to develop an open-source software package. This yielded considerable benefits for UDOT, as well as several other agencies that would continue to use the software UDOT developed.

GDOT had similar executive support for its implementation. A few years after Utah's initial investments in open-source software, the implementation process was documented with assistance from GDOT, which has added its own contributions to the software. PennDOT is a larger agency, in terms of the total number of signals in the state. Nearly all the signals in the state are managed by local agencies, but the state has undertaken several initiatives to help improve signal operations. Here again, there was strong support at the top level to improve the management of traffic signals in the state.

Most agencies did not have a formal planning process for the ATSPM system. They gained information about the technology through outreach from the FHWA and AASHTO Innovation Initiative or pooled fund study and decided to deploy it. FHWA promotes a systematic approach to implementation that considers the impact on the workforce, business processes, and appropriate use of systems engineering to inform design and procurement.

It is imperative that any agency that intends to make an impact on the signal operations in the state has a leadership that shares those goals and provides all the resources needed to implement them in a consistent manner.

Cultural Shift to Performance-Based Prioritization

At many agencies, a culture shift will be required to fully integrate signal performance measures. The technology has the capacity to inform systemwide decisions and can replace or enhance some traditional decision-making methods. For example, instead of waiting for calls to come in from the public or making changes based on a set schedule, an agency can shift to a daily monitoring process in which traffic signal maintenance and operational improvements are prioritized based on performance. To start this shift from traditional signal retiming to performance-based management, an agency should consider using pilot projects, which will allow practitioners to test signal performance measures at low-risk locations.

Sharable Reports

Signal practitioners sometimes need to share progress with executive staff, elected officials, the public, or the media. Most practitioners are currently limited in what they can present, but with the implementation of signal performance measures, agencies can create executive summaries and dashboards and can respond efficiently to Freedom of Information Act requests. It is important for agencies to share performance measures that are easy to understand, such as travel time or travel time reliability.

Quantitative Performance Tracking

Agencies can develop a standard procedure for quantitatively tracking and documenting progress with agency staff, decision-makers, and the public, potentially through a newsletter or annual update. A routine process for disseminating successes can facilitate information sharing between agencies and notify decision-makers about program activities. For example, an agency can report an increased number of equipment upgrades, reductions in delay, or improvements in travel time over the course of a year.

Identify District Goals and Limitations

The quantifiable goals for each agency (TxDOT districts) will have to be identified. These goals will influence the use of ATSPM for the day-to-day operation as follows.

Efficient Maintenance

An example is to maintain the health of the signal infrastructure consisting of signal controllers, signal cabinets, communication infrastructure, and detection at a level that meets the district goals.

Proactive Operations

An example is to maintain the state of signal operations at a level that minimizes user complaints and optimizes corridor operations in a proactive manner by targeting the arrivals on green at or above a certain threshold.

Personnel Needs

The upper management will have to provide adequate resources in the form of personnel to have a successful ATSPM deployment. This includes dedicated personnel to operate the ATSPM system by constantly monitoring the health of the signal infrastructure as well as trained personnel to maintain all components of the ATSPM system. This includes effective coordination and cooperation with other departments, including the IT department.

Setting Up of an ATSPM

This process requires a significant cooperation and interaction with the IT department of the agency. The agency may also consider hiring a vendor or a consultant to do the design, installation, and short-term operation of the ATSPM system to train the agency personnel. The upper management should allocate adequate personnel to oversee the installation and to be trained in the operation of the system. The agency may also consider pooling/sharing the resources with other agencies (other TxDOT districts) to supplement low staff resources. Agency personnel will also have to be trained in the configuration of detection zones to obtain enhanced high-resolution data from the intersections. This exercise should involve the design and configuration of detection channels within the cabinet in a consistent manner so that the interpretation of the high-resolution data is made easier.

Operations of an ATSPM

A fully functional ATSPM system will *only* be successful when the agency has a clear vision about assessing the performance of the signal system. A critical part of the success is the system design that facilitates ease of use by the operators. This system should have adequate automation so that the personnel that operate the system do not have to expend a lot of time to identify the issues to address. The system should have a dashboard that provides a status of the system health and identifies trouble spots easily. The dashboard should be customizable so that different users can get the information that is relevant to them rapidly.

The system should also have the capability to generate alerts for any issues that the system automatically identifies. These alerts should be customizable so the proper alerts are sent to the right personnel in a prioritized manner. The operators should also be trained to investigate the ATSPM system for any complaints that are received from the traveling users and to resolve them in an expedited fashion.

Infrastructure Needs

Signal performance measures can help prioritize short-term maintenance needs and inform replacement cycles for equipment. Many agencies find it easier to acquire capital funds than maintenance funds. By tracking the degradation of equipment over time using an ATSPM, an agency may be able to break out of a capital-based replacement cycle. The agency will need to have a plan to prioritize the deployment of equipment. The equipment is listed below.

Modern Traffic Signal Controllers

The agency will need to select corridors as a base minimum, a district as a whole, or an agency to upgrade the signal control equipment. This upgrade is the first step toward the deployment of ATSPM.

Effective Communication

Once traffic signal controllers that can collect/generate high-resolution data are installed, the agency needs to prioritize upgrading the communications equipment. Deployment of communications can be done in a fashion like the deployment of signal control equipment. Deployment of communications would not only be a big step for the deployment of ATSPM but also for the regular operations and maintenance of the signal systems.

Intersection Detection

Proper intersection detection is essential for providing effective ATSPM performance measures. Figure 46 illustrates an ideal configuration for detection. Each district will have to prioritize the deployment of detection to take advantage of the ATSPM system, since implementing an extensive detector configuration can be very expensive.

Figure 46. Ideal Detection Configuration for ATSPM Performance Measures.

DRAFT SPECIFICATIONS

The ATSPM system shall provide reports and dashboards that can help TxDOT signal technicians and engineers proactively respond to traffic and maintenance issues/events while recognizing that performance report generation is dependent on the level of existing detector channels map per intersection. The ATSPM system shall also provide reports and dashboards for use by decision makers for internal purposes or for conveying agency accomplishments to the public.

MINIMUM CAPABILITIES

The system shall include the following minimum capabilities.

Signal Performance Measures

- Purdue Phase Termination.
- Split Monitor.
- Pedestrian Delay.
- Preemption Details.
- Turning Movement Counts.
- Purdue Coordination Diagram.
- Approach Volume.
- Approach Delay.
- Arrivals on Red.
- Approach Speed.
- Yellow and Red Actuations.
- Purdue Split Failures.
- Purdue Link Pivot.
- Approach Link Comparison.
- Upstream and Downstream Arrivals on Green.
- Predicted Purdue Coordination Diagrams.
- Aggregated Corridor Summary Reports.

System Self-Monitoring

The system shall include self-monitoring for data errors such as logical errors (i.e., multiple loop off chronologically without loop on, concurrent green phases for conflicting movements, and duplicate records).

System Responsiveness

The reports shall be quarriable by time of day and day of week within a selected time and data range for a signal. The system shall provide a response within 15 seconds to any report request for a signal. For reports across multiple signals, the system shall respond within 30 seconds. Delay from transmission caused by the internet connection shall not be deemed to be part of the delay. To capture this effect, multiple attempts will be made of the same group of signals and the fastest responses used. If there is a clear pattern that appears to be due to issues other than internet connection speed, another methodology maybe used by the department for accessing compliance, at the department's discretion.

Retention Requirement

The system shall retain records for a minimum of seven years. All the data shall be fully accessible by the system for reporting purposes.

Testing, Verification, and Acceptance

The installer of the system shall develop and submit Verification and Acceptance Test Procedures that meet TxDOT's requirements. The Acceptance Test Procedures shall serve as a guide to operationally test the system. The Acceptance Test Procedures must describe the means, methods, tools, and acceptance criteria to verify that the system is working as designed. They should also describe any information needed from TxDOT, any impact to normal daily operations, and normal operating conditions and failure conditions. The testing shall include tests for the ATSPM software, any hardware/equipment associated with the ATSPM system, communications, detection inputs, IT equipment, and traffic signal controller equipment necessary for the operation of the ATSPM system to demonstrate conformance to the system requirements. The final testing shall demonstrate that:

- All system requirements have been met.
- The user interface is configured properly for all use cases.
- The system is storing and retrieving data per the requirements.
- The system is free of errors.
- The integration with TxDOT's traffic signal controller equipment is free of errors and is not impacting normal operations of the traffic signal equipment.
- Reporting functionality is working.
- Security measures are in place and verified.
- The system can be updated remotely free from errors.

