PHASE 1 REPORT

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

on

Project 03-122: Performance-Based Management of Traffic Signals

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from

Kittelson & Associates, Inc.
& Purdue University

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NCHRP Project 03-122: Performance-Based Management of Traffic Signals

Working Paper No. 1
Agency Interviews and Panel Member Surveys

Prepared for the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

by

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1.1 EXECUTIVE SUMMARY

Through both phone interviews and written surveys, staff from 16 public agencies provided information about their use of signal performance measures (ATSPMs), which will be used to guide the development of NCHRP 03-122: Performance-Based Management of Traffic Signals. Agencies were asked about their current and planned use of ATSPMs, as well as which ATSPMs they viewed as important for (a) requesting resources and reporting information to stakeholders and (b) adjusting traffic signal operations. The number of comments received about each group of ATSPMs is summarized in Figure 1-2. The ATSPMs that were referenced most often relate directly to the traffic signal system hierarchy of needs (shown in Figure 1-1):

1. Corridor progression
2. Green time allocation at intersections
3. Detection and communication failures

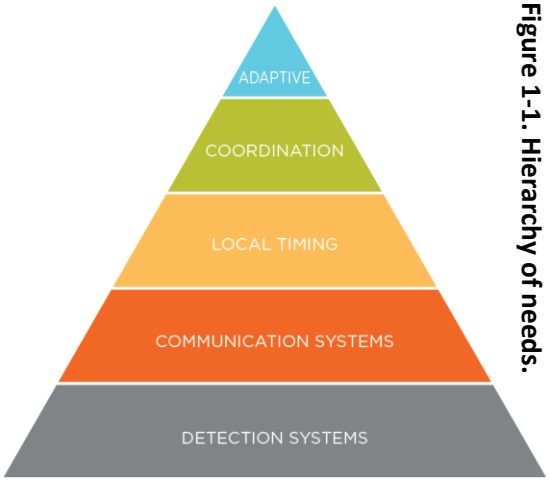
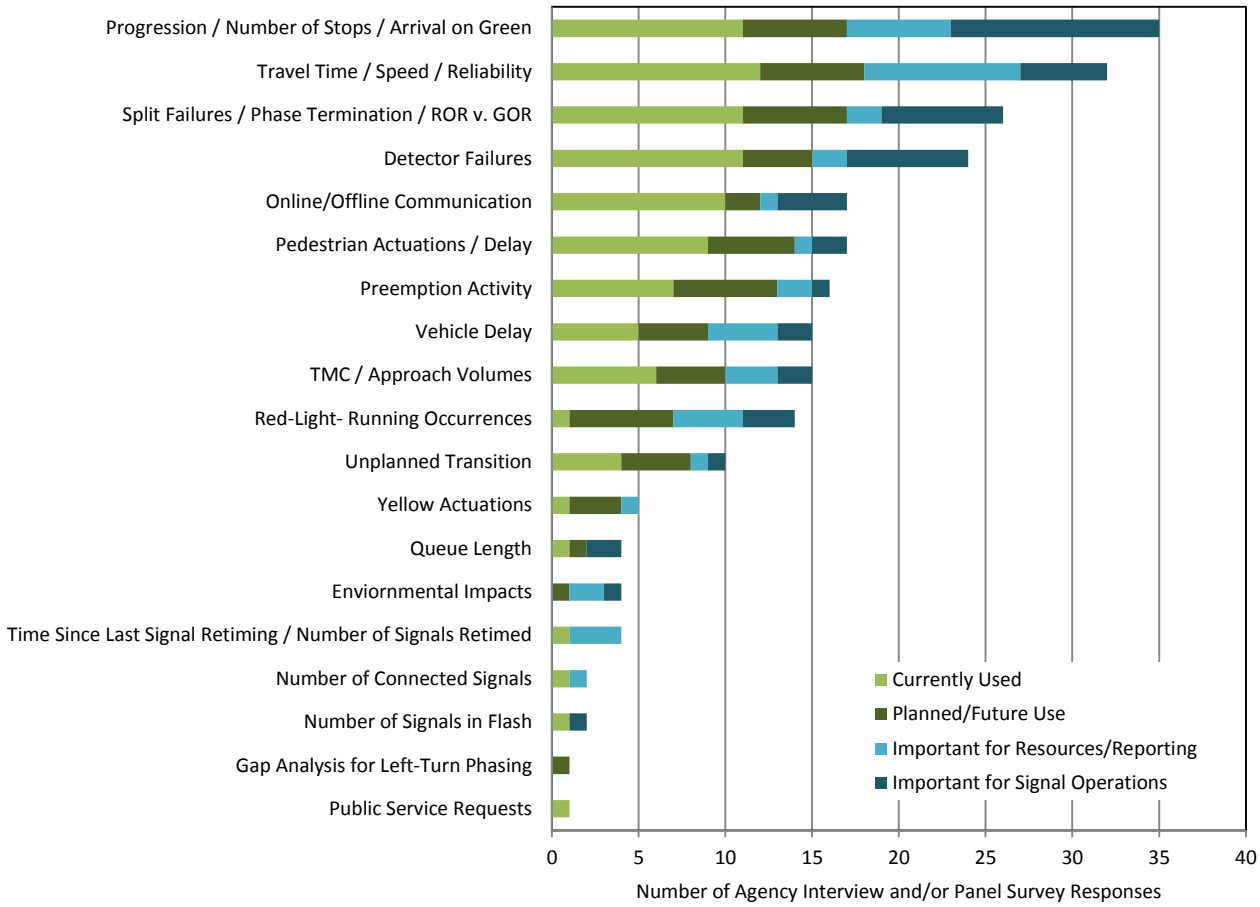


Figure 1-1. Hierarchy of needs.

Figure 1-2. Signal performance measures organized by number of responses.



1.2 KEY POINTS

In addition to producing a list of useful ATSPMs, the interviews and surveys resulted in some consistent themes amongst public agencies. The following summarizes key points from the interviews and surveys:

- Agencies often use ATSPMs for the following activities:
  - Identifying and prioritizing short-term maintenance needs (e.g., intersection in flash).
  - Identifying and prioritizing long-term equipment replacements (e.g., detector failure).
  - Identifying and prioritizing signal retiming locations (e.g., instead of retiming every intersection on a set schedule).
  - Determining adjustments to the signal timing.
  - Evaluating operational changes (e.g., addition of TSP).
  - Evaluating operations to report to external groups (e.g., public, elected officials, etc.).
  - Sharing data with other groups (e.g., giving volume data to planning group).
- Some agencies are unsure how to use ATSPMs to adjust signal timing effectively, and would find it helpful to have thresholds to compare against.
- Many agencies want to make ATSPMs part of daily operations, but need a way to summarize all the data being collected. Planned/desired ideas include:
  - Dashboard that summarizes multiple ATSPMs.
  - Automated reports that aggregate data (corridor versus intersection-level).
  - Use of an index that combines multiple ATSPMs.
- Common obstacles to using ATSPMs include:
  - Limited resources to develop code for new ATSPMs.
  - Culture shift; many engineers/technicians are more comfortable making adjustments based on field assessments versus ATSPMs.
  - Access to the central network (i.e. getting past firewalls). Some agencies maintain their own network outside of IT, while others work with IT staff that is part of a separate department. Agencies are often educating IT staff about traffic signal system needs.
- Many agencies use data beyond high-resolution controller data, such as probe data (e.g., INRIX, Google, and Waze).
- The relationship between traffic signals and ITS groups varies widely.
  - Some agencies differentiate ITS and traffic signals groups based on the type of equipment managed. For example, the ITS group manages all equipment other than traffic signals.
  - Some agencies differentiate ITS and traffic signals groups by facility type. For example, the ITS group manages equipment on freeways, and the traffic signals group manages equipment on arterials.

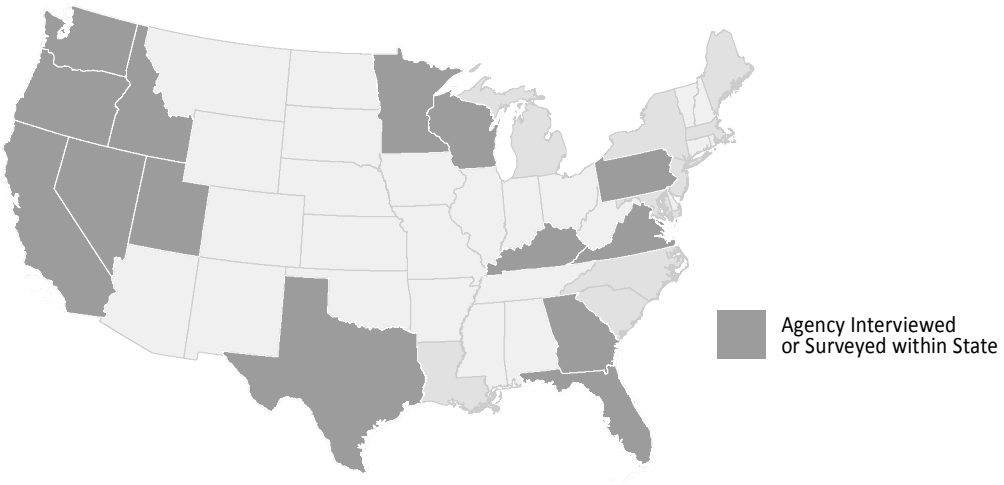
1.3 PUBLIC AGENCIES

Ten public agencies and six panel members provided information about their use of ATSPMs. Table 1-1 summarizes the agency contacts, and Figure 1-3 shows the distribution of agencies across the U.S.

Table 1-1. Agency and panel member contacts.

AGENCY	CONTACT	INTERVIEW/SURVEY
Ada County Highway District, ID	Jim Larsen	Interview
Caltrans	Martha Styer	Interview
Clark County, WA	Rob Klug	Interview
Florida DOT	Raj Ponnaluri	Interview
Georgia DOT	Alan Davis	Interview
Las Vegas, NV	Shital Patel	Interview
Minnesota DOT	Steve Misgen	Interview
Seminole County, FL	Charlie Wetzel	Interview
Virginia DOT	Ling Li and Nhan Vu	Interview
Wisconsin DOT	Joanna Bush	Interview
College Station, TX	Troy Rother	Survey
Kentucky Transportation Cabinet	Telma Lightfoot	Survey
Oregon DOT	Julie Kentosh	Survey
Pennsylvania DOT	Dan Farley	Survey
San Diego, CA	Phil Rust	Survey
Utah DOT	Mark Taylor	Survey

Figure 1-3. Agency distribution.



In addition to geographic diversity, the public agencies varied in their characteristics. As shown in Figure 1-4, the level of experience with ATSPMs was split. While many agencies were currently using ATSPMS, others were interested but had yet to implement ATSPMs as part of their traffic signal management. The agencies ranged in size, managing anywhere from 5,000 traffic signals to none (as shown in Figure 1-5), and the context of the traffic signals was equally as varied. Agencies identified that they had traffic signals operating across all levels of urbanization, facility type, and mode (as shown in Figure 1-6).

