U.S. Department of Transportation
Federal Highway Administration

A METHODOLOGY AND CASE STUDY

Evaluating the Benefits and Costs of Implementing Automated Traffic Signal Performance

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16. Abstract

This primer describes a methodology to evaluate the benefits and costs of objectives- and performance-based traffic signal operations and maintenance. The methodology includes a quantitative component supported by a subjective analysis. The intent of the methodology is to describe advantages and disadvantages of using a performance-based traffic signal monitoring process, executed through the automated traffic signal performance measures (ATSPM), when compared to the traditional approaches of monitoring and retiming traffic signals. The methodology is intended to validate the attainment of traffic signal program objectives and agency goals as articulated in a Traffic Signal Management Plan, Transportation System Management and Operations Plan, or other strategic planning document(s).

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SI* (MODERN METRIC) CONVERSION FACTORS

FACTORS APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in.^{2}	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1,000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in.^{2}	poundforce per square inch	6.89	kilopascals	kPa

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

SI* (MODERN METRIC) CONVERSION FACTORS (CONTINUED)

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
mm	millimeters	0.039	inches	in.
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	$in.^2$
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ACS	adaptive control system
ADT	average daily traffic
ADOT	Arizona Department of Transportation
a.m. peak	morning peak
ATC	adaptive traffic control
ATSPM	automated traffic signal performance measures
ATMS	active traffic management system
AZ	Arizona
CAV	connected and automated vehicle
CCTV	closed-circuit television
CHIPR	County Highway Improvement Program Request
CIP	Corridor Improvement Program
CMAQ	congestion mitigation and air quality improvement
CMM	capability maturity model
ConOps	concept of operations
CPU	central processing unit
CR	crash reduction
CV	connected vehicle
DOT	department of transportation
EV	emergency vehicle
FHWA	Federal Highway Administration
FTE	full-time employee
FYA	flashing yellow arrow
GcOST	goals, context, objectives, strategies, and tactics
GDOT	Georgia Department of Transportation
h	hour
h/wk	hours per week
I–76	Interstate 76
I–79	Interstate 79
IDOT	Illinois Department of Transportation
IL	Illinois
IL–22	Illinois Route 22
IN	Indiana
INDOT	Indiana Department of Transportation
IP	internet protocol
IT	information technology
ITE	Institute of Transportation Engineers
ITS	intelligent transportation systems

LIST OF ACRONYMS (CONTINUED)

LCDOT	Lake County Department of Transportation
LOS	level of service
MAG	Maricopa Association of Governments
MARK 1	Measurement, Accuracy, and Reliability Kit
MCDOT	Maricopa County Department of Transportation
MOE	measure of effectiveness
mi	miles
mo	month
NCHRP	National Cooperative Highway Research Program
NPV	net present value
OSADP	Open Source Application Development Portal
PCD	Purdue Coordination Diagram
PDO	property damage only
PS&E	plans, specifications, and estimate
PE	professional engineer
PennDOT	Pennsylvania Department of Transportation
PM	performance measures
PTOE	professional traffic operations engineer
PTZ	pan, tilt, zoom
qtr	quarter
RTOP	Regional Traffic Operations Program
RTSO	Regional Traffic Signals Program
RFP	request for proposal
ROW	right of way
SBIR	small business innovation research
SCAT	signal coordination and timing
sec/h	seconds per hour
sec/veh	seconds per vehicle
SPaT	signal phasing and timing
SR 37	State Road 37
STIC	State Transportation Innovation Council
STORM	Statewide Traffic Operations and Response Management
mi^2	square miles
TMC	traffic management center
TOD	time of day
TSMP	traffic signal management plan
TT	travel time
UDOT	Utah Department of Transportation
US	United States

LIST OF ACRONYMS (CONTINUED)

US 421	US Route 421
veh	vehicle
veh/day	vehicles per day
VM	virtual machine
WA	Washington
WSDOT	Washington Department of Transportation
WisDOT	Wisconsin Department of Transportation
wk	week
wk/yr	week per year
yr	year

EXECUTIVE SUMMARY

Automated traffic signal performance measures (ATSPM) are recent tools available to agencies that manage traffic signal systems. They have been shown to greatly enhance agencies' situational awareness regarding operation and maintenance of their signals that was previously only available through field operations or time-consuming analysis. ATSPMs have helped agencies quickly identify and proactively respond to operational and maintenance issues, improve traffic signal timing, and easily communicate outcomes internally and to decision makers and the public. ATSPMs can also improve the capabilities of agencies and help move away from reactive management that responds to problems as they are reported, and toward proactive management that takes action based on direct measurement of performance.

At present, ATSPMs have been embraced by many early adopters, but to expand implementation to the early majority market segment, more information is needed about implementation benefits and costs. A method for estimating benefits and costs would be useful to many agencies considering an implementation but unsure of potential return on investment. This report helps fill this gap by proposing a methodology for estimating benefits and costs. In addition, the report includes detailed information from six case studies of early adopters of ATSPMs, and summarizes key factors of successful implementations.

COST-BENEFIT ESTIMATION METHODOLOGY

The methodology in this report for estimating benefits and costs is intended to be flexible, allowing analysts to include any factors relevant to their agency's situation, and to exclude irrelevant factors. The methodology is also intended to cover analysis of both short-term implementation benefits and long-term benefits sustained over the life cycle. The methodology includes 16 cost items and 12 benefit items, as summarized in figure 1, next page. For each cost item, a formula is provided using input data that should be obtainable by analysts in consideration of their current practices or by examining previous implementations. Benefit items are estimated based on anticipated improvements in agency practices and signal timing. A method is presented for estimating each benefit, including terms that can be estimated from reductions in time needed for tasks reduced through ATSPM, and potential benefits to the public from improved signal timing that result in increased safety or reduced delays.

Costs

1. Controller procurement.
2. Firmware upgrades.
3. External data collection.
4. Communications system investments.
5. Communications system maintenance.
6. Detection system investments.
7. Detection system maintenance.
8. Detector reconfiguration.
9. Detector documentation.
10. New server procurement.
11. Server maintenance.
12. Software license.
13. Software installation.
14. Maintenance/troubleshooting.
15. Business process integration.
16. Active use of ATSPMs.

Benefits

1. Replace manual data collection.
2. Avoid unneeded retiming and maintenance activities.
3. Reduce response time to public service calls.
4. Value of performance documentation.
5. Fix failed detectors.
6. Fix broken communication.
7. Fix equipment failures.
8. Improve inefficient green distribution.
9. Improve poor coordination.
10. Resolve pedestrian issues.
11. Resolve preemption issues.
12. Improve safety.

Source: FHWA

Figure 1. Illustration. Primary items in the benefit-cost methodology.

LESSONS LEARNED FROM CASE STUDIES

As part of this research, six early adopter agencies were interviewed. 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). In addition, personnel from Cranberry Township, PA, were included to focus on a local Pennsylvania agency perspective, where the State directly manages few signals, but is working to provide ATSPM as part of a package of tools to local agencies.

Support of Leadership Yields Successful Implementations

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—it took on considerable risk by investing thousands of in-house labor hours to develop an open-source software package that provides performance measures through a web-based front end, and automatically downloads and manages a database repository for the high-resolution from which the metrics are calculated. 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. Through a combination of several parallel efforts, both agencies have made ATSPMs available to nearly all traffic signals in their respective States.

PennDOT is a larger agency, in terms of the total number of signals in the State. Nearly all of 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. ATSPMs are being integrated into an overall corridor modernization program as one tool among many to help streamline signal improvement, and help local agencies within the State improve their signal management practices. Cranberry Township, PA is one such agency and is among the first in the State to begin early implementation efforts.

The other local agencies included in the study are smaller and did not have the same scale of resources as the larger State DOTs. The three local agencies involved in this study had been undertaking programs to improve their operations and maintenance of traffic signals. ATSPMs were discovered by the agencies in the middle of carrying out these existing initiatives, and it was realized that an implementation could be integrated with those initiatives relatively easily. Clark County had been actively upgrading and adding capabilities to their traffic signal system for about a decade; they worked with their vendor to develop the capability to obtain ATSPMs within their system, and initiated research to identify ways to integrate the performance measures into their practices. LCDOT had a similar experience. ATSPMs are seen as an important component of their overall signal operations; their implementation has benefited from the agency having cultivated open communication with leadership and signal operators. Maricopa County has a history of investment in Intelligent Transportation Systems (ITS) infrastructure throughout the Phoenix metropolitan area through the AZTech regional traffic management partnership. The administrative infrastructure was therefore in place to support a technology initiative such as the ATSPM implementation.

Considerations for Implementation and Integration

Larger agencies with adequate information technology (IT) staff have successfully implemented ATSPM using the UDOT open-source code. However, this is not the only option for ATSPM and it may not be the best for smaller agencies that don’t enjoy the same level of IT resources. Among the six agencies interviewed in this study, Clark County and LCDOT have used software from controller vendors to provide ATSPMs. This was likely a feasible option because both agencies had a working relationship with those vendors. However, several companies presently offer ATSPM software that would work with equipment from multiple vendors.

Communication to the intersection enables automatic downloading of high-resolution data to provide ATSPMs, while detection at the intersection reveals operational details of traffic performance. In addition, that information will be more valuable if the detectors are configured with separate lanes. Agencies across the United States (US) vary widely in regard to their existing infrastructure capabilities, with many signals not having communication to permit transfer of data. Some also lack detection, or would require changes to detector configurations to allow some performance measures to be collected. Perhaps unsurprisingly, agencies that successfully implemented ATSPMs had taken the initiative to develop this traffic signal infrastructure at a high level, even prior to beginning their ATSPM implementations.

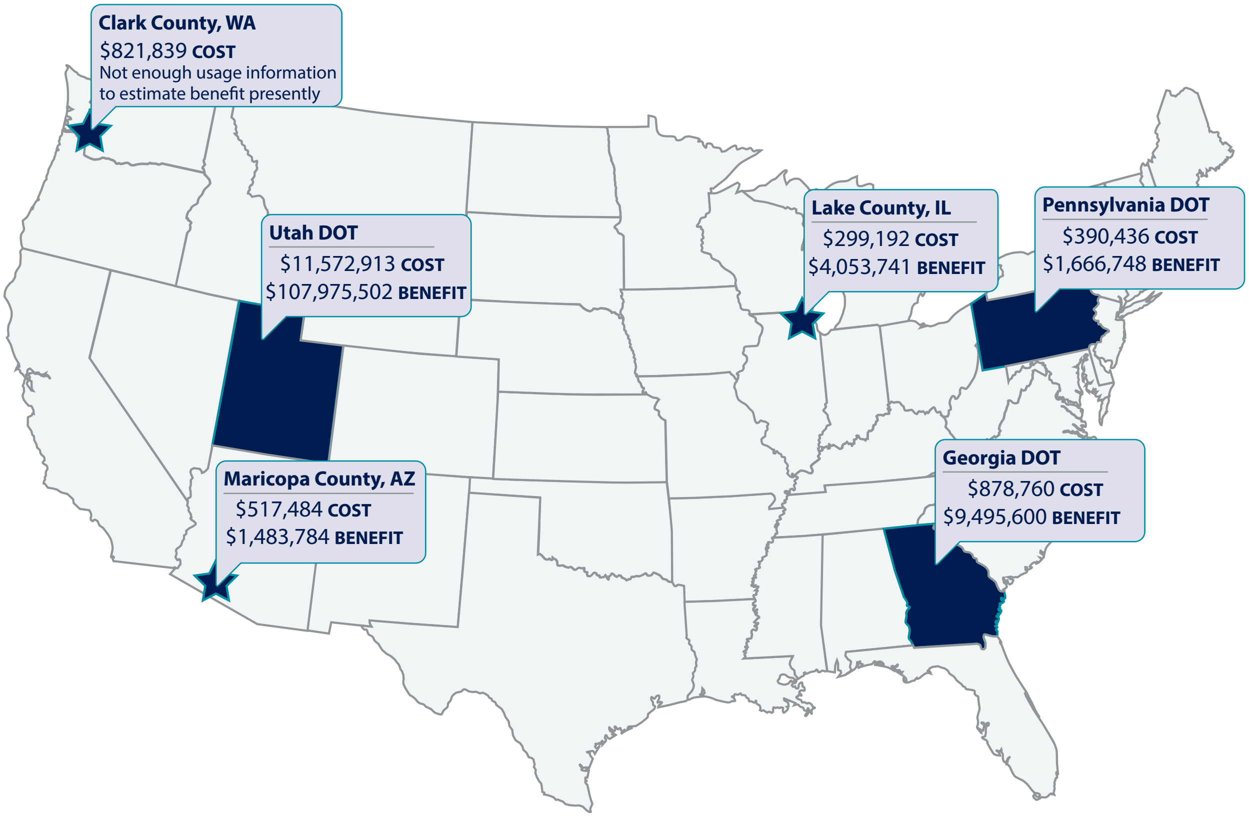
One of the most important findings of the study is that agencies' operational practices are not always well integrated into their business models. Agencies that have a clear operational plan for operating their signals are more likely to be able to leverage ATSPMs to execute improvements and to document those successes. However, agencies that do not have such a plan will probably not be able to execute the same degree of benefit from ATSPMs. The wealth of data provided by ATSPM systems will probably not affect their day-to-day operations because they will not necessarily have clarity on what tasks the data should be employed for improving practice. For this reason, any discussion of ATSPM implementation should probably be predicated with development of a systematic approach to describing an agency's plans, goals, and objectives for managing and operating its traffic signal system. This would help provide clarity and identify which performance measures are applicable to specific tasks. From the case study interviews in this research, it is apparent that having clear operational objectives correlates with successful integration of performance measures into practice.

Another related issue is that the wealth of data that can be obtained by technologies like ATSPM poses a new problem; most agencies do not have the resources to scan these data sets to identify problems. ATSPMs, for example, are an excellent tool for checking the extent of known problems and verifying that a solution has a positive impact. Searching for unknown problems is more difficult. The development of methodologies to carry out this process would help improve the benefit gained from ATSPM implementations. Some recent software innovations, such as the Measurement, Accuracy, and Reliability Kit (MARK 1) tool developed by GDOT, are moving in this direction by providing a means of aggregating data from many locations into a succinct summary. Adding the mechanism to filter through volumes of data to spatially and temporally locate issues would be a next step for future research.

Estimating Benefits and Costs

At present, none of the agencies implementing ATSPMs have comprehensively tracked benefits and costs resulting from those activities. Some previous case studies (mostly by Indiana Department of Transportation [INDOT]) have documented estimated annualized public benefits resulting from before-and-after studies facilitated by ATSPM. While those results are summarized in this report, and they may provide a sense of the scale of benefits that could be realized, it is difficult to draw general conclusions from those studies, and the transferability of outcomes to other locations is unknown.

To try to broaden the overall picture of ATSPM impact, benefit and cost information was obtained in the six case study interviews carried out under this research. The results are summarized in figure 2, with details supplied with the case study information, including estimates of overall costs required for each implementation and preliminary estimates of benefits obtained from those implementations. The cost information obtained from these case studies is probably the most valuable piece of information for agencies considering implementations. With regard to benefit information, most agencies, at this point, had enough knowledge of the effort they had been spending on activities, such as responding to failed detection or public complaint calls, to estimate the reduced effort of such activities. Therefore, agency benefits were calculable for all case study agencies, and in most cases, benefits were greater than the cost of implementation. However, the amount of public benefit was not immediately estimable for most of the agencies, with the exception of UDOT. Although agencies are making use of ATSPMs to provide such benefits, extraction of the amount of benefit would require additional resources. In theory, the ATSPM systems themselves might be able to assist in estimation of those benefits, but this capability has not yet been introduced. Developing methods to do so would be a beneficial topic of future research.



Source: FHWA

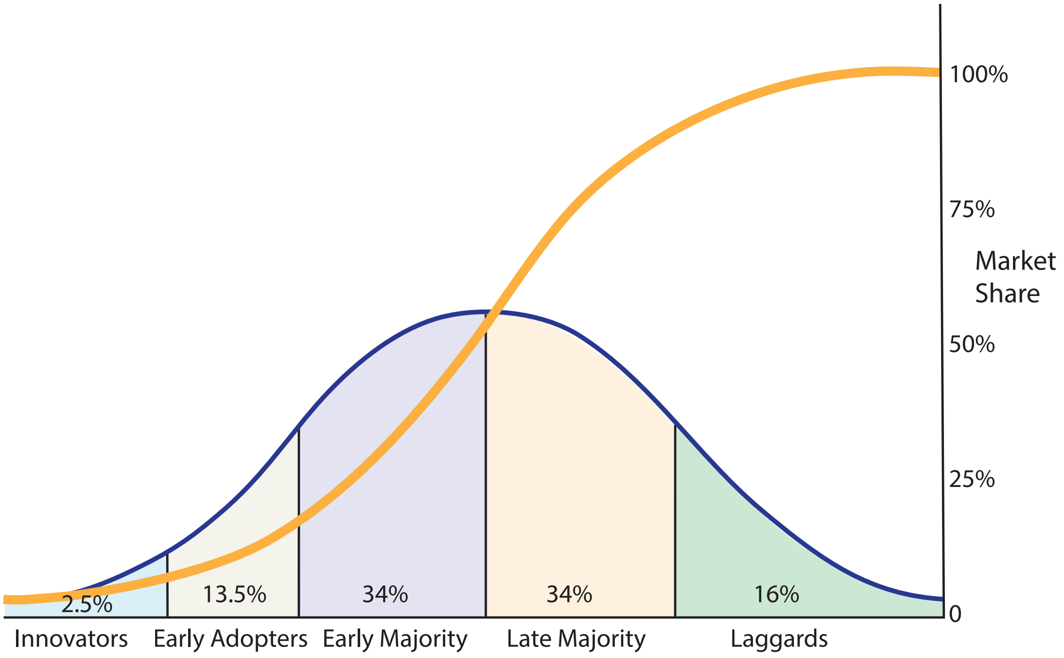
Figure 2. Illustration. Overview of case study benefits and costs.

CHAPTER 1. INTRODUCTION AND CONCEPTS

More than a decade of collaborative research and development within the academic, public and private sector transportation community has contributed to the development of automated traffic signal performance measures (ATSPM). The Federal Highway Administration's (FHWA) Every Day Counts 4 ATSPM technology initiative continues to actively promote implementation of the technology with the goal of transforming traditional reactive approaches to traffic signal timing to objectives- and performance-based management and operations that proactively support attaining transportation goals including safety, mobility, and efficiency.

ATSPMs are a suite of visual aids and data analysis tools combined under a single platform to: 1) collect high-resolution traffic signal and detection data, 2) derive relevant performance measures, and 3) visualize those measures in a format that helps traffic signal staff to operate, maintain, and manage traffic signals to improve safety, mobility and efficiency of signalized intersections for all users.

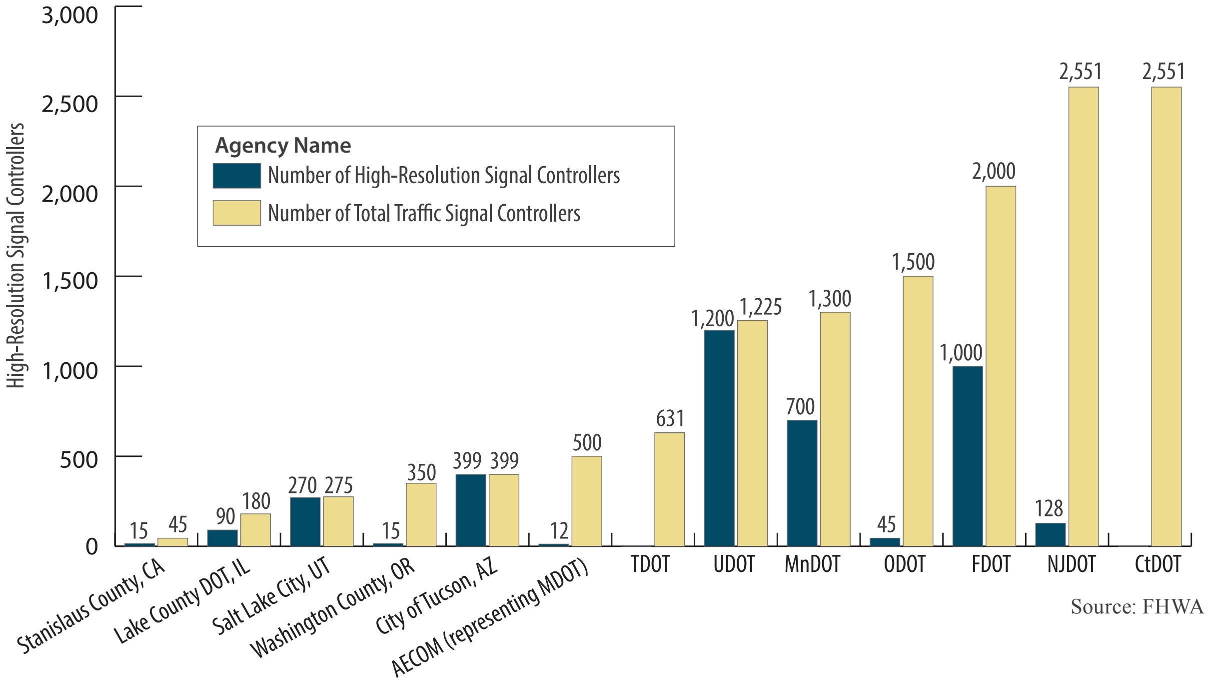
As the widespread implementation of ATSPM continues, it is timely to reflect on the progress in terms of diffusion of innovation theory (figure 3). Significant implementation has occurred in the categories of innovators and early adopters. To advance implementation among early and late majority adopters, sound evidence of benefits and costs of objectives- and performance-based management of signal systems is needed.



Source: FHWA (adapted from Everett Rogers)

Figure 3. Graph. Diffusion of innovations according to Rogers.

The FHWA estimates that more than 300 downloads of the open-source software for ATSPM have occurred from the FHWA Open Source Application Development Portal (https://its.dot.gov/code/). Through collaborative efforts with Utah Department of Transportation (UDOT), the software was migrated to the GitHub platform (https://github.com/OSADP/ATSPM). At the time of this writing, the conversion rate from downloads to implementation was unknown. Interviews and ongoing discussion with organizations that have implemented the software indicates only a small subset of implementers possess the workforce capability and resources to incorporate use of ATSPMs into operations and maintenance business practices. The information available to support implementation of ATSPM continues to emerge and develop. National Cooperative Highway Research Program's (NCHRP) Project 03-122: Performance-Based Management of Traffic Signals (Tanaka et al., forthcoming) described helpful practices for collecting high-resolution data at the traffic signal controller level and converting that data into performance measures that indicate how well the system is operating. The outcome of pooled fund study TPF-5(258) Traffic Signal Systems Operations and Management (INDOT, forthcoming), includes two publications that discuss the use of high-resolution data to develop outcome-oriented performance measures and an approach for integrating measures in agency business practices. Figure 4 illustrates some agencies' adoption rates of high-resolution signal controllers.



Source: FHWA

Figure 4. Bar Chart. Select agency adoption of high-resolution controllers as of 2019.

Documentation of effective practices and quantitative benefits and cost information may help to continue the evolution of traffic signal management and operations business processes from reactive to proactive. This primer documents case studies and describes effective practices, benefits, and costs of objectives- and performance-based management of traffic signal programs.

BACKGROUND

Traditionally, the transportation community has taken a reactive approach to traffic signal operations. With the development of the ATSPM tool, the academic and public and private sector transportation communities are promoting proactive traffic signal operations by using an objectives- and performance-based management approach. These objectives support an agency's transportation goals, including safety, mobility, and efficiency, and these goals can be monitored using ATSPMs.

Early adopters of ATSPM that possess the workforce and resources to effectively incorporate ATSPMs form a small subset of potential implementers. These early adopters have (anecdotal) knowledge of the benefits and costs of objectives- and performance-based management of signal systems—but quantitative information that can be widely shared will likely increase the number of agencies investing in training to integrate these practices into their workforce.

In recent years, several innovations have emerged that have provided new resources and tools to agencies. This includes traffic signal controllers that collect high-resolution data (Smaglik 2007) and software that creates ATSPMs, which greatly enhances agency situational awareness. Additionally, the basic service model concept (Denney 2009) establishes a starting point for agencies to develop objectives for their traffic signal programs. Some agencies have made considerable progress integrating these tools. However, many agencies using the same resources have faced challenges implementing performance-based management. In such cases, awareness of lessons learned from agencies that overcame such challenges could be quite helpful.

Support for implementation of ATSPM is increasing, but there is an opportunity to develop and document a comprehensive methodology for evaluating benefits and costs of objectives- and performance-based traffic signal operations and maintenance. This primer presents a methodology for estimating benefits and costs, and documents effective agency practices, through a series of case studies, that facilitate ATSPM implementation. Integration of ATSPMs into agency practice is a helpful activity for ensuring investments in ATSPMs and other performance-based management tools have a direct payoff in improved traffic signal operations and maintenance and agency organizational management.

MOTIVATION FOR AUTOMATED TRAFFIC SIGNAL PERFORMANCE MEASURES

In the previous decade, awareness of the need for improved traffic signal management has grown, as highlighted by efforts such as the Traffic Signal Report Card (National Transportation Operations Coalition 2012). That report was widely cited as evidence that a critical need of improvement has been system monitoring and data collection. Current practices for many agencies rely on manual techniques and few agencies have practices to generate actionable operational information on a widespread basis. Most agencies' signal management activities focus on reacting to public complaint calls and preventative maintenance and retiming, as resources allowed.

Performance-based management uses a proactive rather than reactive approach to the problem, necessitating a robust monitoring program. ATSPMs have emerged in the past decade, offering a potential means to this end. Research efforts in Indiana, including State-funded research projects NCHRP 3-79A (Day 2010b) and pooled fund study TPF-5(238) (Indiana Department of Transportation, forthcoming), led to the development of a portfolio of performance measures and extensive documentation of their use in field applications. UDOT's open-source ATSPM software was released several years ago, establishing a nominally free tool that several agencies have implemented, while stimulating development of new vendor products. The Every Day Counts program and NCHRP 03-122 (Tanaka et al.) have focused on implementation of ATSPMs. Use of performance measurement tools enabled by ATSPMs and similar technologies helps an agency to:

- Quickly identify issues.
- Proactively respond to issues.
- Efficiently operate the traffic signals via better timing parameters.
- Easily communicate outcomes to engineers, decision makers, and the public.

Today, ATSPMs are becoming a mainstream tool for signal operations. At present, ATSPM software has been provided by several vendors in addition to the open-source software, including:

- Utah open-source ATSPM software.
- Live Traffic Data Corp.
- Iteris® Signal Performance Measures (SPM)™.
- Kimley-Horn Traction SPM.
- TraffOp.
- Econolite Centracs® SPM.
- Intelight MAXVIEW.
- Trafficware Cloud SPM.

With all tools, knowledge is helpful for applying them to the best advantage. As the technology moves from the realm of early adopters into the mainstream, it is beneficial for the accompanying knowledge to spread. At present, a significant knowledge gap is in the magnitude of benefit that can be attained from investment in performance-based management of signal systems.

INTEGRATION INTO BUSINESS PRACTICES

Implementation of new technology is sometimes thought of as procurement and installation. However, there is a human side to the problem often overlooked. A review of the history of the traffic industry reveals numerous occasions when new technology was regarded as the solution to a longstanding problem, yet the advantages did not fully materialize or were not sustained over the long run because the technology was not used to its full potential, or it could not be maintained. Tools that have endured are those that have been integrated into agencies' culture and business practices. More documentation of the benefits of changing practices and methodologies for quantifying those benefits is highly desirable.

Integration of performance-based management into practice can be facilitated by connecting those performance measures to agency needs. Building the capability will not, alone, lead to improved performance. It is helpful to understand what the agency is trying to achieve—and, consequently, what it could attempt to measure. A framework of goals, context, objectives, strategies, and tactics (GcOST) has been encouraged by FHWA as a means of articulating key activities for agencies in operating and maintaining traffic signal systems and connecting those activities to specific performance measures (Fehon 2015).

- Goals are the desired end state the organization strives to realize. Goals are typically driven by the vision of system owners: the public through elected officials and the officials' appointees. Typical goals include having a program that is safe, efficient, sustainable, and so on.
- Context refers to the environment in which the signal program operates. It would include users of traffic signals, modes represented in the network, traffic and travel patterns through the network, interaction with neighboring agencies, and the topology of the road network.
- Objectives are specific and actionable measures of attainment that support the achievement of a goal that involve a measurable outcome. For example, the goal of efficient signal operation—a desirable end state—can be further articulated with an actionable objective of balancing capacity allocation. Attaining that objective could be measured through one of the signal performance measures previously mentioned.
- Strategies represent programs of activities that should be carried out to realize an objective. For example, an objective of improving capacity allocation can be realized by the strategy of signal timing adjustments to balance capacity allocation at signal-controlled intersections where that objective is in force. Note that activities include things done by staff, including implementing supporting systems, aimed at attaining the related objectives.
- Tactics are the specific actions that carry out a strategy. Continuing with the example of optimizing capacity allocation as a strategy, this could be achieved by the following tactic: Use Critical Movement Analysis to adjust green times to balance saturation by moving relatively unused green time to phases with higher green time usage. If ATSPM is available, it can be tactically used with this alternative tactic: Adjust green times to achieve similar measured green time utilization on critical phases. Note that demonstrating the attainment of an objective is a different tactic, e.g., review green time utilization measures daily to demonstrate the objective of balancing capacity allocation is being attained. Clearly, if the same measure is used to attain and to demonstrate attainment, then demonstration comes at little cost, so using performance measures for attaining objectives becomes less costly than using traditional model-based methods and then separately using performance measures to demonstrate attainment.

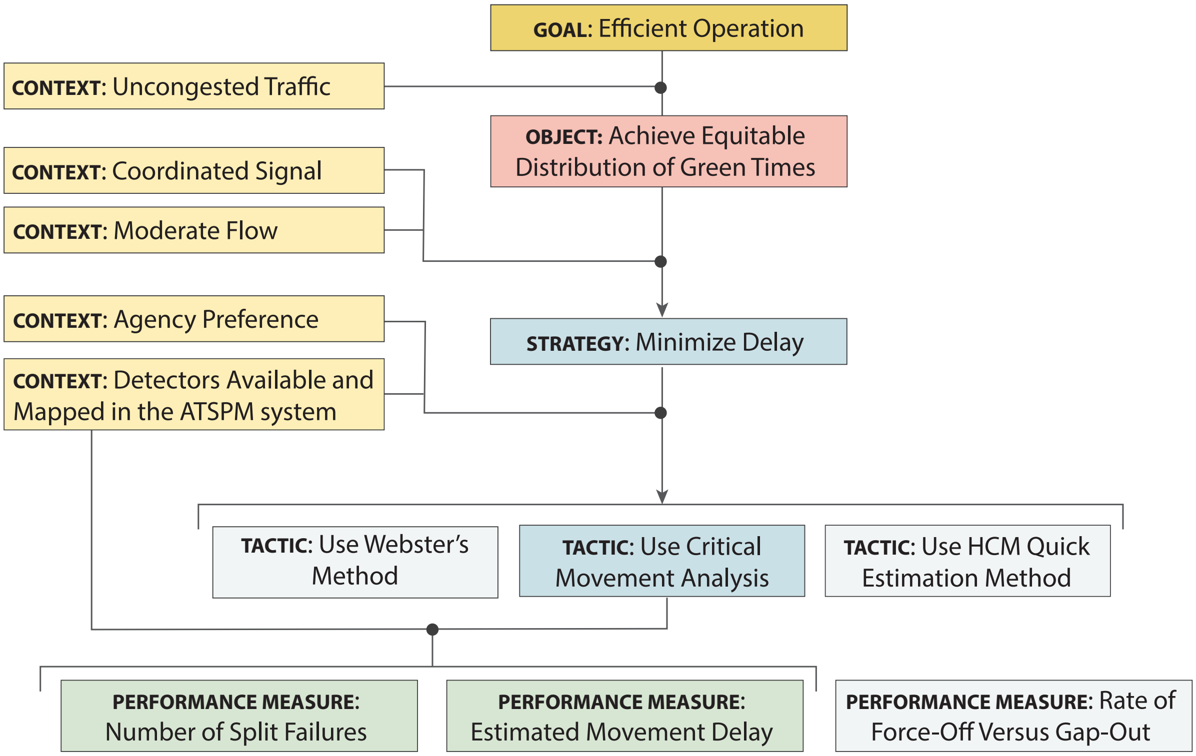
The GcOST framework is a foundation for articulating benefits and costs because each activity generating benefit or cost will ideally be related to a particular objective, strategy, and tactic falling within a particular context.

Figure 5 provides an example of an agency's goal of efficient operation—such a goal would be one among others, such as safe operation. Under the umbrella of efficient operation there are many possible objectives. In the context of uncongested traffic, an appropriate objective is to seek equitable distribution of green times. With further contextual knowledge of a traffic signal's environment—in this example, a signal in a coordinated network with moderate flow—a strategy of minimizing delay is identified, and possible tactics are suggested based on that strategy.

In this example, based on agency preference, critical movement analysis is selected as a means of adjusting the signal timing to respond to demands. At this point, selection of performance measures can be carried out to evaluate whether these efforts have achieved the desired objective. Further context helps narrow the decision; in this example, detectors are available at the location and "mapped" into the ATSPM system (i.e., definitions allow the system to know which detectors belong to which movement/phase), allowing the selection of specific performance measures.