Licenses

The system installer shall provide all licenses required for the operations and maintenance of the system, including, but not limited to, third-party software applications, databases, network components, and servers (if applicable), for unlimited use by TxDOT. The terms and conditions of any software license will be incorporated into the final contract. Prior to finalizing the contract, TxDOT reserves the right to negotiate terms of use of any relevant software licenses.

Technical Support

The system installer shall provide technical support to TxDOT for the life of the contract. Technical support includes, but is not limited to, the following:

- Troubleshooting of the system.
- Routine questions.
- Configuration questions or changes.
- Customized reporting.
- Support terms, including response times, communication methods, and hours of availability.

FUNCTIONAL AND TECHNICAL REQUIREMENTS

Table 3 lists the categories as well as system requirements within each category. These requirements are further classified as required or desired.

Table 3. Functional and Technical Requirements.

Category	ID	Requirement	Required	Desired
General Data Requirements	1.1	The ATSPM system shall be a vendor-provided web-hosted traffic data collection and traffic data analytics product.	X	
	1.2	The ATSPM system shall utilize industry standard communication protocols.	X	
	1.3	The ATSPM system shall provide all services and software necessary for retrieving high-resolution controller data.	X	
	1.3.1	The ATSPM system shall capture high-resolution data on a user-defined basis as frequent as a tenth of a second.	X	
	1.3.2	The high-resolution data shall be date and time stamped.	X	
	1.3.3	The high-resolution data shall include their associated event parameters.	X	

Category	ID	Requirement	Required	Desired
	1.3.4	The event parameters shall contain data used to identify the source or nature of the event.	X	
	1.4	The ATSPM system shall be able to generate reports of high-resolution data for the performance measures.	X	
	1.5	The high-resolution data shall be able to be pushed to the cloud host for storage, processing, and retrieval.	X	
	1.6	The high-resolution data shall be owned exclusively by the agency.	X	
General Access Requirements	2.1	The ATSPM system shall be accessible from a Windows-based desktop or laptop.	X	
	2.3	The ATSPM system shall be accessible from a tablet using Apple iOS, Google Android, or Windows for mobile devices.	X	
	2.4	The ATSPM system shall be accessible from a mobile phone using Apple iOS, Google Android, or Windows for mobile devices.	X	
	2.5	The ATSPM system shall be accessible using Internet Explorer.	X	
	2.6	The ATSPM system shall be accessible using the Safari web browser.	X	
	2.7	The ATSPM system shall be accessible using the Chrome web browser.	X	
	2.8	The ATSPM system shall be accessible using the Firefox web browser.	X	
User Accounts	3.1	The ATSPM system shall support authentication of individual users via individual usernames and passwords.	X	
	3.1.1	The ATSPM system shall not limit the number of user accounts that can be created to allow and grant access.	X	
	3.1.2	The ATSPM shall provide varied levels of data access and analytic functionality that are tiered by multiple user types.	X	

Category	ID	Requirement	Required	Desired
	3.1.3	The ASTPM system shall allow an "admin" access to restrict access for up to five user types.	X	
	3.1.4	The ASTPM system shall allow user types to be tied to user logins.	X	
	3.1.5	The ASTPM system shall restrict access to specific performance measures based on user type.		X
	3.1.6	The ATSPM system shall be able to restrict access to data on specific corridors based on user type.		X
General Display Features	4.1	The user web interface shall consist of a front-page dashboard customized by user profile.	X	
	4.2	The dashboard shall provide for multiple saved views by user profile.	X	
	4.3	The dashboard shall display user-selected performance measure graphs over a user-defined time.	X	
	4.4	Dashboard views shall include an indication of overall system health or performance.	X	
	4.5	The dashboard shall be capable of displaying graphic representations of user-customized SPMs.	X	
	4.6	The dashboard shall provide a list of signals with performance measures at user-defined intervals.	X	
Map Display	5.1	The ATSPM system shall display a map view of the entire system.	X	
	5.1.1	The map view shall display user-defined performance measures.	X	
	5.1.2	The map shall provide heat-map views that highlight problem areas.	X	
	5.1.3	The map shall allow a user to zoom, click, and drag to identify specific intersections in more detail.	X	
	5.1.4	The user shall be able to click on an intersection to access a variety of SPM charts relating to the intersection.	X	
	5.1.5	The ATSPM system shall be capable of showing locations for	X	

Category	ID	Requirement	Required	Desired
		degraded performance measures on a map.		
	5.1.6	The map view shall display performance measures using user-defined graphical thresholds.	X	
Data Storage and Analytics	6.1	The ATSPM system shall support the ability to statistically compare differences between data series by user-defined time period.	X	
	6.2	The ATSPM system shall store high-resolution and system configuration data.	X	
	6.3	The ATSPM system shall support performance report analytics that can be exported to Microsoft Word, Excel, Access, CSV, and Adobe PDF.	X	
	6.4	High-resolution data shall be stored and retrievable for at least three years.	X	
	6.5	The ATSPM shall support storing and retrieving data older than three years.	X	
Detector Diagnostics	7.1	The ATSPM system shall be capable of providing a separate list of intersections with degraded detector performance.	X	
	7.2	The ATSPM system shall be able to identify and report detectors that may not be fully operational.	X	
General Signal Performance Measures	8.1	The ATSPM system shall generate user-defined performance measure reports at user-defined intervals.	X	
	8.2	SPM charts shall provide a user-selectable date selection.	X	
	8.3	SPM tables shall provide a user-selectable date selection.	X	
	8.4	The ATSPM system shall provide the means to compare various performance metrics over user-definable date ranges.	X	

Category	ID	Requirement	Required	Desired
	8.5	The ATSPM system shall provide a tabular comparison of SPMs with indications of improvement or degradation of the desired MOEs.	X	
	8.6	The ATSPM system shall support the comparison of historical trends to a baseline data set.	X	
	8.7	The ATSPM system shall be able to provide recommendations for improving SPMs based on historical trends.	X	
Arrivals on Red and Arrivals on Green	9.1	The ATSPM system shall track and report metrics relating to the volumes of traffic arriving at an intersection during the red interval.	X	
	9.2	The ATSPM system shall provide an arrival on red chart that shows the volume of vehicles arriving at the intersection on red and the percent of vehicles arriving on red for each cycle during a 1-day/24-hour interval based on a user-defined data and time period.	X	
	9.3	The ATSPM system shall provide the arrivals on red chart for each phase of a signal that meets detection requirements.	X	
	9.3.1	The ATSPM system shall provide arrivals on red at an intersection level.	X	
	9.3.2	The ATSPM system shall provide arrivals on red at a corridor level.	X	
	9.3.3	The ATSPM system shall provide arrivals on red at a system level.	X	
	9.4	The ATSPM system shall track and report metrics relating to the volumes of traffic arriving at an intersection during the green intervals.	X	
	9.5	The ATSPM system shall provide an arrivals on green chart for each phase of a signal that meets detection requirements.	X	

Category	ID	Requirement	Required	Desired
	9.5.1	The ATSPM system shall provide arrivals on green at an intersection level.	X	
	9.5.2	The ATSPM system shall provide arrivals on green at a corridor level.	X	
	9.5.3	The ATSPM system shall provide arrivals on green at a system level.	X	
Pedestrian Events	10.1	The ATSPM system shall provide a pedestrian delays chart that displays the amount of delay introduced by the pedestrian actuation.	X	
	10.2	The ATSPM system shall provide the pedestrian delays chart for individual approaches of a signal.	X	
	10.3	The ATSPM system shall provide the pedestrian delays chart as a combined report for all approaches of a signal.	X	
	10.3.1	The ATSPM system shall provide pedestrian delay at an intersection level.	X	
	10.3.2	The ATSPM system shall provide pedestrian delay at a corridor level.		X
	10.3.3	The ATSPM system shall provide pedestrian delay at a system level.		X
	10.4	The ATSPM system shall track and report number of pedestrian actuations per phase.	X	
Power Failures	11.1	The ATSPM system shall track and report metrics relating to power failures.	X	
	11.1.1	The ATSPM system shall highlight individual intersections that have experienced power failures over a user-specified date.	X	
	11.1.2	The ATSPM system shall highlight individual corridors that have experienced power failures over a user-specified date.	X	
	11.1.3	The ATSPM system shall display systemwide power failures over a user-specified date.	X	
Communications Failures	12.1	The ATSPM system shall track and report metrics relating to communication failures.	X	