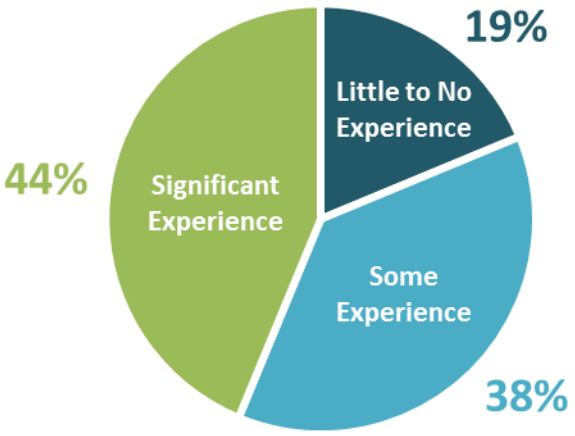


Figure 1-4. Agency Experience level.

Figure 1-5. Number of traffic signals managed.

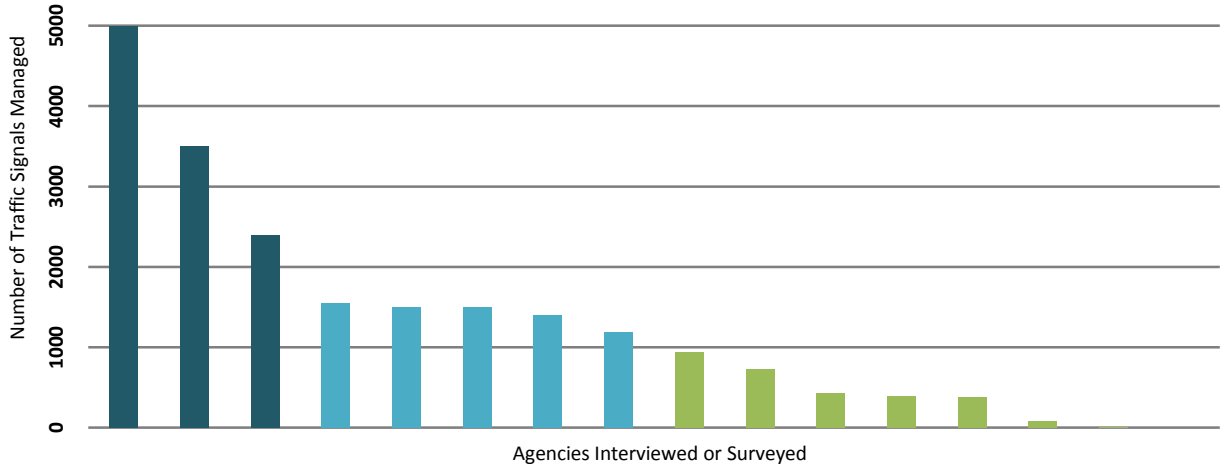
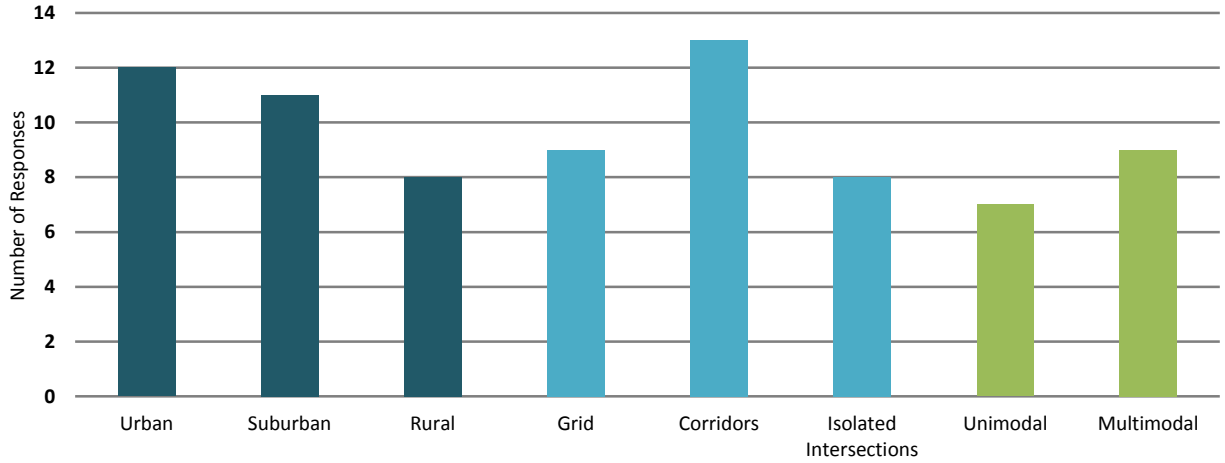


Figure 1-6. Traffic signal context.



1.4 INTERVIEW/SURVEY QUESTIONS

Agencies were asked to describe their current ATSPM practices as well as any planned or desired future plans using the questions below.

1. How would you describe your agency's traffic signal environment?
   a. Urban/suburban/rural?
   b. Grid/corridor/isolated intersections?
   c. Unimodal/multimodal?
2. How many traffic signals does your agency maintain and operate?
3. What type of traffic signal equipment does your agency use?
   a. Controllers?
   b. Detection?
   c. Central system/software?
4. Specifically, what type of communication network do you use for remote access to your traffic signals?
   a. Dial-up?
   b. Cellular?
   c. Ethernet?
   d. Private copper?
   e. Fiber?
   f. Unlicensed radio?
   g. Licensed radio?
   h. Others?
5. How does your agency integrate traffic signals with ITS? For example, are traffic signals under the ITS umbrella?
6. Describe your asset management program as it relates to traffic signals.
   a. What type of documentation is there for traffic signal assets (e.g., electronic database, cabinet prints, etc.)?
   b. Which assets are documented?
   c. How often is documentation updated?
7. How many traffic engineering staff members does your agency utilize?
   a. Engineers?
   b. Technicians?
   c. IT staff?
   d. Others?
8. Is communication networking managed under a central IT group? Or within the traffic signal department?
9. What is the IT procedure for procurement?
10. Do you use contractors/consultants to manage traffic engineering activities (e.g., signal timing, detection, etc.) and/or IT/networking activities? To what extent does your agency manage those activities in-house?

11. What is your experience with Signal Performance Measures (ATSPMs)?
    a. Little to none?
    b. Some experience?
    c. Significant experience?
12. What performance measures are you using to monitor performance of your signal system?
    a. Progression (Purdue Coordination Diagram/Arrival on Green)?
    b. Split failure?
    c. Online/offline communication?
    d. Detector failures?
    e. Preemption activity?
    f. Pedestrian push button actuations?
    g. Unplanned transition (due to pedestrian or preemption activity)?
    h. Others?
13. What performance measures do you want to use but are not currently? What is preventing you?
14. If you are currently using automated performance measures, what was the critical obstacle you had to overcome?
15. What data do you have available to measure performance of your signal system?
    a. Signal system data?
    b. Probe data?
    c. Others?
16. Which performance measures do you think are important for acquiring resources and/or reporting to elected officials? Why?
17. Which performance measures do you think are important for signal operations? Why?
18. How do you apply performance measures to the management of your signal system? What decisions does this influence?
19. What plans do you have in place to enhance and upgrade your signal system?

NCHRP Project 03-122: Performance-Based Management of Traffic Signals

Working Paper No. 2
Traffic Signal Performance Measure Objectives

Prepared for the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

by

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ABSTRACT

This paper discusses uses for traffic signal performance measures. First, the role of performance measures is explored using the framework of Goals, Context, Objectives, Strategies, and Tactics (G-COST). Common goals for managing traffic signal systems are discussed. Next, context is explored including the hierarchical nature of signal system components, the operating environment, and agency capabilities. An examination of various practitioner activities is presented, which shows potential uses of performance measures in a series of examples. Practitioner activities are examined relevant to the time scales ranging from near-term to long-term. These considerations provide a framework on which individual performance measures can be organized, based on practitioner activity time-scale and system element. The paper concludes by developing a vision for performance measure implementation.

2.1 INTRODUCTION

Automated traffic signal performance measures (ATSPMs) have been extensively demonstrated in several previous research studies and in numerous pilot implementations across the U.S. Their utility has been further highlighted by the selection of the technology by the AASHTO Innovation Initiative and by USDOT as part of Every Day Counts. The main objective of NCHRP 3-122 is to develop guidance for agencies interested in using SPMs, necessitating an understanding of the barriers to implementation, and how these may be mitigated.

This working paper provides background on automated signal performance measures and describes the potential uses for ATSPMs in the context of operating and maintaining existing traffic signal systems, as well as how these can support higher level operations related to planning and policy. This discussion is framed by considering the Goals, Context, Objectives, Strategies, and Tactics (G-COST) relevant to the agency relative to the signal system life cycle. A number of example uses are presented for near-term and long-term activities. Finally, these activity examples are distilled into a series of tables that relate them to the system components, time scale and goals, and to individual performance measures and data sources.

2.2 MOTIVATION FOR SIGNAL PERFORMANCE MEASURES

Performance measures are the mechanism by which a system is evaluated, and elements of its operation can be managed. By doing so, performance measures connect the objectives of the system owner to those of the actual system operation. Performance measures have many roles. They help improve an agency's situational awareness, and determine impacts of actions that are taken. They help agencies find problems faster, optimize mobility, and improve safety. What this means in more specific terms will vary considerably by agency, depending on the agency's objectives and capabilities. However, a unified vision can be built around concerns that are common to most signal systems. The purpose of this document is to connect ATSPMs to their various potential uses by an agency and help develop a road map for interested agencies to begin using ATSPMs.

Traffic signal systems have been used on streets and highways for about 100 years, and over that time a number of performance measures have been used, but historically these have been difficult to obtain in an automated manner, across a large system inventory. It was necessary to collect data manually, or develop custom-made data collection systems. A number of early systems were developed for collecting detailed data and extracting useful performance information from them [1,2]. The effort needed to develop such systems, and particularly the lack of any standard set of data definitions, probably limited these developments. In the absence of robust, widespread data collection, agencies often evaluated their performance in terms of the amount of investment they were making in their systems, such as the number of traffic signals retimed within a year, or amount of money spent on system upgrades. These might be called *input-oriented* performance measures.

Indeed, it is sometimes remarked that the dialog on signal systems is often geared toward procurement and deployment of new equipment, rather than on the outcomes achieved by doing so. This is a potential reason

for the gap that often exists between what is promised and what is actually delivered [3]. The lack of good information from the field, in turn, may also limit traffic signal practitioners and the traffic control more generally from being able to ask for more resources, in contrast with endeavors such as pavement management or safety, where performance is routinely quantified and the effects of treatments are generally well-documented.

There is certainly a need for improved performance measurement practices in traffic signal systems. From 2007 through 2012, the National Transportation Operations Coalition (NTOC) conducted a self-assessment called the *Traffic Signal Report Card* where voluntary participants were scored on a variety of categories. During each survey, the area of traffic monitoring has received a score of "F" on a national scale [4].