ATSPM technology represents an opportunity for increased capability maturity. It is an initial step toward performance-based management of traffic signals, which is becoming readily accessible to agencies, even though information and training are often needed. At present, most of the performance measures are movement-based, but ongoing efforts seek to aggregate and synthesize these to yield intersection, corridor, and system level metrics. When combined with a solid benefit-cost methodology, as this research will provide, the resulting framework will enable an agency to monitor benefits and costs on a regular basis (e.g., daily, weekly, monthly). In addition, this will create opportunities for consulting companies to be strongly involved and help provide turnkey signal monitoring and retiming services. This is likely to improve signal operations and maintenance, if there is a comprehensive and clear methodology to evaluate the success of private signal operators.

A further opportunity to improve agency outcomes, however, is when they are able to replace traditional methods (such as critical movement analysis), which largely depend on volume-based modeling ranging from very simple to highly complex, with actual observation of operation. Not only will this improve the attainment of the objectives, but will build in the ability to demonstrate that attainment for little additional cost. The process depicted in figure 5 will at that time change, become more direct, simple, and less costly. Based on the case studies, much remains to be accomplished, and thus the estimates of benefits and costs discussed in the next sections are still limited.



Source: FHWA

Figure 5. Flowchart. Connections between context, objective, strategy, tactics, and performance measures.

ASSESSING BENEFITS AND COSTS OF PERFORMANCE-BASED MANAGEMENT

Performance-based management is a transformational concept that has the potential to improve traffic signal system operation and maintenance. ATSPMs require implementation of systems and technology to develop metrics and support data collection. Existing systems and technology may be leveraged but some costs are likely to be incurred, particularly when legacy infrastructure and systems are present. ATSPMs require a system to collect data and deliver metrics to the end user. To extract the most useful metrics from the system, adaptive traffic control (ATC) controllers, detection systems, and communications infrastructure may be used. Some of these costs may be conflated with ordinary expenses associated with operating a functional traffic signal system. For example, detection is necessary for basic traffic signal operations and can also be used by the ATSPM system. Adding detection or repairing broken detection will likely improve basic operation and allow proactive operations, deriving a benefit. This benefit will increase as the use of ATSPM's become part of the basic operation, not just a byproduct of the same infrastructure. Table 1 shows a summary of quantified user benefits from previous studies. These numbers were derived from estimates of vehicle travel time and travel time reliability from probe data. They may be considered a first-order approximation of benefits to the public; the benefit per signal (the total amount divided by the number of signals) is also shown here, which provides some insight into the scale of improvement that may be attainable across agency signal inventory. These costs are largely related to travel time savings; additional benefits not specifically explored in these previous analyses include:

- Fleet wear-and-tear costs for additional vehicle miles traveled.
- Reduced fuel consumption.
- Reduced public health impact in pollution-sensitive areas.
- Potential safety benefit from reduced property damage only (PDO), injury, and fatality crashes where reductions in running red lights might be attained from location analysis.

Table 1. Quantified benefits of performance-based management in previous studies.

System Location and Synopsis	Annual User Benefits Quantified
Offset optimization using high-resolution data on State Road 37 (SR 37) in Noblesville, IN (Lavrenz 2016b).	$3.7 million ($370,000 per signal)
Maintenance and operational improvements on SR 37 in Johnson County, IN (Li 2015).	$3 million ($270,000 per signal)
Maintenance benefits from detector repairs facilitated by high-resolution data on US Route 421 (US 421) in Indianapolis, IN (Day 2016).	$900,000 ($150,000 per signal)
Benefits of various signal timing improvements across five corridors in Pennsylvania measured with probe vehicle data (Krohn 2017).	$11 million ($180,000 per signal)

Furthermore, there may be benefits to the agency from performance-based management that directly affect agency budgets. For example, in some cases, with improvements to signal timing, geometric improvements to intersections might be postponed for a number of years at a location, which can be monetized in terms of saved capital costs. Proactive management, enabled by improved system intelligence, allows unknown problems to be discovered and addressed, improves agencies' abilities to leverage personnel to prioritize tasks, and enables agencies to quantify their needs and make a better case to decision makers for resources. These benefits can partly be understood from case study results, but also in terms of the road not taken, i.e., the absence of such benefit had those agencies not implemented performance-based management—a potential opportunity cost for those agencies presently considering or unaware of performance-based management as an option. Table 2 provides a tentative picture of the fork in the road and how the outcomes are likely to affect agencies making such decisions.

APPROACH TO BENEFIT-COST ESTIMATION METHODOLOGY

In developing an approach to benefit-cost estimation, the authors built from existing studies and past research on benefit-cost analysis (FHWA 2013), including previous estimations of user benefits outlined in table 1. The core of the methodology was the mathematical expressions that control the estimation outcomes. This analysis tool can be incorporated into a Microsoft® Excel spreadsheet, or a similar format, allowing the analyst to quickly adjust values and obtain the desired numbers. The authors had previously developed such tools for previous studies for internal use.

Table 2. Costs and benefits for performance-based management.

Approach	Costs	Benefits
Performance-based management	▪ Initial deployment costs (e.g., hardware components, labor). ▪ System maintenance. ▪ Expertise/consulting services, training, etc. ▪ Subscription-based services (e.g., cloud-based hosting).	▪ Better monitoring capability. ▪ Better operational outcomes from retiming based on continuous retiming. ▪ Organizational benefits: better leveraging of operations personnel, and potential improvements in related areas (planning, design, etc.).
Traditional management (Reactive)	▪ Accumulated disbenefits from lack of system knowledge.	▪ Unspent costs of deployment and maintenance of technology to facilitate performance-based management.

CHAPTER 2. RELEVANT PRIOR WORK

This chapter presents background on signal monitoring concepts that enabled automated traffic signal performance measures (ATSPM) to be developed. It also provides an overview of previous studies in which the performance measures were developed and their utility was demonstrated through applications to various real-world use cases.

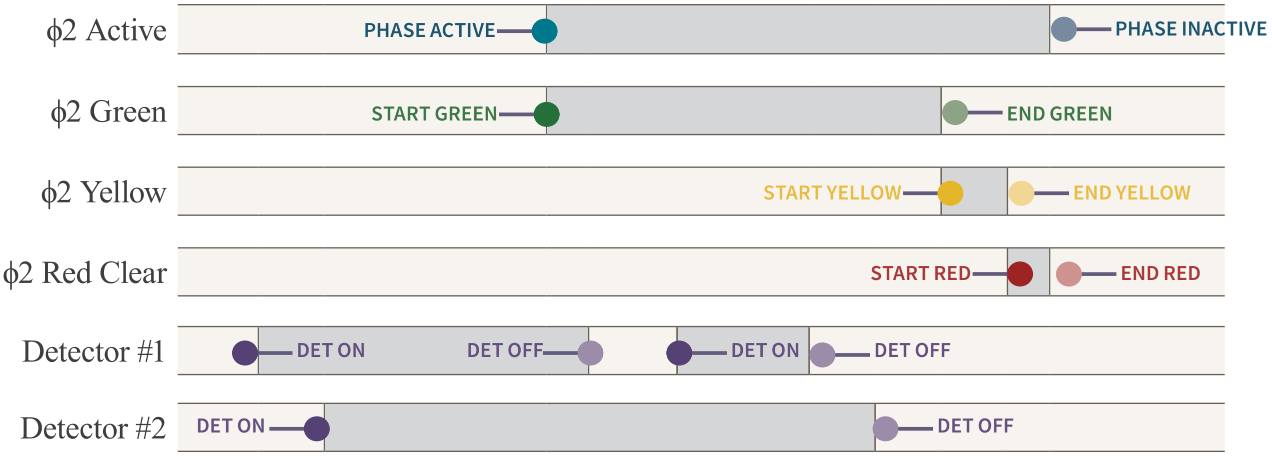
EVENT DATA CONCEPT

The core data used in ATSPMs is high-resolution data, which is a digital record of events occurring within the signal controller, such as times when signal outputs changed (e.g., transitions between green, yellow, and red for phases or overlaps), detector states changed from "on" to "off" or vice versa, and other control events. In theory, any change in information within a signal controller could be registered as an event. The present enumerations list 101 types of events, and some vendors have independently added more.

In the past, limitations of hardware and communication used in traffic signal systems restricted the availability of detailed data-collection capabilities. Some advanced technologies, such as adaptive signal control, required collection of similar types of data. However, most adaptive systems did not report this internal data. One exception was ACS Lite, whose records of signal and detector state data could be extracted in raw form (Gettman 2007).

In the early 2000s, researchers began to explore use cases in signal control evaluations that required logging of real-time detector and phase states. One use case was the evaluation of new detection systems. The measurement of detector on-time latency made it necessary to record state changes at time resolutions less than 1 second; this led to the creation of an intersection testbed where state changes were logged in real time. Researchers soon realized the data used for evaluating detectors contained useful information for measuring intersection performance (Smaglik 2007; National Transportation Operations Coalition 2012). Around the same time, researchers in Minnesota began to log intersection data in a similar manner, with the goals of evaluating corridor progression by estimating queue lengths to predict travel times of virtual probe vehicles (Liu 2009).

Figure 6 illustrates an example of high-resolution data. In this example, an instance of phase 2 ($\phi 2$) is shown. The time when the controller is managing the timing of phase 2 includes its green, yellow, and red clearance intervals. The start and end of each interval is marked by a corresponding event. The input states of two detector channels are also shown; transitions from an "on" to "off" state, and vice versa, are recorded by events. From these data, assuming the two detector channels represent stop-bar detectors, it's possible to determine when vehicles are waiting for the phase to begin (when the detector turns on), and when the phase is finished serving vehicles (when the detectors turn off).



Source: FHWA

Figure 6. Illustration. Example of states and event data.

PERFORMANCE MEASURES AND USE CASES

Research into signal performance measures using high-resolution data has been ongoing for more than a decade, and these data have been applied to numerous use cases. A functional classification of use cases for signal performance measures was suggested by researchers (Day 2015), based on the idea that interdependencies of system elements suggest different roles of performance measurement. An illustration of this hierarchy is presented in figure 7; this is slightly modified from earlier representations, reflecting input received from practitioners.

From bottom to top, the five layers are:

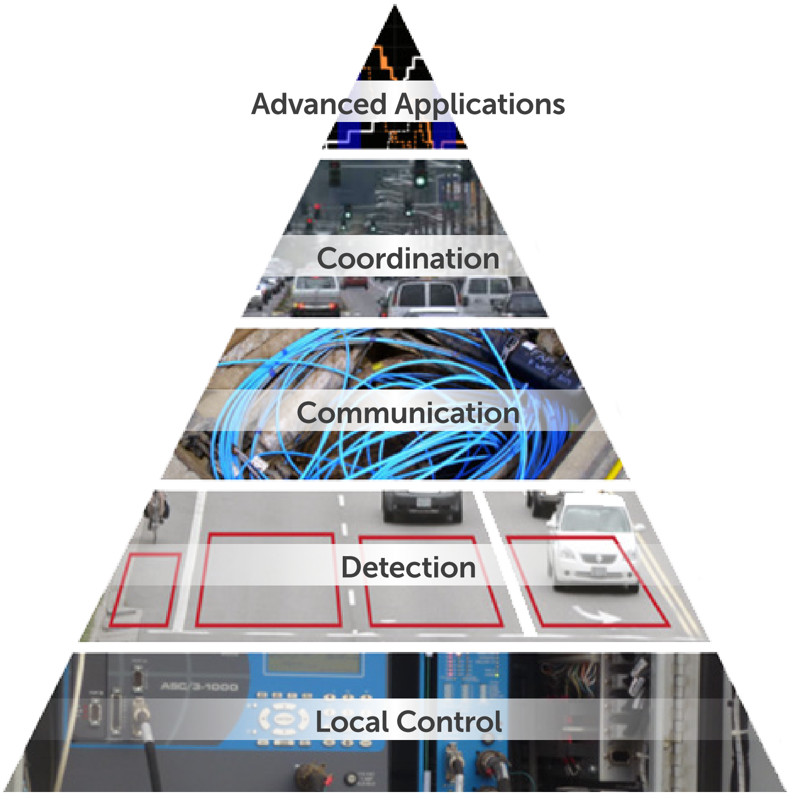
1. Local control appears at the base of this hierarchy. This represents the phase-switching operation carried out by the local controller, which is the most basic operational function of a traffic signal. As long as the signal has power and appropriate basic programming, it will be able to operate in a rudimentary manner, even if no other part of the system is working. Traffic signal systems are fairly robust in maintaining this basic level of operation.

2. Detection is the next layer. Detectors (vehicle and pedestrian) can substantially improve the quality of local control by enabling the controller to adjust green times to match measured traffic demands, thus implementing actuation. Because actuation is only possible if basic local control is also operational, operating detection sits on a higher level in the hierarchy. The quality of local signal operations can be evaluated when the detector information is available.

3. Communication comes next; this represents the ability of the local controller to communicate with the outside world. This is needed to synchronize clocks for coordination, and to transmit data externally for performance measurement.

4. Coordination is the fourth layer; this represents the operation of multiple intersections in a cooperative manner to promote progressive traffic flows (or other objectives requiring choreography of multiple signal controllers). Coordination depends on the ability of controllers to talk to each other, or at least to receive a common reference time source to remain synchronized. Good quality coordination is also dependent on the functionality of the detection and local control layers.

5. Advanced applications is the topmost layer, representing higher-order management applications that could be used in a signalized intersection, such as traffic responsive or adaptive control. The ability of these tools to have a positive impact on system operation is contingent on the working condition of the underlying layers.



Source: FHWA

Figure 7. Illustration. A hierarchical view of signal system functionalities and areas for performance measurement.

Each layer has its own maintenance or operation concerns. At a basic level, it is helpful to ensure the system components are functional, such as detection and communication systems. Many agencies invest a lot of time in keeping these systems up and running. The impact of signal timing is also important to quantify; the quality of that service can be described in many different ways, depending on the type of objective of the operation. For example, the distribution of green times affects the service of individual movements; inadequate green time leads to the buildup of vehicle queues; excessive green times on other phases during the same cycles indicate an inefficiency that likely could be corrected.

Table 3 presents a list of objectives for each functional hierarchy layer, with examples of performance measures that have been applied in literature to assist in achieving these objectives. Example studies are highlighted where quantitative user benefits have been demonstrated as an outcome of using performance measures to manage the system. There are only a handful of studies where this is the case; these used external data sources to measure travel times, and converted the change in travel time to annualized user benefits. A few other studies included changes in delay and other similar metrics, but did not include user benefit documentation.

Table 3. Mapping of objectives to performance measures.

Functional Layer	Objective	Performance Measures	Documented User Benefit
Basic Local Control	Ensure that controllers are functioning.	Tracking occurrences of intersection flashing operation.	(Huang 2018)
	Troubleshoot challenging controller programming.	Visualization of track clearance operation. (Brennan 2010)	
		Timing and actuation diagram (UDOT, n.d.).	
Detection and Actuated Signal Timing	Ensure that detectors are not malfunctioning.	Identification and visualization of failed detectors (UDOT, n.d.; Lavrenz 2017; Li 2013, 2015).	(Lavrenz 2017)
	Provide for equitable distribution of green times during undersaturated conditions.	Volume-to-capacity ratio (Smaglik 2007a; Day 2008, 2009, 2010).	
		Green and red occupancy ratios (Freije 2014; Li 2017).	
		Phase termination (Li 2013).	
		Delay estimates from stop-bar detector occupancy (Sunkari 2012; Lavrenz 2015; Smith 2014).	
		Split monitor (UDOT, n.d.).	
	Maximize throughput at the stop bar during oversaturated conditions.	Throughput (Day 2013).	
	Minimize occurrences of red light running.	Red light running (Lavrenz 2016a).	
		Red and yellow actuations (UDOT, n.d).	
	Provide adequate service to nonmotorized users.	Conflicting pedestrian volume (Hubbard 2008).	
Communication	Ensure that controllers are able to communicate with each other.	Tracking occurrences of communication loss (Li 2013, 2015; An 2017).	(Li 2015)

UDOT = Utah Department of Transportation.

Table 3. Mapping of objectives to performance measures. (continuation)

Functional Layer	Objective	Performance Measures	Documented User Benefit
Coordination	Provide timing plans that promote smooth traffic flow.	Percent on green and arrival type (Smaglik 2007a, 2007b).	
		Cyclic flow profile and coordination diagram (Day 2010a, 2011; Hainen 2015; Barkley 2011; Huang 2018).	(Day 2011)
		Time space diagram (Zheng 2014, Day 2016).	
		Queue length and delay estimates from advance detection (Sharma 2007; Liu 2009; Hu 2013).	
		Estimated travel time (Liu 2009).	
	Decide when to coordinate neighboring intersections.	Coordinatability index (Day 2011).	
	Minimize impacts of excessive queuing during oversaturation.	Temporal and spatial oversaturation indices (Wu 2010).	
Advanced Applications	Assess impacts of adaptive signal control functionalities.	Various applications of the above metrics (Richardson 2017; Day 2012, 2017).	

UDOT = Utah Department of Transportation.

The lack of documentation of monetized user benefits does not mean that benefits do not exist. However, for the most part, the extra steps necessary to obtain a quantitative record of such changes is beyond the scope of most studies or agency resources. Directly measuring these changes can be expensive, in that some external method of obtaining travel times is generally needed. It is possible the data itself could provide such estimates, but this has not yet been applied in a conversion to user benefits. Table 4 provides a list of studies that have documented user benefits from studies that provided benefits as an annualized dollar amount.

Table 4. Studies presenting documentation of user benefit from active management of traffic signal systems.

System Location	Synopsis	Amount of User Benefit
SR 37, Noblesville, IN (10-intersection corridor)	Impact of offset optimization for a single time-of-day plan (Day 2011).	$550,000 ($55,000 per signal)
	Impact of offset optimization over a 5-year period (Day 2012).	$3,700,000 ($370,000 per signal)
SR 37, Johnson County, IN (11-intersection corridor)	Repair of broken communication, misaligned time-of-day plan, and offset optimization (Li 2015).	$3,000,000 ($270,000 per signal)
US 421, Indianapolis, IN (X-intersection corridor)	Repair of broken detection throughout corridor (Lavrenz 2017).	$900,000 ($150,000 per signal)

X = number of intersections is unknown.

IMPLEMENTATION

Activities promoting implementation of traffic signal performance measures were elements of research and development from an early stage. Research in both Indiana and Minnesota led to the development of scalable systems for bringing in field data. In Minnesota, this led to the development of a commercial system, while in Indiana, a prototype system was cooperatively developed between Purdue University and the Illinois Department of Transportation (IDOT). In 2012, Utah Department of Transportation (UDOT) began developing its own system, taking inspiration from the work done in Indiana, and investing considerable resources to develop a stable software package. The code was made available as an open-source license, and offered under the Federal Highway Administration's (FHWA) Open Source Application Development Portal (OSADP) in 2017, when FHWA's fourth Every Day Counts program started. Around this time, UDOT named the overall data and performance measure methodology "automated traffic signal performance measures" (ATSPM).

Indiana's research included outreach to traffic signal vendors. Through collaborative discussions between academia and industry, State, and local agencies, a common data format was agreed upon and became a de facto standard for high-resolution data. By 2016, all major controller manufacturers in the U.S. had implemented high-resolution data collection in at least one model. In addition, third-party vendors had introduced products that could collect high-resolution independent of the controller. Many of these vendors also began to develop their own systems for delivering ATSPMs to the user. At the time of this writing, there are many commercial choices for implementation in addition to the open-source software.

The growth of interest in and development of tools was accelerated in 2014 by the selection of ATSPMs as an American Association of State Highway and Transportation Officials (AASHTO) Innovation Initiative focus technology, and the FHWA's fourth Every Day Counts program in 2017–2018. These programs made hosting numerous workshops possible across the U.S., which increased awareness and implementations of ATSPMs. As of December 2018 (see figure 9), the technology has been implemented by at least 39 State departments of transportation (DOTs) at a demonstration stage, or higher, and institutionalized in four States. Many local agencies have also implemented ATSPMs, or are in the process of doing so. Presently, most of these systems are still in the early phases, many with pilot intersections or corridors with ATSPMs available, but over time the number of intersections has been growing. With ATSPMs themselves having transformed from a research topic to a tool available to practitioners by various means, an emerging focus for new research is utilization of the measures to facilitate performance-based management, as described in Chapter 1: Introduction and Concepts.

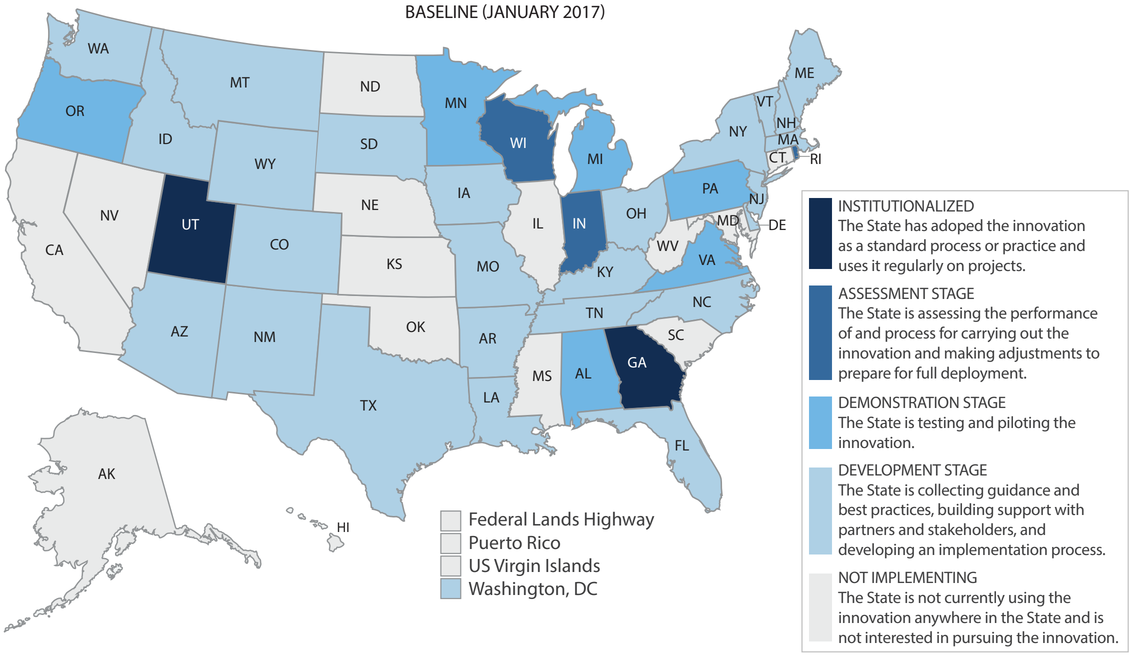
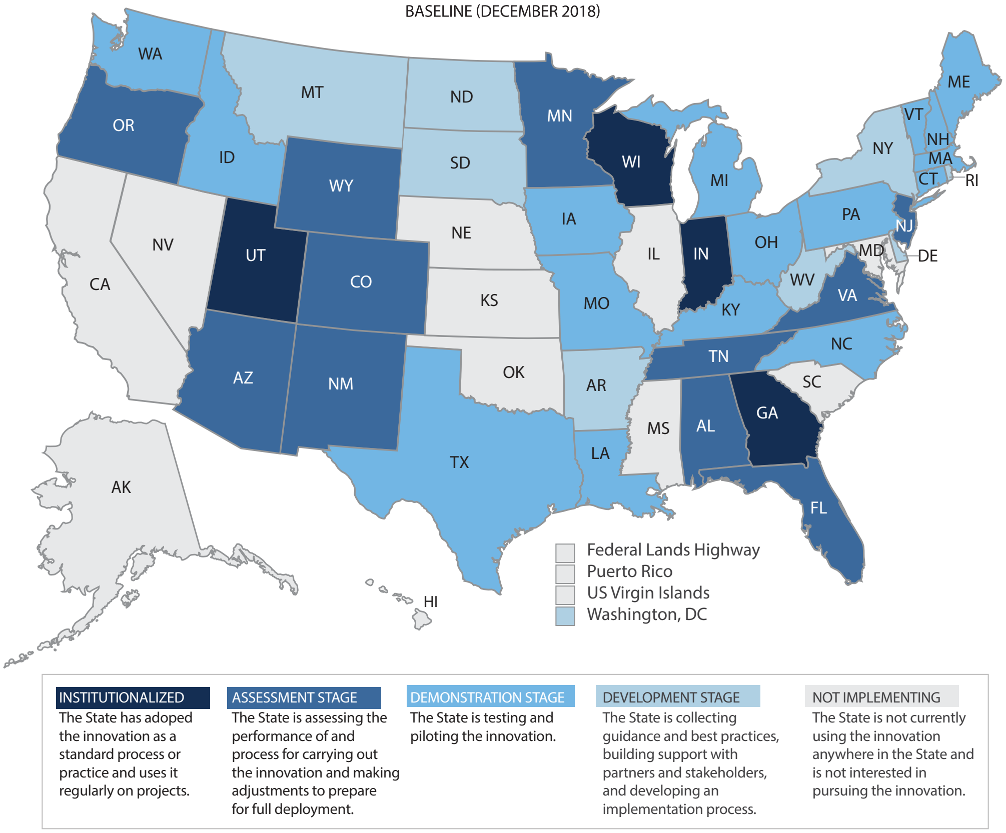


Figure 8. Map. Status of automated traffic signal performance measures implementation in January 2017.

Source: FHWA



Source: FHWA

Figure 9. Map. Status of automated traffic signal performance measures implementation adoption in December 2018.

CHAPTER 3. BENEFIT-COST METHODOLOGY

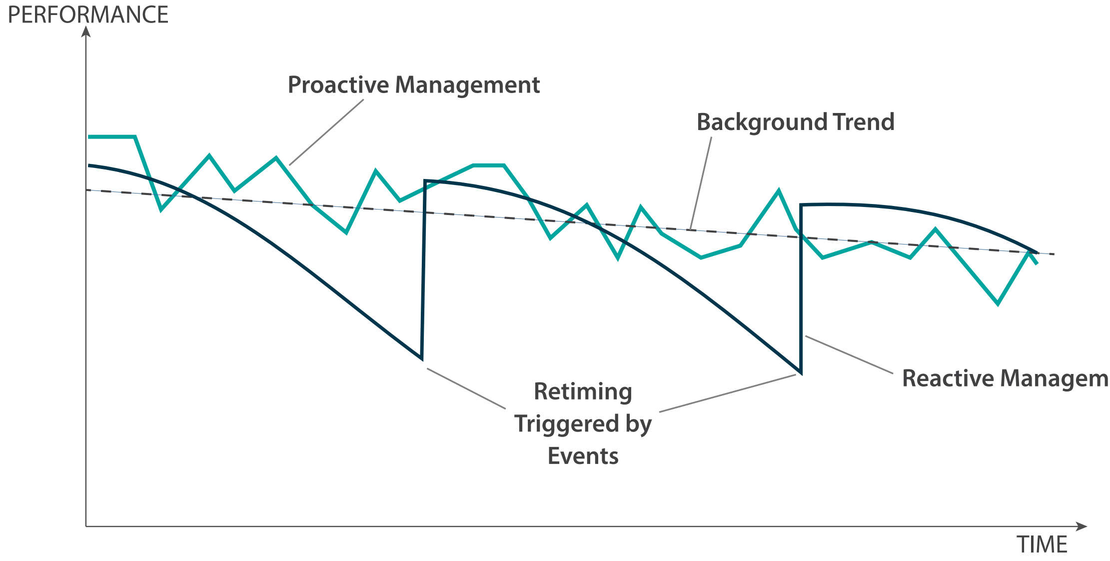
DOCUMENTING BENEFITS

According to the theory on diffusion of innovation, transitioning the market share beyond innovators and early adopters involves new technologies to clearly demonstrate quantitative benefits. Similarly, automated traffic signal performance measures (ATSPM) can move beyond qualitative demonstration of benefits (and may clearly demonstrate quantitative benefits) to gain market share among the early majority of the market sector. Many agencies considering adopting ATSPMs want a strong justification before investing resources in the technology. This study proposes a framework for quantifying potential benefits and costs of ATSPMs. There are some challenges in assessing benefits and costs of ATSPMs. At present, there are not enough documented case studies of ATSPM deployments to broadly survey the benefits. This report includes case studies that attempt to improve this body of information; however, few early-adopter agencies have documented their level of quantitative benefits because it is likely unnecessary, given the strong support of executive leadership who understand the enhanced capabilities to improve operations, maintenance, and quality customer service objectives. The amount of quantitative data available is rather limited and in many cases users of the methodology may rely on rough estimates.

Another challenge is that ATSPMs and active management practices represent a fundamental shift in the way systems are operated. Traditional data-collection practices cannot provide the same level of coverage; or, perhaps more accurately, considerably more effort would have to be expended to achieve the same outcome in terms of data collection. Comparisons between traditional practice and active management with ATSPM may consider the increase in an effort required under traditional methods to achieve the same outcome. An analogy can be drawn from pavement management, in which a series of mill-and-overlay activities periodically carried out can maintain higher pavement quality over a longer time period than less-frequent reconstruction. Figure 10 illustrates the difference in outcome over time between proactive and reactive management. The dashed line in the chart shows the background trend in the performance, which in this example shows gradual degradation over time—perhaps this is a corridor where demand is steadily growing. The other lines show the potential performance under proactive or reactive management.

Reactive management reflects the traditional signal retiming practices that produce plans that are narrowly focused, on the peak 15 minutes to 1 hour as an outcome of methods based on a small set of manually collected data. For traffic conditions outside the peak period, the timing is less effective and will result in degraded performance whenever traffic conditions are not consistent with the signal timing optimization design period. This suggests that as traffic demand changes over time, signal timing becomes inappropriate for conditions and will induce degraded intersection performance. In those cases, as the variance in traffic patterns increases, the performance of narrowly focused signal timing plans becomes more recognizable, generally resulting in poor performance and complaints. The effectiveness of the current signal timing practices is thus constrained by limitations in manually collected data and the tools available to process the data.

Proactive management has the potential to sustain performance at a higher level, because issues can be addressed before degradation is prolonged. An agency that proactively manages its signals would not be able to assess its level of performance had they not undertaken that activity. Rather, they may only see the background trend, which as in this example, could reflect a decrease in performance over time. However, the true value of proactive management is avoidance of larger and more rapid decreases that can occur without responsive monitoring.



Source: FHWA

Figure 10. Graph. Comparison of proactive and reactive management.

Variability of timescale of a deployment is another challenge in understanding benefits and costs. Two perspectives can be taken. The first is the potential short-term benefits of improved management in a short time frame after ATSPM deployment. The second is the benefit associated with sustained management of that performance over time. The former can be approached with a traditional before-and-after analysis, while the latter would need to estimate avoided loss in the performance, represented by the area between the reactive management and proactive management curves in figure 10.

Another challenge in assessing benefits and costs of ATSPMs is the overlapping purpose of certain components of the system. It is easy to conflate certain implementation costs (and benefits) with those related to operating a traffic signal system, with or without ATSPMs. The costs of communication and detection—part of the infrastructure of signal systems—are examples. These are both needed for performance measurement, but are also components of the signal system serving purposes that may not have anything to do with performance measurement. Agencies that clearly state operational objectives have a mechanism to drive what infrastructure and technology is required to support attainment of those objectives. This also clarifies the relevant performance measures. While objectives should drive selection of detection and communications needs, it is worthwhile to state that, historically, traffic signals have been treated like commodities and the concept of objectives- and performance-based management is still emerging. As objectives- and performance-based management become normal practices, relevant infrastructure investments (which support both operations and performance monitoring) may become more aligned with objectives and eventually become a standard.

The methodology presented here allows for analysis of benefits and costs from a variety of perspectives, with individual benefit and cost items defined for both short- and long-term time frames. Further, the methodology allows analysts to consider benefits and costs related to ATSPM, but which have a separate operational purpose (such as communication and detection systems). This is intended to permit analysts some flexibility in establishing parameters of their analyses.

ELEMENTS OF BENEFIT-COST ANALYSIS

Lists of potential cost (table 5) and benefit items (table 6) are compiled and described in this section. These items were largely identified from documentation in previous studies and one of the authors' previous interactions with agencies that had adopted ATSPMs. Each item is categorized according to its scope: short-term, long-term, or both. The benefit and cost items are further sorted into categories and benefit-cost types.

Cost types refer to the type of investment incurring the cost, such as:

- Labor—direct use of personnel time by the agency.
- Equipment—procurement and installation of new devices, parts, software, etc., for effective utilization of the ATSPM.
- Infrastructure—procurement of traffic signal control equipment. In many cases existing equipment may be used; new equipment procured may deliver its own benefits to the operation independent of ATSPM use. This scenario is discussed later in the paper.

Benefit types include benefits to the public and agency. Public benefits are further categorized among the potential ways they can materialize, such as:

- Travel time (TT)—the public incurs less delay when traveling on signalized facilities.
- Crash reduction (CR)—risk of crashes is reduced.

Table 5. List of cost items.

Line	Scope	Category	Item	Cost Type
1	S	Data logger	Procuring new controllers or controller add-on equipment/firmware.	Labor, infrastructure
2	S	Data logger	Updating existing controller firmware.	Labor
3	S	Data logger	Procuring external data collection devices.	Labor, infrastructure
4	S	Communication	New communication system added.	Infrastructure
5	L	Communication	Communication system maintenance.	Infrastructure
6	S	Detection	New detection systems added.	Infrastructure
7	L	Detection	Detection system maintenance.	Infrastructure
8	S	Detection	Reconfiguration of existing detection systems.	Labor, equipment

ATSPM = automated traffic signal performance measures. S = short term. L = long term.