Category	ID	Requirement	Required	Desired
	12.1.1	The ATSPM system shall highlight individual intersections that have experienced communication failures over a user-specified date.	X	
	12.1.2	The ATSPM system shall highlight individual corridors that have experienced communication failures over a user-specified date.	X	
	12.1.3	The ATSPM system shall display systemwide communication failures over a user-specified date.	X	
Preemption Events	13.1	The ATSPM system shall track and report metrics relating to preemption.	X	
	13.1.1	The ATSPM system shall provide a summary of each preemption event for a selected intersection.	X	
	13.1.1.1	The summary shall indicate each preemption event's start time for a selected intersection.	X	
	13.1.1.2	The summary shall indicate each preemption event's duration for a selected intersection.	X	
	13.1.2	The ATSPM system shall provide a summary of preemption information (i.e., number of calls, number of granted calls) on user-selected intersections.	X	
Purdue Coordination Diagram	14.1	The ATSPM system shall provide a PCD that shows the volume (vehicles per hour) during each cycle.	X	
	14.2	The ATSPM system shall provide a PCD that shows start of green during each cycle.	X	
	14.3	The ATSPM system shall provide a PCD that shows the start of yellow during each cycle.	X	
	14.4	The ATSPM system shall provide a PCD that shows the start of red during each cycle.	X	

Category	ID	Requirement	Required	Desired
	14.5	The ATSPM system shall provide the PCD chart for each coordinated phase of a signal that meets detection requirements.	X	
Split Failures	15.1	The ATSPM system shall track and report metrics relating to split failures.	X	
	15.2	The ATSPM system shall provide a Split Failures Report for each phase that plots red occupancy ratio for each cycle.	X	
	15.3	The ATSPM system shall provide a Split Failures Report that plots green occupancy ratio phase terminations for each cycle.	X	
	15.4	The ATSPM system shall provide the Split Failures Report for each phase of a signal that meets detection requirements.	X	
	15.4.1	The ATSPM system shall provide the Split Failures at an intersection level.	X	
	15.4.2	The ATSPM system shall provide the split failures on a corridor level.		X
	15.4.3	The ATSPM system shall provide the split failures for the system.		X
Split Monitor	16.1	The ATSPM system shall provide a split monitor chart that plots by phase the phase termination reason summarizing all cycles throughout the day (e.g., force off or gap out).	X	
	16.2	The ATSPM system shall provide the split monitor chart for each phase of a signal that meets detection requirements.	X	
	16.2.1	The ATSPM system shall provide the split monitor chart by intersection.	X	
	16.2.2	The ATSPM system shall provide the split monitor chart by corridor.	X	
	16.2.3	The ATSPM system shall provide the split monitor chart for the system.	X	
Delay	17.1	The ATSPM system shall provide the average delay per vehicle.	X	

Category	ID	Requirement	Required	Desired
	17.2	The ATSPM system shall provide the vehicle delay report for each phase of a signal that meets detection requirements.	X	
	17.3	The ATSPM system shall provide vehicle delay at an intersection level.	X	
	17.4	The ATSPM system shall provide vehicle delay at a corridor level.	X	
	17.5	The ATSPM system shall provide vehicle delay for the system.	X	
Volumes	18.1	The ATSPM system shall provide turning movement counts for each signal that meets detection requirements—tabular and map displays.	X	
	18.2	The ATSPM system shall report metrics relating to vehicle volumes at the intersection level—tabular and map displays,	X	
	18.3	The ATSPM system shall report metrics relating to vehicle volumes at the corridor level—tabular and map display.	X	
Queues	19.1	The ATSPM system shall report queue lengths on all approaches for intersections that meet detection requirements.	X	
Yellow and Red Actuations	20.1	The ATSPM system shall provide yellow and red actuations charts at signals that meet detection requirements.		X
Approach Speed Charts	21.1	The ATSPM system shall provide approach speed charts for signal approaches that meet detection requirements.		X
Travel Time	22.1	The ATSPM system shall generate point-to-point travel time calculations by integrating external data sources.		X
	22.2	The ATSPM system shall support calculation and viewing of travel time data within 15 minutes of capture.		X

Category	ID	Requirement	Required	Desired
	22.3	The ATSPM system shall support generation and overlay of historical travel time trends over any period throughout the three-year data set.		X
	22.4	The ATSPM system shall support generation of historical variability statistics of travel time over any period throughout the three-year data set.		X
Origin-Destination Information	23.1	The ATSPM system shall capture vehicle presence via a traffic probe utilizing vehicle identification technology.		X
	23.2	The ATSPM system shall transmit vehicle identification to the server at least once per minute.		X
Alerts	24.1	The ATSPM system shall display real-time status of all active SPM alerts. This requirement includes all SPMs defined in the requirements above, including each SPM subcategory for Requirements 8 through 22.	X	
	24.1.1	The ATSPM system shall provide historic and real time alerts with alert time.	X	
	24.1.2	The ATSPM system shall provide historic and real time alert notifications.	X	
	24.1.3	The ATSPM system shall provide historic and real time alert resolution.	X	
	24.1.4	The ATSPM system shall support user-defined pushed email and SMS alerts.	X	
	24.1.5	The ATSPM system shall support user-defined alerts based on performance thresholds.	X	
	24.1.6	The ATSPM system shall support user-defined alerts based on detector failures.	X	
Security	25.1	The ATSPM system shall have geographic redundancy for server hosting locations.	X	

Category	ID	Requirement	Required	Desired
	25.2	The ATSPM system shall utilize industry standard security methods for data storage and access.	X	
	25.3	The ATSPM system shall employ industry standard encryption to ensure user login names and passwords are secure.	X	
	25.4	The system shall allow the system admin to implement password rules and password change requirements.	X	
Support	26.1	The ATSPM system vendor shall provide two training sessions for up to five city staff members.	X	
	26.2	The vendor shall provide bug fixes for three years.	X	
	26.3	The vendor shall provide a three-year warranty for all hardware components.	X	
	26.4	The vendor shall provide software updates, including new features, for three years.	X	
	26.5	The vendor shall provide technical support and maintenance for three years.	X	
	26.6	The vendor shall demonstrate that a minimum of five ATSPM systems have been installed and are currently operating in the United States.	X	

RECOMMENDATIONS

SPECIFICATIONS FOR STATEWIDE DEPLOYMENT

This project developed the draft specifications and functional and technical requirements for ATSPM. These requirements were generated by reviewing the experiences of ATSPM deployments across the country by numerous operators and by getting input from TxDOT districts across the state. These requirements should support TxDOT to draft formal specifications to procure an ATSPM system for statewide deployment. A critical component for the successful deployment of an ATSPM system is to build the human capital to support and sustain the system apart from meeting technical and funding requirements. This includes system integrators, system operators, and decision-makers that champion the cause of monitoring system performance. This is achieved in two steps.

Identify Safety Division, Information Technology Division, and District Roles in Statewide Deployment

A review of the constraints that TxDOT districts face revealed a wide disparity in the knowledge of ATSPMs, awareness of the benefits of the system, identification of use cases, availability of human resources to operate the system, and availability of the expertise to understand and maintain the system. Many districts indicated a need to get operational support from a central agency like the Safety Division or adjacent districts and/or support for system integration and maintenance from ITD. Hence it is critical that roles of each entity are identified and well defined before a successful deployment is initiated. All successful deployments of ATSPMs have a plan to weave signal performance measures into a TSMP. This plan facilitates the generation of resources, identifies traffic system needs, prioritizes activities, and defines "basic service" for a traffic signal system.

To achieve these objectives, it is critical to establish how the Safety Division can help the districts implement and operate ATSPMs. This is especially critical for smaller and rural districts that may not have a large signal system to operate and thus do not have the staff large enough to dedicate to operate and maintain the ATSPM system. Signal shops in such districts may also lack the expertise to identify operational problems and address them proactively. Some of the larger urban districts like Houston or Fort Worth may not have these limitations and may have the bandwidth to support smaller districts. Hence identification of a support system will alleviate any concerns and minimize hesitancy on the part of districts to embrace the deployment of ATSPMs. It is also important to consider and integrate any vendor-based SPM system that a district may already be using into the statewide ATSPM deployment system. Districts should also be consulted in the locations of the initial deployment of the ATSPM system. Districts are more aware about the local traffic systems and their performance. Getting their input in the selection will increase the probability that the system will be used more effectively.

Gather Support/Commitment from Administration

A successful deployment of ATSPM requires the allocation of human and financial resources. This will be possible upon a commitment from the leadership at all levels. First at the district level, the leadership should coordinate with the district IT department, Safety Division, and leaders in adjacent districts to draft agreements to support district engineers and signal technicians to operate and maintain the ATSPM system. The leadership must also allocate adequate time for the engineers and technicians to be trained in how to use the system and, more importantly, time to use the ATSPM system by monitoring the dashboards to identify any trouble spots in a proactive manner to achieve the agency's objective of basic service.