A few developments have taken place in the past 15 years that have enabled automated ATSPMs to be deployed in a scalable manner. One of these is the emergence of *high-resolution data* [5,6]. This data set comprises a listing of timestamped events as they occur in a signal controller, such as phase and detector state changes. This data has actually been in existence since the very beginning of traffic signal operation, as the electrical or logical states have always existed in some form or another within the controller, but were simply not logged. Many systems such as central systems with real-time status displays, or adaptive control systems, necessarily had to track these states to produce the display or facilitate an adaptive adjustment. However, those systems were not really intended for widespread, interoperable deployment across all signalized intersections in general, nor were they very tolerant of high-latency communications that can occur in geographically distributed signal systems.

The more recent concept of high-resolution data has its roots in *hardware-in-the-loop simulation*, a method of simulation in which a signal controller is attached to inputs that are generated by traffic microsimulation. Data is exchanged between the simulation and the controller though a Controller Interface Device (CID). This information includes the detector states, which are passed from the simulation to the controller, and the phase states, which are passed from the controller to the simulation [7]. Collectively, this bundle of information contains all of the essential information about the controller state.

The same data collection process used in the CID was later applied to real-world systems to evaluate new detection technologies. In this setup, two detector types were co-located in the same physical space, as closely as possible. The trial detection type would be compared to inductive loops. Discrepancies between reported occupancy of the two detector types would be compared, as well as latencies in detector on and off times, relative to the signal state [8,9]. To develop such data, it was necessary to log individual detector state changes as well as phase state changes. To do so, two intersection testbeds were developed in Indiana, which included an entire second cabinet to accommodate data collection [10]. In parallel to this work, an external data collection system was developed in Minnesota [11] that sampled signal events using a much more compact external device. Some additional data collection systems have also been developed to collect similar data [12,13].

A variety of performance measures were initially developed based on these early data collection efforts [5,14]. In 2008–2010, the project NCHRP 3-79a was launched to extend the work on ATSPMs that had taken

place in Indiana [15]. This was subsequently followed up with several additional studies [16,17,18,19] that extended the application of high-resolution data to multimodal performance, optimization, calibration, and other potential objectives.

During the same time frame as this research, the Indiana Department of Transportation (INDOT) began working with a consortium of vendors to develop a data logger that could be run on existing signal controllers. As a result of this collaborative effort, the first controller-borne data logger was launched in 2006, and a common set of data enumerations was developed [20]. Starting in 2012, the Utah Department of Transportation (UDOT) developed a web-based system to transform high-resolution data into ATSPMs, which has been made available as open source software. ATSPMs were selected as a focus technology by the AASHTO Innovation Initiative, and as of 2016 had been selected for mainstreaming by inclusion in FHWA's Every Day Counts program. Today, data loggers are available on newer controller models from five different vendors, and high-resolution data has been transformed from a boutique research contrivance to a management tool.

In parallel to the development of high-resolution data, the proliferation of smartphones and other mobile devices has led to the development of new data sets for monitoring traffic in an exogenous manner. This includes direct measurement of vehicle travel times using Bluetooth and Wi-Fi sensing, physical detector signature-matching, and probe vehicle segment speed data based on processing timestamped vehicle position data by private-sector providers with access to that information, through navigation services and mobile apps [21]. When paired with high-resolution data, a more complete picture of signal performance can be developed than either data set can independently provide [22]. For example, the travel time along a corridor can be quantified using travel time data, but the reason *why* it is higher or lower during certain periods can be explained by examining the patterns of vehicle arrivals at intersections, as revealed through high-resolution data. In the next few years it is anticipated that more and better traffic data will emerge, particularly with the emergence of connected vehicles with vehicle to infrastructure communication. In the more distant future, vehicle-to-vehicle communication and vehicle automation will continue to increase the amount of available data as well as enhance performance. This can be expected to further expand the available performance measures for signal systems [23,24].

2.3 AGENCY SURVEY

One of the initial tasks of NCHRP 3-122 is to conduct a series of agency interviews to develop an understanding of agency perspectives on performance measure needs. A total of sixteen interviews were conducted with six local agencies and ten state agencies, as shown in Figure 2-1. The survey results included a series of background questions about the number of signals managed by the state, staffing levels, and other information about signal operation. In addition, agency interest in specific performance measures was gauged. Some of the agencies in the survey are early adopters of ATSPMs or are interested in pursuing their deployment.

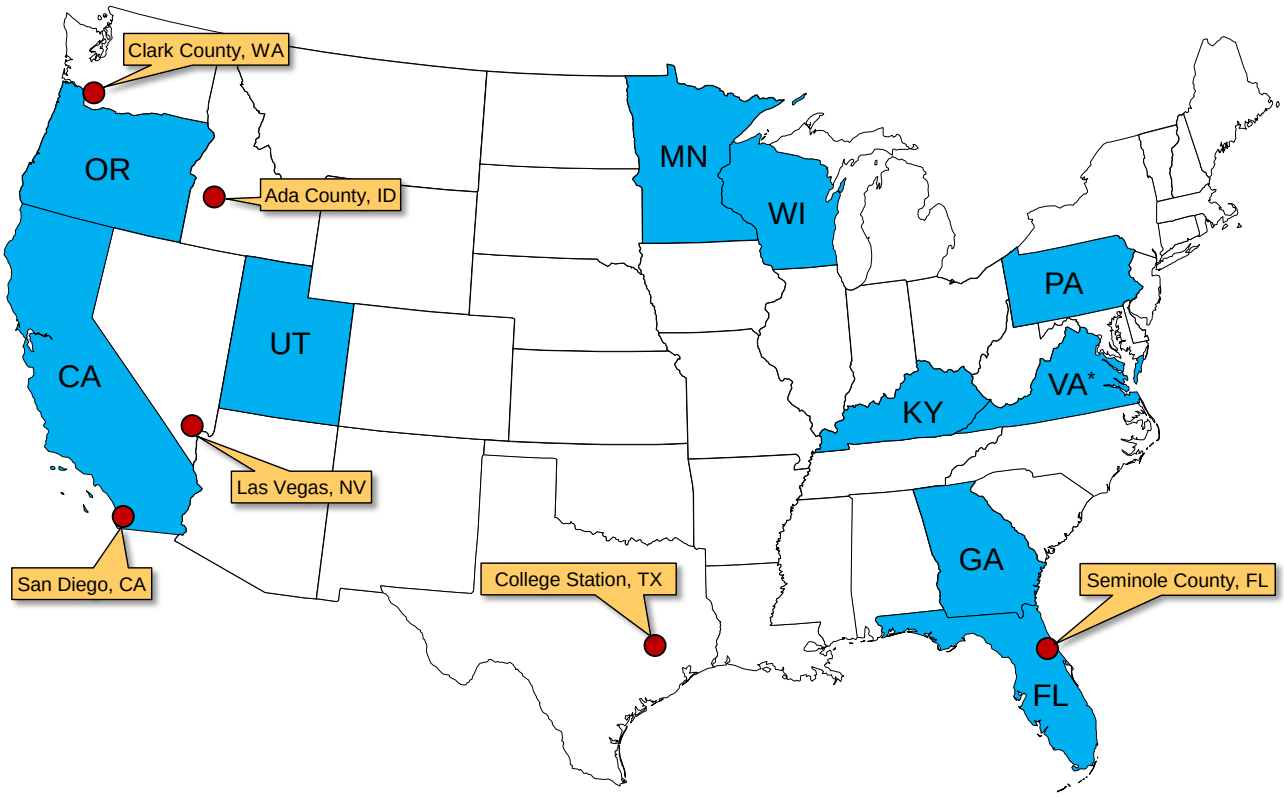
Figure 2-2 shows the results of the performance measure component of the survey. The results for each performance measure were ranked according to the number of positive responses to questions of whether

the performance measure is currently in use, planned for future use, or whether the performance measure is considered important for resources and reporting or for signal operations. The survey respondents had the highest number of positive responses for system-level metrics such as progression metrics and travel time, while split failure metrics came in third place and maintenance metrics for detection and communication fell into the fourth and fifth spots. The other performance measures tended mostly related to various issues related to local control timing and special features such as preemption. The results align well with conceptualizations of the system hierarchy that are discussed in the next section.

These results should be considered as a snapshot of current opinion about ATSPMs, and the results may be skewed by what could be called the "cool factor" of metrics such as those for coordination. As agencies develop more experience with ATSPMs, they mind find that their day-to-day activities are helped more by other specific metrics. For example, some engineers at UDOT would strongly value the ability to find and troubleshoot detector problems and correct them before public complaint calls are generated. They would consider the daily email generated by the system reporting new detector outages as the most important specific metric. Therefore, over time, these opinions will likely evolve.

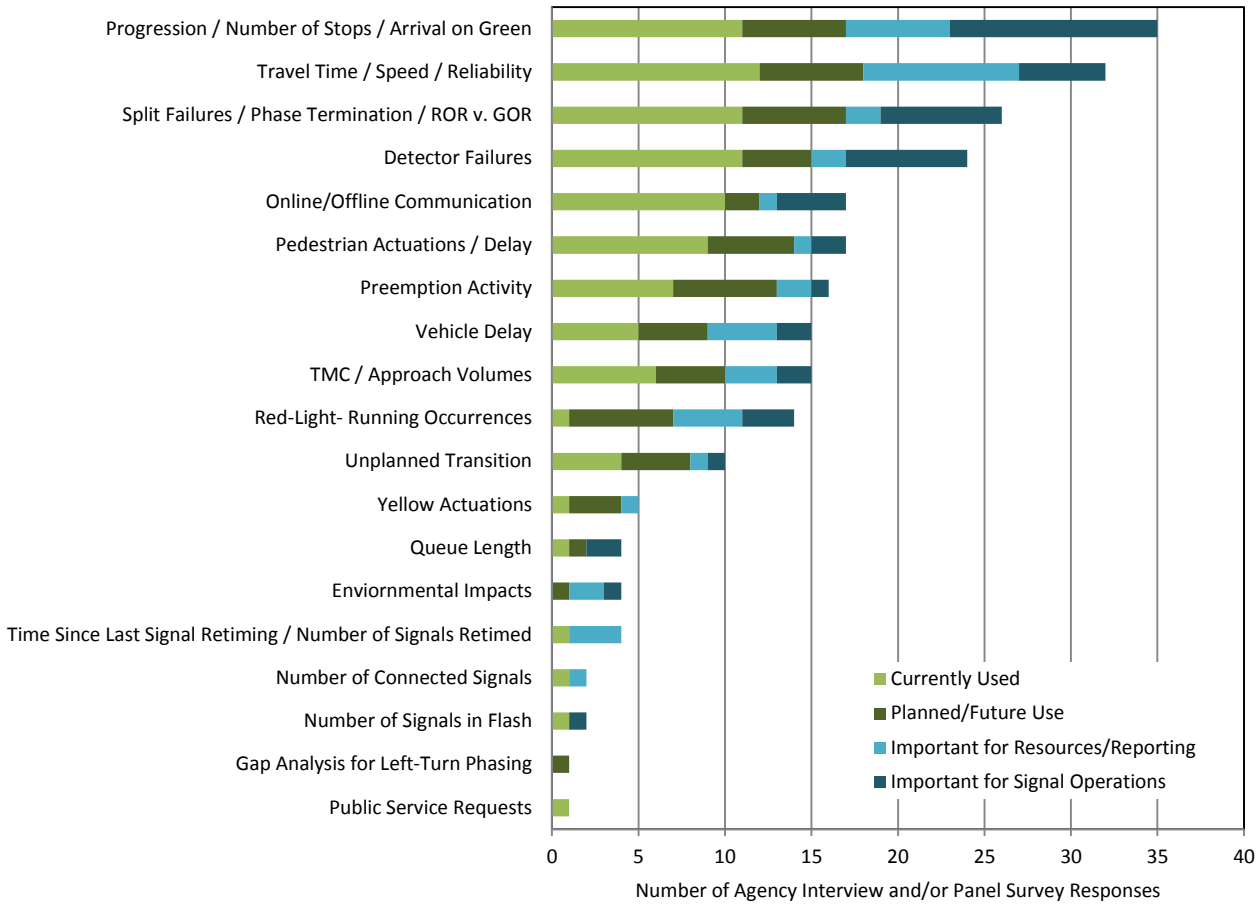
The complete results of the survey are documented in Working Paper 1.