Table 5. List of cost items. (continuation)

Line	Scope	Category	Item	Cost Type
9	S	Detection	Documentation of detector assignments.	Labor
10	S	Server	New server procurement.	Equipment, labor
11	L	Server	Server maintenance and database management.	Labor
12	S	Software	Software license cost.	Equipment
13	S	Software	Installation cost.	Labor
14	L	Software	Maintenance and troubleshooting.	Labor
15	S	Integration	Business process integration.	Labor
16	L	Integration	Active ATSPM management/operations cost.	Labor

ATSPM = automated traffic signal performance measures. S = short term. L = long term.

Table 6. List of benefit items.

Line	Scope	Category	Item	Benefit Type
1	L	Organizational	Avoidance of manual data collection.	Agency
2	L	Organizational	Avoidance of unneeded retiming/maintenance activities.	Agency
3	L	Organizational	Reduced public complaint response time.	Agency
4	L	Organizational	Value of performance documentation.	Agency
5	Both	Maintenance	Discovery and repair of failed detectors.	Public (TT)
6	Both	Maintenance	Discovery and repair of broken communication.	Public (TT)
7	Both	Maintenance	Discovery and repair of other equipment failures.	Public (TT)
8	Both	Operations	Discovery and resolution of inefficient green distribution.	Public (TT)
9	Both	Operations	Discovery and improvement of poor coordination.	Public (TT)
10	Both	Operations	Discovery and mitigation of pedestrian operational issues.	Public (TT)
11	Both	Operations	Discovery and resolution of preemption-related issues.	Public (TT)
12	Both	Operations	Identification of locations with potential safety issues.	Public (CR)

CR = crash reduction. L = long term. TT = travel time or delay.

It should be noted that not every cost and benefit may occur in any given ATSPM deployment. In particular, the benefits could align with agency objectives as appropriate to an agency's signal management plan or other strategic planning documents. For example, an agency whose objectives primarily focus on improving signal timing practices regarding its pedestrian operation may not wish to include a coordination-related improvement, particularly if those aspects of operation will not be analyzed by performance measures, or are otherwise unlikely to drive action.

The following sections present notes on each item in turn. First, agency cost items are discussed, followed by benefit items. Where previous studies have quantified the amount of benefit on a specific item, notes from the relevant documentation are included.

Potential Costs of Automated Traffic Signal Performance Measures

Procuring new controllers or controller add-on equipment/firmware. Where existing equipment does not provide the ability to log high-resolution data, new controllers may be acquired, or, in some cases, existing controllers can be upgraded with new add-on equipment (such as a physical module) or firmware that may incur cost. These will incur a certain unit cost, typically between $2,500 and $5,000 at the time of writing, but often influenced by quantity of units procured. Newer traffic signal controllers may bring other added functionality beyond the ability to collect high-resolution data, so they are considered an infrastructure cost type.

Updating existing controllers. Many existing traffic signal controllers can log high-resolution data. Sometimes a firmware upgrade and additional configuration steps are needed to turn on the controller logging capability. These activities require personnel time investment to accomplish; there may be an additional cost, depending on the specific relationship of the agency to its vendors and distributors.

Procuring external data-collection devices. As an alternative to controller-based data loggers, several different commercial devices have been developed by vendors to collect high-resolution data. Some devices may provide additional functionality beyond data collection, and, therefore, are included in the infrastructure category. The addition of probe vehicle data (and other external data sources) might also be considered; cost for that data would fall under this category.

New communication system added. Some form of communication infrastructure is typically needed for coordinated traffic signal systems. Communication systems are also needed to automatically harvest high-resolution data for ATSPMs; in particular, these must permit transmission of the data. Therefore, in some cases an upgrade may be needed to allow for ATSPMs to be deployed. This is considered an infrastructure cost. Where no communications to a central system is available, an alternative approach would be to manually retrieve the data at intervals (e.g., once a week, month, etc.). Such costs should be included here.

Communication system maintenance. As noted above, communication systems are necessary for both traffic signal control and ATSPM deployment. Maintenance of such systems is necessary and also listed as an infrastructure cost.

New detection systems added. Similar to communication systems, detection systems have a primary use in traffic signal control, but may also be used for data-collection purposes. Certain types of ATSPM analyses are only possible with certain types of detection. For example, to measure vehicle arrivals, advance detection is needed (other types of analysis are still possible without it). Detection may sometimes be added in conjunction with an ATSPM deployment. However, since new detection can potentially be used to improve traffic signal operation independent of ATSPMs, it is listed here as an infrastructure cost.

Detection system maintenance. Similar to communication systems, new detection systems will bring maintenance needs. This is listed as an infrastructure cost as well; such items may be conflated with the cost needed primarily for ATSPMs. This is discussed in detail later in the primer.

Reconfiguration of existing detection systems. The configuration of existing detection zones has an influence on the outcomes of an ATSPM analysis. In some cases, the agency may wish to reconfigure its detection zones to improve the quality of performance measures. For example, some agencies may combine many detection zones on a single channel to simplify how detection zones are received by the controller (e.g., channels 1–8 mapped to phases 1–8). This can cause problems with data analysis. For example, a channel that combines both advance and stop-bar detectors cannot provide accurate arrival information. In such cases it may be possible to reconfigure the detection zones to separate channels. Regardless of whether such reconfiguration is needed, documentation of detector channel assignments is also desired for most performance measures. Sometimes this may involve only labor cost (e.g., changing video detection zones). In other cases, some equipment cost may be used (e.g., resplicing loops).

Documentation of existing detection systems. Most ATSPMs (one exception being a phase termination analysis) involve documenting and entering the detector mapping into the performance measurement system. Agencies vary considerably in their practices of documenting detector configurations. In some cases, agencies may already possess a database that stores each intersection's configuration in detail. In other cases, the information may not be readily available. Some amount of labor may be needed to capture the detector assignments for purposes of developing ATSPMs. In general, many agencies have found this cost to be quite unexpected because many States' design documents delegate detector number and configuration to signal technicians and drawings, which only reside in the cabinet as sketches.

New server procurement. A system for data storage, processing, and delivery of ATSPMs may be used. In some cases, new server hardware may be used. In other cases, existing server hardware could be leveraged. Another option is to use cloud computing rather than conventional server hardware. In any case, some cost may be applied toward procurement. Some labor cost may also be applied toward server installation and configuration.

Server maintenance and database management. In addition to procurement costs, a server may bring related maintenance costs; service fees would likely apply for cloud computing. This line item reflects such costs.

License costs for existing systems. Some commercial ATSPM systems (or add-on modules to ATMS or other existing systems) may require a license cost. These may be subscription-based or one-time costs, or follow a different pricing model. These costs would not be incurred with open-source software (although that could incur higher installation costs).

Installation cost. This item reflects the labor needed to install the software for an ATSPM system. For commercial systems this likely will be lower than open-source software.

Maintenance and troubleshooting. This pertains to labor costs specifically needed to maintain the ATSPM software over time. This may be rolled up into the procurement cost for commercial systems. Users of open-source software may incur a cost associated with upgrading to newer versions over time.

Business process integration. Agencies may consider how ATSPMs will fit in their overall programs, and plan for some costs related to integrating them into day-to-day activities, such as training programs or integration into existing agency procedures and manuals. The Federal Highway Administration's (FHWA) Traffic Signal Capability Maturity Framework (FHWA 2016) provides the following model for describing levels of integration:

- Level 1, ad hoc (low capability).
- Level 2, managed (medium capability).
- Level 3, integrated (high capability).
- Level 4, optimized (highest capability).

An ATSPM deployment championed by a few individuals in an agency is unlikely to advance beyond level 1, and that capability may evaporate if those individuals leave the agency or move to other positions. Some costs associated with effort to achieve at least the third level of capability may be considered.

Active ATSPM management/operations cost. This is the cost of staff who monitor and fix signal timings in the ATSPM software when such activities are not invoked by external complaints. The amount of time spent using ATSPM may be balanced against time invested in other activities to accomplish the same purpose. This cost category is a counterpart of the traditional method of retiming traffic signals on arbitrary schedules (e.g., once every few years), which is reflected in the benefit category of "avoidance of unneeded retiming/maintenance activities" described in the next section.

Potential Benefits of Automated Traffic Signal Performance Measures

Avoidance of manual data collection. Traditionally, many agencies have relied on manual data collection to develop turning movement counts at intersections. In current practice it is becoming common to use automated systems to develop such data, with counting devices temporarily deployed. Another common traffic study method is to use tube counters to develop average daily traffic (ADT) for links. ATSPMs can facilitate use of detectors to provide count data, potentially reducing the need for other count methods. Floating-car studies or other methods of travel time data collection might be eliminated with data sets such as probe vehicle data.

Avoidance of unneeded retiming/maintenance activities. Without performance monitoring, agencies often rely on scheduled maintenance and retiming activities to manage their systems. This means these activities are performed whether or not they are needed. By shifting to performance-based monitoring, some of these activities can be reduced.

Reduced public complaint response time. Many agencies spend considerable effort responding to public calls about traffic signal operation. Common examples include excessive delay spent at a location, or apparently malfunctioning signals. These calls can require a lot of time to track and troubleshoot, particularly with intermittent problems or those that occur outside ordinary working hours. ATSPMs can simplify these identification tasks. They can also be used to verify that a problem has been addressed. In addition, ATSPMs may also be able to help an agency proactively identify and mitigate situations that generate complaint calls.

Value of performance documentation. ATSPMs introduce some capability to document system performance, including both current performance and how that trends over time. This may provide opportunities to improve public relations of the agency and to document needs or show return on investment to decision makers. An example is the Utah Department of Transportation (UDOT) statistic in the following headline: "Odds of hitting a red light in Utah? Just 1-in-4" (Davidson 2013).

Discovery and repair of failed detectors. ATSPMs can improve management of vehicle detectors, pedestrian buttons, and similar actuation devices. Failed detectors can have a substantial impact on traffic signal operation, since they often must be compensated with default to fixed-time operation on the affected movements. A comprehensive evaluation of the cost of failed detection has not been done, but "wasting" green time on movements that may not have demand can increase delays on all other movements at the affected intersection. A study in Indiana (Day et al., 2015) found that for a single corridor, annualized benefits of $900,000 were realized through detector repairs. In that study, seven different detectors had failed at the six-intersection corridor.

Discovery and repair of broken communication. Maintaining working communication is helpful to keeping controller clocks synchronized, which is helpful for coordination. ATSPM systems can facilitate better management of communication links to intersections. A study by Li et al. (2015) assessed user benefits from the repair of communication failures, finding an annualized user benefit of about $420,000 for a corridor with 12 intersections. This benefit was assessed by examining the difference in median travel times before and after correction of issues that led to incompatible patterns being run at neighboring intersections.

Discovery and resolution of inefficient green distribution. Allocation of capacity by the distribution of green times is a key operational function of traffic signals; inefficiencies in green time distribution can accumulate delay. ATSPMs include metrics that can be used to assess whether individual movements are experiencing degraded performance and if green times can be reallocated to address these issues, potentially reducing delays. Freije et al. (2014), for example, examined a chance in the number of split failures before and after the implementation of a split change. That study did not directly examine the conversion of such numbers to a numerical benefit; Smith (2014) explored a delay estimate. The next section describes potential ways to estimate such benefits in greater detail.

Discovery and improvement of poor coordination. Another key aspect of traffic signal operation is the achievement of progression with coordination. Poor quality progression may occur due to the provision of offsets that are poorly suited to the traffic conditions. This may occur for a variety of reasons, such as divergence in traffic patterns over time; an example would be a change in how often a side-street phase gaps out—which leads to a change in early return to green and consequently the arrival and departure patterns of vehicles. A study by Lavrenz et al. (2015a) examined the management of traffic signal offsets over a 5-year (yr) period through use of ATSPMs and three separate retiming activities on a corridor experiencing a 36 percent increase in volumes during that time period. When the changes in travel time and travel time reliability were converted into annualized user benefits, a total of about $3.7 million was estimated over the 5-yr period. This was a corridor of nine intersections. The previously mentioned study by Li et al. (2015) attributed $2.9 million in annualized benefits to an improvement of offsets on a 12-intersection corridor.

Discovery and mitigation of pedestrian operational issues. Locations with high pedestrian delay can be identified using ATSPMs; one way to identify this is examining the time to service for pedestrian calls. This may lead to potential improvements in traffic signal timing; to date, this use case has not been explored in detail.

Discovery and resolution of preemption-related issues. Preemption and priority control at traffic signals can sometimes require complex configuration, and includes interfacing with equipment of other entities or organizations (railroad operators, emergency services, transit operators, etc.). The ability to identify and mitigate issues is a potential use case of ATSPM. An example presented by UDOT demonstrated the use of ATSPM to evaluate a public complaint about malfunctioning railroad preemption. Performance measures were able to reveal that an excessive number of preemptions were occurring, which was rectified by making the railroad operator aware of the issue.

Identification of locations with potential safety issues. One potential benefit of ATSPMs is their application to intersection safety. At present, this potential use has not been extensively explored. The UDOT open-source software allows detector actuations during red to be visualized, which can serve as a screening tool for identifying locations for enforcement. Lavrenz et al. (2015b) developed an estimate of the number of red light violations, and examined how the estimate changed after a split adjustment was made. Hubbard et al. (2008) investigated a measure of vehicle-pedestrian conflict by considering the amount of conflicting vehicular flow coincident with pedestrian calls for service, which seems likely to correlate with pedestrian-vehicle conflicts. In practice, identifying high-risk locations might lead to countermeasures that may reduce the number of crashes. Some countermeasures may involve further investments (e.g., changing intersection configuration), but there is some value associated with discovery of those issues. Crash reductions related to changes in traffic signal timing would be more appropriate to attribute to ATSPM.

Assessing Benefits and Costs of Infrastructure Investments beyond Automated Traffic Signal Performance Measures

Some cost items in the preceding analysis were identified as improvements in traffic signal infrastructure. While some of these costs are needed to allow ATSPM deployment, the improvements also have intrinsic value independent of ATSPM deployment. For example, installing a detection system at an intersection that does not have one would enable actuation, and, therefore, allow the operation to be changed from fixed-time to actuated control. This operational change would see some differences in the system performance independent of ATSPM.

The degree to which this issue will affect a benefit-cost analysis will largely depend on the starting point of the agency seeking to deploy ATSPM. Agencies that have previously invested in detection systems to obtain coverage of most movements, or communication systems that can reach most intersections, will not have to make many investments of this type. Other agencies that have not had such practices may need to make this investment. For example, the Indiana Department of Transportation (INDOT), one of the earliest users of ATSPMs, had existing standard detector design practices that allowed for stop-bar detection on all minor phases at every intersection, with advance detection on all major phases. In this case, all that was needed to implement ATSPMs was a controller that could collect data and a means of retrieving the data. Not all agencies that have adopted ATSPMs are working from a similar starting point.

The present methodology assumes that it may be possible to attribute portions of the cost to ATSPMs. It is challenging to develop guidance on how such portions should be attributed, and it will likely have to be considered on a case-by-case basis. For example, the case of installing new detection will incur some cost; the agency may choose to consider that cost fully as part of ATSPMs, a separate cost item, or some percentage split between the two. Another option is that such costs would have been encountered as part of upgrading or maintaining the traffic signal system independent of the ATSPM effort; these could be considered sunk costs that can be excluded from the benefit-cost analysis since they were already spent, or would have been expended even if ATSPMs were not implemented. Ultimately the decision to include these cost items must be made by the analyst in computing benefits and costs. A key consideration in how costs are attributed is the purpose and need associated with funding that is acquired to support implementation. If the purpose and need of the funding are expressly identified to implement ATSPM, then devices and infrastructure procured and installed that enhance operations could be attributed to ATSPM implementation. If the purpose and need of funding acquired are expressly identified to provide for intersection operational improvements, then associated cost for devices and infrastructure need not be attributed as cost for ATSPM, and instead may be considered as sunk cost. If purpose and need for funding support both operational improvements and ATSPM, then the cost could be divided and attributed appropriately. These choices are at the discretion of the evaluator. The following methodology seeks to estimate benefits of ATSPM deployments without regard to unrelated benefits of adding new technology such as detection. This part of the analysis assumes that the intersections have already been brought to the point where ATSPMs can be implemented, although in practice that may not be the case. When measuring changes in performance under these circumstances, the analyst may bear this in mind.

METHODOLOGY

The benefit-cost methodology consists of two major steps. The first step is to quantify the amount of cost or benefit for each item identified in the first section. For this report, these items have been defined with the assumption that it will be possible to yield realistic estimates of their value. At the time of writing, there are few existing studies where such estimates have been explored, so this is an area where further research is desired. The second step is to total the benefits and costs to estimate the net value.

This methodology intends to produce a benefit-cost analysis over a design life. The user may define that design life; the examples presented here consider a life of 10 years. Depending on whether that value is too long or too short, it can be adjusted. The analysis could also be shortened to only consider short-term benefits, as a more limited before-and-after study, by excluding long-term elements. It should be noted the long-term benefits, in particular, are not well-documented by previous studies, and their analysis will have to heavily rely on broad estimates.

Some benefit and cost items are envisioned as short-term benefits mostly incurred at the beginning of implementation. Many one-time costs to procure and install system components fall in this category. Similarly, an increase in user benefits often can be anticipated shortly after implementation due to discovery of maintenance problems and operational inefficiencies that were unknown before data about the system could be obtained. The long-term benefits and costs are due to recurring maintenance costs per year and recurring benefits from changes in practice.

Cost Items

The total estimated cost is the sum of the line items in table 5:

$$C = C_1 + C_2 + \ldots + C_{16} \qquad \text{Equation 1}$$

C_1 is the procurement cost of controller improvements or upgrades:

$$C_1 = \sum_i N_i u_{1,i} \qquad \text{Equation 2}$$

where N_i is the number of intersections of controller type i, and $u_{1,i}$ is the cost associated with readying a controller of type i for ATSPM. Where the controller must be replaced, that cost would be equal to the cost of replacement with a new controller.

C_2 is the labor cost of upgrading controller firmware:

$$C_2 = NL_2T_2 \qquad \text{Equation 3}$$

where N is the number of intersections affected, L_2 is the labor cost per hour, and T_2 is the number of person-hours per intersection.

C_3 is the procurement cost of external data logging devices:

$$C_3 = \sum_i N_i u_{3,i} \qquad \text{Equation 4}$$

where N_i is the number of intersections to be equipped with device of type i, and $u_{3,i}$ is the unit cost of device type i.

C_4 is the cost of communication system development:

$$C_4 = P_c U_4 \qquad \text{Equation 5}$$

where P_c is the percentage of communication infrastructure cost attributable to ATSPM and U_4 is the unit cost of the infrastructure investment.

C_5 is the cost of communication system maintenance:

$$C_5 = P_c \cdot \sum_{i=1}^{n} \frac{M_{5,t}}{(1+i)^t} = P_c M_5 \left[\frac{1-(1+i)^{-n}}{i} \right] \qquad \text{Equation 6}$$

where P_c is the percentage of communication infrastructure cost attributable to ATSPM; $M_{5,t}$ is the value of maintenance costs during year t, summed over years 1 through n, using interest rate i for determining net present value; and M_5 is used if the same cost is assumed for each year.

C_6 and C_7 can be defined similarly:

$$C_6 = P_d U_6 \qquad \text{Equation 7}$$

$$C_7 = P_d \cdot \sum_{i=1}^{n} \frac{M_{7,t}}{(1+i)^t} = P_d M_7 \left[\frac{1-(1+i)^{-n}}{i} \right] \qquad \text{Equation 8}$$

where P_d is the percentage of detection infrastructure cost attributable to ATSPM; M_6 is the total cost of new detection; $M_{7,t}$ is the value of maintenance costs during year *t,* summed over years 1 through *N,* using interest rate *i*; and M_7 can be used if the same cost is assumed for each year.

C_8 is the cost of detection system reconfiguration:

$$C_8 = N(L_8 T_8 + U_8) \qquad \text{Equation 9}$$

where *N* is the number of intersections affected, L_8 is the labor cost per hour, and T_8 is the number of person-hours per intersection needed. U_8 is the total equipment cost (if any) required to accomplish reconfiguration.

C_9 is the labor cost of documenting the detection configurations:

$$C_9 = N L_9 T_9 \qquad \text{Equation 10}$$

where *N* is the number of intersections affected, L_9 is the labor cost per hour, and T_9 is the number of person-hours per intersection needed.

C_{10} is the cost of a new server procurement. This is a single-unit cost specific to the site. In some cases, the agency may be able to leverage an existing server and would not incur a cost.

C_{11} is the cost of server maintenance over the analysis period:

$$C_{11} = \sum_{i=1}^{n} \frac{F_{11,t} + L_{11,t} T_{11,t} + U_{11,t}}{(1+i)^t} = (F_{11} + L_{11} T_{11} + U_{11}) \left[\frac{1-(1+i)^{-n}}{i} \right] \qquad \text{Equation 11}$$

where $F_{11,t}$ is the value of the annual fee, $L_{11,t}$ is the labor cost per hour, $T_{11,t}$ is the total number of person-hours, and $U_{11,t}$ is the unit cost of hardware replacements, for year *t*, summed over years 1 through *n*, with interest rate *i*. The terms F_{11}, L_{11}, T_{11}, and U_{11} can be used if these quantities are assumed to be the same during each year.

C_{12} is the cost of a software license:

$$C_{12} = A_{12}t + U_{12}$$ Equation 12

where A_{12} is a subscription-based cost of a system (if any), t is the number of time units associated with it (i.e., number of payments made, most likely annually), and U_{12} is a one-time unit cost (if any) of the license.

C_{13} is the installation cost of the software. The cost to the agency could be 0, for example, if it is rolled into a system procurement. In cases where labor is required, it could be estimated from the following expression:

$$C_{13} = L_{13}T_{13} + U_{13}$$ Equation 13

where L_{13} is the labor cost per hour, T_{13} is the number of person-hours required, and U_{13} is a one-time unit cost (if any) of software installation.

C_{14} is the cost of maintaining the software. There may be no such cost to the agency if the cost is included in a system procurement. The following expression considers the possibility of a recurring cost for maintenance:

$$C_{14} = \sum_{t=1}^{n} \frac{A_{14,t} + L_{14,t}T_{14,t}}{(1+i)^t} = \left(A_{14} + L_{14}T_{14}\right)\left[\frac{1-(1+i)^{-n}}{i}\right]$$ Equation 14

where $A_{14,t}$ is an annual subscription-based cost for system maintenance (if any), $L_{14,t}$ is the labor cost per hour, and $T_{14,t}$ is the number of person-hours required, for year t, summed over years 1 through n, with interest rate i. The terms A_{14}, L_{14}, and T_{14} can be used if these quantities are assumed to be the same during each year.

C_{15} is the cost associated with business process integration. C_{16} provides an estimate of the amount of effort associated with use of ATSPMs in the long term to achieve the benefits. These are considered as labor costs, formulated similarly to other such costs:

$$C_{15} = L_{15}T_{15}$$ Equation 15

$$C_{16} = \sum_{t=1}^{n} \frac{L_{16,t}T_{16,t}}{(1+i)^t} = L_{16}T_{16}\left[\frac{1-(1+i)^{-n}}{i}\right]$$ Equation 16

where L_{15}, $L_{16,t}$ are the labor cost per hour, and T_{15}, $T_{16,t}$ is the number of person-hours required. In the case of C_{16}, the annual costs are established for year $t = 1$ through n, with interest rate i. The terms L_{16} and T_{16} can be used if these quantities are assumed to be the same during each year.

Benefit Items

The total estimated benefit is the sum of line items in table 6:

$$B = B_1 + B_2 + \ldots + B_{12} \qquad \text{Equation 17}$$

The first four benefit items are long-term items; for each of these, the equations are set up to find the net present value for years 1 through n, at interest rate i.

B_1 is the benefit associated with the reduction of agency labor used for manual data collection:

$$B_1 = P_1 \sum_{t=1}^{n} \frac{\left(L_{1,t}T_{1,t} + U_{1,t}\right)}{\left(1+i\right)^t} = P_1\left(L_1T_1 + U_1\right)\left[\frac{1-\left(1+i\right)^{-n}}{i}\right] \qquad \text{Equation 18}$$

where P_1 is the overall percentage reduction in manual data-collection activities, $L_{1,t}$ is the unit cost of labor associated with these activities, and $T_{1,t}$ is the total number of person-hours dedicated to these activities. $U_{1,t}$ represents cost reduction from data-collection equipment that may not be needed if ATSPM replaces it. These occur in year t, with interest rate i. The terms L_1, T_1, and U_1 can be used if these quantities are assumed to be the same during each year.

B_2 and B_3 are the labor savings from a reduction in person-hours needed for the respective tasks of arbitrarily scheduled maintenance or retiming, or responding to complaint calls. These are formulated similarly:

$$B_2 = P_2 \sum_{t=1}^{n} \frac{\left(L_{2,t}T_{2,t} + U_{2,t}\right)}{\left(1+i\right)^t} = P_2\left(L_2T_2 + U_2\right)\left[\frac{1-\left(1+i\right)^{-n}}{i}\right] \qquad \text{Equation 19}$$

$$B_3 = P_3 \sum_{t=1}^{n} \frac{\left(L_{3,t}T_{3,t} + U_{3,t}\right)}{\left(1+i\right)^t} = P_3\left(L_3T_3 + U_3\right)\left[\frac{1-\left(1+i\right)^{-n}}{i}\right] \qquad \text{Equation 20}$$

where P_2, P_3 are the overall percentage reduction in the associated task, $L_{2,t}$, $L_{3,t}$ are the unit cost of labor appropriate to each task, and $T_{2,t}$, $T_{3,t}$ are the total number of person-hours dedicated to each task. Terms $U_{2,t}$, $U_{3,t}$ reflect the potential costs for agencies that contract these activities to consultants and for which the cost may be better estimated as a unit cost totaled over the time period, as opposed to a labor cost. As before, these each occur in year t, while the terms L_2, L_3, T_2, T_3, U_2, and U_3 can be used if these quantities are assumed to be the same during each year.

B_4 is the value of performance documentation. It does not necessarily represent a labor reduction. This is a difficult cost to express monetarily; the value would strongly depend on the specific needs of the agency performing the analysis. An example of a quantitative benefit related to this would be the ability of the agency to successfully request funds with the help from data documented by ATSPMs. If considered as a recurring annual benefit, it could be converted into net present value as shown earlier.

B_5 through B_{11} are the public benefits that have both a short- and a long-term component, as well as a reduction in complaint calls and travel times or delays. The following equation is proposed to encapsulate all three aspects. It is intended to be calculated for different roadway elements—either routes or movements, as appropriate:

$$\begin{aligned} B_k &= f_0 N_0 D_{k,0} o_0 q_0 + \sum_{t=1}^{n} \frac{f_t N_t \Delta_{k,t} o_t Q_t}{(1+i)^t} \\ &= f_0 N_0 D_{k,0} o_0 q_0 + f N \Delta_k o Q \left[\frac{1-(1+i)^{-n}}{i} \right] \end{aligned}$$

Equation 21

In the above, $k = 5, 6, \ldots 11$ indicates a specific benefit item as described in table 6.

The first term is the short-term component:

- f_0 is the value associated with a unit of delay in year 0.
- N_0 is the number of elements affected in year 0.
- $D_{k,0}$ is the average delay reduction per roadway element associated with short-term gains shortly after deployment.
- o_0 is the average vehicle occupancy for year 0.
- q_0 is the average flow rate per movement in year 0.

The second term is the long-term component:

- f_t is the value associated with a unit of delay in year t.
- N_t is the number of coordinated routes affected during year t.
- $\Delta_{k,t}$ is the total avoided performance loss per route during year t.
- o_t is the average vehicle occupancy for year t.
- Q_t is the average flow rate per route associated with long-term avoidance of performance loss during year t.

As before, if the above five quantities are assumed to be the same for each year in the analysis period, then the form of the equation using f, N, Δ, o, and Q can be used.

It is intended the above would be applied either for individual movements or individual routes, depending on whether the benefit is accumulated for individual movements or along routes. Benefits B_6 and B_9 are probably best considered on the basis of routes; the others would be better estimated in terms of movements.

The above estimate could be tabulated on a per facility basis, e.g., summing for each movement and route at locations where ATSPMs are to be deployed. For estimates considering a broad deployment affecting many movements and routes, it may be more expedient to come up with nominal values for typical movements and routes.

One other detail is that of vehicle classes. For different vehicle classes, different values of f and o would be applicable. That is, a separate analysis could be done for passenger cars, buses, trucks, etc., according to the breakdown of users on the roadway.

B_{12} is the value of safety improvements facilitated through ATSPM. As mentioned earlier, this perspective has not been given much consideration in previous studies, and it may be difficult to attribute safety improvements to ATSPMs when those improvements were obtained through substantial further investments.

The following expression assumes that some number of crash reduction could be obtained through traffic signal timing improvements identified by ATSPM:

$$B_{12} = \sum_{t=1}^{n} \frac{V_F X_{F,t} + V_I X_{I,t} + V_{PDO} X_{PDO,t}}{(1+i)^t}$$

$$= \left(V_F X_F + V_I X_I + V_{PDO} X_{PDO}\right)\left[\frac{1-(1+i)^{-n}}{i}\right]$$

Equation 22

where V_F, V_I, and V_{PDO} are the values associated with fatal, injury, and property-damage only crashes, respectively; and $X_{F,t}$, $X_{I,t}$, and $X_{PDO,t}$ are the corresponding numbers of prevented crashes of each associated type, for year t, summed from years 1 through n, with interest rate i. As before, the second term is presented where the reductions are assumed to be the same for each year, using the constant values X_F, X_I, and X_{PDO}.

Example Application

Consider a hypothetical local agency interested in deploying ATSPMs on 40 intersections along five coordinated routes. This represents only part of the agency's overall network but it covers areas where the agency has the most operational concerns and may expand in the future.

An interest rate of 2 percent is used for the future costs and benefits in this example.

This agency has controllers that require a firmware upgrade to enable high-resolution data collection. Thus, the agency has a controller procurement cost C_1 = \$0, but will incur some labor cost for controller firmware upgrades. The assumption is made that no additional cost is required to obtain updated firmware. Assuming that all 40 intersections are affected, the average labor cost is \$80/hour (h), and each intersection requires 4 h to accomplish the upgrade, then this cost works out to be, from equation 9:

$$C_2 = NL_2T_2 = (40 \cdot \$30 \cdot 4) = \$12{,}800.$$

Since this agency is not using external data collectors, cost C_3 = \$0. In this example it is further assumed the agency has existing communication systems that will permit data transfer; therefore, C_4 = \$0 and C_5 = \$0.

The agency has decided to add new detection to eight of its intersections to be able to measure vehicle arrivals; it is procuring these systems at a cost of $16,000 per intersection, yielding a total cost of $128,000. The agency attributes 50 percent of this cost to ATSPM deployment; thus, C_6 = $64,000. Maintenance is anticipated to cost $1,000/yr over a 10-yr period; the net present value of this can be found using the second form of equation 8:

$$C_7 = P_d M_5 \left[\frac{1-(1+i)^{-n}}{i}\right] = (0.5 \cdot 1000)\left[\frac{1-(1+0.02)^{-10}}{0.02}\right] = \$4,492$$

Maintenance for the system (C_7) is anticipated to cost $4,492 over a 10-yr period.

Most of the other existing detectors will need to be reconfigured to add detection zones for data-collection purposes. This is anticipated to require 3 hours per intersection. The labor cost is estimated at $80/h. According to equation 3 the total cost is:

$$C_8 = N(L_8 T_8 + U_8) = (40)[80 \cdot 3 + 0] = \$9,600.$$

Detector documentation is expected to require 1 hour per intersection. Using equation 10, the cost is:

$$C_9 = N L_9 T_9 = (40)(80)(1) = \$3,200$$

The agency is procuring a new server at a cost of C_{10} = $24,000. Server maintenance is anticipated to require 40 hours per year (h/yr), or 400 h over a 10-yr period, with an average labor cost of $80/h. No annual fee is assumed to exist (F_{11} = 0). Each year, hardware replacements of $1,000 are anticipated. From equation 11, the server maintenance cost is:

$$C_{11} = (F_{11} + L_{11} T_{11} + U_{11})\left[\frac{1-(1+i)^{-n}}{i}\right] = (0 + 80 \cdot 40 + 1000)\left[\frac{1-(1+0.02)^{-10}}{0.02}\right] = \$37,727$$

The agency has decided to use open-source ATSPM software, so its license cost is C_{12} = $0. However, it has hired a consultant to install and set up the system at a unit cost of $20,000. In addition, that work is anticipated to use 80 h of staff time at a labor cost of $35/h. From equation 13 the total cost of server setup is:

$$C_{13} = L_{13} T_{13} + U_{13} = (80 \cdot 80) + (20,000) = \$26,400$$

Maintenance of the software is estimated to have similar requirements as server maintenance, about 40 h/yr (400 over a 10-yr period) at a cost of $80/h. No annual subscription fee is assumed to exist (A_{14} = 0). Using equation 14:

$$C_{14} = (A_{14} + L_{14} T_{14})\left[\frac{1-(1+i)^{-n}}{i}\right] = (0 + 80 \cdot 40)\left[\frac{1-(1+0.02)^{-10}}{0.02}\right] = \$28,744$$

For business process integration, the agency plans to invest 240 hours in training activities, at an average cost of \$80/h, to bring agency capability to level 3 of the capability maturity framework. From equation 15:

$$C_{15} = L_{15}T_{15} = \left(80 \cdot 160\right) = \$19,200$$

For usage of ATSPMs to achieve benefits, the agency estimates it will use 160 h/yr at an average cost of \$80/h. From equation 16:

$$C_{16} = L_{16}T_{16}\left[\frac{1-\left(1+i\right)^{-n}}{i}\right] = \left(80 \cdot 160\right)\left[\frac{1-\left(1+0.02\right)^{-10}}{0.02}\right] = \$114,977$$

The sum of these costs is \$345,139.