INVESTIGATE THE USE OF PROBE-BASED SIGNAL ANALYTICS

In the last few years, availability of connected vehicle data has grown. Connected vehicle data are data being transmitted from newer models of vehicles that may have a version of an on-board unit (OBU) to an online platform (cloud) that is maintained by the vehicle manufacturer. These data usually consist of various attributes of the vehicle operations obtained every 3 to 4 seconds in the vicinity of the intersection. These attributes include vehicle speed, hard brakes, turn indications, and wind shield wiper status among others. Connected vehicle platforms like INRIX (*22*) and Wejo (*23*) have contracted to use these data to analyze them and develop metrics that are indicative of intersection and arterial performance. These metrics are generated from vehicle trajectory data and do not depend on availability of any data from the traffic signal infrastructure. Hence, in the absence of any infrastructure, like communication and detection, these means provide some level of performance metrics. TxDOT should investigate the accuracy of the performance metrics being generated by INRIX and Wejo compared to metrics being generated by typical ATSPM systems. TxDOT should also consider fusing the metrics from connected vehicle data with metrics from ATSPM data to get a better picture of the individual intersection performance as well as arterial travel time.

GUIDANCE TO DISTRICTS FOR ATSPM DEPLOYMENT

Once a decision has been made to deploy a statewide ATSPM system, with some deployments in a district, it is essential to plan the deployment in a manner that is consistent with the guidelines identified earlier. Following are some of the steps to be considered when deploying an ATSPM system in a TxDOT district.

Identifying a Champion

It is extremely critical to identify a champion who is a senior level executive/engineer. The primary role of the champion is not only to provide the resources needed but also to be a spokesperson to illustrate/motivate how the use of the ATSPM system is consistent with the goals of the organization and the traffic system the ATSPM supports. Resources include personnel as well as their time to monitor, identify, diagnose, and respond to events in the ATSPM system effectively.

Develop the Architecture to Integrate ATSPM into the Statewide Network

This architecture will consider the connectivity existing between the field devices, their signal shop, and their connection to the statewide communication network. The architecture should also consider any existing vendor-based closed-loop system, which also may have a vendor-based SPM system.

Implement the Guidelines for ATSPM Implementation

Once a champion is identified, an ATSPM system will need to be implemented in a step-by-step process as described in the chapter earlier in the report. The primary steps in the process are listed below:

- Select Performance Measures.
- Determine Implementation Scale.
- Conduct System Requirement Gap Assessment.
- Procure Resources.
- Configure System.
- Verify System.
- Apply Performance Measures.
- Integrate ATSPM Deployment into Statewide Architecture.

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APPENDIX A—ATSPM DRAFT SPECIFICATIONS

AUTOMATED TRAFFIC SIGNAL PERFORMANCE MEASURES (ATSPM) SYSTEM.

Background.

Texas Department of Transportation (TxDOT) strives to improve arterial operations and enhance safety at signalized intersections throughout the State of Texas by deploying an Automated Traffic Signal Performance Measures (ATSPM) system. An ATSPM system will provide information/tools needed to actively monitor signal performance and proactively identify and correct deficiencies before they negatively impact arterial operations. Deploying an ATSPM system is a cost-effective way to improve traditional retiming processes by providing continuous performance monitoring capability using high-resolution data and real-time performance measures.

The ATSPM System will enable TxDOT to make informed decisions about strategies to manage their traffic signals and measure the performance of the intersections and project corridors. The ATSPM system will allow the TxDOT personnel to access real-time, remote traffic signal data and performance measures to proactively identify maintenance and operational issues, determine their causes, and address them effectively. Finally, the ATSPM System will provide data to enable decisions about how to use limited human and financial resources in an optimal manner.

General Scope.

TxDOT is seeking an off-the-shelf ATSPM system with minimal customization to connect to all online signalized intersections and diamond interchanges (~3500 intersections). The system should be able to categorize/zone traffic signals separately for each TxDOT district. The Safety Division in Austin should have the capability to access all the traffic signals that are online in the state. Personnel in each TxDOT district should have the capability to access all the traffic signals online within their district. These personnel should also have the authorization to give access of the signals within their districts to personnel in other TxDOT districts to provide/receive technical support as well as facilitate intra-department training.

Deployment Size:

The ATSPM system should have the capacity to incrementally increase the capacity to incorporate signals as they come online into an ATSPM system. The system shall ultimately have the capability to incorporate all traffic signals within TxDOT control (~3,500 signals). These traffic signals shall be a mixture of different manufacturers controllers. The vendor’s system shall incorporate high resolution signal controller data from controller software in the industry standard format (Cubic/Trafficware, Econolite, Intelight, Siemens).

Configuration:

- The ATSPM system shall have the capability to connect to traffic signals irrespective of any ATSPMs deployed by individual districts.
- The system should facilitate districts to autoconfigure new signals and/or existing signals channel mapping based on the data being received from the controller; and
- The Vendor's shall connect to and poll the traffic signal controllers in the field

ExampleS of ATSPM Software/SYSTEMS

Utah DOT ATSPM

Utah Department of Transportation (DOT) implemented an Automated Traffic Signal Performance Measures (ATSPM) system as a cost-effective way to measure and display signalized intersection performance. This system requires traffic controllers capable of logging high-resolution event data. UDOT's ATSPM program benefited from its partnership with Purdue University, FHWA, and the Transportation Pooled Fund Program[1]. ATSPM enables UDOT to proactively manage traffic signal timing and quickly identify maintenance issues that affect traffic flow. UDOT's ATSPM contains a suite of data visualization reports that can be used to evaluate the quality of traffic progression along corridors and identify unused green time for allocation to other intersection movements. System reports of vehicle delay, volumes, and speeds can be used to evaluate the effectiveness of signal timing adjustments. ATSPM visualizations can also be used to inform UDOT staff of vehicle and pedestrian detector malfunctions, saving staff time during maintenance operations. ATSPM tools speed up decision making and help UDOT staff prioritize operation and maintenance efforts. UDOT's ATSPM also features a public-facing website (Figure 47) that allows users to generate charts for numerous performance metrics.

Since implementing its ATSPM program, UDOT has noted a significant drop in public complaints and requests for traffic signal retiming. The ATSPM system quickly identifies problems such as failed detectors and sends a simple email notification. These alerts allow UDOT to respond to issues before they become public nuisances and prolonged threats to mobility.

UDOT is collecting ATSPM at 96 percent of its 1,223 traffic signals. Partner agencies have connected 79 percent of their 852 signals and report data through the same centralized operation. Utah's end goal is to have all signals statewide connected and contributing data to their existing ATSPM system.

[1] https://ops.fhwa.dot.gov/publications/fhwahop18048/index.htm

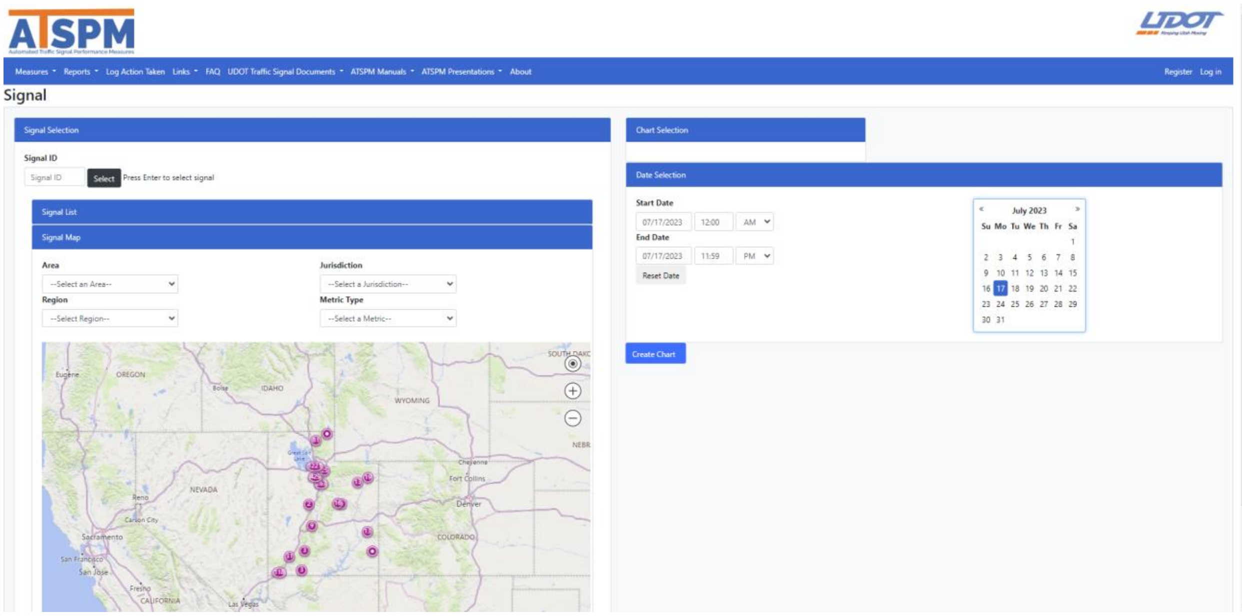

Figure 47. Utah DOT's ATSPM System.