Figure 2-1. Agencies included in the practitioner survey.



* Virginia DOT Northern Region

Figure 2-2. Performance measure survey responses. The list is sorted by the number of positive responses for each type of performance measure included in the survey.



2.4 THE ROLE OF PERFORMANCE MEASURES

Performance measures are not implemented for their own sake. Rather, performance measures are used to determine the degree to which the goals and objectives of an organization are being realized by that organization's activities (strategies and tactics), within the context of its operations. Figure 2-3 illustrates a framework developed by FHWA to provide a perspective on the role of performance measures. This is the G-COST pyramid, which includes Goals, Context, Objectives, Strategies, and Tactics. Each of these elements plays a role in the development of an agency's plans for managing its signal systems [25].

- *Goals* represent an articulation of the desired condition of the system. It represents what the agency wants to achieve.
- *Context* represents all of the background affecting the agency's activities with regards to traffic signal systems, ranging from the characteristics of the agency itself to the location of individual traffic signals. These give definition to the scope of the objectives.

- *Objectives* are more specifically stated activities that must be undertaken in order to realize the more broadly defined goals. Whereas a goal represents the condition that the agency wants its system to have, the objective represents something *actionable* that advances toward the goal.
- Strategies are *capabilities* of an agency that is employed in the delivery of an objective.
- Tactics include the specific *activities* and measures used to realize an objective.

In this framework, performance measures serve to help document the effectiveness of tactics, used within strategies, at achieving the objectives. Ultimately those objectives aim to advance the system toward the desired state articulated in the goal.

Consider the following example. One potential goal of an agency would be to have all of the traffic signals operated by the agency in a "good state of repair." An objective that would promote the attainment of that system condition would be to regularly check the system for detector failures and to correct these. A strategy that facilitates that objective would be to develop the capability of performing such a check in an automated fashion, such as by data collection and automated performance measurement. Finally, a tactic that spells out in detail how the agency will actually do so, would be to implement a system for automated signal performance measures that examines detector status and sends alerts when outages are detected.

The goals of agencies are likely to be quite diverse when considering all of the different jurisdictions of various sizes and geographic extents. However, it is still possible to offer insight into likely common goals, by considering the idea of "good basic service" that was identified in a FHWA report [3] based on results from the National Traffic Signal Report Card and extensive agency interviews. This culminated in the following statement that presents a reasonable aspiration for any signal system operator:

> "We will do our best to avoid making drivers stop, but when we must make them stop, we will delay them as little as possible, within the context of safe operation."

This statement really contains two key elements that reflect signal operation. The first of these is the element of *mobility*. Traffic signals control the right-of-way and necessarily stop drivers whenever there is a significant amount of traffic. Well-designed local and coordinated timing can reduce the number and impacts of those stops. The other element is *safety*, which means that right-of-way is transferred between competing movements at intersections with the least amount of collision risk for all road users. These two elements relate to how the traffic signal system affects the public.

Another element that is strongly related to both mobility and safety is that of maintaining the field equipment such that it operates reliably—in other words, keeping traffic signal equipment in a *good state of repair*. Besides the fact that this equipment represents an investment of resources, operation will suffer as components cease working. This third element also relates to how the signal system affects the public, albeit in a less direct manner.

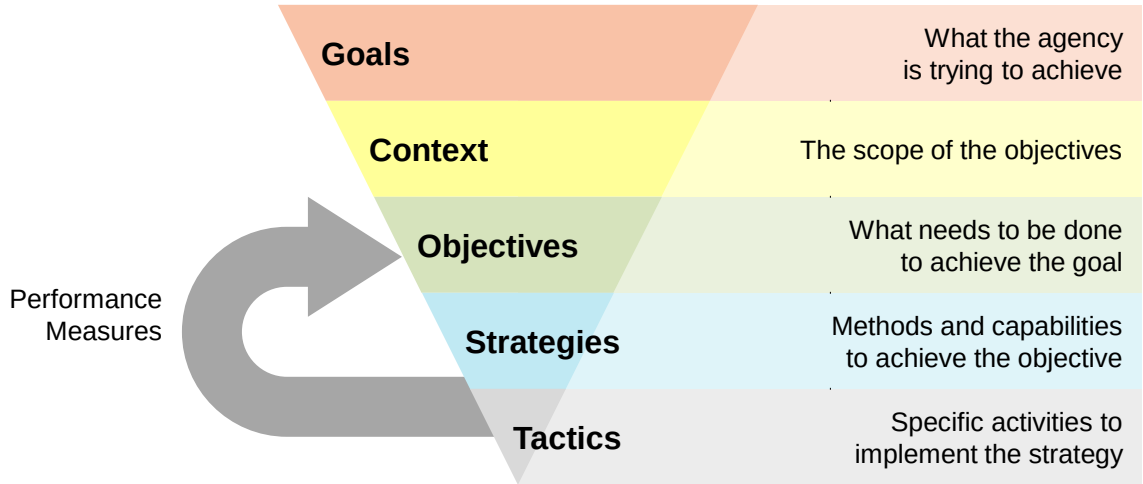
Such goals may be in tension with each other. For example, tradeoffs are made between safety and mobility. The relative importance of each goal is different for individual agencies.

The following section of this working paper discusses matters of context. First, the characteristics of the system are discussed. Traffic signal systems have a hierarchical nature that distinguishes both the manner in which they are maintained and operated as well as assessed. Next, the environmental characteristics of signal systems (that is, their location) are discussed. Finally, the characteristics of the agency are examined by consideration of agency capabilities.

After the discussion of context, a discussion of agency *activities* is presented which serves to relate the nature of objectives, strategies, tactics, and performance measures by example. Activities are considered for near-term and long-term time frames, and with relation to the five goals stated above.

Finally, the working paper concludes with a summary that connects agency activities to goals, performance measures, and potential data sources for those performance measures.

Figure 2-3. The GCOST framework: Goals, Context, Objectives, Strategies, and Tactics [25].



2.5 CONTEXT: SYSTEM AND AGENCY CHARACTERISTICS

2.5.1 System Characteristics

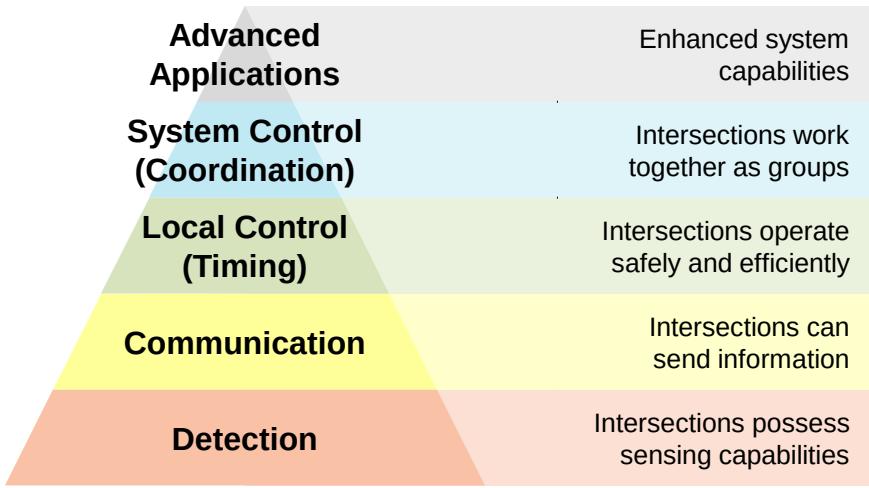
The term “traffic signal system” is often used to refer to groups of intersections that operate as coordinated “systems”. While some intersections and corridors will naturally be more critical than others, in this working paper we will adopt a more general definition of a signal system, meaning all of the signal-controlled facilities that an agency is responsible for. Ultimately, the goal would be to provide a good quality of service on all facilities, however that is defined by the agency.

As with any complex system, traffic signal systems contain a number of subsystems which operate with different functions. These vary widely with the geographic context and the specific components selected for

deployment, but it is possible to develop a generalized framework to show the interdependency among these components. Figure 2-4 shows this as a block diagram with five stacked components.

In general, each layer in this diagram represents a function that depends on the lower levels in order to operate at its best level of performance. Presuming that the most basic elements of the system (the signal heads, and a cabinet with a controller) are in place, *detection* is the most fundamental component where useful discussion of system needs begins. Without detection systems, signals must operate as fixed time, and it is impossible for the system to use even the most basic methods to respond to traffic conditions, or develop intelligence about conditions. Detectors measure the presence of traffic demand (vehicle, pedestrian, and other modes). Keeping detection systems in working order is typically the most time consuming maintenance activity for signal systems, or ITS in general.

Figure 2-4. The conceptual hierarchy of needs for traffic signal systems [18].



Communication systems are necessary to remotely access intersections, retrieve data from the field, and facilitate coordination. Signal systems feature several different kinds of communication systems: internal connections within the cabinet; communications between intersections along a coordinated system; and communications to the outside world.

Local control refers to the timing elements that are determined at the local controller level, typically controlling details of the phase-switching operation—such as the duration of the yellow change interval. These parameters enable the intersection to operate independently of the rest of the world, as occurs at all times by design for isolated intersections; during certain times of day in locations where there is little benefit to coordinating the system; or by accident when the mechanisms for implementing coordination has failed. Although the signal will continue to operate in absence of detection or external communication, the quality of that operation will be degraded.

System control refers to the timing of groups of controllers to provide coordinated timing for signalized corridors, interchanges, and grid networks. This functionality can profoundly impact the quality of service of

the facility, and will be considerably degraded if any of the individual intersections is not synchronized with the others.

Advanced applications refer to enhanced system capabilities that depend on the functionality of the lower levels to be effective. Adaptive control is an example. It is not possible without working communication or detection, and adaptive decisions at the system level must ultimately be implemented at the local level.

These five categories of system needs define the types of performance measures that can be developed with regard to specific uses, when the context of the system is considered. Ultimately, these provide answers to the five general questions that a signal practitioner would likely have about the condition of their system:

- Are the detection systems working?
- Are the communication systems working?
- Are there any opportunities to improve local control?
- Are there any opportunities to improve system control?
- Are the advanced systems achieving their intended operation?

The level of detail needed to formulate the answers to the above questions—that is, to identify the appropriate performance measure and the amount of data to include—depends on the specific activity being undertaken. The next section discusses practitioner needs relative to those activities.