On the benefit side, the reduction of labor for manual data collection represents a potential cost savings. For a fair comparison, the labor involved in this task could consider not only current data-collection practices, but could also reflect an increase in data collection needed to bring operations to the same level. In this example, the agency estimates that for its 40 intersections, collecting 16 hours of turning movement counts four times per year would require 2,560 h/yr. Manual data collection is estimated to cost \$30/h as an estimated loaded rate for an entry-level worker. The agency estimates this activity can be completely eliminated using ATSPMs. Using equation 18:

$$B_1 = P_1\left(L_1T_1 + U_1\right)\left[\frac{1-\left(1+i\right)^{-n}}{i}\right] = \left(1\right)\left(30 \cdot 2560 + 0\right)\left[\frac{1-\left(1+0.02\right)^{-10}}{0.02}\right] = \$689,863$$

The agency estimates it spends about \$500 per intersection per yr on preventative maintenance checks and scheduled retiming, which scales up to about \$20,000/yr for 40 intersections. The agency believes it can reduce this level of effort by about 25 percent. Using equation 19, the benefit for this item is:

$$B_2 = P_2\left(L_2T_2 + U_2\right)\left[\frac{1-\left(1+i\right)^{-n}}{i}\right] = 0.25\left(0 + \$20,000\right)\left[\frac{1-\left(1+0.02\right)^{-10}}{0.02}\right] = \$44,913$$

The agency estimates it spends an average of 2 hours per intersection per year responding to public complaint calls. This scales up to 800 hours over a 10-yr period. The average labor cost for this activity is estimated at \$80/h. It expects this effort can be reduced by 50 percent. Using equation 20, the associated benefit is:

$$B_3 = P_3\left(L_3T_3 + U_3\right)\left[\frac{1-\left(1+i\right)^{-n}}{i}\right] = \left(0.5\right)\left(80 \cdot \$80 + 0\right)\left[\frac{1-\left(1+0.02\right)^{-10}}{0.02}\right] = \$28,744$$

While acknowledging a benefit to possessing data for performance documentation, the agency decided not to include a monetary estimate of this benefit in its analysis, so B_4 = \$0.

Moving on to the public benefits described by B_5–B_{11}, the agency decided to include the short-term benefits by considering annualized benefits of the first year, and then estimating long-term benefits in similar terms. In its analysis, the agency has excluded benefits due to miscellaneous equipment failures, improved pedestrian service, and preemption issues, thus setting B_7, B_{11}, and B_{12} to \$0. These were not considered major issues at the intersections under consideration.

For failed detection, the agency roughly estimated that 20 percent of all movements in its system, or 64 total, likely would be affected by detector failures in the short term; this would be equivalent to having one or more detector failures at eight intersections, affecting multiple movements. It assumed these would have lasted an average of 12 weeks. An average delay of 30 seconds was anticipated from these failures. Assuming that, on average, 200 vehicles per day per movement were affected, over a 12-week period this would lead to an average of 16,800 vehicles affected for each failure.

For the long-term analysis, the same 20 percent of movements experiencing 30 seconds of delay was retained. However, the time to discovery was assumed to be far less, so that only an average of 840 vehicles (5 percent of 16,800) would be affected, on average, for each failure. A value of \$17.50/h was used for the value of time, and an average vehicle occupancy of 1.1 passengers per vehicle. The following brings these terms together using equation 21:

$$
\begin{aligned}
B_5 &= f_0 N_0 D_{5,0} o_0 q_0 + fN\Delta_5 oQ\left[\frac{1-(1+i)^{-n}}{i}\right] \\
&= \left(\$17.50\cdot 64\cdot\frac{30}{3600}\cdot 1.1\cdot 16800\right)+\left(\$17.50\cdot 64\cdot\frac{30}{3600}\cdot 1.1\cdot 840\right)\left[\frac{1-(1+0.02)^{-10}}{0.02}\right] \\
&= \$172,480+\$77,466 \\
&= \$249,946
\end{aligned}
$$

For failed communication, it was assumed that one corridor would lose communication within the first year that ordinarily would take about 12 weeks to respond to. Here it was also assumed that about 30 seconds of delay would be accumulated, affecting an average of 2,400 vehicles per day (veh/day), or 201,600 over the 12-week period. For the long-term analysis, the same terms were retained except that instead of 12 weeks, the failures were anticipated to be resolvable within 1 day, so that only 2,400 vehicles would be affected. Other terms remained the same as in B_5:

$$
\begin{aligned}
B_6 &= f_0 N_0 D_{6,0} o_0 q_0 + fN\Delta_6 oQ\left[\frac{1-(1+i)^{-n}}{i}\right] \\
&= \left(\$17.50\cdot 1\cdot\frac{30}{3600}\cdot 1.1\cdot 201,600\right)+\left(\$17.50\cdot 1\cdot\frac{30}{3600}\cdot 1.1\cdot 2400\right)\left[\frac{1-(1+0.02)^{-10}}{0.02}\right] \\
&= \$32,340+\$3458 \\
&= \$35,798
\end{aligned}
$$

Benefits from improved capacity allocation were anticipated as affecting 80 movements; an average performance improvement of 10 seconds of delay was used, affecting an average of 400 veh/day. For the short-term benefit, this was annualized across weekdays: 400 × 5 × 52 = 104,000 vehicles affected per movement on average. For the long-term analysis, the same assumptions were made but delay improvements were estimated about 10 percent as large as the initial benefit, or 1 second on average. The other terms remained the same as in earlier analyses:

$$
\begin{aligned}
B_8 &= f_0 N_0 D_{8,0} o_0 q_0 + fN\Delta_8 oQ\left[\frac{1-(1+i)^{-n}}{i}\right] \\
&= \left(\$17.50\cdot 80\cdot\frac{10}{3600}\cdot 1.1\cdot 104{,}000\right)+\left(\$17.50\cdot 80\cdot\frac{1}{3600}\cdot 1.1\cdot 104{,}000\right)\left[\frac{1-(1+0.02)^{-10}}{0.02}\right] \\
&= \$444{,}889+\$399{,}625 \\
&= \$844{,}514
\end{aligned}
$$

Finally, the benefit from improved progression was anticipated as affecting all five routes, with an average travel time reduction of 30 seconds affecting 2,400 veh/day. To annualize over the first year over 5 weekdays: 2,400 × 5 × 52 = 624,000 vehicles total. For the long-term analysis, these terms remained the same except that 10 percent of the initial benefit was assumed, or 3 seconds on average. Other terms in the formula were the same as earlier:

$$
\begin{aligned}
B_9 &= f_0 N_0 D_{9,0} o_0 q_0 + fN\Delta_9 oQ\left[\frac{1-(1+i)^{-n}}{i}\right] \\
&= \left(\$17.50\cdot 5\cdot\frac{30}{3600}\cdot 1.1\cdot 624{,}000\right)+\left(\$17.50\cdot 80\cdot\frac{3}{3600}\cdot 1.1\cdot 624{,}000\right)\left[\frac{1-(1+0.02)^{-10}}{0.02}\right] \\
&= \$500{,}500+\$449{,}578 \\
&= \$950{,}078
\end{aligned}
$$

The total benefit from all of the above items is $2,843,856. In comparison with the cost of $345,139, this yields a total benefit-cost ratio of 8.2.

The above analysis is a very tentative example, with many introduced quantities that would require careful consideration from the agency. However, the overall analysis is intended to be as straightforward as the previous example. The previous analysis lands at resulting numbers similar in magnitude to those in previous field studies described earlier. In fact, this example is quite conservative regarding the overall benefit, given those studies focused on shorter time periods.

This example used an interest rate of 2 percent. Table 7 below shows how the results vary with different discount rates. As shown in table 7, the larger the interest rate, the smaller the net present values of benefits and costs and resulting benefit-cost ratios, since many upfront cost items do not recur in subsequent years.

Table 7. Effect of interest rates.

Interest Rate (%)	Total Cost ($)	Total Benefit ($)	Benefit-Cost Ratio
0	365,530	3,035,855	8.30
1	355,011	2,936,003	8.27
2	345,139	2,843,856	8.24
3	336,001	2,758,561	8.21
4	327,531	2,679,501	8.18
5	319,670	2,606,126	8.15

CONCLUSIONS AND FUTURE WORK

This chapter presented the preliminary vision for a methodology for calculating benefits and costs relative to ATSPM deployments. The methodology includes 16 potential cost items and 12 benefit items that can be considered by analysts. Each item is described and provided a basic formula for calculating using a set of relevant inputs. An example is applied to this methodology to yield a benefit-cost analysis for a hypothetical deployment.

A challenge in making this tool useful for agencies planning an ATSPM deployment will be in quantifying all elements in these formulas. At present, it is difficult to make recommendations on what the values should be, simply because there have only been a few previous studies that documented such outcomes. A further challenge is assigning quantitative value to benefits generally felt to be qualitative. An example presented here is the ability of ATSPMs to help agencies better communicate with decision makers and the public. The true value of this contribution may not easily be reduced to a number; it may be better reserved outside of a numerical analysis. Some costs are also not easily quantified; for example, shifting toward performance-based management involves a degree of cultural change in agency practices, which may involve more than training activities to overcome.

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

This chapter presents summary findings of the six case studies. More details about these case studies can be found in Appendix A: Case Studies. These case studies summarize agencies' experiences from the three major points of their automated traffic signal performance measures (ATSPM) implementations: planning for the system, procuring and deploying the system, and operating the system. Table 8 shows an overview of important operational characteristics of the agencies.

Table 8. Major agencies' characteristics.

Agency	Number of Signals	Number of Signal Operations Staff	Use of Automated Traffic Signal Performance Measures	Type of Deployment
Clark County	▪ 98 traffic signals. ▪ 3 HAWK signals. ▪ 24 signals for other agencies.	▪ 1 engineering manager. ▪ 1 signal engineer. ▪ 1 intelligent transportation systems engineer ▪ 6 signal technicians. ▪ Consultants (as needed – project specific).	As needed (now); continual (future).	Trafficware ATMS.now
Cranberry Township	▪ 49 signals.	▪ 4 engineers. ▪ 1 technician.	In early deployment.	Econolite + Edaptive
Georgia Department of Transportation	▪ 6,804 (all capable of collecting high-resolution data, approximately 80% configured to create reports).	▪ 70–80 full-time employees, including consultants.	Continuous.	UDOT open-source ATSPM software.
Lake County Department of Transportation	▪ 180 signals; 133 signals under ATSPM, the rest will be under ATSPM by the end of 2019; 100% of signals have stop-bar detection. ▪ 100% of signals have advanced mainline detection. ▪ 87% of signals have advanced detection on all approaches.	▪ 1.5 full-time employees, excluding sporadic engagement consultants.	On a daily basis.	UDOT open-source ATSPM software version 4.0.2 (looking to replace with vendor solution).
Maricopa County Department of Transportation	▪ 170 (117 monitored with ATSPM) operated by MCDOT, over 3000 total in Maricopa County.	▪ 3 on-call consultants for traffic operations. ▪ 1 on-call systems integrator. ▪ 1 full-time engineer. ▪ 1 full-time analyst.	Automated alerts; as needed, mainly for responding to public calls.	UDOT open-source software.

Table 8. Major agencies' characteristics. (continuation)

Agency	Number of Signals	Number of Signal Operations Staff	Use of Automated Traffic Signal Performance Measures	Type of Deployment
Pennsylvania Department of Transportation	▪ 2	▪ Many (not relevant).	To support others.	Intelgiht MAXVIEW
Utah Department of Transportation	▪ 2,120 traffic signals in Utah. ▪ 1,252 traffic signals owned and operated by UDOT. ▪ 63 HAWK signals in Utah. ▪ 19 HAWK signals owned and operated by UDOT.	▪ 1 engineering manager (management in both timing and maintenance) ▪ 2 statewide timing engineers (timing only) ▪ 4 region signal engineers (management, plan review; & a little maintenance & operations) ▪ 4 statewide timing technicians (timing only) ▪ 8 signal maintenance technicians (maintenance only) ▪ 3 signal timing consultant firms (timing only)	Continuous.	Utah DOT open-source ATSPM software.

ATSPM = automated traffic signal performance measures. MCDOT = Maricopa County Department of Transportation.
UDOT = Utah Department of Transportation.

PLANNING FOR THE SYSTEM

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 the impact on the workforce, business processes, and appropriate use of systems engineering to inform design and procurement. Many downloaded the UDOT source code (and had internal staff install, configure, and maintain). The size of implementations varied from 50 to 5,000 signals. Once a system is deployed, adding intersections is pretty simple (given the appropriate infrastructure). For larger agencies, the approach was to equip and configure every intersection, which made the change in business processes easier. For smaller agencies, the approach was to start small and make sure they saw the benefit in using the system, then expand to different corridors or metrics as the need arose.

UDOT and GDOT are probably the only agencies, to date, that have taken a systematic approach to integrating ATSPM in their signal operations and maintenance efforts. This is not a surprise considering they have been leaders in ATSPM development and implementation. UDOT has committed significant resources to develop the software and continues to enhance and update the system. Its support for innovative methods like ATSPM has been crucial in developing the ATSPM. UDOT's executive staff vision to establish a world-class traffic signal system was further championed by agency staff, who saw a means to reach this goal by building the capability to monitor signal conditions with performance measures. This was a great symbiosis of visionary leadership and knowledgeable staff to recognize which technologies should be acquired, and also how to enhance and further develop such technologies for the benefit of real-world applications.

GDOT also had strong executive support for improving agency operations, which was capitalized through a formal program of improvements of the State's signal infrastructure, such as controllers, communications, and detection. GDOT included data-logging capability, based on the Indiana Department of Transportation (INDOT) ATSPM data enumerations, as a requirement of its controller specification. Both UDOT and GDOT represent examples where great leadership skills were aided by technologically capable staff in a resource-rich environment. Under such conditions their ATSPM applications have flourished, and they were able to make contributions that have not only benefited themselves, but also the broader traffic signal agency community.

On the other hand, a number of smaller traffic signal agencies did not have all the resources of their larger State counterparts. Such agencies have been planning for their signal operations and maintenance outside of the ATSPM scope, but they saw an opportunity and adjusted their plans to fit the framework of opportunities offered by ATSPM. Such examples are Clark County, WA; Lake County Department of Transportation (LCDOT), and MCDOT. All of them had previously developed plans for signal operations improvement before they learned about ATSPM, and they have been adjusting those plans to include ATSPM ever since the technology caught their attention. Clark County, for example, has been upgrading its signal system for the past 10 years, after a period of diminished attention. It has been making significant investments to improve operations of signalized intersections (e.g., controllers, detection, and communications) and felt that ATSPM is the right technology to apply on top of other efforts. The story of LCDOT is similar—a relatively small agency, with limited resources and very knowledgeable and resourceful staff, that has recognized ATSPM technology as the next building block. This is on top of already suitable communication and detection infrastructure, to reach the next level of signal monitoring and operations. What has been especially helpful in LCDOT's case is a smooth communication between upper management and signal operations, which removes many institutional barriers to implement ATSPM and similar technologies.

Similar to other local agencies, MCDOT also benefited from a previous history of agency investments in traffic control infrastructure. Particularly interesting for MCDOT's case is its regional partnership with AZTech, a regional traffic management agency in the Phoenix metropolitan area that guides application of intelligent transportation system (ITS) technologies for managing regional traffic. This partnership carefully integrates individual traffic management strategies and technologies for the region's benefit while preserving operational control protocols important to individual jurisdictions.

The combined case of PennDOT and Cranberry Township involves a somewhat different approach. While Cranberry Township's story is similar to the aforementioned counties (e.g., planning for improvement of signal operations but only recently adding ATSPM in the overall framework), the PennDOT story is slightly different. With practically no signals owned and a desire to help many small counties, townships, and boroughs manage their signals, PennDOT has dedicated a lot of effort to plan for better signal operations and especially improve coordination among various signal stakeholders. As a part of its Corridor Modernization program, PennDOT started to investigate the possibility of changing ownership of traffic signals on certain critical corridors. Thus, the ATSPM initiative has been seen (and supported) by PennDOT as another tool to help the State streamline signal improvement efforts and improve coordination with local stakeholders.

Of the seven agencies studied, only two are quantitatively tracking (not comprehensively) benefits and costs associated with ATSPM. Frequently, the cost appears to be absorbed within existing Corridor Improvement Program (CIP) projects (related to general traffic signal costs) or as part of typical staff duties. Benefits could be calculated if an agency specifically tracked the number of hours and costs associated with operation and maintenance in the before-and-after ATSPM condition. Driver benefits (reduced delay due to a fixed detector or updated coordinated timings) are more difficult to quantify and may need a more detailed methodology for agencies to document or estimate.

PROCURING AND DEPLOYING THE SYSTEM

It seems that UDOT's ATSPM open-source code is a good choice for larger agencies with adequate information technology (IT) resources, but may not be as effective for smaller agencies. Issues some agencies face are various—from inadequate resources to cope with constant hardware and software updates to having the latest version of source code to the need to customize source code, which often involves additional resources. This indicates that some of the interviewed agencies had issues with stability of the open-source software, but such stability is not seen as an issue at larger agencies (that have applied ATSPM software on a larger number of signals). The consequence of such issues is that many small agencies may find software as a service maintained by commercial vendors a better fit for their individual needs for signal monitoring based on the high-resolution performance measures. Some larger agencies like UDOT and GDOT have opened up their ATSPM systems to incorporate signals operated by local agencies within their States.

The systematic approach to transportation system management and operation employed by UDOT and GDOT allows the agencies to position resources and leverage strong integration between information technology and traffic management, and disseminate advancements to the broader community. UDOT's approach is particularly interesting because at the outset of its investment in developing the open-source software, it did not fully understand what benefits it would be able to achieve by using signal performance measures, yet it still risked committing those resources. Its ongoing efforts to maintain and update communication and detection systems and controllers enabled it to implement ATSPMs with relative ease. In many cases, data collection was simply enabled as a controller feature, while minimal changes to detector configurations were made in some cases. However, it is important to note that not every traffic signal in the State of Utah could immediately be integrated into the system, and even now, not every signal can report every metric. However, the base infrastructure now exists to enable those capabilities in future.

At the time GDOT initiated ATSPM deployment, it was in a good state with making investments in communication, detection, and updated controllers as a matter of maintaining its signal infrastructure. As mentioned earlier, GDOT made the high-resolution data-logging capability a requirement for procurement of traffic controllers. Implementation of ATSPM built upon the existing system with minimal investment. Like UDOT, GDOT was also able to fully commit to operations and maintenance of its own software and server, which resulted in quick familiarity with the system and contributions to the broader community. For example, GDOT invested resources in the first software and use-case ATSPM manuals, which were prepared by consultants to the general public's benefit. Similarly, soon after the first couple of versions of the ATSPM software were released, GDOT developed an add-on module that used some of the ATSPM data to calculate business-case ATSPM summaries, compiled under a tool called Measurement, Accuracy, and Reliability Kit (MARK 1). Although some parts of Georgia are well covered with commercial versions of ATSPM tools, GDOT actively participates in maintenance and enhancement of ATSPM open-source software.

Other smaller entities were not always able to stay with the open-source version for a long period of time. Clark County, for example, was getting ready for an ATSPM-like approach, which was evident because of its innovative use of logs and reports available in Trafficware ATMS.now, the county's central signal system used to manage its signal system. In doing so, it realized the importance of good detection and communications and continued to invest in signal infrastructure. It also installed a Bluetooth sensor system to collect and track travel time along different corridors. In 2013, it began working with Trafficware to develop a software application. This application would use high-resolution data to create reports, similar to what UDOT has developed. In 2014, Clark County asked Trafficware to create five reports so it could monitor operations based on their operational objectives. Clark County is one of those agencies that understood the limitations of owning and maintaining an open-source software, and, thus, went with a commercial version of ATSPM from the very beginning.

LCDOT, on the other hand, had a quite different approach. In short, it went through multiple ad hoc decisions and actions to test various options. It first installed a version of open-source ATSPM software on its own, and maintained it for a while. When a new version arrived, it understood how cumbersome installation could be and hired a local consultant to help with installation. However, even after successful installation it had issues with software crashes and limitations of adding and modifying features to address its specific needs. Finally, LCDOT decided to develop a request for proposal (RFP) and select a commercial solution from a vendor. In the RFP process, LCDOT staff took a proactive role and challenged potential vendors to propose and implement new functionalities that would address specific objectives of LCDOT's signal operations. The process went smoothly, and LCDOT has selected a vendor to supply a commercial ATSPM system, which has embedded a number of enhancements above and beyond the original UDOT source code.

MCDOT's path was perhaps more similar to the two DOTs than to the other smaller agencies. This is not surprising because Maricopa County itself is a larger entity than some States. Over the years, MCDOT has made a commitment to keep its traffic control infrastructure up to date and functional. For the ATSPM project, specifically, detection needs were largely met through a parallel effort to make signals ready for deployment of other advanced technologies. MCDOT is still in the initial phases of using the open-source ATSPM software, and so far it has not had server crashes or other strong reasons to consider commercial ATSPM implementations.

While both PennDOT and Cranberry Township could be considered early adopters of ATSPM, their approaches to ATSPM implementation differ from each other's quite significantly. While PennDOT's efforts are purely driven by a strategic desire to support various signal jurisdictions in the State (the State does not directly control any signals), it seems its early efforts with UDOT's open-source code have not led to a full success. After replacing the ATSPM platform (supported by PennDOT) with a commercial system (Intelight MAXVIEW), operations have stabilized, yet are still imperfect, and it is still uncertain how many local agencies in Pennsylvania have capitalized on this opportunity.

On the other hand, Cranberry Township has taken its own path, with some early tests through Purdue University followed by a fully commercial Econolite platform. In terms of system procurements, Cranberry Township even went one step ahead of many others by deploying a commercial adaptive traffic control (ATC) system based on ATSPM (Econolite Edaptive). However, neither the ATSPM nor Edaptive has been fully utilized—they are procured and installed but still not fully operational with clearly tracked benefits.

OPERATING THE SYSTEM

Most of the surveyed agencies use their ATSPM systems on a daily basis but their operational practices may not always be well integrated into their business models, which connect agencies' goals with operational objectives and field strategies. For example, if an agency has a clear plan for how to operate signals along a corridor, it is more likely the agency will be more successful documenting its operation success by using the ATSPM. On the other hand, if an agency does not know exactly how to use reported performance measures, an abundance of data from the ATSPM system will not necessarily have a significant impact on its day-to-day operations. On the other hand, some agencies do not have a "know-how" problem, but lack sufficient time to extract relevant information from the enormous amount of data ATSPM systems can provide, connect that information with potential implementable strategies, execute those strategies, and validate whether the activities had impact. While ATSPMs provide a useful tool to investigate problems already known, identifying issues with the most pressing need can be a bit like finding a needle in a haystack. Methods to improve or automate this process are the subject of current research.

As in many other aspects of ATSPM, UDOT has been a leader in actively using this technology. In this case, the agency's traffic signal staff immediately saw the utility of the metrics and identified ways to use them to solve many different problems in traffic signal operations and maintenance. Examples included new methods of evaluating signal timing, identifying maintenance issues, and triaging public complaint calls. To align support of its consultants with new ATSPM practices, UDOT has restructured its contracts to refocus consultant activities from the traditional process of signal retiming toward using ATSPMs. This effort has been successful, with many consultants in Utah now actively using ATSPMs.

Other agencies have sought to achieve similar successes through various means. Clark County, for example, wants to address the matter of identifying issues by setting a triggering mechanism that would detect abnormal operations (in a particular context) and report an issue. It plans to fine-tune such a mechanism once ATSPMs are enabled at all its intersections. Clark County developed a measure of effectiveness (MOE) framework for each corridor to determine the most important metrics given the context by creating “corridor atlases” to document operational issues and objectives at each intersection.

LCDOT still has not made full use of its ATSPM capabilities, but it quickly realized its resources will be better used if ATSPM operations are done by a commercial vendor rather than in-house. Thus, it decided to hire a consultant who will be responsible for both maintenance of the hardware, software, and routine daily operations of the ATSPM. In its previous practice it has confirmed (although not fully documented) proactive use of ATSPM reduces complaint calls and costs associated with infrastructure malfunctioning. LCDOT’s in-house staff will still be responsible for decision making, but retrieval of relevant information from the abundance of ATSPM data will be done by a commercial vendor. This labor division is supposed to ensure efficient use of ATSPM over a long period of time.

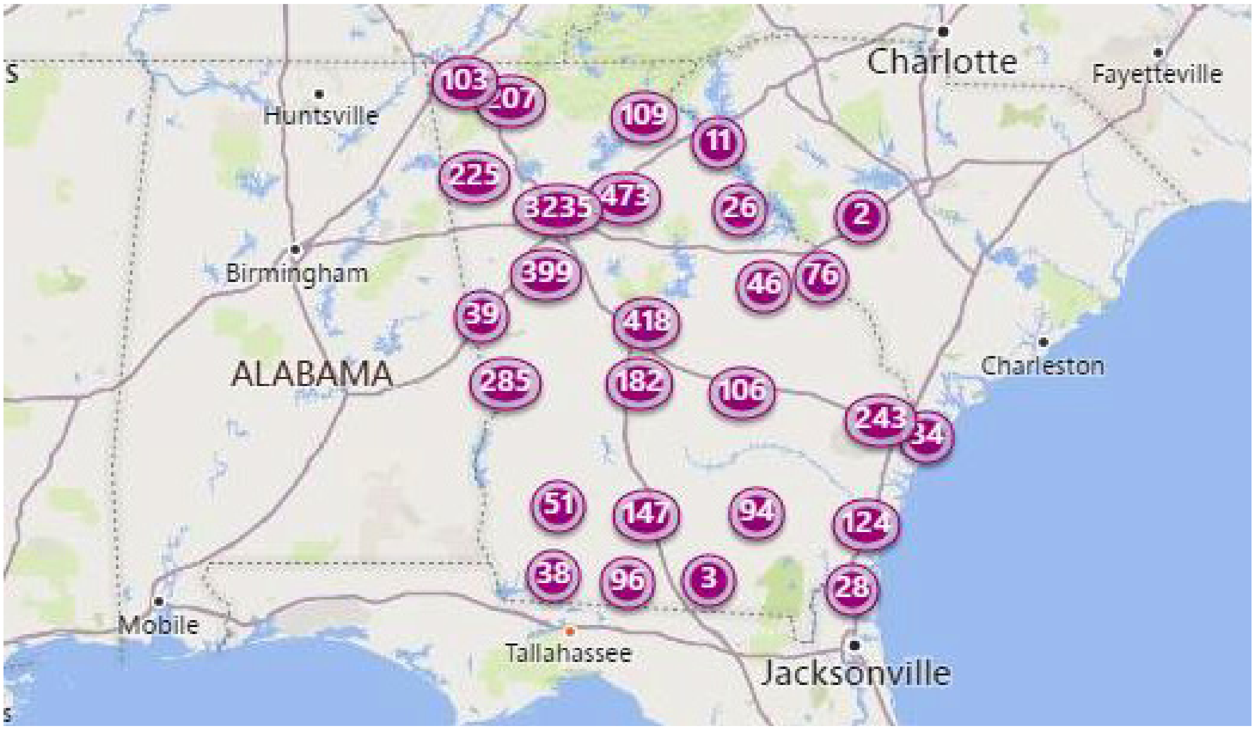
MCDOT is an example of an agency that has seen successes in its early use of ATSPM. It identified three directions of transitioning its practices toward active management and operations: (1) the low level at which most of the metrics are reported (individual movements), (2) a need to orient performance measures toward specific tasks, and (3) a need for additional training to bring traffic management center (TMC) operators and other signal operations staff up to speed on using the metrics. To overcome these issues, MCDOT is waiting for further development of the open-source software by innovators to address the first two points (although it may explore solutions using its own consultants), and anticipates documentation and training activities for the third point.

In Pennsylvania, the two interviewed agencies have quite different paths for ATSPM operations. PennDOT, which does not interfere in daily operations of the signals, expects investment in a statewide commercial Intelight license will attract more local jurisdictions to use ATSPM. On the other hand, Cranberry Township is only a few months away from achieving some concrete benefits of its ATSPM and Centracs® Edaptive deployments. Cranberry Township may be the first system in the country where benefits of an adaptive system will be conveniently and easily measured through ATSPM, which may be a good example of how to merge the strengths of ATSPM’s powerful graphics and reporting with automation of an adaptive traffic control system.

GEORGIA DEPARTMENT OF TRANSPORTATION

Georgia Department of Transportation (GDOT) operates and maintains approximately 6,800 traffic signals across the State, plus 200 ramp meters in the Atlanta metro area. Additionally, approximately 100 local agencies rely on GDOT to help operate and maintain their traffic signals. GDOT has seven districts across the State, each with its own traffic operations group, consisting of engineers and technicians to operate and maintain traffic signals.

This is the largest deployment of traffic signals equipped with high-resolution data-collection capability. All GDOT traffic signal controllers log high-resolution data. Open-source software for automated traffic signal performance measures (ATSPM), developed by Utah Department of Transportation (UDOT), provides tools and reports for traffic signal monitoring.



Original map: © 2019 Microsoft® Bing™ Maps. Map overlay: Georgia Department of Transportation.

Figure 11. Map. Traffic signal quantities and locations in Georgia.

GDOT has changed the way it manages traffic signals by using data and reports from the ATSPM system. It uses the ATSPM system to review data at a finite level (e.g., phase termination, coordination diagram, split monitor) to optimize operation and at an aggregated level (e.g., volume, split failures, progression) to track trends.

Table 9. Georgia Department Transportation agency characteristics.

Number of Signals	Number of Signal Operations Staff	Use of Automated Traffic Signal Performance Measure	Type of Deployment
6,804 (all capable of collecting high-resolution data; approximately 80% configured to create reports).	70–80 full-time employees, including consultants.	Continuous.	UDOT open-source ATSPM software.

ATSPM = automated traffic signal performance measures. UDOT = Utah Department of Transportation.

Business Processes and Signal Systems Benchmarking

GDOT manages a large number of its traffic signals via two main programs:

1. Regional Traffic Operations Program (RTOP)—more than 1,900 traffic signals in the Atlanta metro area. RTOP has multiple consultant contracts for signal maintenance and operations within seven zones. Each consultant contract has dedicated signal timing, communications, and maintenance teams to assist GDOT.
2. Regional Traffic Signal Operations (RTSO)—focused on providing operations and maintenance support outside of the Atlanta metro area. RTSO has consultant contracts to support each of the seven regions with remote monitoring of the traffic signals.

GDOT is considered an innovator with regard to the diffusion of innovation concept. Its system is robust, it knows where it wants to go, and it chooses to take on higher risks than other agencies. It is building upon what UDOT and Purdue University have started, and is trying to make it even better for the majority of agencies. GDOT has a high level of capability and maturity when it comes to operating and maintaining its signal system. The following is a summary of its capabilities in each of the categories:

- **Systems and technology**—traffic signal infrastructure is connected to a management system that can alert operators to equipment malfunctions and assist with managing timing plans. The agency has capability to remotely manage that system but management decisions are operator-driven with little automated decision support. Consistency in design and operations is achieved by using standard designs and hardware specifications. Systems and technology can support preplanned responses and advanced concepts such as transit signal priority and work zone management.
- **Performance measurement**—the agency has defined performance measures to assess project implementations (such as before-and-after evaluations). The agency may collect output-oriented performance measures for operations and maintenance activities. Operational and management decisions are based on periodic manual observations in the field.
- **Organization and workforce**—staff are well versed in both basic and advanced traffic signal control and management concepts and can execute solutions using existing technologies. Workforce development efforts focus on expanding breadth of competencies and providing redundancy in core competencies. The agency can dedicate staff resources to high-priority corridors and areas on a limited basis.

- **Culture**—traffic signal management is recognized as one of many functions in the organization, but no special emphasis is placed on performance. The agency supports teams dedicated to traffic management functions, but there is no broad acknowledgment or awareness by agency leadership as to what they do. Outreach to policy makers and the public regarding traffic signal operations occurs on an as-needed basis, primarily related to projects.
- **Collaboration**—information and data are archived internally and shared with other stakeholders upon request. The agency collaborates with internal and external stakeholders on a case-by-case or project basis, but these collaborations are not sustained over time.
- **Business processes**—traffic signal management, planning, design, operations, and maintenance decision making generally operate in silos and are not well integrated; resource allocation decisions are primarily focused on maintaining infrastructure reliability.