Iteris SPM

Iteris SPM is an example of third-party (non-controller vendor) cloud-based solution. Iteris installation package includes full implementation and phase setup and includes ongoing maintenance and system reviews. This system does not require special cabinet hardware but does require traffic signal controllers with high resolution data logging capabilities. It should be noted that at least one firmware version of every TxDOT approved controller provides this feature. Iteris SPM system leverages client (a city or DOT) agency's communications and detection infrastructure. The system uses an FTP application installed on the agency server to grab high-resolution data from controllers configured in the system using their IP addresses. The data is then uploaded to the cloud and processed into alerts and reports. A web-based application provides access to this processed data. According to information provided by Iteris staff, upfront cost of system installation and configuration ranges from $500 to $700 per intersection depending on the level of staff-effort required. In addition, average yearly cost of maintenance is around $400 per intersection. Groups of intersections (called Regions) can be configured to allow better management of intersections owned by the client. The system can be set up to provide alerts for different regions to different people.

Figure 48 shows the dashboard for Iteris SPM. This is the first screen a user sees after logging in. The main part of this screen is divided into two parts. The left side provides information about current operational (pink circle with an exclamation symbol) and maintenance (black circle with a wrench symbol) alerts. This information includes the number of alerts in each category followed by a listing of each alert together with a description of that alert and a suggested performance measure to look at. The right side shows a map highlighting intersections meeting the selected criterion (in this case all intersections with at least zero alerts) using the slider bar at the top. Small circles with magenta color identify signals with 0 alerts, small circles with any other color identify intersections with one alert, and larger circles identify intersections with multiple alerts. Pink circles identify intersections with operational alerts, black circles identify intersections with maintenance alerts and pink plus black circles identify intersections with both types of alerts.

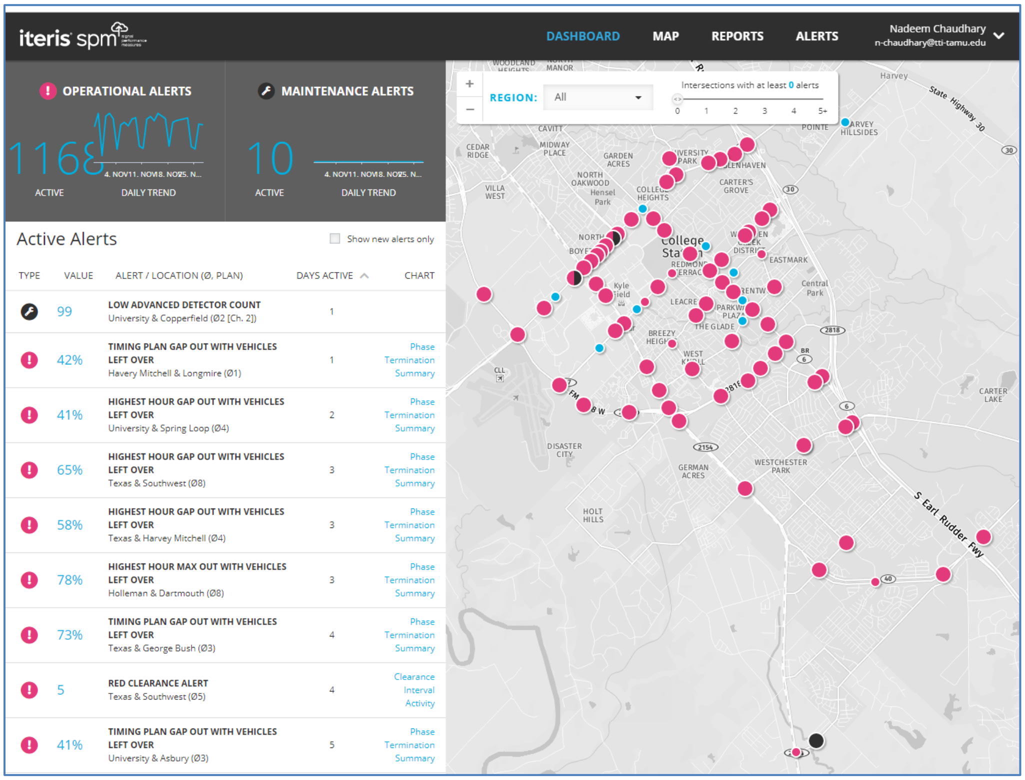

Figure 48: Iteris SPM Dashboard.

Miovision ATSPM

Miovision ATSPM system uses a proprietary hardware device – called TrafficLink – to collect controller event data[2]. It sends collected controller event data via a cellular connection to a cloud via a secure VPN channel. TrafficLink can be installed in any existing cabinet, eliminating the need for upgrading the controller or cabinet. Wireless communication allows the system to be installed in remote locations. TrafficLink also supports WiFi and uses snooping techniques to grab MAC addresses of devices to assess their travel time between multiple points. Even though a MAC address does not contain any personally identifiable information, Miovision uses encryption techniques to ensure that a single driver's commute cannot be correlated over time[3]. TrafficLink connectivity is provided via a single wireless antenna capable of both WiFi and cellular communication. For locations lacking detection, Miovision also offers a single camera-

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[2] http://www.cttraffic.com/PDFs/MIO_CT_Florida_TL_Brochure_Digital.pdf. Accessed on November 29th 2019.
[3] https://miovision.com/blog/arterial-performance-measures-apms/. Accessed on November 29th 2019.

based solution (Smartview 360) to provide vehicle and pedestrian detection at all approaches at an intersection.

PERFORMANCE MEASURE REPORTS:

ATSPM System shall provide reports and dashboards that can support TxDOT signal technicians and engineers proactively respond to traffic and maintenance issues/events while recognizing that performance report generation is dependent on the level of existing detector channels map per intersection. The ATSPM System shall also provide reports and dashboards for use by decision makers for internal purposes or for conveying agency accomplishments to the public.

Minimum Capabilities

The system shall include the following minimum capabilities.

Signal Performance Measures

- Purdue Phase Termination
- Split Monitor
- Pedestrian Delay
- Preemption Details
- Turning Movement Counts
- Purdue Coordination Diagram
- Approach Volume
- Approach Delay
- Arrivals on Red
- Approach Speed
- Yellow and Red Actuations
- Purdue Split Failures
- Purdue Link Pivot
- Approach Link Comparison
- Upstream and Downstream Arrivals on Green
- Predicted Purdue Coordination Diagrams; and
- Provide aggregated corridor summary reports

System Self-Monitoring:

The system shall include self-monitoring for data errors such as logical errors (i.e., multiple loop off chronologically without loop on, concurrent green phases for conflicting movements and duplicate records).

System Responsiveness:

The reports shall be query-able by time of day and day of week within a selected time and data range for a signal. The system shall provide response within 15 seconds to any report request for a signal. For reports across multiple signals the system shall response within 30 seconds. Delay from transmission caused by the internet connection shall not be deemed to be part of the delay. To capture this effect, multiple attempts will be made of the same group of signals and the fastest responses used. If there is a clear pattern that appears to be due to issues other than internet connection speed another methodology maybe used by the Department for accessing compliance, at the Departments discretion.

Retention Requirement:

The system shall retain records for a minimum of seven (7) years. All the data shall be fully accessible by the system for reporting purposes.

Testing, Verification and Acceptance:

The installer of the system shall develop and submit Verification and Acceptance Test Procedures that meet TxDOT's requirements. The Acceptance Test Procedures shall serve as a guide to operationally test the system. The Acceptance Test Procedures must describe the means, methods, tools, and acceptance criteria to verify that the system is working as designed. They should also describe any information needed from TxDOT, any impact to normal daily operations, and describe normal operating conditions and failure conditions. The testing shall include tests for the ATSPM software, any hardware/equipment associated with the ATSPM system, communications, detection inputs, IT equipment, and traffic signal controller equipment necessary for the operation of the ATSPM system to demonstrate conformance to the system requirements. The final testing shall demonstrate that:

- All system requirements have been met
- The user interface is configured properly for all use cases
- The system is storing and retrieving data per the requirements
- The system is free of errors
- The integration with the TxDOT's traffic signal controller equipment is free of errors and is not impacting normal operations of the traffic signal equipment.
- Reporting functionality is working.
- Security measures are in place and verified; and
- System can be updated remotely free from errors

Licenses:

The system installer shall provide all licenses required for the operations and maintenance of the system, including, but not limited to, third-party software applications, databases, network components, and servers (if applicable) for unlimited use by TxDOT. The terms and conditions of any software license will be incorporated into the final contract. Prior to finalizing the contract, the TxDOT reserves the right to negotiate terms of use of any relevant software licenses.