2.5.2 Environmental Characteristics

The environment surrounding a traffic signal system plays a critical role in setting the context for goals as they can be applied to that particular system. The *Signal Timing Manual* [27] includes a more comprehensive discussion of operating environments for signal systems. The following discussion highlights elements that are relevant to performance measurement.

Modes of travel. The modes of travel that are served by a traffic signal will define the scope of analysis relevant to the signal, and which elements of performance are relevant to the users of the signal. While the vehicle mode is present at all signalized intersections, other considerations include pedestrians and bicyclists; transit vehicles; and preemption for emergency vehicles, rail, and drawbridges. In some locations, freight and heavy vehicles may pose a special consideration for performance measurement.

Road class. The road class plays a role in determining the objectives of operation as well as user expectations. The objectives are different for arterials, interchanges, collectors, and local streets, on a spectrum ranging between more mobility to more accessibility.

Signal system location. The characteristics of the area will have some influence on the objectives of the operation, and hence the relevant performance measures. For example, isolated intersections will not have coordination as a primary interest, whereas for arterials this is will be one of the most important

considerations. The characteristics of the operation will also vary depending on whether the location is more urban or more rural, and whether growth is occurring in the area.

Other geographic characteristics. The degree of signal density may influence the means of implementing performance measures. For example, a smaller agency such as a city may be well positioned to establish communication to each intersection, while a larger and more dispersed agency might not be able to do so as easily.

Temporal characteristics. The characteristics of signal system operation can change considerably depending on many factors related to time. Conditions change by time of day, day of week, and seasonally. Some locations may have very predictable patterns, where others may have unpredictable patterns.

2.5.3 Agency Capability Maturity Characteristics

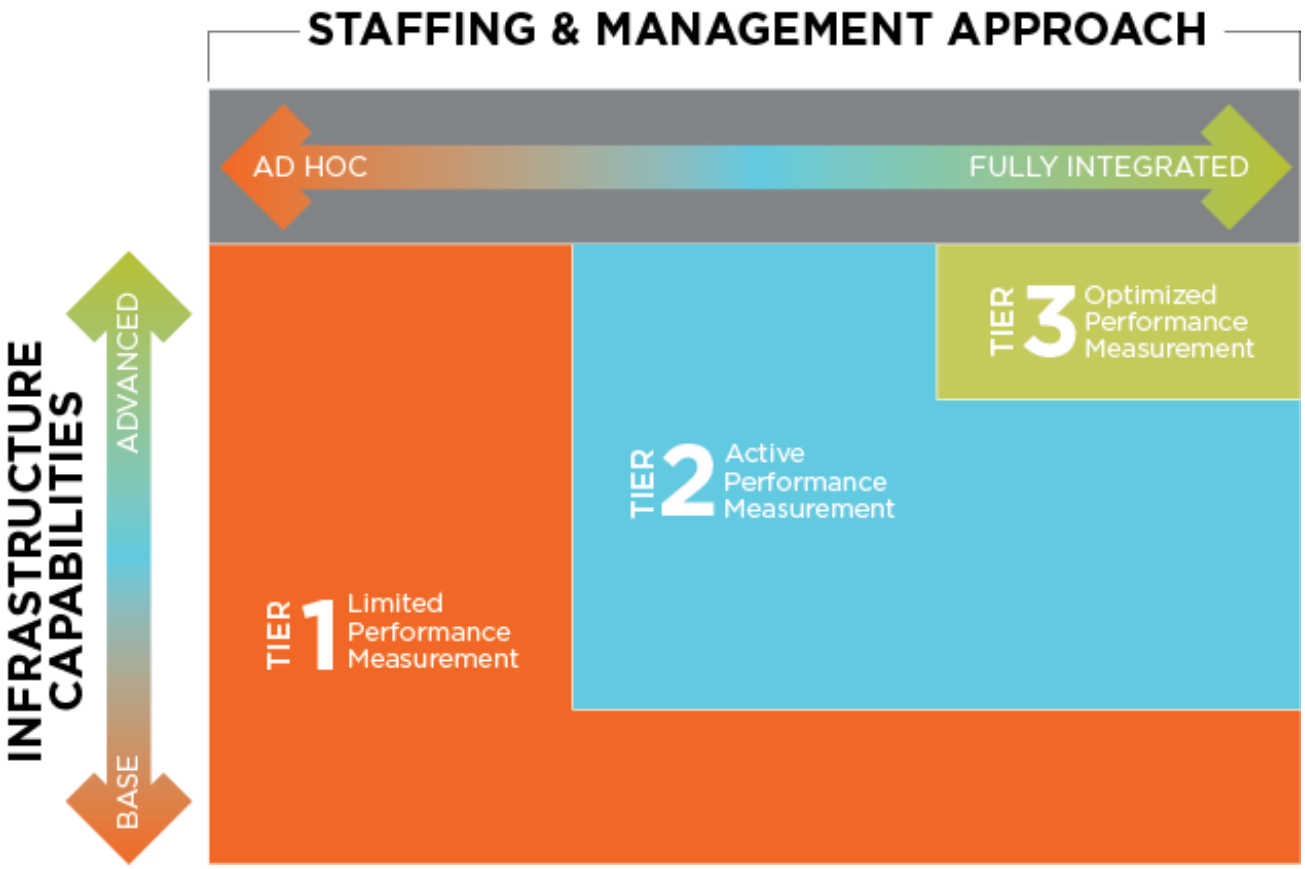
Another important consideration relevant to signal systems context is the *capability* of the agency. The initiation of a signal performance measure program can enhance those capabilities, but like other technological solutions, it will build upon existing infrastructure and personnel resources, and introduce some new components that have to be implemented and maintained.

The Capability Maturity Model (CMM) is a concept that originates in software engineering, but which has been applied to numerous processes. It describes the relative state of development of processes on a spectrum from initial, ad hoc actions to managed and optimized procedures. In the context of traffic signal systems, infrastructure capability is an important enough consideration that it can be considered as a second dimension in addition to the procedural approach. Thus, a two-dimensional CMM chart is developed, as shown in Figure 2-5. This diagram shows a conceptual space with a vertical dimension showing infrastructure capabilities, and a horizontal dimension showing the level of process integration in the staffing and management approach. The outlined region is divided into three tiers.

- Tier 1 represents the initial situation. It is possible to develop performance measures on an as-needed basis, but considerable effort is required to do so. This is true when the infrastructure capability is low, but even if the infrastructure is more advanced, a lack of procedural integration will lead to the same situation.
- Tier 2 indicates the level at which the processes have matured beyond initial and ad hoc activities, to documented and repeatable processes which can be used on a regular basis. To execute a evaluation based on ATSPMs, the practitioners do not have to start from the very beginning each time, but can rely on established tools. A minimal level of infrastructure capability is needed to achieve that, as well as some investment in resources to begin integrating ATSPMs into agency business processes.
- Tier 3 indicates a potential level of maturity where ATSPMs are fully integrated into business processes, and the effort in developing those tools are no longer focused on developing new capability, but more on optimizing existing capabilities. To function at this level, the infrastructure

capability is no longer considered provisional, but is a dedicated system component. Also, the technology is no longer considered experimental but is an integrated part of system management.

Figure 2-5. A two-dimensional capability maturity model for traffic signal systems.



Although infrastructure capability is essential, it is not necessarily required to invest a high level of resources to develop that capability. Although it would be possible to develop ATSPM capability by means of a capital project, this is not the only way to do achieve that end. Incremental upgrades of equipment and revision of policies and procedures to allow more gradual growth is another way.

For example, consider that when a new intersection is constructed, an agency is already committed to buying and maintaining the necessary signal equipment, as well as electrical service costing a certain amount per month. The additional investment for communication is marginal, and could be built in to all systems being developed from some point forward, laying the groundwork for future capabilities. Similarly, detection is another area that varies considerably. Most intersections feature some sort of detection to actuate the traffic signals. The creation of a few additional detection zones (if needed) to facilitate performance measurement requires a marginal increase in the level of resource investment, and reflects a place where small changes in policy or practice can develop future capability. Improvements to technology may reduce or eliminate the cost of these changes.

The next working paper will discuss data requirements in much more detail. For now, there are three basic infrastructure components needed to implement ATSPMs. The first is the data collection system, which could be built into the controller or provided by an external data collection device. The second is the development of a means to communicate that data from the field. The third is a system to manage that data and compile it into ATSPMs. The UDOT performance measure system represents one way to achieve the third component.

The staffing capability is another important consideration worth discussion at this point. This varies considerably by agency, largely depending on the number of traffic signals that have to be managed. Some smaller agencies really have one part-time signal practitioner, while larger ones may have a staff of several engineers and technicians. Some agencies rely on contractors to do certain parts of the enterprise, such as signal timing or maintenance. In addition to these traditional roles, there will be an increased role of information technology (IT) staff in the implementation of performance measures, which may be a new approach for some agencies. All of these individuals will be stakeholders in the development of an ATSPM system. The types of performance measures that are desired for implementation should reflect the needs of the potential users, so the activities mentioned earlier may not necessarily be strictly confined to those of the agency itself, but might also include contractors or partner agencies as well.

2.6 PRACTITIONER ACTIVITIES

Specific objectives, and the strategies and tactics applied to achieve them, will vary considerably by agency. Rather than try to enumerate these in a prescriptive manner, this working paper explores the nature of objectives based on the time scale involved, and then offers an example-based discussion of the various *activities* undertaken relative to some of the five goals presented earlier.

The life cycle of a signalized facility comprises all of the aspects of the signal system that have to be attended to by practitioners. Figure 2-6 presents a block diagram that illustrates the conceptual stages in the life cycle. These represent various activities that are undertaken by practitioners. Next to this block diagram are two arrows that represent that there is a transition during system life cycle between both the time scale of the activities and the types of data that can be applied to each.

As the system moves from planning to operation, the time scale shrinks from long-term to near-term. Planning and design activities are interested in predictive estimates of system condition over the entire life cycle. Related activities such as setting policies for existing systems will be interested in a review of system conditions over a longer time period. Meanwhile, as those designs and policies are implemented in real systems, the operation and maintenance will be more concerned with both the day-to-day operation as well as short-range trends that pinpoint where problems may be growing.

Early in the life of a facility, there is often a lack of field data that can be used to facilitate analysis. Some measured data may be relevant at this level—such as the volumes of parallel or crossing streets and other facilities in the region, or for existing volumes for reconstruction. However, because the facility of interest might not yet physically exist, its performance would in most cases need to be modeled, at least to establish

initial timings to be refined later (perhaps assisted by ATSPMs). In the pre-design stages, such analyses are often made at a very high level, in the context of the overall transportation system. After the decision has been made to proceed with the development of a facility, the design stage will also proceed with modeled data at a more detailed level. This is followed by construction, where those designs are implemented.