Approach to Implementation

Historically, GDOT has had strong support from management for traffic signal operations, starting more than 20 years ago with standardizing on a single software platform prior to the 1996 Summer Olympic Games. In 2013, GDOT participated in pooled fund study TPF-5(258) (INDOT, forthcoming), which led to creation of the high-resolution data enumerations and resulting ATSPMs. GDOT staff saw the benefit of using the high-resolution data to measure quality of service in its system and better manage traffic signal operations. In 2017, GDOT upgraded its local controllers and central traffic signal system and included requirements for local controllers to collect high-resolution data. The upgraded system would provide new tools to measure and monitor performance. The communication infrastructure was upgraded where necessary as the new controllers were deployed in the field.

GDOT started using ATSPMs to remotely assess signal operations and troubleshoot issues before deploying staff to the field. Much of this is focused on detection maintenance. The data are useful to help determine what equipment, such as a bucket truck, may be needed for a field visit. ATSPMs also provided the tool to determine appropriate timing adjustments to reduce intersection delays when detection failures occurred. In recent years, GDOT has developed several documents to help it efficiently operate and maintain its signal system, including:

- Statewide Traffic Operations and Response Management (STORM) program Concept of Operations (ConOps) documents the GDOT traffic signal program, including existing conditions, user needs, and envisioned operations. The ConOps also includes a list of performance measures, which are traced to operational goals.
- Draft Traffic Signal Management Plan (TSMP) provides a framework of operations for management of traffic signals in the State of Georgia. The plan outlines the agency’s goal and objectives related to operations and maintenance of traffic signals, along with strategies to accomplish them.
- ATSPM installation manual provides detailed instructions on how to configure and install the ATSPM software.

- ATSPM component details compiles the website components and describes steps to configure the system using the UDOT ATSPM source code software.
- ATSPM reporting details describes creating reports and how to interpret and use the reports created by the ATSPM system.

The first two documents are geared toward operating the traffic signals in Georgia. The last three documents are geared toward any agency that plans to install and use the ATSPM source code software. To support creation of the ATSPM reports, GDOT reviewed and updated the detection design standards to accommodate creation of the various metrics. Most intersections had appropriate vehicle detection needed to create the common performance metrics; however, not every intersection can collect data to produce every metric. GDOT's new vehicle detection standard layout (using radar) is used at all new installations. Configuring detection for each intersection to align with ATSPM requirements is time consuming on its own. It has become part of the GDOT business process and one of the tactics to operate and maintain their system.

GDOT is well resourced from a staffing perspective, using both internal staff and consultant resources. Traffic control personnel were trusted by executive staff to direct investments in innovative technology, and the agency had adequate resources to carry out the implementation. It has been able to demonstrate an adequate return on that investment. A wide range of personnel use ATSPM data and reports, including GDOT engineers and technicians and supplemental consultant staff. There has been a paradigm shift in traffic signal operations and maintenance, with virtually all traffic signal staff using information provided by ATSPM data for one reason or another. GDOT's website analytics reveal more than 450 unique monthly users. The ATSPM website is public-facing, and GDOT believe some of this traffic comes from external users, such as consultants, other agencies curious about the system, or the general public, and not from users for specific operational purposes. In the draft TSMP, GDOT has identified the following 11 objectives for the traffic signal program:

1. Provide for safe and efficient operations of traffic signals.
2. Be proactive in the maintenance and operations of traffic signals.
3. Provide for consistent operations and maintenance of traffic signals.
4. Define success and performance goals of traffic signals based on operational context.
5. Efficiently allocate financial and contract resources.
6. Utilize data and data analytics to inform decision making.
7. Utilize resources and technology to achieve a full situational awareness of traffic signal maintenance and operations.
8. Be responsive to customer service needs and continue to build and maintain public trust.
9. Practice flexibility, accountability, scalability, and transparency throughout the program.
10. Demonstrate agility in processes, policies, procedures, tactics, strategies, and objectives.
11. Pursue regional and statewide cooperation in the sharing of infrastructure, tools, resources, and programs.

These objectives are meant to guide the traffic signal program. On-street operational objectives are more specific; they are based on intersection/corridor context and used to determine the metric(s) GDOT monitors. The TSMP has a section devoted to measuring performance, divided into maintenance, design, and operations.

Automated Traffic Signal Performance Measures Use

GDOT is using ATSPMs for both day-to-day operations (proactive operations and maintenance) and project-specific tasks (corridor retiming).

Day-to-Day Operations

Prior to implementing the ATSPM system, GDOT relied on phone calls and complaints as the trigger to dispatch staff to review operations in the field. Sometimes this resulted in 2 hours (h) of driving to observe intersection operations to troubleshoot the issue and possible additional time to fix the problem. Using ATSPM, it can review the intersection operation remotely (once the complaint is received) to do initial troubleshooting and send out staff with the appropriate resources. It is also able to discover problems before getting calls from the public by configuring the system to send real-time alerts and develop summaries that can be reviewed daily.

Project Specific

The approach to data collection for signal timing projects has moved away from manual methods. Before implementing the ATSPM system, GDOT engaged in a traditional signal retiming process, which happened every few years (based on available funds). This involved field data collection (sending out crew to collect traffic counts), building a Synchro model, and performing before-and-after travel time and delay studies. This model was for project-driven signal retiming, whereas day-to-day signal fine-tuning and adjustments were mostly triggered by complaints from the public. According to GDOT, the process of updating signal timings was done “slowly, manually, and with a lot of paperwork.”[1] Most of the evaluation was based on limited field data collection (1 day), including floating-car studies and manual observations, which had opportunities for unintentional (or perhaps intentional) bias and provided a small snapshot of performance. Many metrics were based on modeled or simulated results; for example, congestion mitigation and air quality improvement (CMAQ) projects requiring estimates of quantities such as emissions, speed and travel time, or number of stops.

GDOT has started to use the ATSPM system for corridor signal timing. The biggest change is related to data collection. Turn movement counts now can be collected using high-resolution data from the traffic signal controller instead of manual counts. This not only saves money, but also provides the opportunity to review data from more than a single day. The other benefit of using ATSPMs for signal timing is using the volume and performance data to determine if and when signals timings need to be updated. This changes the process from a time-based event to a needs-based event. Performance measures for signal timing projects now focus on operational objectives related to the context (reduce delay, smooth flow, equitably serve green times, minimize phase failures), and is not solely the floating-car travel time survey.

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[1] Interview with Alan Davis, April 16, 2019, Georgia Department of Transportation.

Most-Used Metrics

The following performance measures are the most frequently used, with the Purdue Phase Termination and Coordination Diagram the top-queried measures:

- Phase Termination Diagram.
- Purdue Coordination Diagram.
- Split monitor.
- Approach volumes.
- Split failures.

At present, GDOT primarily has used data from the ATSPM system for maintenance and operations, as opposed to communicating with decision makers or the public. Nevertheless, the data have allowed GDOT to "tell the story" about the results of its signal management efforts with greater confidence, since the data enable GDOT to verify the impact of the efforts.

Benefits and Costs

Controller Upgrade Costs

GDOT recently chose a new local controller/software and central signal system to replace its legacy system. The new standard local controller is an adaptive traffic control (ATC) operating MAXTIME firmware. Part of the signal system upgrade project was to replace all legacy Type 170 and Type 2070 controllers with ATC controllers capable of collecting high-resolution data. Therefore, GDOT did not have a cost related to traffic signal controller upgrades, specific to ATSPM.

Communications and Detection Costs

Existing communication and detection systems at most intersections were adequate to provide high-resolution data back to the central and produce most ATSPM metrics. GDOT wants remote access to every traffic signal in the State and would need the communications infrastructure regardless of whether it was collecting ATSPM data. Therefore, no specific cost is associated with the communications network. The detection at each intersection was capable of providing inputs for efficient traffic signal operations, but may not have been configured for ATSPM metrics. GDOT included field verification of detector input wiring as part of the routine maintenance inspection and estimated that 20 percent of intersections needed detection reconfiguration (e.g., redefining detection zones in a noninvasive detection system). Three hours per intersection were estimated for this task at a labor rate of \$50 per hour (h).[2] Assuming \$50/h × 3 h/signal × (0.2)*5,784 signals = \$173,520. Additionally, GDOT estimated that configuring intersection detection in the ATSPM system (assigning the inputs) took about 30 minutes of staff time at \$50/h for all 6,804 signals. Assuming \$50/h × 0.5 h/signal × 5,784 signals = \$144,600. These are both classified as deployment costs.

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[2] This rate is an average of the direct rates for a junior engineer and a senior engineer.

Server and Software Costs

GDOT leveraged existing efforts that allowed it to reduce overall implementation costs. GDOT recently upgraded and installed new servers to accommodate multiple applications for traffic operations, including the new central signal system. Server requirements for the ATSPM system did not call for additional equipment; therefore, the server and server maintenance were estimated to have no additional costs. These functions were already being undertaken by the agency's information technology (IT) staff and did not drastically change with implementation of ATSPM. As new data storage is desired, additional server space (or cloud service) may be added.

GDOT is using open-source software developed by UDOT as the ATSPM system, which is free for agencies to download (no license costs). The cost to deploy the open-source software system was approximately $200,000 (consultants to configure and set up reports). GDOT estimates that about one quarter of a full-time employee's (or 500 h) is spent operating and maintaining the ATSPM system during a year. A labor cost of $50/h and a 10-year (yr) life cycle were assumed. As the open-source software is updated, it will be necessary for GDOT staff to update the version on the server. Some costs and benefit items are estimated for the 10-year life cycle. Assuming a discount rate of 5 percent, the (P|A) factor for determining net present value is 7.72. The present value of this 10-year cost is 500 × $50 × 7.72 = $193,000 (included in operation cost).

Training and Usage Costs

GDOT provides periodic training for traffic operations and maintenance staff (GDOT and consultants). There is specific training for ATSPM use, since it is a new topic/procedure and will be integrated into normal operations training in the future. GDOT estimated each ATSPM training costs $3,000 for a 2-hour session, plus staff time. The training is offered four times per year. The present value of this 10-year cost is 4 × $3,000 × 7.72 = $92,640 (included in operation cost). GDOT also had the three manuals listed above developed at a cost of approximately $75,000 (included in deployment cost).

Benefits

For this case study, only agency direct benefits were considered, such as reduction of staff time and resources, as this was the agency's the most readily available data. The benefits to the public (reduction in delay and stops) have not been estimated in this initial analysis. The benefits of ATSPMs can be observed for day-to-day operations and also for specific projects, such as corridor retiming or a special event. Before implementing ATSPM, GDOT relied on phone calls and complaints as the trigger to dispatch staff to review operations. Sometimes this resulted in 2 hours of driving to observe intersection operations to troubleshoot the issue and possible additional time to fix the problem. Now GDOT can review the intersection operation remotely to do initial troubleshooting and send out staff with the appropriate resources. It is also able to discover and appropriately address detection problems before getting a call from the public.

GDOT estimates staff spent many more hours troubleshooting issues prior to ATSPM. For one program, it used to visit 1,500 intersections each month for field checks of detection. Now those detector checks are limited to locations where trouble tickets have been created or where the ATSPM system alerts there may be a problem. This has resulted in a 70 percent reduction in the number of locations that require field visits, and many of the issues can be resolved remotely. If each field visit takes 1 hour, with a labor rate of $50/hour, and the number of intersections is reduced by 1,050 × 12 = 12,600, the yearly benefit is $630,000. The present value of this 10-year cost is $630,000 × 7.72 = $4,863,600.

GDOT estimated a savings of $600,000 in one district (across 17 signal timing projects) by using ATSPM data versus the traditional signal timing approach. The cost savings were due to reduced effort in field data collection, simulation, fine-tuning, and before-and-after comparison. These benefits were spread across numerous activities and were realized in a relatively short time after system implementation. The present value of this 10-year cost is $600,000 × 7.72 = $4,632,000. The benefits discussed above result in cost savings of $12,230,000/yr and represent just a small portion of the signal system. It should be noted that public benefits in terms of travel time savings or delay reductions have not been estimated in this case study.

Lessons Learned

GDOT provides an excellent example of how executive support for agency operations is valuable for establishing a strong program. Georgia's ATSPM system was relatively easy to implement given the large scale of other programmatic improvements to the State's signal infrastructure, such as controllers, communications, and detection. Further, the State had a strong IT program that had already been undertaking numerous roles in managing systems requiring servers and other computing infrastructure, making it easy to include the new ATSPM system. GDOT participated in the pooled fund study and recognized the systemwide benefits that could be afforded at a relatively low cost. It documented the system goals and objectives and incorporated performance measurements into its normal processes.

At the time GDOT was deploying ATSPM, it was making investments in communication, detection, and updated controllers as a matter of maintaining good condition of its signal infrastructure. Implementation of ATSPM built upon the existing system with minimal investment. The value of ATSPM includes providing data collection at a fraction of the cost of traditional methods, plus the ability to remotely troubleshoot operational issues before dispatching staff.

GDOT is able to maintain a level of quality (on-street operations) more efficiently by using ATSPM data and reports. Measuring the benefit of using ATSPMs for day-to-day operations is difficult, since the tasks have been incorporated into the signal operations and maintenance process. There was no good, clear data on how much time and money were spent troubleshooting issues before implementing ATSPM to provide a comparison.

Benefit-Cost Methodology Application Tables

Table 10. Georgia Department of Transportation implementation and life cycle costs.

Cost	Description	Sunk Cost	Deployment Cost	Operation Cost
1	Controller procurement.	0	0	0
2	Firmware upgrades.	0	0	0
3	External data loggers.	0	0	0

Table 10. Georgia Department of Transportation implementation and life cycle costs. (continuation)

Cost	Description	Sunk Cost	Deployment Cost	Operation Cost
4	Communication system development.	0	0	0
5	Communication system maintenance.	0	0	0
6	Detection system development.	0	0	0
7	Detection system maintenance.	0	0	0
8	Detection system reconfiguration.	0	$173,520	0
9	Detection system documentation.	0	$144,600	0
10	New server.	0	0	0
11	Server maintenance.	0	0	0
12	Software license cost.	0	0	0
13	Installation cost.	0	$200,000	0
14	Maintenance cost.	0	0	$193,000
15	Integration/Training cost.	0	$75,000	$92,640
16	Usage cost.	0	0	0
Total		**0**	**$593,120**	**$285,640**

Table 11. Georgia Department of Transportation post-implementation and life cycle agency benefits.

Cost	Description	Benefit
1	Manual data collection avoided.	$4,632,000
2	Scheduled maintenance avoided.	0
3	Complaint response time reduction.	$4,863,600
4	Performance documentation.	0
Total		**$9,495,600**

Table 12. Georgia Department of Transportation post-implementation and life cycle public benefits.

Cost	Description	Benefit
5	Respond to failed detection.	0
6	Respond to failed communication.	0
7	Responds to other equipment failures.	0
8	Capacity benefit.	0
9	Progression benefit.	0
10	Pedestrian service benefit.	0
11	Preemption improvement.	0
12	Reduction in crashes.	0
Total		**0**

UTAH DEPARTMENT OF TRANSPORTATION

The Utah Department of Transportation (UDOT) is one of the first agencies to implement ATSPMs systematically on a statewide basis. As one of the first agencies, it invested considerable resources to develop software that uses high-resolution data from traffic signal controllers to provide reports that help more efficiently manage and maintain the signal system. It has made the software available as an open-source release, saving this effort for others. It also has provided limited technical support to local agencies that have downloaded the UDOT source code software to use with their signal system.

The agency rated itself at Level 4 in categories of performance measurement, organization and workforce, culture, and collaboration, and at Level 3 in categories of business processes and systems and technology. This rather high-level result is consistent with the proactive approach exhibited by UDOT in its signal management practices, and the leadership role it has fallen into. This leadership has included development of open-source ATSPM software and considerable outreach to other agencies and practitioners through numerous workshops, webinars, and other forums. In the diffusion of innovation theory, UDOT clearly exhibits characteristics of innovators with regard to its traffic signal practices. The development of the open-source software is the strongest evidence of this, but integration of that software with its business practices may be even more innovative. Indeed, usage of the technology and variety of practical examples UDOT has communicated to other practitioners has been important to the spread of ATSPM in traffic engineering practice.

Approach to Implementation

Utah's involvement with ATSPMs began in 2011. UDOT Executive Director John Njord challenged the agency to figure out what would be needed for UDOT to establish "world-class traffic signal maintenance and operations" (UDOT 2011, ES-1). This question inspired the following further questions:

- How effective is traffic signal timing in Utah?
- What is the trend in signal operations? Improving, staying the same, or getting worse?
- What are the areas with the greatest need?

UDOT's signal operations staff found it did not have good answers to these questions, so they formed a Quality Improvement Team to look at its program in more detail. This team examined levels of funding, staffing, organizational structure, policies, and business practices, and came up with several recommended actions for UDOT that would make its system world-class. The following three recommendations had a particularly strong impact on the future of UDOT's signal operations:

- Maintain communication and detection during construction.
- Transition from reactive to proactive signal maintenance and operations.
- Implement real-time monitoring of the system.

At the 2012 Transportation Research Board Annual Meeting, the director of UDOT's Transportation Management System met with Darcy Bullock, from Purdue University, and Jim Sturdevant, from INDOT, who were beginning a pooled fund study to continue their work in developing performance measures for signal systems. Shortly after this meeting, UDOT began to develop a system to harvest high-resolution data from signal controllers and deliver performance measure graphics to users through a web interface. Ultimately, UDOT invested 12,000 person-hours to create that system, using existing in-house information technology (IT) resources. This investment has since paid dividends not only for UDOT in establishing ATSPM as a resource for the State DOT, local State agencies, and consultants, but also for numerous agencies across the US that have been able to implement the software through UDOT's open-source release. Additionally, several vendors have developed commercial ATSPM delivery systems that use the UDOT source code as the base.

Although UDOT's development costs were relatively high, it faced a unique situation as the first agency to take on the task of implementing at a large scale. Other agencies have been able to benefit from UDOT's work, since they are generally able to avoid repeating UDOT's effort. UDOT's ATSPM program probably would not have been successful had it not been for the agency staff who became champions for the program. In UDOT's case, several individuals became closely involved in developing the open-source software. Two members of the engineering staff, who had both a hand in the process and roles managing signal operations for the State, would come to act not only as champions for UDOT's signal performance measure program, but for ATSPMs in general, leading numerous workshops and presenting several webinars. They were Mark Taylor, PE, PTOE, traffic signal operations engineer, and Jamie Mackey, PE, PTOE,[3] statewide signal engineer. It is largely through their efforts, use of performance measures, and strong interest in understanding their impact, that most of the information in this document was originally developed.

Bringing the System Together

The large investment Utah made to develop open-source ATSPM software was the critical component for implementation of performance measurement. The open-source software began from the foundation laid by INDOT and was brought to the level necessary to roll out ATSPMs statewide; the software has since been used by other State and local agencies, including some that have perhaps 3–4 times as many signals as Utah, thus demonstrating the system's ability to scale agencywide.

This investment in the development of the open-source software would only have reached a small number of signals in the State if UDOT had not also been proactive in its communication and detection practices. For several years preceding the ATSPM effort, UDOT had prioritized establishment of communication to intelligent transportation systems (ITS) and signal assets throughout the State. It accomplished this by exchanging right-of-way access for communication links from telecommunications operators in the State. Between 2006 and 2015, the State's fiber network expanded from 731 miles (mi) (with 100 traded mi) to approximately 1,960 mi (with about 1,000 traded mi). As a result, the State had working communication to nearly all signalized intersections in the State.

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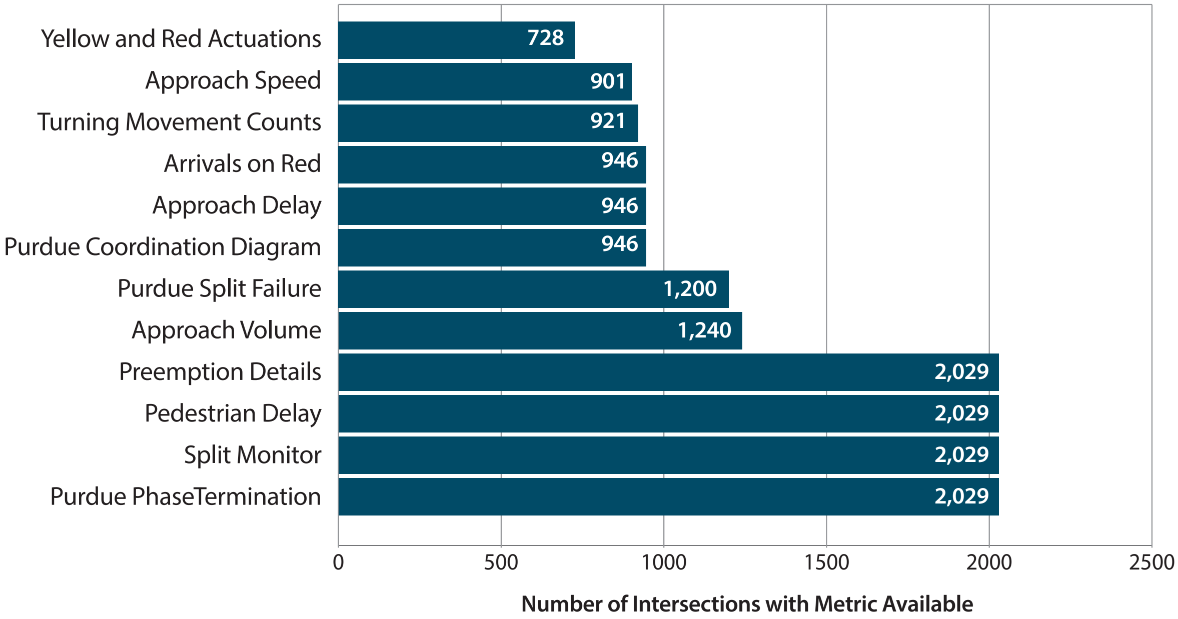
[3] Taylor and Mackey are both licensed Professional Engineers who have further obtained Professional Traffic Operations Engineer certification.

Similarly, the State's previous practices in its controller and detection system made UDOT well positioned to implement ATSPMs. The State had previously invested in upgrades to its controller inventory and had proactively maintained them with the newest firmware versions. Consequently, most of the controllers in the system were already capable of recording high-resolution data. In addition, the State had established uniform practices for its detection systems, and most intersections already were set up for ATSPMs, although in some cases detection zones in nonintrusive systems needed to be revised. For example, a desired revision in some places was to break apart large approach detection zones into smaller lane-by-lane zones. However, as noted by UDOT Traffic Signal Engineer Mark Taylor, in many presentations given on ATSPMs, even without fine-tuning detection zones, useful information can still be acquired out of high-resolution data. For example, the phase termination charts can be used to view the proportion of max-outs versus gap-outs, providing a basic view of phase utilization.

Figure 12 shows the number of intersections in Utah for which certain metrics are available through UDOT's website. Metrics for Preemption Details, Pedestrian Delay, Split Monitor, and Purdue Phase Termination are available for all 2,029 intersections without detector mapping. The other metrics involve both detector mapping and certain detector types in some cases. For example, Purdue Coordination Diagram, Approach Delay, and Arrival on Red metrics all use setback detection data, while Approach Speed uses radar speed sensor data. Some of the metrics with lower numbers likely represent signals where detector mapping has not been entered, or where setback or radar speed detectors are not deployed.



Source: FHWA

Figure 12. Bar Chart. Performance measure availability (based on analysis of intersections with metrics available on the Utah Department of Transportation website on May 31, 2019).

Given that most of UDOT's intersections had compatible controllers, communication, and detection systems, once the ATSPM system was functional, intersections could be integrated into that system by providing information about detector mapping (i.e., assignment of detectors to phases) and other information such as controller IP address; internal interfaces were included in the ATSPM system to permit users to do so; these changes only affected the display of the performance measures, meaning that users could not reach the signal controller itself through the system. This separation of access enabled a secure web-based system (in that none of the actual control systems could be reached) and also promoted inclusion of multiple vendor products, which was a vital concern from the beginning of ATSPM research in Indiana.

Integration of Automated Traffic Signal Performance Measures into Agency Practices

A vision statement of "traffic data for everyone" associated with ATSPMs has been reiterated in several presentations given by UDOT engineers. What it means is that the traditional approach of clustering agency personnel into task-oriented silos that rarely communicate with each other brings inefficiencies that can undermine an agency's purpose. A breakdown of individual performance measure usage for 2018 shows that turning movement counts and approach volumes have a combined usage rivaling the Purdue Phase Termination diagram. This indicates growing use by planners and consultants. Importantly, this breakdown of metrics usage reflects only the metrics delivered by the web front end. It does not include automated email alerts provided to technicians and others for maintenance uses.

Institutionalization through Usage

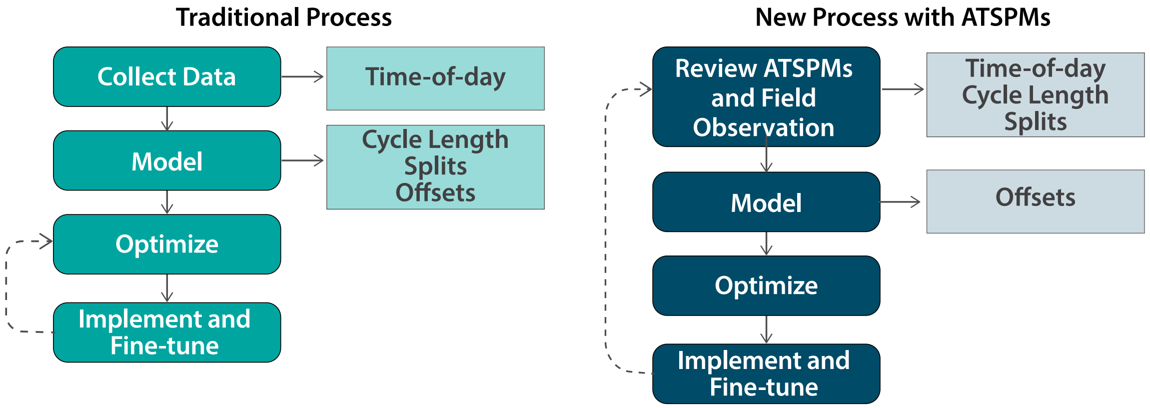
UDOT's position as the first agency to implement ATSPM statewide necessitated the involvement of many of its signal engineers during development, which made the engineers intimately familiar with the system's function. UDOT institutionalized ATSPMs among its engineering staff through usage. For its technicians, UDOT has training sessions approximately every 3 months. Other agencies and consultants in Utah would have likely learned of ATSPMs because of attention they have received in the past few years as a focus technology of the American Association of State Highway and Transportation Officials (AASHTO), the Every Day Counts program, and through UDOT workshops, technical meetings, and Train the Trainer sessions intended to enable participants to inform others. It remains to be seen whether using ATSPM will continue to be self-sustaining, but the high level of use is likely to promote this.

New Methods of Managing Signal Timing

The availability of ATSPMs has completely transformed the way UDOT manages its signal timing. Figure 13 highlights the differences between the traditional and new process.

- Under the traditional process, data collection mostly consisted of turning movement counts, which were used to establish time-of-day coordination plans. Signal modeling/optimizing software uses these volumes as inputs to produce the recommended signal timing parameters (cycle length, splits, and offsets). The modeling software is typically used to develop the timings, but the system does not provide any feedback in real time. Supplemental data collection was necessary to measure impact. Prior to ATSPMs, UDOT devoted one full-time employee (FTE) to carry out floating-car studies (the typical metric for before-and-after comparison). The sole task of this employee was to travel around the State of Utah and drive corridors to measure travel times.

- With ATSPMs, a wealth of detailed operational data can be obtained from the field. Consequently, the signal timing process focuses much more on real-time field observations. The performance measures are used to assess signal timing rather than relying on a model. The most important aspects of signal timing can be evaluated using ATSPM. Split allocation, progression quality, and time-of-day plan boundaries can be assessed and areas of oversaturation can be identified. Rather than obtaining the entire timing plan from models, the main purpose of modeling is now limited to the development of offsets. However, even this aspect of signal timing has been supplemented by performance measures to evaluate offsets, and optimization methods based on those measures. UDOT's signal timing contracts with consultants were restructured to reflect these new practices. Since the implementation of ATSPM, UDOT no longer collects turning movement counts using traditional methods, and no longer uses an FTE for floating-car studies.


Traditional Process

New Process with ATSPMs

Source: Jamie Mackey (Utah Department of Transportation)

Figure 13. Flowchart. Transformation from traditional signal timing to a new process enabled by automated traffic signal performance measures.

Improved Response to Public Calls

Prior to ATSPMs, UDOT responded to every complaint call with a field visit. This was necessary because without any feedback from the system, UDOT simply would not know if a complaint call was valid. Further complicating matters, some reported problems were ambiguous about whether they were a signal timing or a detection issue—affecting the type of technician sent to the field. Sometimes, for example, a timing technician would be sent only to find the problem was related to detection, which meant that a different technician would have to make a site visit to resolve the problem. To avoid this, sometimes both a timing and a detection technician might be sent when the source of a problem was unclear. Another issue is that reports often were vague, which meant the technician might not be able to resolve the issue if the problem did not occur while the technician was on site or if it was unclear which approach or time of day the problem occurred.

With ATSPMs, these practices have changed. When fielding calls from the public, the staff member speaking to the caller can retrieve information about the location and discuss the situation with the caller while triaging the problem. In many cases, a site visit can be avoided altogether. In approximately half of complaint calls, a work order is not generated because the problem can be remotely resolved, the reported observation reflects desired operation, or a situation that cannot be resolved through signal timing changes (such as saturation during rush hour conditions). In February 2019, for example, 226 public calls were received and only 137 work orders were generated as a result—compared to 226 work orders as would have been the case previously. When work orders are generated, much more specific information can be given to technicians about the type of problem, where it is occurring, and how it could likely be resolved. The number of wasted trips is thus reduced by targeting technician time and expertise to the problem.

Automated Detector Anomaly Detection

At present, the ATSPM system is proactively used for detector maintenance issues, thanks to an automated checking tool that identifies detection anomalies by analyzing the counts of events on a daily basis. Anomalies are based on a series of heuristics that look for detection channels with missing data, excessive max-outs and force-offs, and too many or too few pedestrian calls. If a new problem is found that was not previously reported, it will be communicated to maintenance staff through an automatically generated email.

Using this tool, malfunctioning detectors are restored before public complaint calls come in; UDOT engineers estimate they may be able to see the problems about a month before a call might come in. Signal timing issues are still frequently identified through public complaint calls, but these calls can be much more efficiently addressed because the problems can be investigated with data before they are checked in the field.

Benefits and Costs

The cost associated with development of the UDOT system can be extracted from the estimated 12,000 person-hours of development time. If a fully loaded labor cost of $84/h is used, this comes to approximately $1 million in labor costs. It is important to note this high level of investment is unique to UDOT as the original developer of a new software system. Further, the hours for this project were spent by staff already employed by UDOT, so this cost represents an allocation of existing resources that otherwise would have gone to other tasks. Considering there are 2,111 signals currently polling high-resolution data for ATSPMs, this investment comes to about $474 per signal. For an agency seeking to adopt the existing open-source software, a UDOT estimate of the potential costs are provided in table 13. The estimated cost per signal for ATSPM deployment (for the system itself, if not added field components) is $230–$400 per signal, with the lower values possible due to economies of scale in larger systems.

Table 13. Estimated cost of implementation according to Utah Department of Transportation.

	Small System (~50 signals)	Large System (~1000 signals)
Controllers with high-definition loggers	Unknown	Unknown
Communication or in-cabinet data storage	Unknown	Unknown
ATSPM open source software	0	0
Server	$3,000	$20,000
SQL database license	$7,000	$100,000
IT consultant (software installation)	$5,000	$10,000
Engineering consultant (detector configuration)	$5,000	$100,000
Total	**$20,000**	**$230,000**
Cost per signal	*$400*	*$230*

ATSPM = automated traffic signal performance measures. IT = information technology.

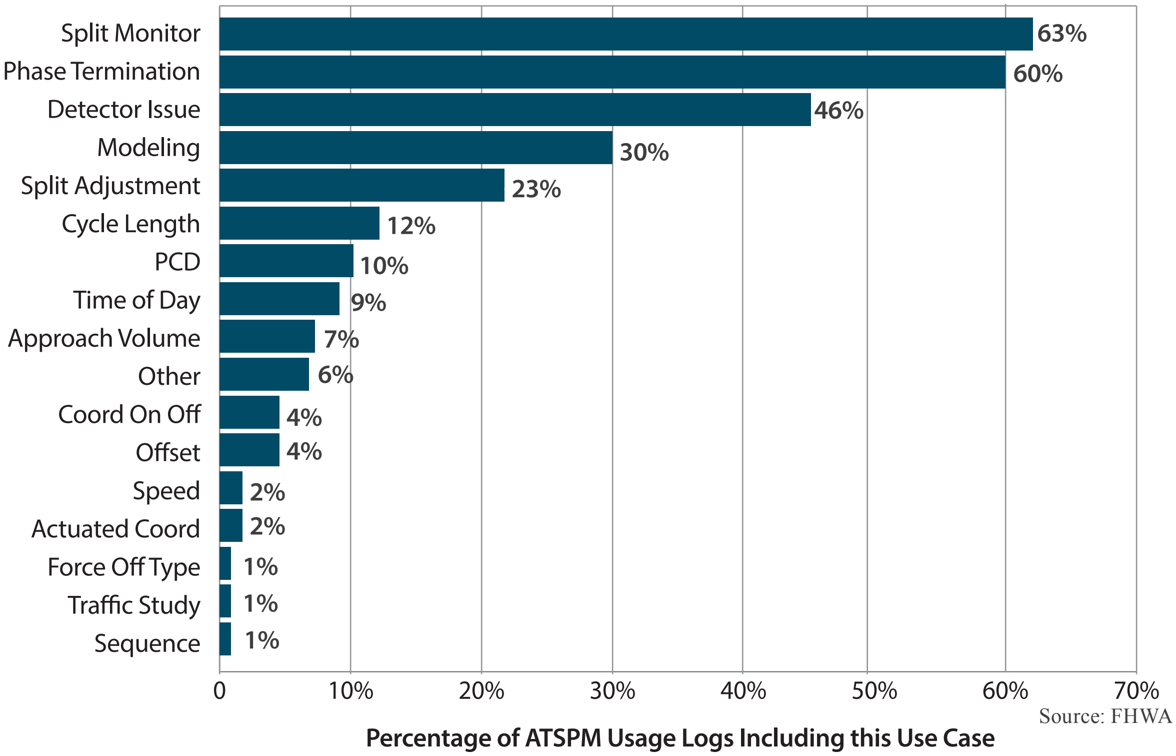
In Utah, most of the signals already had the necessary communication and detection systems in place, along with a controller with up-to-date firmware. Little information was obtained about costs of these investments, as these activities were undertaken as part of the regular program for maintaining functional signal systems in the State. UDOT engineers estimated that about 10 percent of one FTE was needed for maintaining the ATSPM system itself. In general, system maintenance needs are rather minimal; keeping the server functional is integrated into the regular duties of IT personnel and is not available as a separate cost item. What does require some effort is to maintain the detector mapping; this is a critical task because if detector assignments are changed, performance measures no longer accurately reflect conditions in the field. This can happen if a field technician forgets to enter the data after making such a change. According to UDOT engineers, a few hours a week of their time is dedicated to chasing down such problems. The automated system for detecting anomalies is useful for catching such errors.