Technical Support:

The system installer shall provide technical support to TxDOT for the life of the contract. Technical support includes, but is not limited to, the following:

- Troubleshooting of the system
- Routine questions
- Configuration questions or changes
- Customized reporting; and
- Provide support terms, including response times, communication methods and hours of availability.

Functional and Technical Requirements

The following table lists the Categories as well as system requirements within each category. These requirements are further classified as required or desired.

Category	**ID**	**Requirement**	**Required**	**Desired**
General Data Requirements	1.1	The ATSPM system shall be a vendor-provided web-hosted traffic data collection and traffic data analytics product.	X	
	1.2	The ATSPM system shall utilize industry standard communication protocols.	X	
	1.3	The ATSPM system shall provide all services and software necessary for retrieving high-resolution controller data.	X	
	1.3.1	The ATSPM system shall capture high-resolution data on a user-defined basis as frequent as a tenth of a second.	X	
	1.3.2	The high-resolution data shall be date and time stamped.	X	

Category	ID	Requirement	Required	Desired
	1.3.3	The high-resolution data shall include its associated event parameter.	X	
	1.3.4	The event parameters shall contain data used to identify the source or nature of the event.	X	
	1.4	The ATSPM system shall be able to generate reports of high-resolution data for the performance measures.	X	
	1.5	The high-resolution data shall be able to be pushed to the cloud host for storage, processing, and retrieval.	X	
	1.6	The high-resolution data shall be owned exclusively by the agency.	X	
General Access Requirements	2.1	The ATSPM system shall be accessible from a Windows-based desktop or laptop.	X	
	2.3	The ATSPM system shall be accessible from a tablet using Apple IOS, Google Android, or Windows for mobile devices.	X	
	2.4	The ATSPM system shall be accessible from a mobile phone using Apple IOS, Google Android, or Windows for mobile devices.	X	
	2.5	The ATSPM system shall be accessible using Internet Explorer.	X	
	2.6	The ATSPM system shall be accessible using the Safari web browser.	X	
	2.7	The ATSPM system shall be accessible using the Chrome web browser.	X	
	2.8	The ATSPM system shall be accessible using the Firefox web browser.	X	
User Accounts	3.1	The ATSPM system shall support authentication of individual users via individual usernames and passwords.	X	
	3.1.1	The ATSPM system shall not limit the number of user accounts that can be created to allow and grant access.	X	

Category	ID	Requirement	Required	Desired
	3.1.2	The ASTPM shall provide varied levels of data access and analytic functionality that are tiered by multiple user types	X	
	3.1.3	The ASTPM system shall allow an "admin" access to restrict access for up to 5 user types.	X	
	3.1.4	The ASTPM system shall allow user types to be tied to user log ins.	X	
	3.1.5	The ASTPM system shall restrict access to specific performance measures based on user type.		X
	3.1.6	The ATSPM system shall be able to restrict access to data on specific corridors based on user type.		X
General Display Features	4.1	The user web interface shall consist of a front-page dashboard customized by user profile.	X	
	4.2	The dashboard shall provide for multiple saved views by user profile.	X	
	4.3	The dashboard shall display user-selected performance measure graphs over a user-defined time period that may be	X	
	4.4	Dashboard views shall include an indication of overall system health or performance.	X	
	4.5	The dashboard shall be capable of displaying graphic representations of user-customized SPMs.	X	
	4.6	The dashboard shall provide a list of signals with performance measures at user-defined intervals.	X	
Map Display	5.1	The ATSPM system shall display a map view of the entire system.	X	
	5.1.1	The map view shall display user-defined performance measures.	X	
	5.1.2	The map shall provide heat-map views that highlight problem areas.	X	
	5.1.3	The map shall allow a user to zoom and click and drag to identify specific intersections in more detail.	X	

Category	ID	Requirement	Required	Desired
	5.1.4	The user shall be able to click on an intersection to access a variety of SPM charts relating to the intersection.	X	
	5.1.5	The ATSPM system shall be capable of showing locations for degraded performance measures on a map.	X	
	5.1.6	The map view shall display performance measures using user-defined graphical thresholds.	X	
Data Storage and Analytics	6.1	The ATSPM system shall support ability to statistically compare differences between data series by user-defined time period.	X	
	6.2	The ATSPM system shall store high-resolution and system configuration data.	X	
	6.3	The ATSPM system shall support performance report analytics that can be exported to MS Word, Excel, Access, CSV, and Adobe PDF.	X	
	6.4	High-resolution data shall be stored and retrievable for at least 3 years.	X	
	6.5	The ATSPM shall support storing and retrieving data older than 3 years.	X	
Detector Diagnostics	7.1	The ATSPM system shall be capable of providing a separate list of intersections with degraded detector performance.	X	
	7.2	The ATSPM system shall be able to identify and report detectors that may not be fully operational.	X	
General Signal Performance Measures	8.1	The ATSPM system shall generate user-defined performance measure reports at user-defined intervals.	X	
	8.2	Signal Performance Measure charts shall provide a user selectable date selection.	X	
	8.3	Signal Performance Measure tables shall provide a user selectable date selection.	X	
	8.4	The ATSPM system shall provide the means to compare various	X	

Category	ID	Requirement	Required	Desired
		performance metrics over user definable date ranges.		
	8.5	The ATSPM system shall provide tabular comparison of SPMs with indications of improvement or degradation of the	X	
	8.6	The ATSPM system shall support the comparison of historical trends to a baseline data set.	X	
	8.7	The ATSPM system shall be able to provide recommendations for improving SPMs based on historical trends.	X	
Arrivals on Red and Arrivals on Green	9.1	The ATSPM system shall track and report metrics relating to the volumes of traffic arriving at an intersection during the	X	
	9.2	The ATSPM system shall provide an arrival on red chart that shows the volume of vehicles arriving at the intersection on red and the percent of vehicles arriving on red for each cycle during a 1-day/24-hour interval based on a user defined data and time period.	X	
	9.3	The ATSPM system shall provide the arrivals on red chart for each phase of a signal that meets detection requirements.	X	
	9.3.1	The ATSPM system shall provide arrivals on red at an intersection level.	X	
	9.3.2	The ATSPM system shall provide arrivals on red at a corridor level.	X	
	9.3.3	The ATSPM system shall provide arrivals on red at a system level.	X	
	9.4	The ATSPM system shall track and report metrics relating to the volumes of traffic arriving at an intersection during the green intervals.	X	
	9.5	The ATSPM system shall provide an Arrivals on Green chart for each phase of a signal that meets detection requirements.	X	

Category	ID	Requirement	Required	Desired
	9.5.1	The ATSPM system shall provide Arrivals on Green at an intersection level.	X	
	9.5.2	The ATSPM system shall provide Arrivals on Green at a corridor level.	X	
	9.5.3	The ATSPM system shall provide Arrivals on Green at a system level.	X	
Pedestrian Events	10.1	The ATSPM system shall provide a pedestrian delays chart that displays the amount of delay introduced by the pedestrian actuation.	X	
	10.2	The ATSPM system shall provide the pedestrian delays chart for individual approaches of a signal.	X	
	10.3	The ATSPM system shall provide the pedestrian delays chart as a combined report for all approaches of a signal.	X	
	10.3.1	The ATSPM system shall provide pedestrian delay at an intersection level.	X	
	10.3.2	The ATSPM system shall provide pedestrian delay at a corridor level.		X
	10.3.3	The ATSPM system shall provide pedestrian delay at a system level.		X
	10.4	The ATSPM system shall track and report number of pedestrian actuations per phase.	X	
Power Failures	11.1	The ATSPM system shall track and report metrics relating to power failures.	X	
	11.1.1	The ATSPM system shall highlight individual intersections that have experienced power failures over a user specified date.	X	
	11.1.2	The ATSPM system shall highlight individual corridors that have experienced power failures over a user specified date.	X	
	11.1.3	The ATSPM system shall display systemwide power failures over a user specified date.	X	