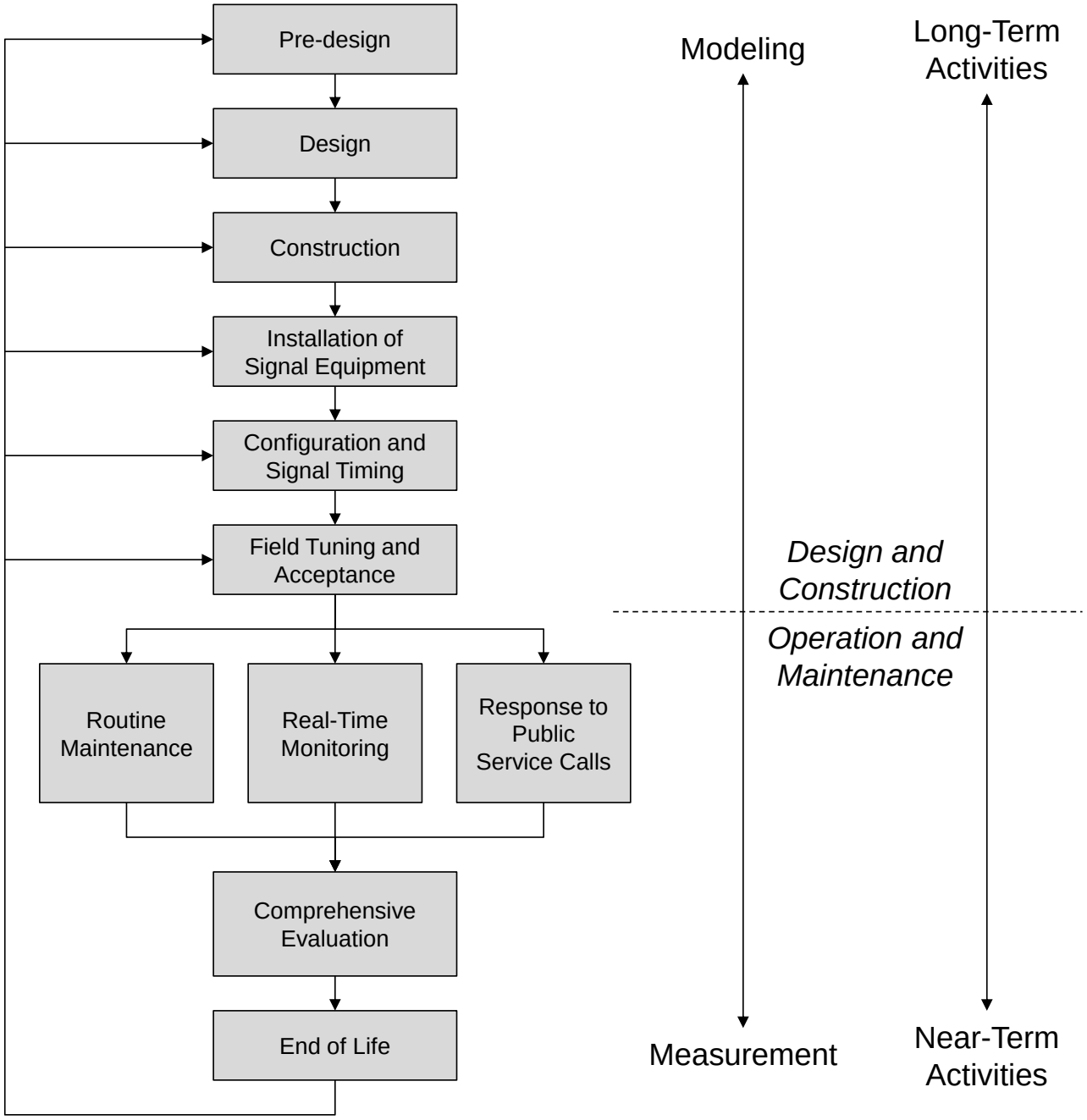
After a facility is opened, it becomes possible to begin collecting data. The balance begins to shift accordingly from modeling to measuring. Models continue to have a role, for example in travel demand forecasting or in modeling "what-if" scenarios. ATSPMs have been used to develop timing plans for a newly opened system, with application of traffic engineering principles and *without* extensive software modeling [26]. One limitation of ATSPMs is that many of the metrics depend on detectors. Several ATSPMs can identify the existence of oversaturation but they cannot tell its full extent. Although ATSPMs cannot entirely replace the insights gained by field observation, it is also not possible to observe every intersection in a system at all times of day. ATSPMs can help identify which locations are worth investing time to observe, and which times of day problems may exist.

While the facility is in use, the immediate activities of signal operators can be augmented by ATSPMs. In current practice, modeling is not commonly done on a day-to-day basis for tasks such as routine maintenance, real-time monitoring, or response to public service calls. However, in absence of field data, agencies often rely on input metrics to drive their activities rather than outcome assessments. For example, retiming and maintenance activities are often done on a rotation basis rather than on need. ATSPMs can be used to prioritize such activities so that resources are better used.

At a planning level, decisions are made to improve or reconstruct roadways, or to make other investments such as the installation of adaptive control and other advanced systems. The "end of life" of a facility, or perhaps more typical of signal systems, the process of replacing and upgrading equipment, involve similar types of decisions. Ideally, a comprehensive evaluation of the facility condition would be used to inform those decisions, and perhaps more importantly, *measure their impact,* not only during peak periods, but over all times of day, and over time.

To outline the objectives for ATSPMs, the framework of the system life cycle will be used. In particular, the time scale of the activities undertaken by practitioners provides a basis for identifying uses of ATSPMs. For each action, the current method of collecting information is considered, and an example use of ATSPMs is presented.

Figure 2-6. The evolving role of performance measures and activity time frames during a conceptual traffic signal system life cycle.



2.6.1 Near-Term Activities

Near-term activities are typically those related to the maintenance and operation of the system. These activities typically fall under the overall banner of "traffic engineering" and often comprise much of the daily activities of practitioners when they are not overtaken by more immediate issues, which are sometimes described as "putting out fires". Some larger agencies may have a traffic management center where these

activities take place, whereas for others, these represent relatively frequent activities of a few practitioners in addition to many other tasks.

Identify broken detection and unreliable communication. Keeping signal systems working involves handling problems with the system components. Detection systems in particular can require considerable effort to maintain in good working order. At present, outside of issues that are discovered and corrected during scheduled preventative maintenance, many agencies rely on public calls or their own observations to find problems with equipment. ATSPMs can provide a number of heuristics to find such issues in an automated fashion.

Figure 2-7 shows the results of a report sent out in email by the UDOT ATSPM system. This report displays signal locations where various indications of detector errors were observed in the high-resolution data. This report would enable a practitioner to potentially address problems before there are substantial operational problems or public calls are generated. Similar reports can be generated for communication systems and other pieces of equipment.

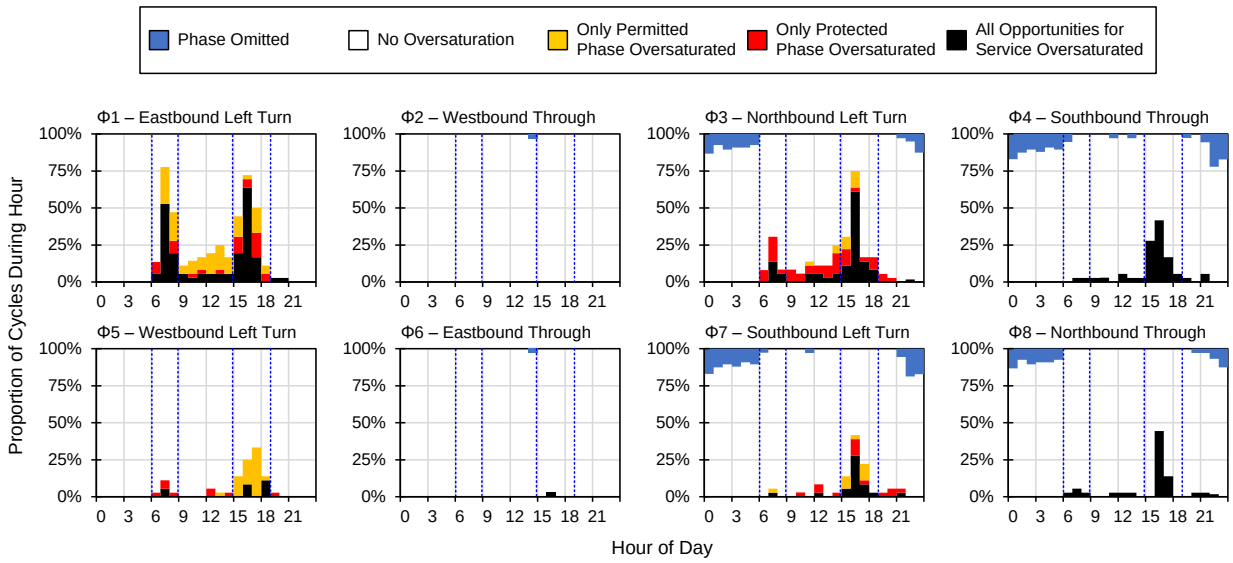
Figure 2-7. An example of an email alert based on analysis of high-resolution data that is generated by the UDOT ATSPM system.

```
 --The following signals had too many force off occurrences:
1019 - 300 West & 800 South - Phase: 2 (Force Offs 100%)
1019 - 300 West & 800 South - Phase: 4 (Force Offs 100%)
1019 - 300 West & 800 South - Phase: 6 (Force Offs 100%)
1019 - 300 West & 800 South - Phase: 8 (Force Offs 100%)
7070 - 3300 South & I-15 SPUI - Phase: 1 (Force Offs 100%)
7070 - 3300 South & I-15 SPUI - Phase: 5 (Force Offs 100%)

 --The following signals had too many  max out occurrences:
1035 - West Temple & 1700 South - Phase: 4 (Max Outs 100%)
1035 - West Temple & 1700 South - Phase: 8 (Max Outs 100%)
1122 - University St & 400 South - Phase: 5 (Max Outs 91.7%)
7635 - 600 South & 300 West - Phase: 2 (Max Outs 100%)

 --The following signals had too few records in the database:
5297 - Main St. (SR-165) & 1700 S (Providence) - Phase: 0 (Missing Records)

 --The following signals had unusually low detector hits:
6045 - US-6 (Spanish Fork) & Canyon Road - Phase: 2 ( Has Unusually Low Counts. )
6045 - US-6 (Spanish Fork) & Canyon Road - Phase: 6 ( Has Unusually Low Counts. )

 --The following signals have stuck ped detectors:
5033 - 2100 South (Wilson) & 1100 West - Phase: 2
5507 - Lincoln & 25th - Phase: 2
```

Respond to public service requests. Public service requests are a familiar reason for agencies to inspect signal operations. The *Signal Timing Manual* [27] discusses sixteen common operational reasons for public calls, and potential things to check in response to each of these. Many of those items require an examination of the timing plan to identify potential reasons for the call to have been generated. This activity may lead to solutions to adequately respond to the call. Field observation would generally be needed to validate whether the public call represents a problem warranting action, or to verify that the action has the desired effect. ATSPMs can assist in this task by potentially showing whether the subject of the complaint has an effect on traffic performance, identifying whether the problem exists, whether it is recurrent, and by demonstrating that adjustments resolved the problem.