Table 14 shows an example calculation of effort over a 10-year period for the UDOT implementation. Because much of the State was ready for implementation, many of the line items represent system elements that did not have to be addressed, hence there are amounts of $0 in much of the table. For development of the system, 12,000 hours of developer time were estimated. A rate of $84/hour was used to calculate this total "installation cost" of $1,008,000. The numbers of hours used for software development, maintenance (management of detector configuration data), training, and use of the software (assumed 10 hours/week) were extracted from the interview with UDOT signal personnel. For maintenance of the system, it is assumed that 50 technician hours are applied per week, each week of the year, with an hourly rate of $58/hour, for a total cost of $150,800 per year. Using an interest rate of 5 percent, the net present value of the cost over a 10-year period is $1,164,176. Training activities are assumed to involve 48 person-hours in each session, with four sessions occurring per year. $86/hour is assumed for this activity, leading to an annual cost of 48 × 4 × $86 = $16,512. Over a 10-year period the net present value is $127,473.

Finally, the cost to make use of the software is estimated based on the following assumptions. First it is assumed that 25 technicians make use of the software for about 10 hours per week on average, with a rate of $58 per hour, while 10 engineers make use of the software, also for 10 hours per week on average, with a rate of $86 per hour. The annual cost arising from these amounts is equal to (25 × 10 × 52 × $58) + (10 × 10 × 52 × $86) = $1,201,200 per year. The net present value over 10 years is $9,273,264. This represents the person-time involved in using the software, which could be offset by fewer hours spent for the same purposes by conventional means. Hourly rates used for effort in these calculations are based on average salaries in the state of Utah for computer programmers (for IT personnel), traffic engineers, and traffic signal technicians. An overhead rate of 150 percent was applied.

Over a 10-month period from August, 2013, to May, 2014, UDOT tracked usage of the ATSPM system for assisting in signal system management. Every time a work order was generated, the system was checked in response to complaint calls, or performance measures were consulted in response to signal timing projects, a log entry was made. The log entries included 804 recorded uses, of which 436 originated from consultants and 368 from State and local governments (the vast majority being State government). There were 419 different intersections represented in the logs, or about 20 percent of the total number of signals in the State.

Figure 14 presents a breakdown of the reported ATSPM uses from this 10-month period. When filling out a log entry, users could select multiple use cases. Some system users selected as many as nine different use cases, but the median was three. The breakdown of selected use cases indicates the system was used for many different needs in both maintaining signal timing and detection. Detection issues were present in 46 percent of recorded use cases, indicating it was one of the dominant uses. The log information also shows modeling as a prevalent use, in addition to numerous aspects of signal timing.



Source: FHWA

Figure 14. Bar Chart. Automated traffic signal performance measures use cases in Utah over a 10-month period from August, 2013, to May, 2014.

Table 15 presents calculations of benefits yielded by implementation and use of ATSPM. The first four items represent cost savings to the agency.

- As mentioned earlier, UDOT had been using one FTE for floating-car studies; elimination of this labor cost would likely be in the range of $58/h × 2,000 hours per year (h/yr) = $116,000/yr.
- The minimum effort needed to maintain up-to-date detector counts using traditional methods was assumed to be achievable by investing 12 hours per quarter (h/qtr), a rather conservative estimate. The 921 intersections for which turning movement count data are available were considered the signals that would have to be addressed by the count measurement. Assuming $58/h × 12 h/qtr × 4 quarter per year (qtr/yr) × 921 intersections = $2,564,064/yr.
- Reduced effort in resolving public complaint calls was estimated based on the assumption of 200 calls per month (mo), which is typical of call frequencies experienced by UDOT, conservatively requiring 4 hours each and an average of 1.5 technicians per call (assuming that two technicians are involved about half the time). The cost per year is 200 call/month × 4 h/call × $56/h × 1.5 technicians/call × 12 months = $806,400 per year.
- It was assumed no changes were to take place to the existing preventative maintenance program.

The total cost reduction per year is therefore $3,486,464. Assuming a 5 percent interest rate, the net present value of this savings over 10 years is $26,915,502.

For public benefits, UDOT had previously developed a very conservative estimate of public benefits, which assigned value to certain activities being taken by the agency such as fixing a broken detector or adjusting an offset. A similar analysis can be formed here:

- This analysis assumes detection changes are identified 30 days earlier than they otherwise would be. Each of these incidents affects 10,000 vehicles per day (veh/day) with a delay time of 10 seconds per vehicle (sec/veh), with a delay cost of $15/h. About 50 such incidents per month are conservatively assumed to occur. This number is based on the approximate 200 reported incidents per month from public complaint calls, assuming that about 25 percent of these calls are valid. The benefit per year is estimated from 30 days. The benefit per year is estimated from 30 days × 10,000 veh/day × 10 sec/veh ÷ 3,600 sec/h × $15/h × 50/month × 12 months = $7,500,000.
- Issues with failed communication or other equipment were not considered. While possible, these maintenance needs were secondary to detection.
- A capacity improvement was assumed to yield a savings of 20 sec/veh of delay, affecting 10,000 veh/day over 30 days, and a delay cost of $15/h. It is conservatively assumed that about 10 such adjustments are made per month. The same assumptions were made for progression improvements. For both items, the public benefit per year is estimated from 30 days × 10,000 veh/day × 10 sec/veh ÷ 3,600 sec/h × $15/h × 50/month × 12 months = $1,500,000.
- Other public benefit items were not considered.

The assumed values are rather conservative estimates, given that other studies have shown much larger benefits for both detection and timing changes, especially when those numbers are annualized. Nevertheless, even using these assumptions, a user benefit of $10.5 million per year in public benefits would result. The net present value over a 10-year period is $81,060,000. Of this, about $58 million is attributed to addressing broken detection. The total benefit including both agency savings and public benefit is approximately $108 million.

Lessons Learned

- For UDOT, executive support for innovative methods like ATSPM has been transformative. The ATSPM effort was initiated by executive staff member John Njord, who set a goal of establishing a world-class traffic signal system. This goal was further championed by agency staff who saw a means to establish this by building the capability to monitor signal conditions with performance measures. Objectives to support that goal were developed by staff with technical expertise to allow them to realize the way forward. It is unlikely that leadership would have identified a solution like ATSPM at the outset. Instead, ATSPMs came about as part of a greater effort to improve traffic signal operations and maintenance.
- ATSPM implementation can be rapid when it is preceded by a robust signal maintenance program. Although UDOT's efforts prior to ATSPM were limited by the lack of information provided by performance measures, its efforts in maintaining updated controllers, working communication systems, and functional detection systems made it easy to implement ATSPMs. In many cases, data collection was easily enabled as a controller feature, while minimal changes to detector configurations were made in some cases. However, it is important to note that not every traffic signal in the State could be immediately integrated into the system, and even now, not every signal can report every metric. However, the base infrastructure now exists to enable those capabilities in future.
- UDOT institutionalized ATSPMs by actively using the technology. In this case, the agency's traffic signal staff immediately saw utility of the metrics and identified ways to use them to solve many different problems in traffic signal operations and maintenance. Examples included new methods of evaluating signal timing, identifying maintenance issues, and triaging public complaint calls. Therefore, in this case, it was unnecessary to train personnel or adjust policies to establish a return on investment among agency staff. However, some changes were made to facilitate similar changes among consultants hired to do signal timing. In this case, contracts were restructured to refocus consultant activities away from the traditional process toward ATSPM. This effort has been successful, with many consultants in Utah now actively using automated performance measures.

Benefit-Cost Methodology Application Tables

Table 14. Utah Department of Transportation implementation and life cycle costs.

Cost	Description	Sunk Cost	Deployment Cost	Operation Cost
1	Controller procurement.	0	0	0
2	Firmware upgrades.	0	0	0
3	External data loggers.	0	0	0
4	Communication system development.	0	0	0
5	Communication system maintenance.	0	0	0
6	Detection system development.	0	0	0
7	Detection system maintenance.	0	0	0
8	Detection system reconfiguration.	0	0	0
9	Detection system documentation.	0	0	0
10	New server.	0	0	0
11	Server maintenance.	0	0	0
12	Software license cost.	0	0	0
13	Installation cost.	0	$1,008,000	0
14	Maintenance cost.	0	$1,164,176	0
15	Integration cost.	0	$127,473	0
16	Usage cost.	0	0	$9,273,264
Total		**0**	**$2,299,649**	**$9,273,264**

Table 15. Utah Department of Transportation post-implementation and life cycle benefits.

Cost	Description	Benefit
1	Manual data collection avoided.	$20,690,094
2	Scheduled maintenance avoided.	0
3	Complaint response time reduction.	$6,225,408
4	Performance documentation.	0
5	Respond to failed detection.	$57,900,000
6	Respond to failed communication.	0
7	Other equipment failures.	0
8	Capacity benefit.	$11,580,000
9	Progression benefit.	$11,580,000
10	Pedestrian service benefit.	0
11	Preemption improvement.	0
12	Reduction in crashes.	0
Total		**$107,975,502**

PENNSYLVANIA DEPARTMENT OF TRANSPORTATION

The original intention for this case study was to cover Pennsylvania Department of Transportation (PennDOT) similar to the other ATSPM-deploying agencies. However, soon after an interview started with PennDOT, it was clear that PennDOT does not control any traffic signals, and its role is to only support other signal-controlling agencies (e.g., counties, townships, and cities). Based on inputs from the interview with PennDOT we reached out to Cranberry Township, which was identified by PennDOT as one of the leading traffic signal control agencies in the State of Pennsylvania. Cranberry Township is a township in Butler County, PA, near the crossroads of Interstate 76 (I–76) and Interstate 79 (I–79) (see figure 15). It is one of the fastest growing areas of the Pittsburgh metropolitan area, and its population is projected to grow from 28,098 in 2010 to around 50,000 by 2030.

Figure 15. Map. Location of Cranberry Township.

The idea was to combine the two agencies in a single case study, with PennDOT assessed as a potential investor in the ATSPM technology and Cranberry Township seen as a beneficiary. However, this plan was slightly disturbed for two reasons. First, Cranberry Township does not yet have much to share because it is on the cusp of implementation. Second, it has never used the UDOT platform. Instead, Cranberry Township has used Econolite's commercial version of ATSPM technology, despite the fact that PennDOT provided a statewide license for Intelight's commercial ATSPM (as a part of a bigger package to cover arterial operations). Due to all of these inconsistencies, one could question the meaningfulness and benefits of this case study. However, we believe this case study can be an excellent compilation of lessons learned, as this situation reflects many similar regional cases (e.g., where central and local governments do not act in unison due to open-market provisions and various operational and political constraints). Such lessons can help identify research questions that in turn can help us propose a solution to improve the overall state-of-practice of signal monitoring and maintenance. Thus, we proceed with this case study by providing parallel inputs for each of the two agencies (PennDOT and Cranberry Township) whenever such inputs are relevant. Table 16 summarizes some of the relevant traffic signal characteristics for PennDOT and Cranberry Township, respectively.

Table 16. Pennsylvania Department of Transportation characteristics.

Agency	Number of Signals	Number of Signal Operations Staff	Use of Automated Traffic Signal Performance Measures	Type of Deployment
Pennsylvania Department of Transportation	▪ 2 signals.	Many (not relevant).	To support others.	Intelight MAXVIEW
Cranberry Township	▪ 49 signals.	▪ 4 engineers. ▪ 1 technician.	In early deployment.	Econolite + Edaptive

ATSPM = automated traffic signal performance measures.

Approach to Implementation (Pennsylvania Department of Transportation)

PennDOT has a long history of studying and actively investing in traffic signals. A corridor modernization program started around 2012 that investigated PennDOT's ownership of traffic signals on critical corridors. PennDOT developed an implementation plan for traffic signals in 2013, which supported incorporating dedicated funding for traffic signals into the comprehensive transportation funding bill passed in November 2013 (commonly called Act 89). The funding stream in Act 89 led to development of the Green Light-Go program, which was originally set up with three elements:

- Local grant element.
- PennDOT project element.
- PennDOT management element.

The PennDOT project element has been mostly phased out due to Act 101 passing in 2016, which allowed more projects to be treated as local grants. The PennDOT management element is the part of the program that would include PennDOT ownership and/or operational control of signalized corridors. This part of the program required legislative changes to allow PennDOT to assume ownership of traffic signals. Act 101 included this provision when passed in 2016, which says PennDOT needs to do a pilot project and prepare a report for the legislature by 2022. PennDOT is currently working on a pilot on arterials parallel to I–76 in Montgomery County and Philadelphia. PennDOT is entering into agreements with each affected municipality that will culminate in an official transfer of ownership of all traffic signal equipment from the local municipality to PennDOT when all preconditions are met. All municipalities except Philadelphia have already signed the agreement.

Regarding ATSPM, PennDOT was an active participant in the ATSPM pooled fund studies 1 and 2 that focused on enhancement of ATSPM. PennDOT started working on its own ATSPM implementation in 2016 when it modified an early version of the UDOT code. From that perspective, PennDOT could be considered an early adopter with regard to the diffusion of innovation theory.

Approximately 13,600 signals exist across the State of Pennsylvania. However, only three are actually owned by PennDOT, while the others are owned and operated by local municipalities. PennDOT does review the signal design processes (provides permits) for traffic signals on its facilities, but it is local agencies' responsibility to operate and maintain the signals once installed. PennDOT has a signal unit in each of the 11 districts that varies between three and 10 staff per district (mostly focused on traffic signal design). It also collaborates after a signal design project is finished and turns on new approved signals, but that is where its involvement ends.

Despite the fact that it does not own traffic signals, PennDOT wants to help local jurisdictions improve their signalized operations. The current level of maintenance of those municipal traffic signals is not very advanced. For this reason, PennDOT felt it is its place to assist local agencies with ATSPM implementation. PennDOT does not have consistent communication with signalized intersections, and there are few traffic controllers capable of logging high-resolution data. For example, PennDOT only has access to 100–200 signals with ATSPM data (mainly in the Philadelphia region). Most of those signals have controllers capable of ATSPM data collection at the time they were originally installed. There were some efforts in the Philadelphia region to build a fiber network between the regional district office and signals in the field. As a result, the district office has started helping local agencies monitor and operate their signals. These efforts have been supported by two consultants and one PennDOT staff within District 6 (Philadelphia region).

PennDOT originally started with the ATSPM implementation of the UDOT open-source software. However, in 2015, PennDOT had issues with servers crashing when it implemented ATSPM at 100–200 traffic signals (all that were equipped at that time). In 2018, PennDOT obtained a statewide Intelight MAXVIEW license; the newer version of this software has the Utah source code software built into it and PennDOT uses it as an ATSPM platform. Despite these upgrades, ATSPM usage by PennDOT staff and consultants is minimal.

Considering the lack of highly developed infrastructure with controllers, detection, or communications, PennDOT decided to leverage the data it was purchasing to support the 511 platform and its message boards. Along these lines, PennDOT worked with Purdue University to come up with performance data for arterials using these purchased data from INRIX. PennDOT was looking for ways to pull meaningful measures out of arterials for performance. PennDOT used a normalization process to normalize travel times based on length of the corridor. PennDOT applied this methodology using some corridors in the Philadelphia area.

PennDOT later worked with University of Maryland to develop an analytic suite platform, which would allow flexibility to expand this software statewide. The platform has many features: it is used to monitor reliability of speed and travel times but also to do a before-and-after analysis of the performance of a corridor (e.g., after retiming, or when adaptive signals are installed). PennDOT does not currently have a way to track the number of users of this platform.

Approach to Implementation (Cranberry Township)

Cranberry Township is at the beginning stages of using ATSPMs. Cranberry Township is currently working on programming Econolite controllers for ATSPM use but it is having some administrative issues (details not given), which are expected to clear soon, and the system is supposed to be in operation in a month or two. In addition to regular use of the ATSPM features (for monitoring of signal operations), Cranberry Township will be the first agency in Pennsylvania to use ATSPMs to adaptively control its traffic signals. This will be achieved through Centracs® Edaptive system, which utilizes Purdue/UDOT ATSPMs to adjust signal timings accordingly. (Centracs® Edaptive is a new cloud-based adaptive signal control product from Econolite that optimizes cycle, offset, and splits using one-tenth of a second high-resolution data.)

Cranberry Township has a total of 49 signals with ATSPMs that are mainly managed by Whitman Requardt & Associates Limited Liability Partnership (WRA LLP) at the traffic operations center. Out of those 49 signals, 18 signals on three corridors are under Centracs® adaptive traffic control (not based on ATSPM), whereas seven signals are tested under Centracs® Edaptive. Operationally, Cranberry Township is facing a constant growth in traffic demand. The township has a very unique mix of commercial and residential developments similar to a suburban environment. The area is becoming a traffic hub on the crossroads of I–76 and I–79, two major freeway routes in the northwest-southeast and north-south directions, respectively. These conditions, with multiple freeway interchanges in the township, create situations where the roadways often operate at or above their capacities.

Staff-wise, Cranberry Township has a total of four technical staff. There is a professional-level operations engineer who manages traffic engineering and operations for Cranberry Township's public works. Another engineer manages traffic communications. There are also two other engineers who assist with Streets & Properties in Cranberry Township's Public Works division. Cranberry Township completed a capability maturity self-assessment offered on the Federal Highway Administration's (FHWA) website. While the detailed answers on the assessment questions are beyond the scope of this study, it is important to note that Cranberry Township staff assessed themselves as follows:

- Business processes—level 4 (88 percent).
- Systems and technology—level 4 (85 percent).
- Performance measurement—level 4 (82 percent).
- Organization and workforce—level 4 (94 percent).
- Culture—level 4 (88 percent).
- Collaboration—level 4 (100 percent).

It should be noted here the above self-assessments are based on subjective opinions of agency staff who answered the survey questions, which may or may not reflect (as with any other agency) the true nature and quality of the components of the self-assessments. From that perspective, one could question Cranberry Township and any other agency's processes and measurements used to derive answers for this assessment. In each case it is important to illustrate how agencies define their signal programs, goals, and objectives, and how their operational strategies and tactics map to those goals and objectives. Although Cranberry Township's business processes for managing and operating traffic signals are focused on proactive operations versus reactive, it still has a long way to go to demonstrate its claims and illustrate exactly how its actions align with its intentions. However, there is no doubt that Cranberry Township staff continually seeks ways to improve business processes and which emerging technologies to adopt.

Cranberry Township does not have a formal traffic signal management plan (TSMP), i.e., similar to the concept proposed and encouraged by FHWA (documenting operational objectives of the agency). The township only evaluates performance measures (PM) annually and uses them for grant applications. That being written, Cranberry Township is very proactive in how it monitors and maintains its signals; township crew members are in the field all the time performing either emergency or routine maintenance. Its operational objectives can be described as follows:

- Striving to be proactive instead of reactive (e.g., identify potential problems before they occur, as opposed to problems happening and reacting to remedy them).
- Quantifying results of the work being done. Currently, the township counts cars and throughputs but it plans to use ATSPMs as a tool to measure how effectively signals are used and provide quantifiable data. Cranberry Township does not seem to have a clear definition of how such effectiveness (of traffic signals) is measured.
- Improving mobility. The township's roadways are often at capacity. Cranberry Township plans to study PMs related to arrivals on greens to maximize and improve traffic flow. Further effort is needed to properly define the operational objectives that can be tied, on one side, with ATSPMs and, on the other side, with the agency's broader goals.

It should be noted here that some of these objectives (e.g., being proactive versus reactive) are not so much operational objectives as they are administrative objectives to ensure good customer service.

It is also interesting to note that Cranberry Township has not capitalized on any ATSPM efforts made by PennDOT. PennDOT installed a server with UDOT open-source ATSPM code, but it moved away from that platform because it was too difficult to maintain, which is an indication of lacking workforce capability. Although PennDOT enabled a statewide ATSPM through Intelight MAXVIEW, Cranberry Township has not used this infrastructure or technical support from PennDOT. Collaboration between the two entities is excellent (e.g., the township got support from PennDOT to receive funding for the ATSPM project; the two entities have video- and data-sharing agreements in place). However, it simply has its own policies and priorities, and its activities are not always synchronized (like many other similar partnerships around the country).

Business Processes and Signal Systems Benchmarking (Pennsylvania Department of Transportation)

PennDOT has not developed a formal TSMP. However, such plans are anticipated to be established in the future; for now, it seems PennDOT closely follows initiatives and developments from the FHWA Resource Center, until its own plans are developed.

Similarly, PennDOT could not identify three formal signal operations objectives. However, its three informal objectives are: ensuring safety (including pedestrians) by not delaying people so much that they are inclined to make unsafe decisions, providing equitable service (trying to make sure there are no split failures), and enabling smooth flows (high percentage of arrivals on green and good progression). It is important to note here that it does not seem that PennDOT has established any specific strategies to attain these objectives (or measure whether or not it is attaining them).

As can be deduced from above—PennDOT uses ATSPMs to meet these operational objectives, but this is occasionally done by connecting some of the ATSPMs to each operational objective, and the process has not been institutionalized yet. PennDOT staff believes one of the obstacles (for broader ATSPM use) is lack of features to automatically identify problems and thus avoid the need to constantly monitor ATSPMs. In this way, the agency’s resources would be more effectively used. The training component is also very important as new employees cannot easily start making decisions based on ATSPM data. PennDOT feels there is a need for a strong ATSPM training program to make it exponentially grow.

Before ATSPM technology was available, PennDOT was using traditional means to optimize traffic signal operations. It would conduct manual traffic counts and run a Synchro model to obtain level of service (LOS) on a network under consideration. Floating-car studies were also used, but not frequently (it was not a standard practice).

Even with ATSPM available, it is not regularly used to report signal performance to decision makers. One reason is because PennDOT’s major focus is freeways. Also, structurally deficient bridges and other deteriorating infrastructure receive higher priority. PennDOT staff have a difficult time justifying investments in signals unless it can be proven that operations are on the verge of capacity or unsafe conditions. However, PennDOT does see the potential of controller-based data as a reporting tool, beyond just reporting to the signal operations group. PennDOT is looking to ATSPMs to help them “tell the story” by providing reliable measures that can be used to classify a segment of road as deficient in terms of operational condition, which somewhat explains its approach to using INRIX data.

PennDOT staff likes that ATSPMs are currently calculated automatically and autonomously, but the results have to be interpreted by someone. It would help if problem identification (i.e., identifying specific sites and corridors) were automated; this would help reduce staff resources needed to use ATSPMs effectively. It seems that PennDOT belongs to a group of agencies hoping to use ATSPMs in the way adaptive traffic control works by delegating its objectives to an automated system. It also believes that to properly integrate ATSPMs in its business model, adequate training is needed. For this reason, ATSPM is one of the innovations being pursued by the State Transportation Innovation Council (STIC). One way PennDOT perceives using ATSPM is to integrate its performance measures in its system of evaluating operations of signalized arterials (and get away from LOS).

Business Processes and Signal Systems Benchmarking (Cranberry Township)

Cranberry Township takes care of maintenance of all of its traffic signals, which are connected to the township's traffic management center (TMC). Cranberry Township has a technician who is solely dedicated to perform traffic signal maintenance. Cranberry Township's main signal consultant (WRA LLP) takes care of analyzing signal data. Cranberry Township has not yet determined which PMs it will be using to meet its objectives. In addition, unlike PennDOT, Cranberry Township is not using any tools to measure travel times on their own (e.g., Bluetooth). However, the agency does use Streetlight data, access to South Pennsylvania Council travel time data, and PennDOT's interstate travel time data. Also, Cranberry Township has developed an algorithm that generates an advanced warning notifying them of events (e.g., crashes) that occur on interstate road segments in the township's boundaries. This algorithm helps estimate when adverse freeway traffic conditions may affect local roads.

Since Cranberry Township gives an important role to proactive maintenance of traffic signals, the agency is institutionally ready to integrate performance measures from the ATSPM platform into its business model. This has been testified through some collaborative efforts with universities. For example, Cranberry Township has worked with Purdue University to turn on logging of high-resolution data and share these data with the university. Given the agency has been active in keeping the existing infrastructure up to date, the cost of implementation (e.g., getting controllers up to date) has been assimilated by this proactive effort and has not been exclusively related to implementing ATSPMs.

Benefits and Costs

There was no direct cost for the original ATSPM implementation, considering that PennDOT used in-house IT resources (time spent establishing the ATSPM platform was not tracked). In addition, a virtual server was used in the initial deployment approach to host the ATSPM open-source code from UDOT. For this reason there were no hardware purchases, either. Later when PennDOT switched to commercial ATSPM in Intelight's MAXVIEW, there were no costs for the ATSPM. Intelight claims the ATSPM module is free when MAXVIEW is purchased for other purposes, and thus no maintenance costs for MAXVIEW can be associated with ATSPM. Intelight staff also helps PennDOT with maintenance of the virtual server, which is located on PennDOT premises. On the other hand, PennDOT spent between $300,000 and $400,000 to develop the previously mentioned tool for monitoring probe speed and travel time data, and purchases such data from INRIX. INRIX data are used to obtain statewide traffic performance measures, understand reliability of speed and travel times, and compare before-and-after traffic conditions in the case of major interventions (e.g., signal retiming).

Some ATSPM investments are helpful for basic signal operation as well. When it comes to costs for upgrading intersections, the major overlap between ATSPM and non-ATSPM operations is detection. PennDOT prefers nonintrusive technologies where it has flexibility to add more zones and move zones, which is not present in traditional inductive loop detection. For example, the detection cost specific to ATSPM may be as low as 0 (e.g., because an intersection is already equipped with detection prior to ATSPM implementation) or as high as $45,000 (e.g., detection specifically installed for ATSPM).

PennDOT staff estimates it costs approximately $7,500 per approach to cover stop-bar detection on the side street for normal operations, not considering ATSPM. It would also have stop-bar detection for mainline exclusive left-turn phases (but not through lanes). Advanced detection is trickier to estimate as PennDOT has been using radar technology for dilemma zone detection, which is estimated to cost around $7,500 per mainline approach. So, a total of $45,000 per intersection is estimated for detection costs. From this number, costs attributed to ATSPM could be anywhere between 0 and $30,000.

In general, Cranberry Township believes it has a very educated staff capable of doing most of the work in-house (e.g., programming and adjusting of detection zones), except for major installation projects. Cranberry Township is still not able to report on the costs of their system, which is somewhat contradictory with the level of institutional readiness to document business processes (level 4)—this will have to wait until after the test period. It is difficult to estimate how much of Econolite's support for Cranberry Township signals is directly related to ATSPM, and how much is related to regular signal operations. One thing is sure—Cranberry Township staff meets with the vendor almost weekly for various reasons, including its detection software, ATSPM module, and the adaptive traffic control systems.

PennDOT has not been able to scale its system enough to be able to quantify the benefits. On the other hand, similar to other ATSPM users, it witnessed cases where a problem was detected before public complaints were received. For example, PennDOT staff were able to identify several stuck pedestrian push buttons. ATSPM was very instrumental in identifying such issues. In addition, Steve Gault helped a town when it was losing communications to a couple of intersections. This type of problem would have taken months to be identified if not for ATSPMs. Without ATSPM, it would have had to wait for someone to complain, with operations affected for weeks. With ATSPM, such problems are identified within a day.

PennDOT also sees strong potential for achieving future benefits. One of the tracks is automating ATSPMs within adaptive traffic control (ATC). Some such systems already use the high-resolution data to inform the adaptive algorithms. It seems that some PennDOT districts jumped in blindly with ATC. One of PennDOT's goals regarding ATSPMs is to evaluate ATC performance. Considering the strong interest in ATC in PA, PennDOT believes some combination of ATC and ATSPM may produce a breakthrough. Similarly, there was an attempt to see how ATSPM could work with the signal phasing and timing (SPaT) messages, but this was done as a demonstration project. Signal controllers that support SPaT can usually support ATSPM. So the interests of connected and automated vehicles (CAV) and ATSPM advocates are aligned. On the executive level, PennDOT is very interested to test innovative technologies and become a pioneer in the CAV industry.

While none of the benefits from ATSPM have yet been realized, the agency anticipates using ATSPMs to primarily make the signals as efficient as possible for drivers (improve mobility) and, secondarily, to use the data to report signal system conditions to decision makers (benefits and costs at small scale). Right now, Cranberry Township has high-resolution data and can create reports of the collected data, but does not have any ATSPMs tied to these data. The report is still very useful, as it provides data related to every cycle for every connected signal. This helps validate information when there is a complaint. Cranberry Township expects ATSPM will help avoid such complaint calls, which represent less than 25 percent of the daily efforts from Cranberry Township's customer service department. Answering such calls is not a big part of its job, but it is an important part of the job.

Cranberry Township plans to start with ATSPMs on one corridor and then scale ATSPM use to the entire signal system after initial testing is done. Cranberry Township also expects ATSPMs will help it secure future grants for signal improvements by using quantitative ATSPM data to justify signal improvements. Cranberry Township also sees the value of using ATSPM to replace its current signal retiming efforts, which are usually done every 2 years. After such retiming efforts, Cranberry Township usually commits before-and-after delays studies by using the floating-car technique (usually done by a WRA consultant).

Lessons Learned

Both PennDOT and Cranberry Township could be considered as early adopters with regard to diffusion of innovation, but for various reasons they have not yet achieved much. While PennDOT's efforts are purely to strategically help various signal jurisdictions in the State (it does not control any signals), it seems its early efforts with the UDOT open-source system have not led to full success. Once the ATSPM platform (supported by PennDOT) has been replaced by a commercial Intelight MAXVIEW system, the operations have been stabilized but it is still uncertain how many agencies have truly capitalized on this opportunity.

Cranberry Township has taken its own way with some early tests through Purdue University, followed by a fully commercial Econolite platform. In terms of system procurements, Cranberry Township went even one step ahead of many others—by deploying a commercial ATC based on ATSPM (Econolite Edaptive). However, neither ATSPM nor Edaptive has been fully utilized—they are procured and installed but still not used operationally. Thus, on one hand we can say both agencies are moving toward very successful ATSPM use. While PennDOT's investment in a statewide commercial Intelight license will certainly bring benefits in the future, Cranberry Township is probably only a few months away from concrete benefits of its ATSPM and Centracs® Edaptive deployments. However, at this point it is very difficult to assess any concrete benefits of these systems, and unfortunately neither agency kept good records of costs made to adopt and implement the ATSPM platforms.

Benefit-Cost Methodology Application Tables

Table 18 below gives estimated benefits and costs of deploying ATSPM at Cranberry Township as the only agency (of the two covered in this case study) that is a primary benefactor and also an agency incurring costs of ATSPM installation, operations, and maintenance. Costs incurred by PennDOT are all for a greater good and cannot ever be justified by relevant benefits, as PennDOT does not control traffic signals in the field. One should also note that, given the early stage of ATSPM deployment in Cranberry Township, the benefit and cost estimates are quite speculative and based on the assumption that ATSPM-supportive infrastructure exists (e.g., detectors and communications) and only traffic controllers (100 for a hypothetical case of scalability) need to be reconfigured to enable ATSPM operations.

Table 17. Cranberry Township implementation and life cycle costs.

Cost	Description	Sunk Cost	Deployment Cost	Operation Cost
1	Controller procurement.	0	0	0
2	Firmware upgrades.	0	$35,000	0
3	External data loggers.	0	0	0
4	Communication system development.	0	0	0
5	Communication system maintenance.	0	0	0
6	Detection system development.	0	0	0
7	Detection system maintenance.	0	0	0
8	Detection system reconfiguration.	0	$13,000	0
9	Detection system documentation.	0	0	0
10	New server.	0	$15,000	0
11	Server maintenance.	0	$5,000	0
12	Software license cost.	0	0	0
13	Installation cost.	0	$30,000	0
14	Maintenance cost.	0	$25,000	0
15	Integration/Training cost.	0	$6,500	0
16	Usage cost.	0	0	$260,936
Total		**0**	**$129,500**	**$260,936**

Table 18. Cranberry Township post-implementation and life cycle benefits.