Category	ID	Requirement	Required	Desired
Communications Failures	12.1	The ATSPM system shall track and report metrics relating to communication failures.	X	
	12.1.1	The ATSPM system shall highlight individual intersections that have experienced communication failures over a user specified date.	X	
	12.1.2	The ATSPM system shall highlight individual corridors that have experienced communication failures over a user specified date.	X	
	12.1.3	The ATSPM system shall display systemwide communication failures over a user specified date.	X	
Preemption Events	13.1	The ATSPM system shall track and report metrics relating to preemption.	X	
	13.1.1	The ATSPM system shall provide a summary of each preemption event for a selected intersection.	X	
	13.1.1.1	The summary shall indicate each preemption event's start time for a selected intersection.	X	
	13.1.1.2	The summary shall indicate each preemption event's duration for a selected intersection.	X	
	13.1.2	The ATSPM system shall provide a summary of preemption information (number of calls, number of granted calls) on user selected intersections.	X	
Purdue Coordination Diagram (PCD)	14.1	The ATSPM system shall provide a PCD that shows the volume (vehicles per hour) during each cycle.	X	
	14.2	The ATSPM system shall provide a PCD that shows start of green during each cycle.	X	
	14.3	The ATSPM system shall provide a PCD that shows the start of yellow during each cycle.	X	
	14.4	The ATSPM system shall provide a PCD that shows the start of red during each cycle.	X	
	14.5	The ATSPM system shall provide the PCD chart for each coordinated	X	

Category	ID	Requirement	Required	Desired
		phase of a signal that meets detection requirements.		
Split Failures	15.1	The ATSPM system shall track and report metrics relating to split failures.	X	
	15.2	The ATSPM system shall provide a Split Failures Report for each phase that plots Red Occupancy Ratio for each cycle.	X	
	15.3	The ATSPM system shall provide a Split Failures Report that plots Green Occupancy Ratio phase terminations for each cycle.	X	
	15.4	The ATSPM system shall provide the Split Failures Report for each phase of a signal that meets detection requirements.	X	
	15.4.1	The ATSPM system shall provide the Split Failures at an intersection level.	X	
	15.4.2	The ATSPM system shall provide the Split Failures on a corridor level.		X
	15.4.3	The ATSPM system shall provide the Split Failures for the system.		X
Split Monitor	16.1	The ATSPM system shall provide a Split Monitor chart that plots by phase, the phase termination reason summarizing all cycles throughout the day (e.g. force off or gap out)	X	
	16.2	The ATSPM system shall provide the Split Monitor chart for each phase of a signal that meets detection requirements.	X	
	16.2.1	The ATSPM system shall provide the Split Monitor chart by intersection.	X	
	16.2.2	The ATSPM system shall provide the Split Monitor chart by corridor.	X	
	16.2.3	The ATSPM system shall provide the Split Monitor chart for the system.	X	
Delay	17.1	The ATSPM system shall provide the average delay per vehicle.	X	

Category	ID	Requirement	Required	Desired
	17.2	The ATSPM system shall provide the vehicle delay report for each phase of a signal that meets detection requirements.	X	
	17.3	The ATSPM system shall provide vehicle delay at an intersection level.	X	
	17.4	The ATSPM system shall provide vehicle delay at a corridor level.	X	
	17.5	The ATSPM system shall provide vehicle delay for the system.	X	
Volumes	18.1	The ATSPM system shall provide turning movement counts for each signal that meets detection requirements - tabular and map displays.	X	
	18.2	The ATSPM system shall report metrics relating to vehicle volumes at the intersection level - tabular and map displays,	X	
	18.3	The ATSPM system shall report metrics relating to vehicle volumes at the corridor level - tabular and map display.	X	
Queues	19.1	The ATSPM system shall report queue lengths on all approaches for intersections that meet detection requirements.	X	
Yellow and Red Actuations	20.1	The ATSPM system shall provide Yellow and Red Actuations chart at signals that meet detection requirements.		X
Approach Speed Charts	21.1	The ATSPM system shall provide approach speeds charts for signal approaches that meet detection requirements.		X
Travel Time	22.1	The ATSPM system shall generate point-to-point travel time calculations by integrating external data sources.		X
	22.2	The ATSPM system shall support calculation and viewing of travel time data within 15 minutes of capture.		X

Category	ID	Requirement	Required	Desired
	22.3	The ATSPM system shall support generation and overlay of historical travel time trends over any period throughout the three-year data set.		X
	22.4	The ATSPM system shall support generation of historical variability statistics of travel time over any period throughout the three-year data set.		X
O-D Information	23.1	The ATSPM system shall capture vehicle presence via a traffic probe utilizing using vehicle identification technology		X
	23.2	The ATSPM system shall transmit vehicle identification to the server at least once per minute.		X
Alerts	24.1	The ATSPM system shall display real-time status of all active SPM alerts. This requirement includes all SPMs defined in the requirements above, including each SPM subcategory for Requirements 8 through 22.	X	
	24.1.1	The ATSPM system shall provide historic and real time alerts with alert time.	X	
	24.1.2	The ATSPM system shall provide historic and real time alert notifications.	X	
	24.1.3	The ATSPM system shall provide historic and real time alert resolution.	X	
	24.1.4	The ATSPM system shall support user-defined pushed email and SMS alerts.	X	
	24.1.5	The ATSPM system shall support user-defined alerts based on performance thresholds.	X	
	24.1.6	The ATSPM system shall support user-defined alerts based on detector failures.	X	
Security	25.1	The ATSPM system shall have geographic redundancy for server hosting locations.	X	

Category	ID	Requirement	Required	Desired
	25.2	The ATSPM system shall utilize industry standard security methods for data storage and access.	X	
	25.3	The ATSPM system shall employ industry standard encryption to ensure user login names and passwords are secure.	X	
	25.4	The system shall allow the system admin to implement password rules and password change requirements.	X	
Support	26.1	The ATSPM system vendor shall provide two training sessions for up to 5 City staff members.	X	
	26.2	The vendor shall provide "bug" fixes for three years.	X	
	26.3	The vendor shall provide a three-year warranty for all hardware components.	X	
	26.4	The vendor shall provide software updates including new features for three years.	X	
	26.5	The vendor shall provide technical support and maintenance for three years.	X	
	26.6	The vendor shall demonstrate that a minimum of 5 ATSPM systems have been installed and are currently operating in the United States.	X	

Guidance to the districts in the implementation of ATSPM

One way to move toward performance-based management is to weave signal performance measures into a Traffic Signal Management Plan (TSMP)[4]. A TSMP can help an agency attract resources by demonstrating needs, prioritizing activities, and defining “basic service” as it relates to the traffic signal system. Once an agency has developed a definition, they can use signal performance measures to:

[4] National Academies of Sciences, Engineering, and Medicine 2020. *Performance-Based Management of Traffic Signals*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25875.

- Identify how well they are meeting expectations.
- Identify where they need to invest in the traffic signal system.
- Communicate those messages to policymakers and elected officials.

Without a clear definition for "basic service," it can be difficult for managers to communicate the value of their program and the impacts of resource allocation and budget cuts[5]. This section builds off that idea and provides additional guidance for creating a TSMP.

Identify a Champion

A study to Evaluating the Benefits and Costs of Implementing Automated Traffic Signal Performance interviewed six early adopter agencies[6]. This included three State agencies: Utah Department of Transportation (UDOT), Georgia Department of Transportation (GDOT), and Pennsylvania Department of Transportation (PennDOT); and three local agencies: Lake County Department of Transportation (LCDOT); Clark County (WA); and Maricopa County Department of Transportation (MCDOT). A common thread among interviewed agencies was they all had strong executive support for making investments such as ATSPM implementation. This was particularly critical for UDOT because it took on considerable risk by investing thousands of in-house labor hours to develop an open-source software package. This yielded considerable benefits for UDOT, as well as several other agencies that would continue to use the software UDOT developed.

GDOT had similar executive support for its implementation. A few years after Utah's initial investments in open-source software, the implementation process was documented with assistance from GDOT, which has added its own contributions to the software. PennDOT is a larger agency, in terms of the total number of signals in the State. Nearly all the signals in the State are managed by local agencies, but the State has undertaken several initiatives to help improve signal operations. Here again, there was strong support at the top level to improve the management of traffic signals in the State.

Most agencies did not have a formal planning process for the ATSPM system. They gained information about the technology through outreach from the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) Innovation Initiative or pooled fund study and decided to deploy it. It is also worthwhile to note that FHWA promotes a systematic approach to implementation that considers

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[5] Denney, Jr., R.W. and P.R. Olsen. 2013. "Traffic Signal Operations Reviews: Common Threads." *IMSA Journal*, Vol. L1, No. 2, pp. 26-32.
[6] Day, C. O'Brien, P. Stevanovic, A. Hale, D., and Matout, N., "A Methodology and Case Study: Evaluating the Benefits and Costs of Implementing Automated Traffic Signal Performance". U.S. Department of Transportation, Report No. FHWA-HOP-20-003, September 2019.

the impact on the workforce, business processes, and appropriate use of systems engineering to inform design and procurement.