An example citizen concern is inadequate green time to proceed through an intersection during one cycle. Figure 2-8 shows a chart showing the proportion of cycles ending in split failure per hour at an eight-phase intersection. From this chart, it would be possible to confirm that reports of inadequate green on several of the turning movements during the peaks are likely true. Given the distribution of split failures across the eight movements, a possible adjustment of green time away from phases 2 and 6 and toward the other phases may be warranted.

Figure 2-8. Proportion of split failures per hour by phase at an eight-phase intersection [28].



Identify intersections with immediate operational issues. Some locations experience traffic dynamics that necessitate continuous monitoring. Objectives of monitoring and immediate adjustment include the following:

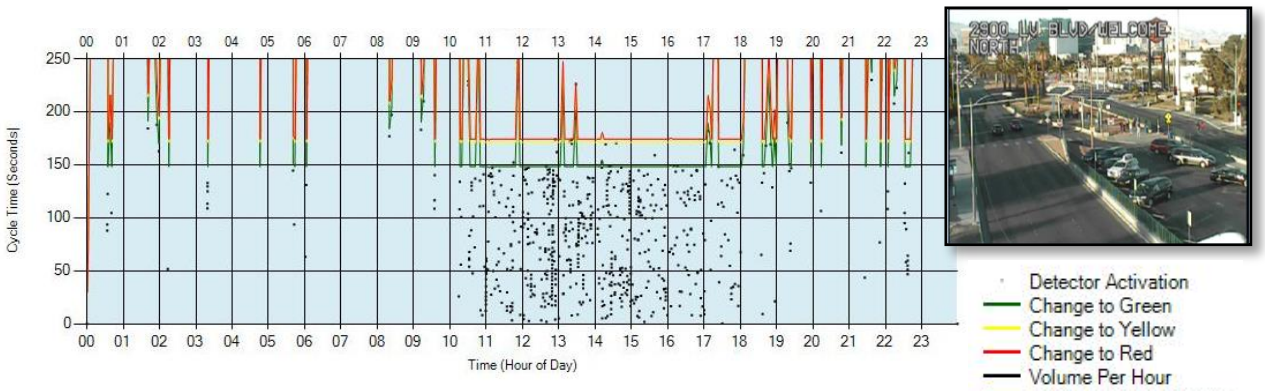
- Identify and fix intersections in flash and duration of flash
- Identify intersections experiencing split failures
- Identify intersections with long vehicle queues
- Identify intersections with long vehicle, bicycle, and/or pedestrian delay
- Identify intersections with high conflicting demand between vehicles, bicycles, and pedestrians
- Identify intersections with high numbers of red-light-running occurrences
- Identify intersections where vehicles are frequently caught in the decision zone
- Identify intersections that are out of sync with the corridor TOD plans
- Identify corridors where vehicles are frequently arriving on red
- Identify locations with a high number of preemption/priority occurrences

At present, this is done mainly through video surveillance and in some cases with real-time status displays. Some agencies will make adjustments to signal timing based on this information. Real-time status show conditions in the present moment, but does not necessarily indicate whether those conditions are anomalous and need attention, leaving that to the practitioner's experience and intuition. The practitioner

could be better informed with the use of ATSPMs, which can provide a recent history to show how long current conditions have been unfolding, and a more extensive history to determine whether those conditions are recurrent or represent a need for action.

Figure 2-9 shows an example of combining a real-time video display with a performance measure visualization showing a more widespread history. The inset graphic shows the view of a pedestrian crossing near a popular tourist attraction, while the performance measure shows the number of pedestrian button actuations distributed throughout the day relative to the phase status of the associated movement. In this case, it would be possible to compare current conditions with a history of actuations on a typical day, to help determine if action is warranted. It is not difficult to imagine the utility of a metric such as this if combined with passive pedestrian detection, particularly in areas with occasional heavy traffic.

Figure 2-9. Real-time monitoring example: Pedestrian actuations on New Years' Day at a pedestrian crossing near the welcome sign in Las Vegas, Nevada [29].



Incident management. Agencies must sometimes attend to prominent problems, sometimes with added pressure from the press or elected officials. This can require extensive investment of resources as well as increased focus on demonstrating results. Incident management objectives include those related to the previous activity of monitoring, as well as the following.

- Identify corridors with long travel times
- Identify corridors with highly variable travel times

In current practice, incident management requires tailoring the signal operation to match the present conditions, such as adjusting signal timing plans on alternative routes or implementing custom timing plans [27]. These can sometimes be planned in advance for special events. ATSPMs enable a more rapid and comprehensive evaluation of incident management measures.

ATSPMs were put to such use in Indiana during an unplanned diversion of Interstate traffic onto a parallel arterial route. Figure 2-10 shows a map of the 62-mile detour route. The route included diversion along an arterial with 12 signalized intersections. For about a week, the main concerns were the installation of temporary signals at two intersections that were formerly under two-way stop control. After that was

accomplished, attention was turned to the existing signalized section, and engineers were sent to implement an emergency plan to progress detour traffic through the system as efficiently as possible.

Figure 2-11 shows a series of coordination diagrams which illustrate conditions shortly after the diversion compared to after the implementation of a special pattern to deal with the detour traffic. Each of these shows the time of individual vehicle arrivals (black dots) relative to the signal status at that time; the green shaded region represents the green interval, so more dots in that region correspond to more arrivals on green (and better progression). Clusters of dots represent platoons. The overall value for each 24-hour period is shown by the number in the corner of each figure.

In Figure 2-11a, c, and e, the impact of the detour traffic on the existing timing plan (which was fully-actuated, non-coordinated except for the AM peak, which had a 90 second cycle length) is seen. There is no coordination for most of the day, and although the percent on green (POG) is high because of the long green times, there are still many arrivals on red, and the patterns are not consistent. Figure 2-11b, d, f, and g show the impact of implementing a special coordination plan. Each intersection has a long green interval with platoons of vehicles densely clustered within that green. Each one exhibits a higher percent on green than before the plan was implemented, confirming that the objectives of obtaining an extremely good quality of progression through the system.

The impact on travel times, measured using probe vehicle data, is shown in Figure 2-12. This chart shows box plots of the distributions of travel time for each hour before and after the implementation of the detour plan. During each hour of the day between 5:00 and 23:00, there was a reduction in the median travel time, and for most a reduction of the variability, as indicated by the total height of the box. The use of ATSPMs from high-resolution data, in conjunction with external measurements such as travel time, is a powerful combination that can demonstrate impact to stakeholders during an incident.

Figure 2-10. Detour of northbound I-65 in August-September 2015.

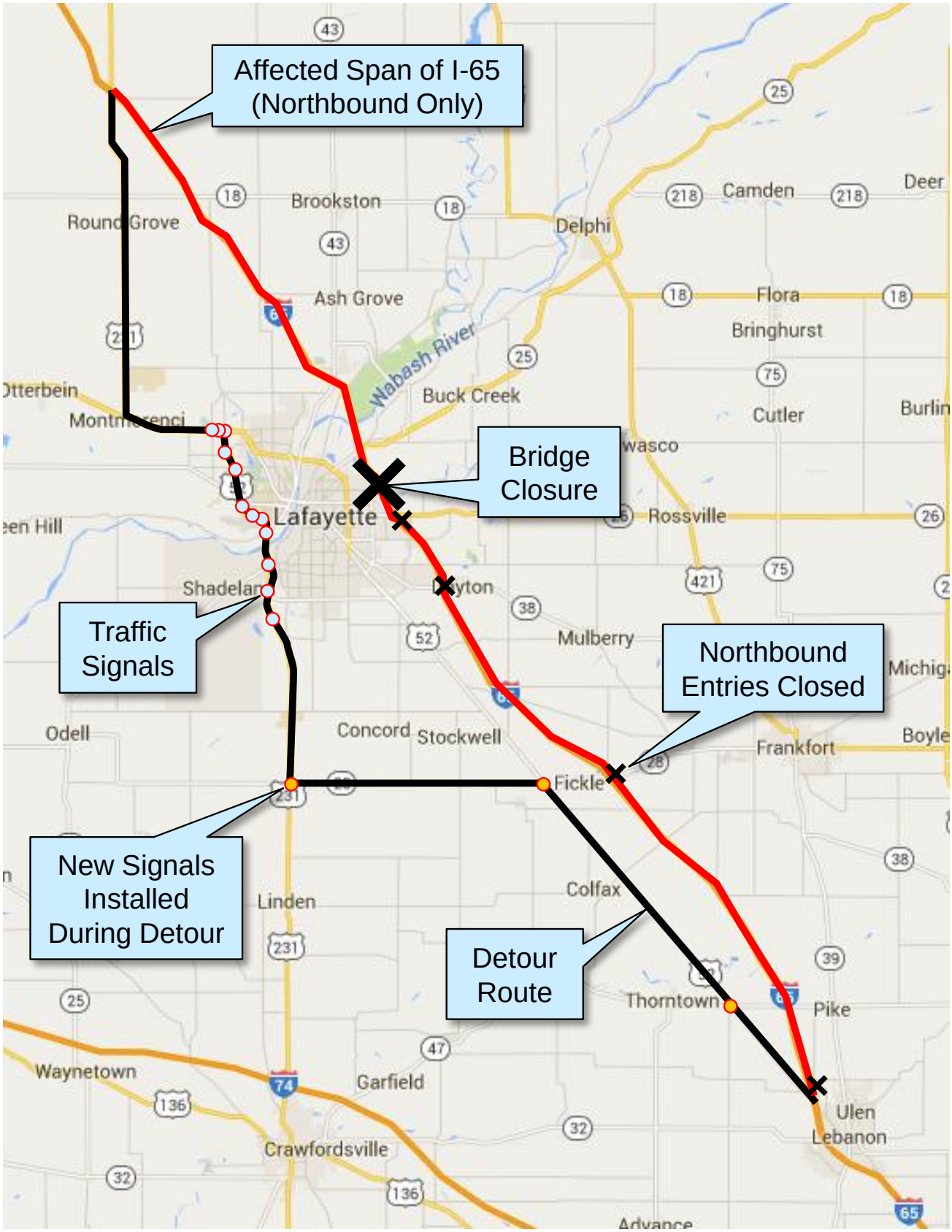


Figure 2-11. Impact of a deployment of an "emergency" timing plan: impact on progression quality. "Before" data is from 8/11/2015 and "after" data is from 9/1/2015.