Cost	Description	Benefit
1	Manual data collection avoided.	$382,140
2	Scheduled maintenance avoided.	$1,023,672
3	Complaint response time reduced.	$260,936
4	Performance documentation.	0
5	Respond to failed detection.	0
6	Respond to failed communication.	0
7	Other equipment failures.	0
8	Capacity benefit.	0
9	Progression benefit.	0
10	Pedestrian service benefit.	0
11	Preemption improvement.	0
12	Reduction in crashes.	0
Total		**$1,666,748**

MARICOPA COUNTY DEPARTMENT OF TRANSPORTATION

Maricopa County, AZ, is the fifth populous county in the U.S., with a population of 4.4 million (larger than 24 States), an area of 9,224 square miles (mi^2) (larger than four States), and several cities and towns with their own independent transportation operations. The Maricopa County Department of Transportation (MCDOT) operates and maintains roadways that are outside of municipalities in the county. Figure 16 shows a map of those roadways, illustrating how they are widely distributed across the county.

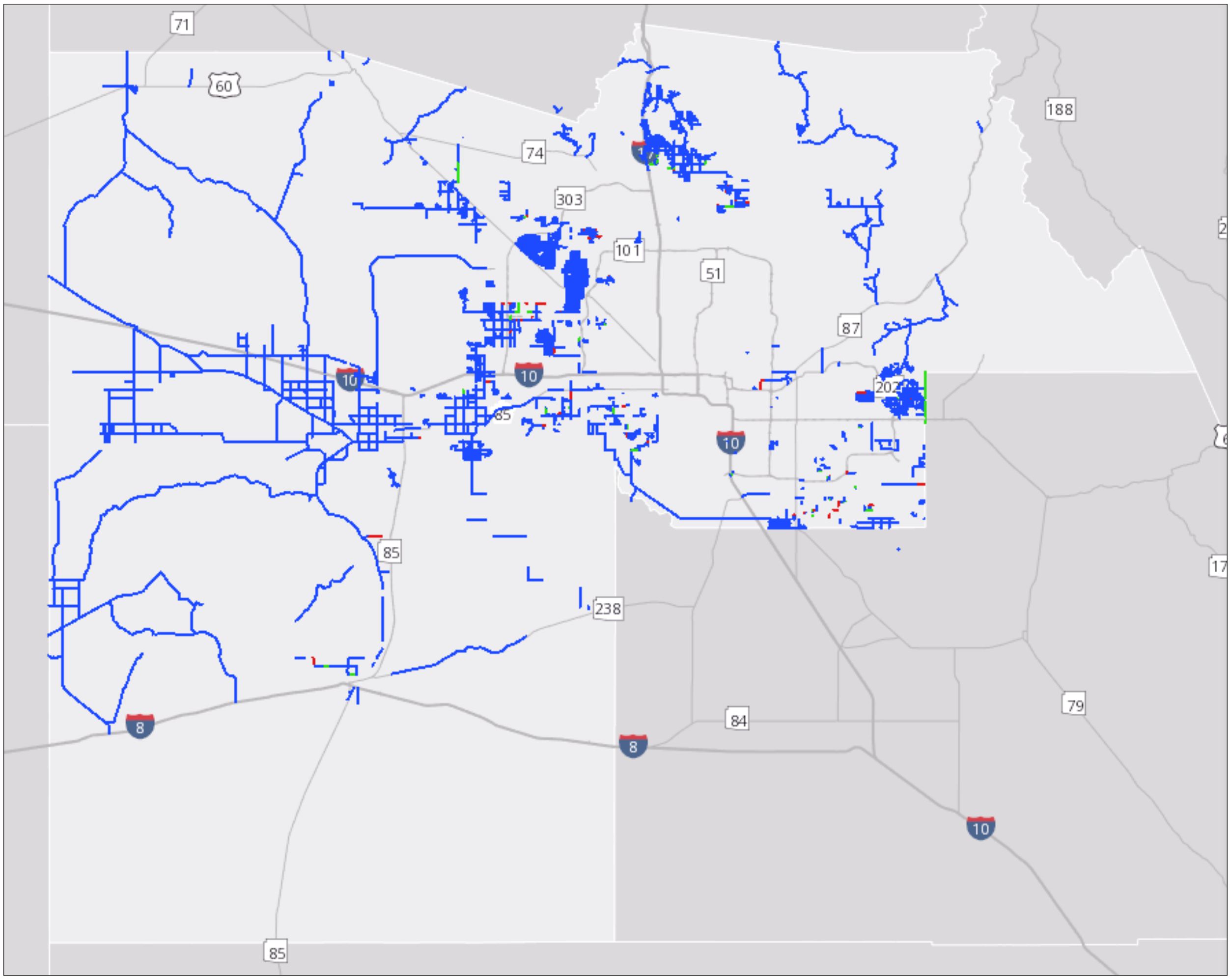


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Figure 16. Map. Roadways maintained by Maricopa County Department of Transportation.

AZTech is a regional partnership among 24 member agencies across the Phoenix metropolitan area, including MCDOT, Arizona Department of Transportation (ADOT), and the Maricopa Association of Governments (MAG). AZTech was formed in 1996 as a federally sponsored Model Deployment Initiative, one of four experimental regional organizations for traffic operations in the U.S. For more than 20 years, AZTech has facilitated deployments of ITS technology in the region, including integrated TMC facilities, traffic monitoring and travel time measurement infrastructure, communications infrastructure, and ramp metering. In recent years, AZTech has published the

Traffic Management and Operations Performance Indicators Book (AZTech 2015), which includes several performance measures of regional transportation system performance, including reports on peak travel times along several key arterial corridors.

The AZTech ATSPM implementation is operated by MCDOT but is a cooperative effort with seven other transportation agencies: the cities of Tempe, Peoria, Gilbert, Scottsdale, Mesa, Phoenix, and ADOT. Of these, MCDOT has the largest number of signals currently reporting data in the ATSPM system: 117 of 170 total signals operated by the county. The other agencies each have between 10 and 108 signals online as part of a regional pilot, with expectations to expand to all signals in the pilot locations that have communications and to other regional agencies interested in participating in the AZTech ATSPM system; altogether, about 10 percent of the more than 3,000 total traffic signals across all agencies in the county are currently reporting data to the AZTech regional ATSPM system. MCDOT's signals are mainly in the outer limits of urban areas or in suburban or rural locations. MCDOT is one of the first agencies other than a State DOT to incorporate data from many different local agencies into one ATSPM system.

In the diffusion of innovation theory, which describes how ideas or products gain acceptance, MCDOT has characteristics of both early adopter and early majority users. The effort to implement ATSPM was initiated by traffic operations management, who recognized the potential of the software and how it could benefit traffic signal operations and transform MCDOT's practices from reactive to proactive. At the same time, as the agency has worked to institutionalize ATSPMs, it has identified the need for more high-level metrics to allow for better use of the overall system. Developing answers to those needs is not a task MCDOT is likely to fill itself, but it is likely to implement such solutions as it emerges through continued development of ATSPM software by innovating users.

An important characteristic that positioned MCDOT to implement ATSPM relatively easily is recognizing the need to keep the system and components up to date, and executive staff has supported these efforts. The ATSPM project was initiated while the county was investing in both adaptive signal control and new detection systems. In that effort, the agency worked with several vendors to identify specifications for detection systems that would support future adaptive systems deployment. At the time of this writing, procurements of those systems are in final stages. MCDOT's engineers saw ATSPM as a potentially valuable tool for evaluating these investments.

Table 19. Maricopa County Department of Transportation agency characteristics.

Number of Signals	Number of Signal Operations Staff	Use of Automated Traffic Signal Performance Measures	Type of Deployment
170 operated by MCDOT (117 monitored with ATSPM); more than 3,000 total in Maricopa County.	▪ 3 on-call consultants for traffic operations. ▪ 1 on-call systems integrator. ▪ 1 full-time engineer. ▪ 1 full-time analyst.	▪ Automated alerts; As needed, mainly for responding to public calls. ▪ Evaluation of new technology (future).	UDOT open-source software.

ATSPM = automated traffic signal performance measures. MCDOT = Maricopa County Department of Transportation.
UDOT = Utah Department of Transportation.

MCDOT's signal systems capability maturity self-assessment revealed the agency ranks itself at level 2 across most categories and level 4 in the area of collaboration. Although this self-ranking is rather modest, agencies that collaborate under the umbrella of AZTech have taken numerous steps that move toward a performance-driven approach to traffic operations. The agency has regularly tracked its performance using a performance dashboard, as published in its annual Traffic Management and Operations Performance Indicators Book (AZTech 2015), which examines high-level metrics, such as percent of miles congested and peak-hour arterial travel times, while considering trends over time. It seems likely the addition of ATSPM will further increase this trend toward performance-based management to which these previous first steps lead.

Approach to Implementation

In 2017, AZTech collaborated with FHWA, the City of Phoenix, and ITS Arizona to host an ATSPM workshop, inviting agencies that had previously adopted the technology and vendors working on related commercial products, to share information with local traffic operations personnel. Interest in ATSPMs was sparked by AZTech Operations Committee members who had participated in a previous workshop in Utah. The AZTech ATSPM Regional Pilot Project was initiated later that year to make the technology available to traffic signal operators in the region. Ten signals from each participating agency were included in the project; this was followed by a second phase to expand the number of signals for MCDOT and the City of Tempe, bringing them to their current numbers. In the coming year, it is anticipated that existing pilot agencies will have the majority of their signals added into the ATSPM system, and agencies in the region wanting to participate will be integrated into the ATSPM system as well. While AZTech initiated the process of bringing ATSPMs to the region, MCDOT has taken on the role of leading development and maintenance of the system for the region. A version upgrade is anticipated to be completed in the upcoming year obtained through the ATSPM GitHub portal.

Implementation of the AZTech ATSPM system was facilitated by the following particular factors:

- The agencies had strong support from upper-level management to implement performance measures. The value of performance measures had been recognized in other ITS applications prior to ATSPM, and their potential value was seen by those in charge of deciding to make the investment.
- The agencies recognized a need for a data-driven decision making process for traffic signal operations.
- The agency previously prioritized keeping its system updated technologically. Although AZTech was initiated to focus on ITS technologies, traffic signal systems in the region have not been an entirely separate entity, but instead have been recognized as part of the larger traffic control system.
- Collaboration from jurisdictions in the Phoenix metro area into AZTech enabled that group to be able to facilitate resources and develop a strategic plan for introducing the technology to the region.

Business Processes and Signal Systems Benchmarking

Prior to implementation of ATSPM, MCDOT and other agencies in Maricopa County had conventional retiming practices. MCDOT would undertake about three coordination projects per year; it tried to develop new base timing plans every 5 years and revisit coordination plans every 3 years. These studies would be typically assessed using floating-car studies and probe data from data sources like https://here.com (HERE 2019). In the future, it wants to eventually replace arbitrarily scheduled activities with triggers based on the data and use metrics from high-resolution data to assess the impact of retiming. Table 20 shows a comparison (Wire 2018) between conventional practice and ATSPMs, as presented by MCDOT Arterial Operations Program Manager April Wire, PE, PTOE.

Table 20. Advantages of automated traffic signal performance measures, as stated by Maricopa County Department of Transportation.

Tasks	Conventional Operations	Operations with Automated Traffic Signal Performance Measures
Signal Retiming	▪ 3-day tube counts. ▪ Develop plans in Synchro. ▪ Tweak plans based on field observation. ▪ Retime every 3–5 years.	▪ Continuous adjustment based on 24–7/365 performance measures.
Responding to Public Complaint Calls	▪ Investigate using central system software. ▪ Observe on CCTV. ▪ Send someone to field to observe.	▪ Show the performance of a particular phase at the exact time of day.
Performance Monitoring	▪ Assumed to be acceptable, unless there is a complaint. ▪ Performance only based on yearly travel time assessment—only shows performance of progression and not side-street or left-turn impacts.	▪ Daily notification whether performance is below or above a threshold.

ATSPM = automated traffic signal performance measures. CCTV = closed-circuit television. MCDOT = Maricopa County Department of Transportation.

One of MCDOT's immediate uses of ATSPM was to proactively identify detector failures using the email alert system in the UDOT open-source software. In addition, MCDOT is also able to validate problems reported by the public. Before ATSPMs, most of the time the agency was simply unaware of detector issues. Problems reported by the public often occurred at unusual times and could not be reproduced. For example, a citizen might call to report a problem such as not getting enough green time. MCDOT's approach to a call was to observe operations using CCTV, or send a technician to the field to examine the problem. However, once the technician arrived at the intersection, the problem was unlikely to recur during the site visit. Either a site visit or remote observation were limited to the time when agency staff could attend to the problem.

With ATSPM, MCDOT staff can now validate whether such problems occur by monitoring conditions 24 h/day. Typical evidence of a detector problem is a phase maxing-out during every cycle during overnight hours, when demand is usually low. With the ability to view this performance, such problems can more easily be assessed. Further, by proactively scanning for such problems, it is possible to mitigate their impact before public complaint calls; and, field visits can often be avoided. Limiting field visits has been key in the success of the system at MCDOT, as staff time can be reprioritized to other competing priorities.

Sometimes, adjustments to signal timing are often found to be necessary to resolve an operational issue that generated a call from the public. MCDOT has used ATSPMs to evaluate adjustments to splits and time-of-day (TOD) plan schedules. At present, the agency has not extensively used performance measures to assess progression, but that is anticipated as it continues to improve its detection systems to become capable of measuring vehicle arrivals. Evaluating the impacts of preemption by assessing the time spent during transition is another important use case it intends to explore in the future.

An additional use of ATSPM strongly anticipated by MCDOT is the ability to establish a baseline to reflect its current performance and assess the impact of new technology, such as adaptive signal control and connected vehicle (CV) applications. The ability to monitor such changes is a core function of traffic signal systems that has not been available in most systems in the past. MCDOT has been able to monitor traffic conditions simultaneously with pilot tests of CV applications in the Anthem, AZ, SMARTDrive test bed. At present, applications related to preemption and priority control are being piloted in the test bed. So far, ATSPMs have not revealed significant changes in the daily signal operation. However, the data also show there is no disruption to the system caused by running these applications.

As MCDOT has worked through implementing ATSPMs, they identified a few additional system needs that were not immediately apparent at the beginning:

- Currently the performance measures are very granular, mostly focusing on individual phases or movements. While this makes the metrics valuable for observing conditions at a specified location and time, it is not easy to use metrics at this level to see the big picture. Higher-level metrics are needed for this purpose. System reports developed by GDOT may be one way to resolve this; MCDOT intends to add them when it performs its next version upgrade later in 2019.
- Beyond simply aggregation, more automation is another opportunity for improving ATSPMs that MCDOT believed would be valuable for its operations and for other agencies to value an investment. An example it gave was to develop dashboards that could summarize a potential "focus for the day" for an operator's activities, as identified by the data.
- Many of the staff who currently manage traffic signals have not adopted ATSPMs into their day-to-day activities. The TMC, in particular, experiences high turnover, and not everyone who joins the team understands signal operation. Those personnel need to learn how to use the tools and communicate what they are seeing in the data to engineers. In the 2020 fiscal year, MCDOT is anticipating a project that will focus on user training and developing shortcut documents to help users less familiar with performance measures understand what the charts show.

User training and development of aggregate, high-level metrics are anticipated to help support future adoption of ATSPM technology in the region.

Benefits and Costs

An important point for the context of MCDOT's implementation costs is that many signal infrastructure components were already in the process of being upgraded. The agency's regular practices prioritized keeping equipment up to date, but an ongoing project seeking to ready signal systems in the region for future technology had increased the agency's preparedness even further. Starting in 2013, an effort to implement adaptive signal control was initiated; the first stages of this process sought to identify system requirements, particularly that of detection systems. Deployment of new detection systems with simplified detector layouts was facilitated by this process, and was nearing completion as of 2019.

As a result of these practices, most controllers had already been upgraded to models and firmware versions that could support high-resolution data collection prior to initiation of the ATSPM project. Therefore, no costs for controller deployment were necessary as part of ATSPM implementation. This finding is also observed in other early adopters, in that organizations that keep infrastructure up to date, usually by spreading out the costs over time, tend to be well-positioned to take advantage of new technologies.

At the start of the implementation, MCDOT worked with consultants to inventory its intersections and analyze the level of readiness for each intersection in the system, using "levels" as defined below.

Level 1	The intersection is ready to begin collecting high-resolution data with no further work needed.
Level 2	The intersection has communication, but lacks appropriate detector configuration, such as separation of detection zones into individual lanes.
Level 3	The intersection does not have communication.

A countywide study was completed to identify the implementation plan for upgrading the detection to accommodate lane-by-lane detector layouts. In total, 38 locations were upgraded. On average, about 4 hours per intersection were needed to accomplish this task for each intersection. Because the detection plans had been standardized, no cost is associated with documentation of the detector layouts. The detection systems were supplied to the contractor for installation. The cost of new detection was about $250,000. Several other costs were also associated with this project, totaling about $765,000. These costs were considered to be sunk costs because these investments would have been made by the county for signal improvements independent of the ATSPM installation.

Of the 170 signals operated by MCDOT, 122 signals (about 70 percent) already had communication via fiber, radio, or cellular modems. The remaining locations are mainly rural intersections beyond the reach of fiber networks. A few additional improvements to communication system were made during the course of readying the system for collecting high-resolution data. Similar to detection system upgrades, these costs were also considered as sunk costs not directly applicable to the benefit-cost analysis, because they represent system investments that would have been undertaken even if ATSPMs were not deployed.

MCDOT uses the UDOT open-source system, so a software license was not required for the ATSPM implementation. The agency did not use the county's IT department to manage the software installation. MCDOT has a dedicated team as part of the ITS branch to manage and oversee the ITS communications network and other resources related to the TMC. The MCDOT team is supported by on-call consultants. The integration cost paid for consultant services was approximately $50,000. MCDOT incurred costs of $1,000 and $2,800 for its server hardware and software licenses.

Some costs and benefit items are estimated for the 10-year life cycle. Assuming a discount rate of 5 percent, the (P|A) factor for determining net present value is 7.722.

It has been less than 2 years since the Maricopa County ATSPM system pilot project was initiated, and during that time, many of the intersections were being upgraded to have new detection systems as part of a separate effort. So far, the performance measures are being actively used for a limited number of use cases, as mentioned earlier. Thus, only items 2 and 3 are listed in the table of benefits. The total benefit amount listed here is therefore probably greatly underestimated since not all of the different possible use cases are yet being realized, which is likely to change after the use of ATSPMs is expanded.

Currently, MCDOT performs intersection counts once every 3 years at an estimated cost of $400 per intersection. Since there are 170 intersections, an average of 57 intersections per year are counted. The present value of this 10-year cost is 57 × $400 × 7.72 = $176,016.

MCDOT currently performs four preventative maintenance visits per year at each intersection. It is assumed that these visits require 4 hours of labor, and that the use of automated alerts from the ATSPM system will enable the number of visits to be reduced from four to one. A rate of $55/hour is used for this calculation. A savings of 3 hours per intersection is assumed for 170 intersections. The present value of this savings is 4 × 3 × 170 × $55 × 7.72 = $866,184.

A reduction in the response time for public complaint calls is identified as another potential benefit yielded under current uses of ATSPM by MCDOT. The number of calls received is estimated at 28 calls per month, or 336 per year; it is estimated that 4 hours can be saved in response time to each call through use of ATSPM. A rate of $55/hour is used for this calculation. The present value of this savings is 336 × 4 × $55 × 7.72 = $570,662.

Finally, the operation cost for the use of ATSPM is estimated as requiring 20 hours per week at a rate of $55/hour. The net present value is 20 × 52 × $55 × 7.72 = $441,584.

Lessons Learned

Similar to other agencies that have served as case studies for this research, MCDOT benefited from a previous history of agency investments in traffic control infrastructure. In this case, Maricopa County had a regional partnership, AZTech. Led by MCDOT and ADOT, AZTech is a regional traffic management partnership in the Phoenix metropolitan area that guides application of ITS technologies for managing regional traffic. It carefully integrates individual traffic management strategies and technologies for the region's benefit while preserving operational control protocols important to individual jurisdictions. Not all ITS-focused organizations have strongly focused on traffic signals. Perhaps because of its large grid network, AZTech has included traffic signals and arterial operations in its repertoire of projects, alongside freeway-oriented efforts, to provide a seamless transportation system to the traveling public. In addition, over the years, MCDOT has made a commitment to keep its traffic control infrastructure up to date and functional. For the ATSPM project, specifically, detection needs were largely met through a parallel effort to make signals ready for deployment of other advanced technologies. The detection upgrade projects were sparked by the pilot implementation of ATSPM and management seeing the benefit of using a data-driven process for signal operations.

While MCDOT has seen successes in early use of its ATSPM system, it has also discovered needs to support a transition to active management and operations: (1) the low level at which most metrics are reported (individual movements), (2) a need to orient performance measures toward specific tasks, and (3) a need for additional training to bring TMC operators and other signal operations staff up to speed on using the metrics. To overcome these, MCDOT appears to be waiting for further development of the open-source software by innovators to address the first two points (although it may explore solutions using its own consultants), and anticipates training activities and creation of documentation for the third point. As ATSPM implementation moves rightward along the adoption curve in the diffusion of innovation theory, such concerns will become increasingly important, as they reflect key needs of the industry: to package the performance measures into useful formats for system-level management for both managers and operators, and to equip staff with the knowledge necessary to use the performance measures to their fullest extent.

Benefit-Cost Methodology Application Tables

Table 21. Maricopa County Department of Transportation implementation and life cycle costs.

Cost	Description	Sunk Cost	Deployment Cost	Operation Cost
1	Controller procurement.	0	0	0
2	Firmware upgrades.	0	0	0
3	External data loggers.	0	0	0
4	Communication system development.	0	0	0
5	Communication system maintenance.	0	0	0
6	Detection system development.	$765,000	0	0
7	Detection system maintenance.	0	0	0
8	Detection system reconfiguration.	0	$22,100	0
9	Detection system documentation.	0	0	0
10	New server.	0	$1,000	0
11	Server maintenance.	0	0	0
12	Software license cost.	0	$2,800	0
13	Installation cost.	0	0	0
14	Maintenance cost.	0	0	0
15	Integration cost.	0	$50,000	0
16	Usage cost.	0	0	$441,584
Total		**$765,000**	**$75,900**	**$441,584**

Table 22. Maricopa County Department of Transportation post-implementation and life cycle benefits.

Cost	Description	Benefit
1	Manual data collection avoided.	$176,016
2	Scheduled maintenance avoided.	$866,184
3	Complaint response time reduction.	$441,584
4	Performance documentation.	0
5	Respond to failed detection.	0
6	Respond to failed communication.	0
7	Other equipment failures.	0
8	Capacity benefit.	0
9	Progression benefit.	0
10	Pedestrian service benefit.	0
11	Preemption improvement.	0
12	Reduction in crashes.	0
Total		**$1,483,784**

LAKE COUNTY DEPARTMENT OF TRANSPORTATION

Lake County Department of Transportation (LCDOT) in Illinois is one of the most active local agencies in following the trends and opportunities of utilizing and applying automated traffic signal performance measures (ATSPMs) for traffic signal monitoring. However, it still has not fully deployed an ATSPM system of its own to gain substantial benefits and make a good case study for the others to follow. The LCDOT controls 180 signals, out of which 133 are currently under an ATSPM system. LCDOT uses the ATSPM, with effectively 1.5 FTEs, in daily operations for monitoring and tweaking of traffic signals. However, so far, the system has not been used to validate the major signal retiming projects although such a use of the ATSPM is planned for the near future. LCDOT is an excellent example of a relatively small agency with limited resources, which has been using its enthusiastic and resourceful staff to implement and utilize the ATSPM technology. LCDOT benefits from the fact that it has a suitable communication and detection infrastructure which makes application of the ATSPM and similar technologies a relatively easy process. Also, the management decision-making processes are quick and smooth which removes some of potential institutional barriers to implement the ATSPM and similar technologies.

Lake County is located in the northeastern corner of Illinois along the shores of Lake Michigan (see figure 17 below). According to the 2010 census, it has a population of 703,462, which makes it the third populous county in Illinois. Also, Lake County is the second wealthiest county in Illinois, per capita income, and the 27th wealthiest county in the nation. These socio-economic characteristics of Lake County may have an important role in the county's ability to maintain proper road infrastructure and invest in ITS. The first ATSPM implementation in Lake County took place in November, 2017, under the leadership of the county traffic signal engineer, who was first exposed to ATSPM while working with the Wisconsin Department of Transportation (WisDOT). His enthusiasm for innovation and interest in improving signal operations were the major driving forces behind adopting the ATSPM in Lake County.

The LCDOT staff plans to use ATSPMs for both day-to-day functions to proactively support operations and maintenance of traffic signals and for stand-alone signal retiming activities. While the former ATSPM use has already been in place, the latter ATSPM use has not yet been fully realized, but there are a few corridor retiming projects on the way, during which impact of the ATSPM will be thoroughly evaluated.

Figure 17. Map. Location of Lake County, Illinois.

Source: ©2019 Google Maps™

Table 23. Lake County Department of Transportation agency characteristics.

Number of Signals	Number of Signal Operations Staff	Use of Automated Traffic Signal Performance Measures	Type of Deployment
180 signals; 133 signals under ATSPM; the rest will be under ATSPM by the end of 2019; 100 percent of signals have stop-bar detection; 100 percent of signals have advanced mainline detection; 87 percent of signals have advanced detection on all approaches.	1.5 FTEs (excluding sporadic engagement of the consultants).	On a daily basis.	UDOT open-source ATSPM software version 4.0.2 (looking to replace with a vendor solution).

ATSPM = automated traffic signal performance measures. FTE = full-time employee. UDOT = Utah Department of Transportation.

LCDOT has access to a total of 740 signals, but only owns 180. The remaining signals are owned by either the Illinois Department of Transportation (IDOT) or local municipalities. These other signals can be monitored but not managed by LCDOT. Of those 740 signals, 602 can be accessed through Centracs® active traffic management system (ATMS) while only 202 are part of the joint ATSPM system. All 180 signals owned by LCDOT are remotely accessible, but only 133 are under ATSPM. LCDOT will replace the remaining 47 signalized intersections controllers (in summer 2019) to meet ATSPM requirements. The entire region (multiple jurisdictions) is expected to have around 300 signals under ATSPM by the end of 2019, as few planned projects will be completed by the end of 2019.

When it comes to capability to generate relevant performance measures—all intersections under LCDOT jurisdiction have stop-bar detectors and are capable of reporting all PMs that are based on stop-bar detection. Similarly, most LCDOT-controlled intersections have advanced detectors. For example, out of 133 currently active ATSPM intersections (owned by LCDOT), 116 have advanced detectors on all (four) approaches, whereas 17 have advanced detection only on mainline approaches.

Approximately 1.5 full-time employees (FTE) (all engineers) currently use ATSPM within LCDOT. This FTE value only denotes staff who are available to be fully utilized (if needed) on ATSPM. In practice this means that two LCDOT engineers use some of their time (information on this is provided later) to work with ATSPM. Data on ATSPM implementation costs, given in table 24 below, show the details on specific use of FTEs for ATSPM operations and maintenance. LCDOT expects the number of FTEs will grow after procurement of a commercially developed and maintained ATSPM system expected to become operational in the second half of 2019. LCDOT has a plan to train TMC operators to use ATSPM on a routine basis. This will increase the number of ATSPM-trained staff to four or five, as two TMC operators and a TMC manager are expected to acquire this knowledge.

LCDOT completed a capability maturity self-assessment offered on the FHWA website. While the detailed answers on the assessment questions are beyond the scope of this study it is important to note that the LCDOT scored as follows:

- Business processes—level 2 (38 percent).
- Systems and technology—level 3 (65 percent).
- Performance measurement—level 2 (50 percent).
- Organization and workforce—level 3 (63 percent).
- Culture—level 2 (50 percent).
- Collaboration—level 2 (50 percent).

More specifically, the following statements describe LCDOT operational conditions:

- **Business processes**—traffic signal management, planning, design, operations, and maintenance decision-making generally operate in silos and are not well integrated. Resource allocation decisions are primarily focused on maintaining reliability of infrastructure.
- **Systems and technology**—traffic signal infrastructure is connected to a management system that can alert operators to equipment malfunctions and assist with managing timing plans. The agency has the capability to remotely manage that system, but management decisions are operator-driven with little automated decision support. Consistency in design and operations is achieved with standard designs and hardware specifications. Systems and technology can support pre-planned responses and advanced concepts, such as transit signal priority, and work zone management.
- **Performance measurement**—the agency has defined performance measures to assess project implementations (such as before-and-after evaluations). The agency may collect output-oriented performance measures for operations and maintenance activities. Operational and management decisions are based on periodic manual observations in the field.

- **Organization and workforce**—staff are well versed in both basic and advanced traffic signal control and management concepts and can execute solutions using existing technologies. Workforce development efforts focus on expanding breadth of competencies and providing redundancy in core competencies. The agency can dedicate staff resources to high-priority corridors and areas on a limited basis.
- **Culture**—traffic signal management is recognized as one of many functions within the organization, but no special emphasis is placed on performance. The agency supports teams dedicated to traffic management functions, but there is no broad acknowledgment or awareness by agency leadership as to what they do. Outreach to policy makers and the public regarding traffic signal operations occurs on an as-needed basis, primarily related to projects.
- **Collaboration**—information and data are archived internally and shared with other stakeholders upon request. The agency collaborates with internal and external stakeholders on a case-by-case or project basis, but these collaborations are not sustained over time.

Approach to Implementation

The overall approach to ATSPM implementation was not exactly planned ahead of time with the specific vision of what LCDOT wanted to achieve through ATSPM deployment, and how. Instead, as is probably the case with many small agencies with a similar institutional profile, the implementation decisions were driven by highly motivated and knowledgeable staff who were ready to try out the latest and greatest affordable techniques. It should be noted here that, like many other cases, the decision to deploy ATSPM was impacted by effective outreach activities supported by UDOT, Purdue University, and FHWA, among others.

LCDOT is in the process of procuring a vendor-supported, commercial ATSPM system. It had a chance to pilot and configure the open-source UDOT system, which gave LCDOT a chance to test how the technology works and what benefits it could bring, and LCDOT realized there were enhancements it wanted to make to the software.

Business Processes and Signal Systems Benchmarking

LCDOT's primary objectives for traffic signal management are very clearly stated but somewhat unorthodox. Its first objective is to optimize mobility, which according to LCDOT,[4] means "being able to facilitate movement of emergency vehicles (EV), transit vehicles, and other higher-priority users by making traffic signals optimal and by equalizing signals' LOS with different weights for various users." Its other objectives are more traditionally defined: "reduce delay and travel time for commuters" and "reduce vehicular emissions."

The LCDOT staff thinks ATSPM helps address the first objective by equally distributing right of way (ROW) through properly balanced green times. Success in attaining this objective is evaluated through split failure, split monitor, and similar performance measures (and relevant charts) for proper allocation of green times. For the second objective, reduction of travel times and delays, it is interesting that LCDOT staff does not identify any specific signal performance measures as a key

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[4] Interview with Justin Effinger, April 24, 2019, Lake County Department of Transportation.

assisting factor; it credits the entire process of using ATSPM. It believes the public benefits (in reduced travel times) from LCDOT's ability to proactively identify problems as opposed to reacting to issues based on citizen complaints. Regarding the third objective of reducing emissions, LCDOT staff is not yet sure how ATSPM can help. However, it recognizes that an increased percentage of arrivals on green provides smoother traffic flows and most likely reduces fuel consumption and emissions. Of all available ATSPM performance measures (and corresponding visual aids), the following four are most frequently used by LCDOT (in descending order):

- Purdue Coordination Diagram.
- Phase termination.
- Pedestrian actuation to service time.
- Preemption event diagram.

Prior to implementing the UDOT source code ATSPM system, LCDOT staff primarily used a responsive approach where a signal (or detection) failure would only be acted upon after receiving a complaint call from the public. Such a call would trigger an action from an LCDOT signal engineer who would spend, on average, a couple of hours trying to identify the issue. Identification of the issue would be followed by contacting a maintenance contractor, who would dispatch a crew to the field to resolve the issue (this process would take, on average, around 4 hours of contractor time).

After initial ATSPM implementation, the process changed as more of the issues could be proactively identified (before receiving complaint calls). For example, an engineer would observe a suspicious trend in the ATSPM (e.g., a phase is on a constant recall) and then investigate the cause, which would lead to identifying the problem (e.g., failed detector). Consequently, it is no longer necessary to wait for a driver to observe abnormal operation in the field and make a complaint call to the engineer, who then dispatches a contractor to the field to find and fix the issue. Such a proactive approach has reduced both the time needed to identify issues and number of events when the contractor has been called to intervene in the field. At this point these numbers are not easy to quantify but there is a plan to develop such functionalities with ATSPM in the future.

Before deployment of ATSPM, LCDOT engaged in a traditional signal retiming process, which happened every few years (based on available funds) and involved collecting field data (sending out a crew to collect traffic counts), building a Synchro model, and performing before-and-after travel time and delay studies. This was a model for project-driven signal retiming, whereas day-to-day signal fine-tuning and adjustments were mostly triggered by complaints from the public.