It is imperative that any agency that intends to make an impact on the signal operations in the state, has a leadership that shares those goals and provides all resources needed to implement them in a consistent manner.

Cultural shift to performance-based prioritization

At many agencies, a culture shift will be required to fully integrate signal performance measures. The technology has the capacity to inform system-wide decisions and can replace or enhance some traditional decision-making methods. For example, instead of waiting for calls to come in from the public or making changes based on a set schedule, an agency can shift to a daily monitoring process in which traffic signal maintenance and operational improvements are prioritized based on performance. To start this shift from traditional signal retiming to performance-based management, an agency should consider using pilot projects, which will allow practitioners to test signal performance measures at low-risk locations.

Sharable reports

Signal practitioners sometimes need to share progress with executive staff, elected officials, the public, or the media. Most practitioners are currently limited in what they can present, but with the implementation of signal performance measures, agencies can create executive summaries and dashboards, and can respond efficiently to Freedom of Information Act (FOIA) requests. It is important for agencies to share performance measures that are easy to understand, such as travel time or travel time reliability.

Quantitative performance tracking

Agencies can develop a standard procedure for quantitatively tracking and documenting progress with agency staff, decisionmakers, and the public, potentially through a newsletter or annual update. A routine process for disseminating successes can facilitate information sharing between agencies and notify decision-makers about program activities. For example, an agency can report an increased number of equipment upgrades, reductions in delay, or improvements in travel time over the course of a year.

Identify District Goals and Limitations

The quantifiable goals for each agency (TxDOT Districts) will have to be identified. These goals will influence the use of ATSPM for the "day-to-day" operation as follows:

Efficient Maintenance

An example is to maintain the health of the signal infrastructure consisting of signal controllers, signal cabinets, communication infrastructure, and detection at a level that meets the district goals.

Proactive Operations

An example is to maintain the state of signal operations at a level that minimizes user complaints and optimizes corridor operations in a proactive manner by targeting the arrivals on green at or above a certain threshold.

Personnel Needs

The upper management will have to provide adequate resources in the form of personnel to have a successful ATSPM deployment. This includes dedicated personnel to operate the ATSPM system by constantly monitoring the health of the signal infrastructure as well as trained personnel to maintain all components of the ATSPM system. This includes effective coordination and cooperation with other departments including the IT department.

Infrastructure Needs

Signal performance measures can help prioritize short-term maintenance needs and inform replacement cycles for equipment. Many agencies find it easier to acquire capital funds than maintenance funds. By tracking the degradation of equipment over time using ATSPMS, an agency may be able to break out of a capital-based replacement cycle. The agency will need to have a plan to prioritize the deployment of equipment. The equipment is listed below.

Modern traffic signal controllers

The agency will need to select corridors as a base minimum, or a district as a whole or an agency to upgrade the signal control equipment. This upgrade is the first step towards the deployment of ATSPM.

Effective communication

Once traffic signal controllers that can collecting/generate high resolution data are installed, the agency needs to prioritizing upgrading communications equipment. Deployment of communication can be done in fashion like the deployment of signal control equipment. Deployment of communications would not only be a big step for the deployment of ATSPM, but also for the regular operations and maintenance of the signal systems.

Intersection Detection

Proper intersection detection is essential for providing effective ATSPM performance measures. Figure 46 illustrates an ideal configuration for detection. Each district will have to prioritize the deployment of detection to take advantage of the ATSPM system as implementing extensive detector configuration can be very expensive.

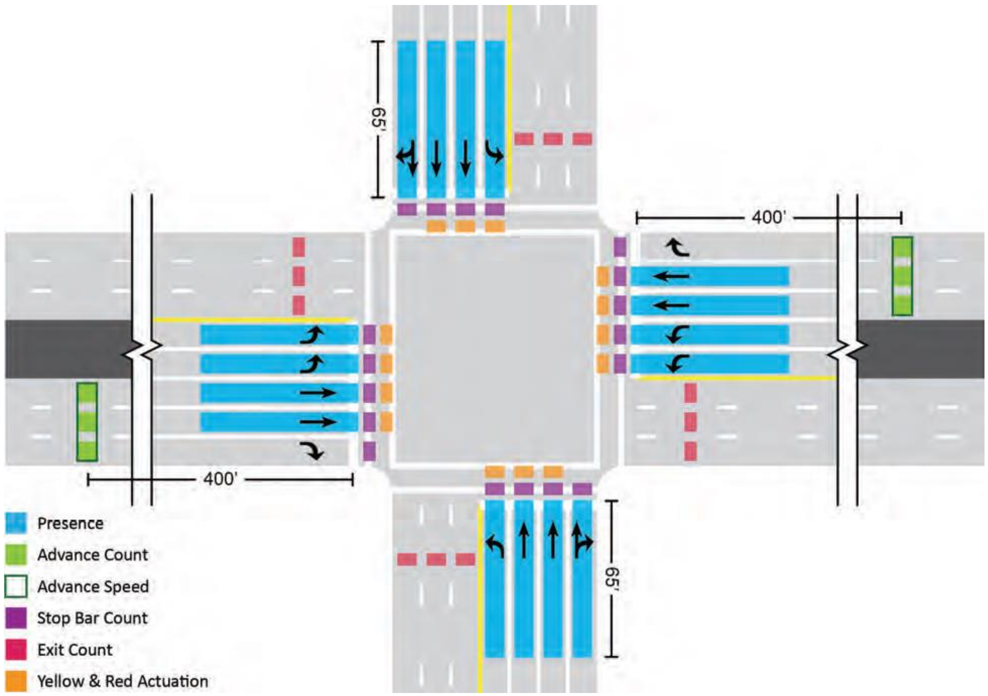

Figure 49. Ideal Detection Configuration for ATSPM Performance Measures.

APPENDIX B—VALUE OF RESEARCH ASSESSMENT

VALUE OF RESEARCH ASSESSMENT

The research team completed a Value of Research (VoR) assessment as part of the project. The VoR assessment was based on the benefit areas selected at the beginning of the project (shown in Table 4).

Table 4. Selected Benefit Areas for VoR Assessment.

Selected	Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both	Definition in context to the Project Statement
X	Improved Productivity and Work Efficiency		X			X		Reduced manual labor for data collection
X	Traffic and Congestion Reduction		X				X	Reduced complaint response time, capacity and progression benefits
X	Reduced Construction, Operations, and Maintenance Cost		X				X	Faster response to detection and other equipment failure.

The VoR assessment is based on the assumption that ATSPM is deployed at about 3000 signals in the first year itself. The assumptions are based on a USDOT study that looked at the benefits to cost ratio of the implementing ATSPM. UDIT which is a leader in the deployment of ATSPM was considered as a case study in the determination of the benefits for this VOR.

The VOR was calculated based on the monetary values of the necessary variables, which are as follows:

- Variable 1: Manual data collection avoided.
- Variable 2: Complaint response time avoided.
- Variable 3: Respond to failed detection.
- Variable 4: Capacity benefits
- Variable 5: Progression benefits.

Table 5 shows the assignment of those variables to the appropriate economic benefit area for the VoR assessment.

Table 5. Value of Variables for VoR Assessment.

Economic Benefit Area	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5	Total
Improved Productivity and Work Efficiency	$41,380,188				-4,599.298	$36,780,890
Traffic and Congestion Reduction		$12,450,816		$46,320,000		$58,770,816
Reduced Construction, Operations, and Maintenance Cost			$115,800,000			$115,800,000
					Total	$211,351,706

The research team entered the values shown in Table 5 into the TxDOT VoR Assessment spreadsheet to calculate the formal VoR measures. Those results are shown in Table 6. The results show that, based on the assumptions provided previously, the research project is estimated to have a benefit-cost ratio of approximately 4507:1 over a 10-year expected value duration, with over $1.9 billion in savings.

Table 6. Results of VoR Assessment for Project 0-7009.

Texas Department of Transportation	Project #	0-7009		
	Project Name:	Implementation of Automatic Traffic Signals Performance Measures		
	Agency:	TTI	Project Budget	$ 389,603
	Project Duration (Yrs)	2.0	Exp. Value (per Yr)	$ 211,351,706
Expected Value Duration (Yrs)		10	Discount Rate	3%
Economic Value				
Total Savings:	$ 1,901,775,751		Net Present Value (NPV):	$ 1,755,960,383