As a matter of fact, LCDOT has yet to employ ATSPM into the process regarding project-specific signal retiming. This is mostly due to limited funds for signal retiming projects. However, use of ATSPM for project-specific signal retiming is firmly planned for the near future. As a matter of fact, LCDOT is planning to use ATSPMs as part of the decision-making process for selecting new projects, as part of the County Highway Improvement Program Request (CHIPR). The goal of this program is to select signal retiming projects for the next 5 years. The county would like to use ATSPM as a partial scoring component for the project selection process. This would help to more efficiently prioritize projects based on need rather than a specific time interval.

Currently, performance measures from the ATSPM system are not reported to anyone outside of the signal operations group but there are plans to do this once the new commercial ATSPM is operational; annual reports with key performance measures will be sent to the Lake County Board of the elected officials.

Benefits and Costs

LCDOT exclusively uses controller-based data collection (no auxiliary equipment to collect high-resolution data). Most controllers were hardware-ready for collection of high-resolution data but required a firmware upgrade. In total, LCDOT upgraded 116 out of 180 controllers (64 controllers already had correct firmware). The firmware licenses were free, but it was necessary to hire a crew of two people (one from a signal maintenance contractor and one from an electrical maintenance contractor) who spent approximately 30 minutes per intersection to complete the upgrade. This resulted in a total firmware upgrade cost of approximately $322 per intersection (approximately $155 for signal maintenance contractor and approximately $167 for the electrical contractor). It should be noted there are still 47 intersections that will soon be upgraded with brand new controllers. This purchase was based on replacing old controllers to enhance normal operations, not specifically for ATSPMs. These 47 signals already have necessary communication and detection infrastructure to support ATSPM. So, the total costs for firmware upgrades were: $322/intersection × 116 intersections = $37,352.

LCDOT's signal network was already well equipped in terms of communication (mostly fiber) and detection infrastructure when the concept of deploying an ATSPM system was originally conceived. Thus, ATSPM installation benefited from a traffic signal infrastructure that already included many of the necessary components. This is indeed very fortunate considering the existing LCDOT programs and procedures do not justify installation of new communications and detectors solely for the purpose of enabling ATSPM functionalities. Thus, ATSPM installation did not incur any additional detection and communication costs.

For detection system reconfiguration (e.g., redefining detection zones in a video detection system), LCDOT staff needed about 2.5 hours per intersection. This reconfiguration was needed for 131 out of 180 intersections, which are equipped with video detection systems. An exact labor rate (including benefits) of the LCDOT staff member (who did detection system reconfiguration) is $63/h. The total costs for detection system reconfiguration were: $63/hour × 2.5 hours/intersection × 131 intersections = $20,633

In addition to detection reconfiguration, the only other cost associated with ATSPM installation is purchasing Ethernet switches, which costs (including purchase, installation, and programming) around $5,000 per a switch. This is an important upgrade when the ATSPM is deployed on the 47 intersections with brand new controllers, which will cost, altogether, around $30,000.

Server and server maintenance costs were not seen (by LCDOT) as significant costs of ATSPM deployment. As a matter of fact, LCDOT classified the cost of acquiring the server as free because LCDOT staff had just created a virtual machine (VM), using a licensed version of Microsoft® Windows Server® 2016, in an existing server. This VM sits on the host server with all the other

VMs and servers. However, had it bought a new one, it would have cost around $15,000. Considering that all network hardware equipment is routinely replaced, we have estimated $15,000 (from a recent purchase of a server by another Lake County division) as a cost of purchasing server hardware when the ATSPM is installed and run locally.

Licensing issues added complexity to the installation program. The original and existing versions of the software required no licensing costs, as the UDOT open-source software was used. However, LCDOT is currently in a procurement process to deploy a commercial version of the ATSPM software and hire a private contractor to maintain the software. A commercial version of the ATSPM will cost around (only an estimate at this point) $100,000 per year for 750 signals. Considering that only 180 of those 750 signals are under jurisdiction of LCDOT, LCDOT estimates that participation in the licensing costs of its future commercial ATSPM license is $24,000 per year.

Applicable for UDOT's platform but not for a commercial platform (which is installed at LCDOT in meanwhile) are actual costs of installation. Installation of UDOT's open-source ATSPM software may require several days by highly technical staff familiar with programing and database management. In the past LCDOT participated in two installations of the UDOT source code ATSPM. The first version of the ATSPM (4.0.1) was installed exclusively with in-house resources. The traffic signal engineer at LCDOT invested around 200 hours (with an hourly rate of $63/per hour) in that process. In the next software upgrade (from 4.1.0 to 4.2.0) LCDOT hired an outside contractor to complete the upgrade. This upgrade incurred a cost of $52,173 and revealed several bugs in the software, which is one of the reasons why UDOT soon released version 4.2.1. So, the total installation costs for LCDOT reached: $63/hour × 200 hours + $52,173 = $64,774.

When it comes to costs of routine server and database maintenance, this is not a big concern to LCDOT. Once the SQL database is up and running its storage is protected from overdrawing because of the implemented "delete commands." So far, the server has needed a couple of reboots. For the future commercial ATSPM system it is difficult to estimate installation costs, but LCDOT staff knows there will be separate expenses from monthly or annual subscription fees.

LCDOT has not engaged in any formal training specifically related to ATSPMs, outside of its regular continuing education activities. Any ATSPM training primarily occurs during normal use of ATSPM when some of the practices and identified issues are informally discussed among LCDOT staff. Normal ATSPM use can be defined as a practice when ATSPM-proficient LCDOT staff spends approximately 2–6 h/wk using the ATSPM. These numbers are anticipated to increase once LCDOT engages TMC operators in daily usage and operations of ATSPM. Such involvement of TMC staff will require additional training provided by LCDOT staff familiar with the system. LCDOT estimates it will take approximately 100 hours to train future TMC operators who will be operating a commercial ATSPM on daily basis. Thus, the costs of training or integration are estimated as $63/hour × 100 hours = $6,300.

When we summarize all these different costs in one total figure (see table 24 below), we get an estimated total cost of ~$300,000 for deploying and using the ATSPM in a 10-year cycle, assuming a discount rate of 5 percent (the [P|A] factor for determining net present value [NPV] is 7.722). Most of these costs are associated with active usage, installation, and maintenance of the ATSPM system.

While these numbers may be significantly smaller than the costs incurred by one of the large DOTs, which significantly invested in the development of the ATSPM concept and system, they may be like the costs that many small agencies would experience when deploying an ATSPM system.

Similarly, to some other case studies, we could not find a lot of information to quantify public benefits from the ATSPM deployed by LCDOT. However, it seems the key benefit is awareness of infrastructure and operations relative to goals and objectives. Such a benefit is not easy to quantify, and the major benefactor seems to be the public (driving population). For this reason, we mainly focused on direct agency benefits, although some overlap with public benefits exists.

LCDOT staff are in the process of validating turning movement count data collected through ATSPM. There is a test intersection for which turning movement counts collected through historical methods are compared with observations from the pan-tilt-zoom (PTZ) cameras and the ATSPM platform. Considering that common stop-bar detectors are longer than optimal for counting cars, LCDOT staff had to create extra zones in its video detection software to ensure proper and fair comparison (already accounted as a detection configuration cost). Once the ATSPM turning counting methods are validated, LCDOT expects (based on its last signal coordination and timing [SCAT] project) an average traffic count savings of $2,600 per intersection. Thus, we estimate that potential benefits/savings from deploying ATSPM to automatically count data equals: $2,600/intersection × 180 intersections × 7.72 (NPV factor for using ATSPM for counting for the next 10 years) = $3,612,960.

When it comes to using ATSPM to identify potential communication failures, LCDOT is not aware of any case when ATSPM was used to identify the communication failures. It has an asset management program, included with its active traffic management system (ATMS), that is used to detect communication failures across all the ITS devices.

LCDOT has not completed any before-and-after studies (e.g., measuring delays or travel times) to provide an estimate of benefits to commuters by reducing travel times. However, there was an intersection case study at Illinois Route 22 (IL–22) and Kelsey Road where LCDOT was able to identify that the signal behaved oddly due to a travel time alert (Waze was used with 170 percent travel time threshold). The problem turned out to be a detection failure caused by a construction contractor who ground out a loop detector. LCDOT was able to reduce the maximum green time for that phase until the loops were replaced. Diagnosis of the failed detector was done in less than 10 minutes, which was a significant benefit to the public as travelers would experience unnecessary delay had the detector stayed in a malfunctioning state by putting a max recall into the signal.

In general, such investigation of public complaints is one of the major benefits that LCDOT has observed while using ATSPM data. Since ATSPM was deployed, it has become normal practice for an engineer to talk with citizens and back up their responses using data provided by ATSPMs. Use of ATSPMs makes such conversations much easier because the engineer’s responses are backed by data and the engineers are better prepared for such conversations. LCDOT has used the split logs and preemption logs to determine if operations of a specific signal were due to a one-time event (EV or pedestrian call) or an ongoing issue. They can also use these data to explain traffic signal operations to the citizen who called with a complaint. While these benefits are difficult to precisely capture we estimate that LCDOT saves around 2 hours of engineers' time and around 4 hours of field crew's time per week. When these savings are accumulated for a period of 10 years their NPV value comes to: ($63/hour × 2 hours + $243 × 4 hours) × 52 weeks × 7.72 = $440,781.

From the safety perspective, LCDOT has not identified ways to use ATSPM data to understand crash patterns and relationships with signalized operations. A barrier to accomplishing this is that the crash data reside with IDOT and are not frequently and timely shared with Lake County.

LCDOT has recognized a potential for reduced maintenance effort with use of ATSPM. LCDOT hires a maintenance contractor to take care of regular traffic signal maintenance and troubleshooting tasks. Thus, it would be logical to expect the number of troubleshooting calls and resulting maintenance costs to be reduced. However, at this point it is difficult to estimate how much benefit can be achieved from avoided maintenance because of ATSPM. Currently, LCDOT's maintenance contracts are competitively bid through the plans, specifications, and estimate (PS&E) process. Thus, it is difficult to quantify the difference between maintenance activity before and after the ATSPM implementation. The lump sum fee per intersection is based on multiple variables, of which most could not be solved with ATSPM (i.e., signal flash, video detection malfunction, ITS equipment malfunction). LCDOT sees the biggest benefit of maintenance-related use of ATSPM in early identification of detection and signal issues. Such early problem identification reduces a potential delay to which drivers are exposed.

After entering in all of the estimated LCDOT benefits, we came up (see table 25 below) with a total benefit, over a 10-year life cycle, of around $4.05 million NPV. These benefits mainly come from the savings on not hiring traffic data collection contractors to collect traffic counts in the field, and from reduced contractor's and LCDOT staff's time involved in resolution of the signal and detector issues. It should be noted, again, that, in this case, the benefits do not include any direct benefits to the public which are arguably much larger than those experienced by the agency itself.

Lessons Learned

LCDOT is an excellent example of a relatively small agency with limited resources that has been using its enthusiastic and resourceful staff to implement and utilize ATSPM technology. LCDOT benefits from the fact that it has a suitable communication and detection infrastructure, which makes application of ATSPM and similar technologies a relatively easy process. Also, the management decision-making processes are quick and smooth, which removes some of the potential institutional barriers to implement ATSPM and similar technologies.

LCDOT has still not made full use of ATSPM capabilities, since it was in the process of procuring a vendor-supplied ATSPM system at the time of this case study. It was quick to realize the benefits laid in integrating ATSPM in daily operations of TMC staff and educating TMC staff to proficiently use ATSPM functionalities. While TMC education and ATSPM technology transfer have not yet happened, it is evident that LCDOT staff have a clear plan for how to accomplish these tasks. Moreover, LCDOT staff realized that using ATSPM has two components: maintenance of the system hardware and software and practical use of ATSPM functionalities for a routine daily activity. While the latter process is determined for the in-house staff of future TMC operators, the former tasks will be assigned to an outside contractor who will support system hardware and software maintenance. It is expected that this type of labor division will ensure ATSPM operations are sustained over a long period of time and usage of ATSPM reaches its full potential in the next few years.

Finally, instead of just soliciting a request for proposal (RFP) that will ask vendors to support existing ATSPM features (prescribed by the standards of the open-source code developed by UDOT), LCDOT staff took a proactive role to challenge potential vendors to propose and implement new functionalities that will address some of the specific objectives of LCDOT's signal operations. In this way, LCDOT has shown leadership in trying to push the boundaries of what can be achieved with the future version of ATSPM as opposed to just requesting to replace existing open-source functionalities with a commercially packaged product. In summary, the case of LCDOT shows how a small, well-staffed, and educated agency with good infrastructure has the potential to become a leader in ATSPM implementation and achieve relatively significant potential for future benefits.

Benefit-Cost Methodology Application Tables

Table 24. Lake County Department of Transportation implementation and life cycle costs.

Cost	Description	Sunk Cost	Deployment Cost	Operation Cost
1	Controller procurement.	0	0	0
2	Firmware upgrades.	0	$37,352*	0
3	External data loggers.	0	0	0
4	Communication system development.	0	0	0
5	Communication system maintenance.	0	$30,000†	0
6	Detection system development.	0	0	0
7	Detection system maintenance.	0	0	0
8	Detection system reconfiguration.	0	$20,633*	0
9	Detection system documentation.	0	0	0
10	New server.	0	$15,000‡	0
11	Server maintenance.	0	0	0
12	Software license cost.	0	0	0
13	Installation cost.	0	$64,744*	0
14	Maintenance cost.	0	$24,000†	0
15	Integration cost.	0	$6,300	0
16	Usage cost.	0	0	$101,163§
Total		**0**	**$198,029**	**$101,163**

* Actual costs incurred by LCDOT.

† Future costs based on a quote (specific to LCDOT).

‡ Hypothetical costs, fairly estimated based on a relevant comparable cost (LCDOT did not have such a cost, but many other agencies would).

§ Projected costs for future based on a sample of incurred costs.

Table 25. Lake County Department of Transportation post-implementation and life cycle agency benefits.

Cost	Description	Benefit
1	Manual data collection avoided.	$3,612,960
2	Scheduled maintenance avoided.	0
3	Complaint response time reduced.	$440,781
4	Performance documentation.	0
5	Respond to failed detection.	0
6	Respond to failed communication.	0
7	Responds to other equipment failures.	0
8	Capacity benefit.	0
9	Progression benefit.	0
10	Pedestrian service benefit.	0
11	Preemption improvement.	0
12	Reduction in crashes.	0
Total		**$4,053,741**

CLARK COUNTY, WASHINGTON

Clark County, Washington, owns, operates, and maintains approximately 100 traffic signals (mix of rural and urban intersections). Clark County is located in southwestern Washington across the Columbia River from Portland, Oregon. It also operates and maintains approximately 25 traffic signals for three small agencies and the Washington Department of Transportation (WSDOT). The local and central signal system is Trafficware. Clark County signals operate in a variety of control modes, including free, time of day coordinated, traffic responsive, and traffic adaptive. It is still figuring out what the right values of the different performance measures are, so it can focus its resources in the best possible way. It should be noted that the City of Vancouver (located in Clark County) operates and manages all of its signals connected to a separate Trafficware central system. The two Trafficware systems are currently not integrated.

Clark County can be considered an early adopter with regard to diffusion of innovation. Its system is robust, it knows where it wants to go, and it chooses to take on higher risk than other agencies. It has innovator tendencies, however, when it comes to ATSPM. It is building upon what UDOT, GDOT, and Purdue University have started, and is trying to make it even better for itself and other agencies.

Clark County has been upgrading its traffic signal hardware and software over the past 10 years with a goal of providing good basic service to the traveling public. It has the equipment in place to collect high-resolution data from the controllers and worked with the central system vendor to develop performance measure reports in the same platform. This made ATSPM deployment straightforward and cost effective. ATSPMs are just one tool it uses to manage the signal system. Its next steps include answering the question of what the right values are for each metric and creating automatic notifications when the values are out of range.

Table 26. Clark County agency characteristics.

Number of Signals	Number of Signal Operations Staff	Use of Automated Traffic Signal Performance Measure	Type of Deployment
▪ 98 traffic signals. ▪ 3 HAWK signals. ▪ 24 signals for other agencies.	▪ 1 engineering manager. ▪ 1 signal engineer. ▪ 1 intelligent transportation system engineer. ▪ 6 signal technicians. ▪ Consultants (as needed and project specific).	▪ As-needed (now). ▪ Continual (future).	Trafficware ATMS.now.

ATSPM = automated traffic signal performance measures. ITS = intelligent transportation systems.

Approach to Implementation

Clark County learned of ATSPMs through a variety of Institute of Transportation Engineers (ITE) papers and presentations. It attended the ATSPM workshop hosted by UDOT in January 2016. Prior to using ATSPMs and high-resolution data to create reports, the county used logs and reports available in ATMS.now as a tool to operate and manage its signal system. In doing so, it realized how important good detection was for local intersection operations, and how important good communication was for remote monitoring. The county also installed a Bluetooth sensor system to collect and track travel time along different corridors. Bluetooth sensors were installed at 55 intersections, and multiple routes can be created to measure travel time.

In 2013, it began working with Trafficware and the local vendor to develop a software application. This application would use high-resolution data to create reports, similar to what UDOT developed. In 2014, Clark County asked Trafficware to create five reports so it could monitor the operations based on its operational objectives. The reports include:

- Purdue Coordination Diagram.
- Purdue Detector Fault.
- Purdue High Resolution Report.
- Purdue Phase Termination Diagram.
- Purdue Split Monitor.

Clark County began collecting high-resolution data at six intersections in 2015. Attending the 2016 workshop at UDOT reinforced confidence that ATSPMs would be a game changer in the signal operations field. It continues to work with Trafficware to deploy ATSPMs at all of its signals and identify enhancements to the base source code. Implementing ATSPMs was relatively straightforward because the county had new controllers, robust detection, and good communications in place. These upgrades happened over many years of capital projects aimed at improving signal operations (after decades of neglect). The only ATSPM-specific improvement needed was to install an advanced central processing unit (CPU) in the controller, which would enable collection of high-resolution data. Almost all traffic signals in the county now collect high-resolution data, which is stored in the cloud.

The county's signal design standards support the ATSPM system with regard to detection layout, controllers, and communications.

Clark County developed a concept of operations (ConOps) to document signal performance measures. The ConOps documents operational needs (intersection and corridor level), lists multiple performance metrics and their applications, and includes several operational scenarios for how Clark County can use the data.

Business Processes and Signal Systems Benchmarking

Clark County completed a capability maturity self-assessment offered on the FHWA website. While the detailed answers on the assessment questions are beyond the scope of this study, it is important to note that Clark County assessed itself as follows:

- Business processes—level 3 (75 percent).
- Systems and technology—level 4 (85 percent).
- Performance measurement—level 3 (75 percent).
- Organization and workforce—level 4 (88 percent).
- Culture—level 4 (100 percent).
- Collaboration—level 3 (75 percent).

It should be noted here that the above self-assessments are based on subjective opinions of agency staff who answered the survey questions, which may or may not reflect (as with any other agency) the true nature and quality of the components of the self-assessments. Clark County's business processes for managing its signal systems are focused on proactive operations versus reactive. It is continually looking at ways to improve process, especially to reduce the burden of reviewing data produced by ATSPMs.

The main signal operation goals are:

- Safe movement of people and freight.
- Efficient movement of people and freight.
- Use technology to leverage the investment in the road network.

The operational objective(s) of a particular intersection or corridor are based on the context (time of day, land use, geometry, etc.) in order to meet the goals. The county developed corridor atlases, which include a map of a corridor (or group of signals) along with operational issues, and what the signal operations should accomplish. It uses these as a guide when developing timings and responding to complaints.

The county uses ATSPM on a regular basis, albeit in ways that are more ad hoc than programmatic. The measures they use most often include:

- Cycle length.
- Green time.
- Green/cycle ratio.
- Vehicle count.
- Phase termination.
- Green occupancy ratio.
- Percent arrival on green.

- Pedestrian actuation to service time.
- Preemption event diagram.
- Preemption duration.
- Detector failure.
- Green occupancy/red occupancy ratio (future—unique detection needed).

Issues

While the county was implementing ATSPMs, an issue arose related to atypical phasing at intersections operating flashing yellow arrow (FYA) for protected/permissive phases. The county programmed the intersections with FYA in a unique way to disallow FYA to be active with the opposing pedestrian phase. The base source code did not recognize this phasing and therefore was not able to produce appropriate reports. A new version of local firmware was developed with enhancements to the FYA operations, and the county is in the process of deploying it. FYA intersections will then be reconfigured in the ATSPM system.

After implementing ATSPM, the county realized the systems provided a lot of data. It is difficult to know what to do with all the data, determine when the data are abnormal, and focus on the most important locations and metrics. The county would also like to understand which metric is the right metric for a specific intersection—for example, at ramp terminals, the side street delay (which could lead to queuing) is more important than mainline progression. It has a general concept of what triggers (abnormal operations) for what context would be useful, and will work to fine-tune this once it has ATSPMs enabled at all intersections. It would also like to create a baseline, such as arrival on green at a specific location during the morning (a.m.) peak, so it knows what values to focus on.

Clark County will use ATSPMs for both day-to-day operations (proactive operations/ maintenance) and project specific tasks (corridor retiming).

Prior to implementation of ATSPMs, the county relied on phone calls and complaints and then had to dispatch staff to review the operations (sometimes this would result in 2 hours of driving to observe the intersection operations). Using split logs and reports from Trafficware, it can review intersection operation remotely to do initial troubleshooting and send out staff with the appropriate resources. It is also able to discover problems with detection prior to getting a call from the public. Once the ATSPM system is fully operational, its goal is to produce daily reports that summarize problem locations so staff can address the issues. It also envisions the system sending alerts when metrics are outside of a typical range (given the context).

Similar to GDOT,[5] prior to the implementation of ATSPMs, the process of evaluating signal operations was done “slowly, manually, and with a lot of paperwork.” Most of the evaluation was based on limited field data collection, including floating-car studies and manual observations. These methods had opportunities for unintentional (or perhaps intentional) bias and provided a small snapshot performance. Many of the metrics were based on modeled or simulated results such as number of stops, delay, and fuel.

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[5] Alan Davis interview, April 16, 2019.

Clark County recently implemented SynchroGreen adaptive signal operations at 28 intersections (three corridors). It will use ATSPMs to evaluate and fine-tune the operations. It will use various performance metrics to evaluate operations across time periods, such as travel time, arrival on green, split times, and split failure.

In summary, Clark County feels that ATSPM is a valuable tool that helps to efficiently operate and maintain signals. It also feels there is room for improvement, especially in the automated component of the system. It has invested time and money to push innovation of ATSPM further and feels there will be a positive return on investment.

Benefits and Costs

It is difficult to distinguish the infrastructure costs associated with ATSPMs from the general traffic signal system. The controller, detection, and communications needed for ATSPMs are also used by the general traffic signal system to provide good basic operational service.

Clark County has been heavily investing in its signal system after many years of inattention and change in technical staff. It has installed Type 2070 controllers, installed new detection, and upgraded the communications infrastructure, using funds from several capital projects aimed at improving signal operations. It was able to leverage the existing hardware and, therefore, all of its signals were set up to easily deploy ATSPMs. The only ATSPM-specific improvement needed was to install a 1-C CPU in the controller, which would enable collection of high-resolution data. This is classified as a deployment cost. The cost of a 1-C CPU is about $1,300 per unit, based on a recent quote. The time required to install the 1-C CPU was 20–30 minutes. A labor rate of $65/h[6] was assumed. Assuming $1,300 /1-C CPU x 125 signals = $162,500 and $65/hr × 0.5 h/signal × 125 signals = $4,062.50.

The county found that firmware upgrades on a 1-C CPU take about 1 minute, compared to 20–30 minutes for a 1-B or 1-E CPU. This has proved to be an unexpected large return on investment.

As a note: a new controller capable of collecting high-resolution data is about $500 more than the Type 2070 controller that does not collect the high-resolution data. The costs of communication and detection system development were not available, since such investments were made over many years preceding the implementation of ATSPM, making it difficult to determine a value.

For detection system reconfiguration (e.g., redefining detection zones in a non-invasive detection system), about 2 hours per intersection was assumed to be needed for this task. This is classified as a deployment cost. Most intersections did not require any reconfiguration, so 10 percent of intersections were assumed to need this. A labor rate of $65/hour was assumed. Assuming $65/h × 2 h/signal × (0.1)*125 signals = $1,625.

Documentation of the detection system and entry of metadata into the ATSPM system were estimated to require about 15 minutes per intersection, as the interface makes this straightforward. This is classified as a deployment cost. This task was assumed to be needed for all 125 intersections, with a labor rate of $65/hour assumed. Assuming $65/h × 0.25 h/signal × 125 signals = $2,031.

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[6] This rate is an average of the rates for traffic engineer, senior signal tech, and journey level signal tech (for high-level estimate).

Clark County uses the Trafficware ATSPM system, a cloud solution, which costs $200 per signal per year (above and beyond the cost for ATMS.now and SynchroGreen). It also has an in-house server used for the ATMS.now central system. The long-term vision for Trafficware is to host everything in the cloud, which will have a fee associated with it, but county staff will no longer need to provide server and system maintenance.

Clark County invested $50,000 in seed money to Trafficware to develop the ATSPM software (enhancements over the base source code) that could run specific reports. The county also invested approximately $150,000 in consultant help to identify the appropriate measures of effectiveness (MOE) on each corridor, plus critical factors that impact them. These are both classified as deployment costs. A signal performance measures ConOps and an MOE framework were developed, and potential graphics and dashboards were created to display the MOEs for further enhancements.

The largest item in the cost estimation is the cost of usage, representing the amount of time that agency staff make use of the system. This represents the other side of the cost reduction items described under benefits. This is classified as an operation cost. The staff currently use the data on an as-needed basis. The level of effort is estimated as 5 percent of the total labor of an FTE, across nine personnel (900 hours/year), over a 10-year period. It is expected this may go up when a more formalized program is developed, and when the SynchroGreen adaptive system is deployed. A labor cost of $65/hour was estimated. Some cost and benefit items are estimated for the 10-year life cycle. Assuming a discount rate of 5 percent, the (P|A) factor for determining net present value is 7.72. The present value of this 10-year cost is 900 x $65 x 7.72 = $469,685.

For this case study, it was difficult to quantify the direct agency benefits. This is because the agency is still building up to full deployment. It previously used logs and reports from ATMS.now to help review operations and troubleshoot issues. The ATSPM system is another tool it is able to use, and not necessarily a wholesale different way of operating. In the future, it expects to see additional benefits with the creation of daily summaries, triggers, and alerts. This will allow staff to focus on issues and solutions without having to wade through all the data. Benefits to the public have not been estimated in this initial analysis.

The county expects to see benefits during the deployment of the adaptive signal system. These benefits include reduced staff time to evaluate and fine-tune the system. Instead of spending weeks or months in the field to observe operations, it will be able to review split logs and percent arrival on green, and make adjustments based on real-time data.

The county’s maintenance costs have significantly decreased due to all of the recently completed system upgrades. It has used alarms and TS2 detector diagnostics for 10 years to determine where problems exist and need to be fixed. ATSPMs will help them to know the system is working (flagging values outside the norm), as opposed to finding problems. For this case study, no maintenance benefit is assumed.

Lessons Learned

Clark County has been upgrading its signal system for the past 10 years, after many years of neglect. One big lesson learned is that investments in the traffic signal system to optimize intersection operation (controller, detection, communication) made ATSPM deployment straightforward and low cost.

A second lesson learned is that large data quantities aren't valuable if you don't know what to do with them. It is difficult to know what to do with all the data, determine when the data are abnormal, and focus on the most important locations and metrics. There is also a benefit to understanding which metric is the right metric for a specific intersection—for example, at ramp terminals, the side street delay (which could lead to queuing) is more important than mainline progression. Clark County has a general concept of what triggers (abnormal operations) in what contexts would be useful, and will fine-tune this once ATSPMs are enabled at all intersections. It would also like to create a baseline, such as arrival on green at a specific location during the a.m. peak, so it knows what values to focus on. The county has invested in developing an MOE framework for each corridor to determine the most important metrics given the context. They created corridor atlases to document operational issues and objectives at each intersection. In this manner, when new timings are developed or complaints responded to, there is a common understanding. Focusing on the appropriate metric (data) results in effective use of staff time.

Benefit-Cost Methodology Application Tables

Table 27. Clark County implementation and life cycle costs.

Cost	Description	Sunk Cost	Deployment Cost	Operation Cost
1	Controller procurement.	0	0	0
2	Firmware upgrades.	0	$166,563	0
3	External data loggers.	0	0	0
4	Communication system development.	0	0	0
5	Communication system maintenance.	0	0	0
6	Detection system development.	0	0	0
7	Detection system maintenance.	0	0	0
8	Detection system reconfiguration.	0	$1,625	0
9	Detection system documentation.	0	$2,031	0
10	New server.	0	0	0
11	Server maintenance.	0	0	0
12	Software license cost.	0	$50,000	0
13	Installation cost.	0	0	0
14	Maintenance cost.	0	0	0
15	Integration cost.	0	$150,000	0
16	Usage cost.	0	0	$451,620
Total		**0**	**$370,219**	**$451,620**

Table 28. Clark County post-implementation and life cycle benefits.

Cost	Description	Benefit
1	Manual data collection avoided.	0
2	Scheduled maintenance avoided.	0
3	Complaint response time reduction.	0
4	Performance documentation.	0
5	Respond to failed detection.	0
6	Respond to failed communication.	0
7	Other equipment failures.	0
8	Capacity benefit.	0
9	Progression benefit.	0
10	Pedestrian service benefit.	0
11	Preemption improvement.	0
12	Reduction in crashes.	0
Total		**0**

APPENDIX B. ADDITIONAL RESOURCES

Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach: https://docs.lib.purdue.edu/jtrpaffdocs/3/.

> This is the first report produced by the pooled fund study. It contains an in-depth description of the methodology for producing a variety of performance measures, including sample calculations and views for example real-world locations. Performance measures for maintenance and operation are presented, along with examples for use of travel time measurements to augment high-resolution data.

Integrating Traffic Signal Performance Measures into Agency Business Practices: https://docs.lib.purdue.edu/jtrpaffdocs/24/.

> This is the second report produced by the pooled fund study. This follows on to the first report, providing an extended discussion of concepts for implementation, including recommendations for detector configurations and requirements for data systems. The report goes on to present many applications of performance measures for evaluating maintenance issues for communication and detection, and for evaluating systemwide performance for capacity allocation and progression. Numerous examples are developed from real-world case studies, most of which are aimed at identifying problems at a high level. This complements the lower-level analysis presented in the first report.

Final Report, NCHRP 3-122: Performance-Based Management of Traffic Signal Systems; (Forthcoming).

> This report, which should be released in the near future, is intended to provide helpful information for agencies implementing ATSPM. The approach is based on concepts from systems engineering. The book contains an overview of the implementation process; a discussion of performance measure selection using an objectives-based approach; an extensive catalog of existing performance measures, with example uses; a procedure for identifying system needs for implementation; a detailed analysis of a typical implementation procedure including discussion of issues likely to be encountered; and information for integration with agency practices.

Utah Department of Transportation (UDOT) automated traffic signal performance measures (ATSPM) website: https://udottraffic.utah.gov/atspm/.

> The UDOT ATSPM website is a public-facing data portal enabling visitors to access performance measures for any signal in Utah, where data are available. Users can select an intersection of interest from a map view, or filter through available metrics. After selecting an intersection, users can then choose which metric to view and what date and time ranges to apply before generating the performance measure. In addition to providing access to many performance measure views, the website also contains links

> to more than 20 different presentations that have been given in ATSPM workshops, in addition to several reports that detail components of the ATSPM system and a walkthrough of installing the software.

Georgia Department of Transportation (GDOT) ATSPM website: https://traffic.dot.ga.gov/ATSPM/.

> GDOT's ATSPM website is another public-facing data portal where visitors can test the software and view performance measures for any signal on their system.

ATSPM workshop: https://docs.lib.purdue.edu/atspmw/.

> This is a collection of presentations and posters presented during the 2-day ATSPM workshop in January 2016. Many of the posters are reprints of posters presented during previous conferences. There are about 30 presentations on a variety of topics, including example implementations by different agencies, methods of leveraging public-private partnerships to build out communication systems, technical details of managing the open-source ATSPM software, and research topics. Some of these contain technical information that has not been compiled elsewhere.

Arterial Performance Measure Tools Project: https://docs.lib.purdue.edu/apmtp/.

> This is a series of reports and working papers produced under an FHWA small business innovation research (SBIR) project carried out by Traffax (now TrafficCast) in partnership with Purdue University. The main product of this research is a report that provides example uses of signal performance measures from high-resolution data in combination with measured travel time data. This report is structured as a series of stand-alone modules accompanied by an executive summary. In addition, several other reports are provided that present a variety of topics related to use of high-resolution data and travel time data for assessing performance of signalized arterials. This includes descriptions of data formats as well as code for some specific applications of travel time data.

FHWA Open-Source Application Data Portal page on ATSPM: https://ops.fhwa.dot.gov/atdm/resources/osadp.htm.

> This website provides a downloadable installation package for the open-source ATSPM software. The software can be installed on a Microsoft® Windows server and requires a license for Microsoft® SQL Server. Installation instructions are included. A discussion forum is also available on this website.

ATSPM GitHub page: https://github.com/udotdevelopment/ATSPM.

> This GitHub repository stores the source code for the open-source ATSPM software, for those users who wish to compile the software themselves or develop or adjust system components.

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