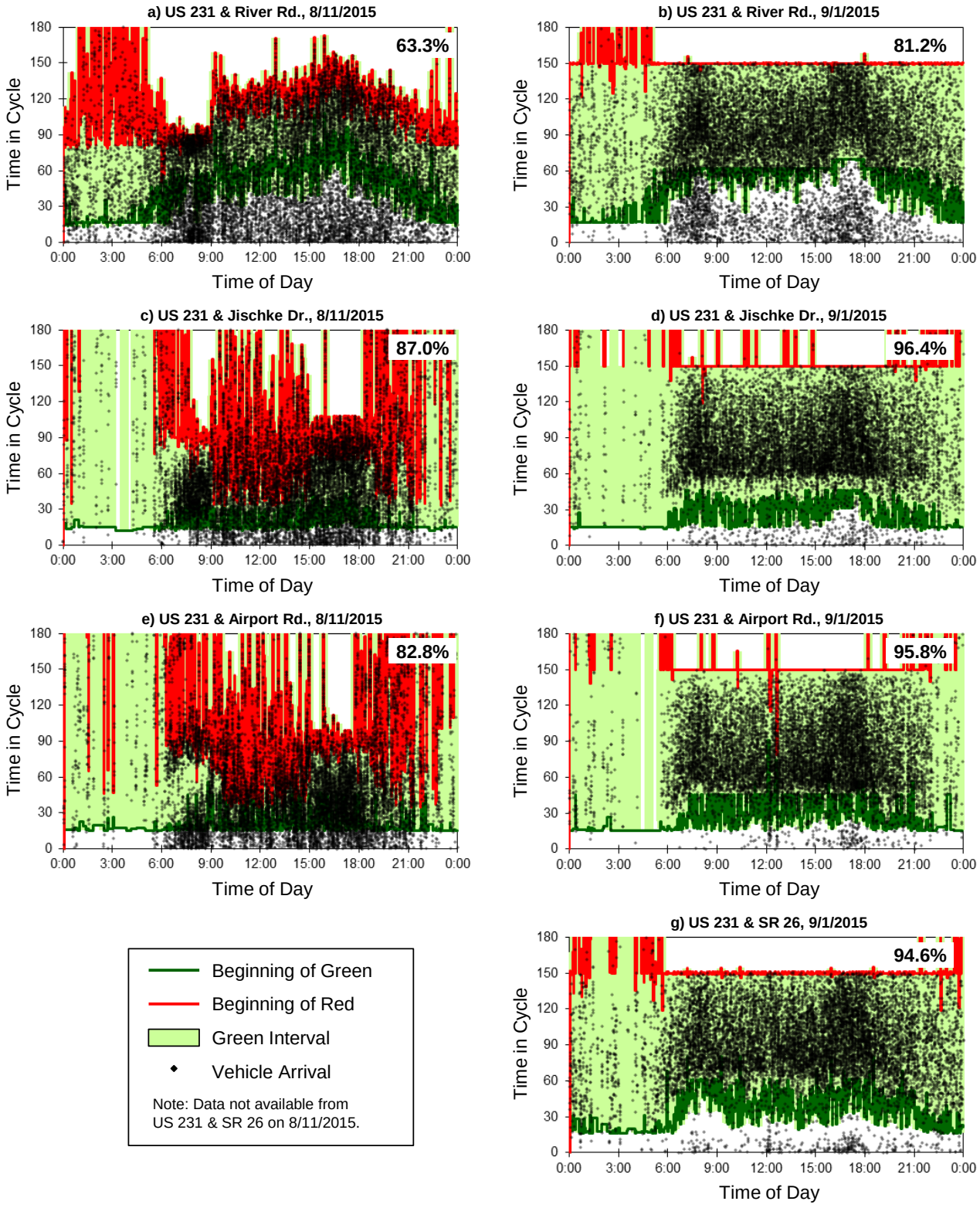
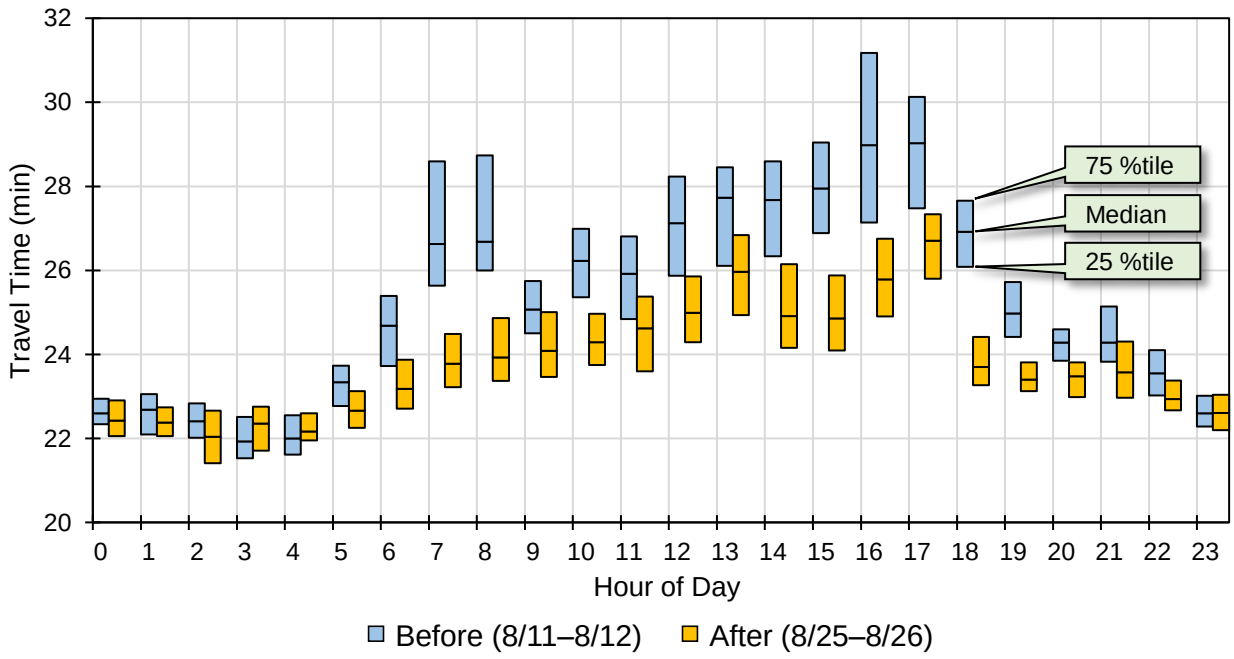


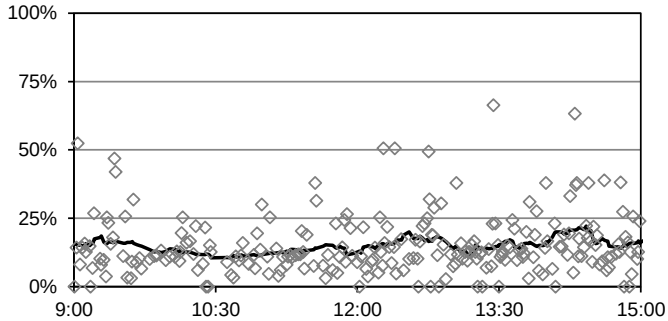
Figure 2-12. Impact of a deployment of an "emergency" timing plan: impact on travel times [30].



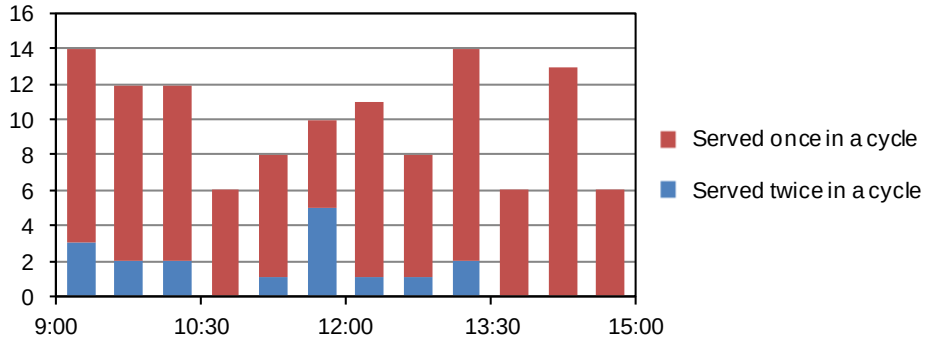
Configuration and field tuning. Implementing signal timing plans is a common activity of signal practitioners. Sometimes, the task of programming plans involves some translation from the intended design and the actual programmed parameters. In current practice, signal practitioners typically rely on their own experience and intuition to navigate these sorts of issues. New and less familiar features are usually tested on the bench before used in the field. Even then, conditions are often very different between the two, so often extensive field observation is needed to verify whether programming has achieved the desired operation. ATSPMs can help extend that observation to cover a larger time period, to assist in that task.

Figure 2-13 shows an example of an application of relatively simple performance measures used to evaluate the impact of a controller feature called phase reservice. Often during coordinated operations, a controller will dwell in main street green when not serving other calls. After the permissive periods for the minor movements are expired, ordinarily demand on those phases will have to wait till the next cycle. Phase reservice allows the controller to break out of the dwell state and serve those phases earlier. Figure 2-13 demonstrates the impact of this feature at a "T" intersection with minor movements of the side street (phase 8) and a mainline left (phase 1). It is possible to determine if any capacity problems were created for the mainline through phase (phase 2), by looking at volume-to-capacity ratios (Figure 2-13a). In addition, the number of times that phase reservice was put into effect can be seen, as analyzed by Figure 2-13b, c, and d.

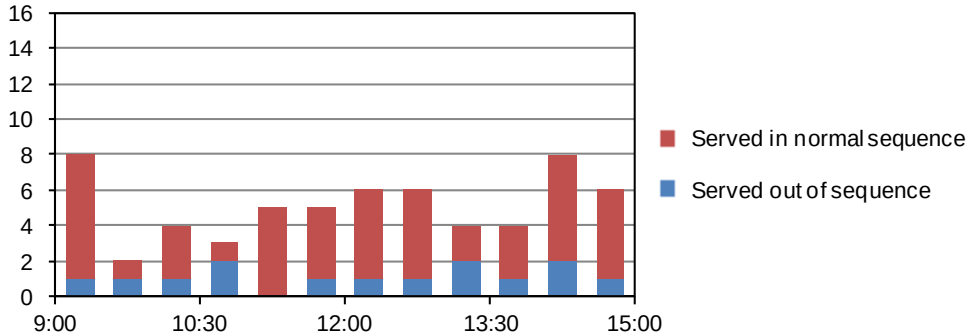
Figure 2-13. Examination of the effects of using a phase reservice feature at a signalized intersection [26].



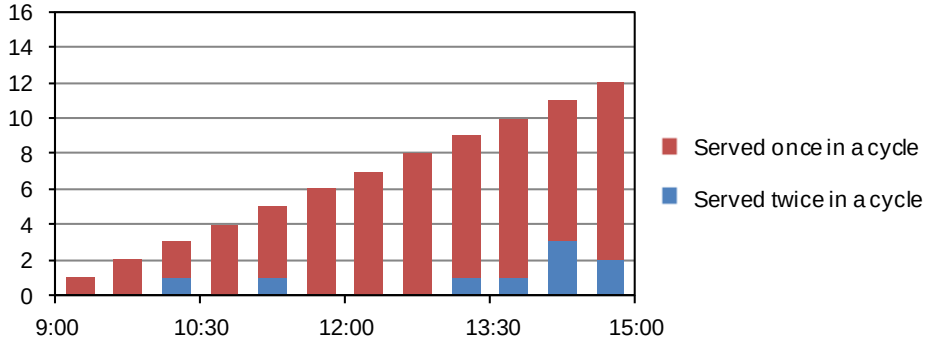
a) Volume capacity ratio for Φ2 while phase reservice was being run



b) Number of times where Φ1 was served in the 0900-1500 timing plan on 2/3



c) Number of times where Φ1 and Φ8 were served in the same cycle in the 0900-1500 timing plan

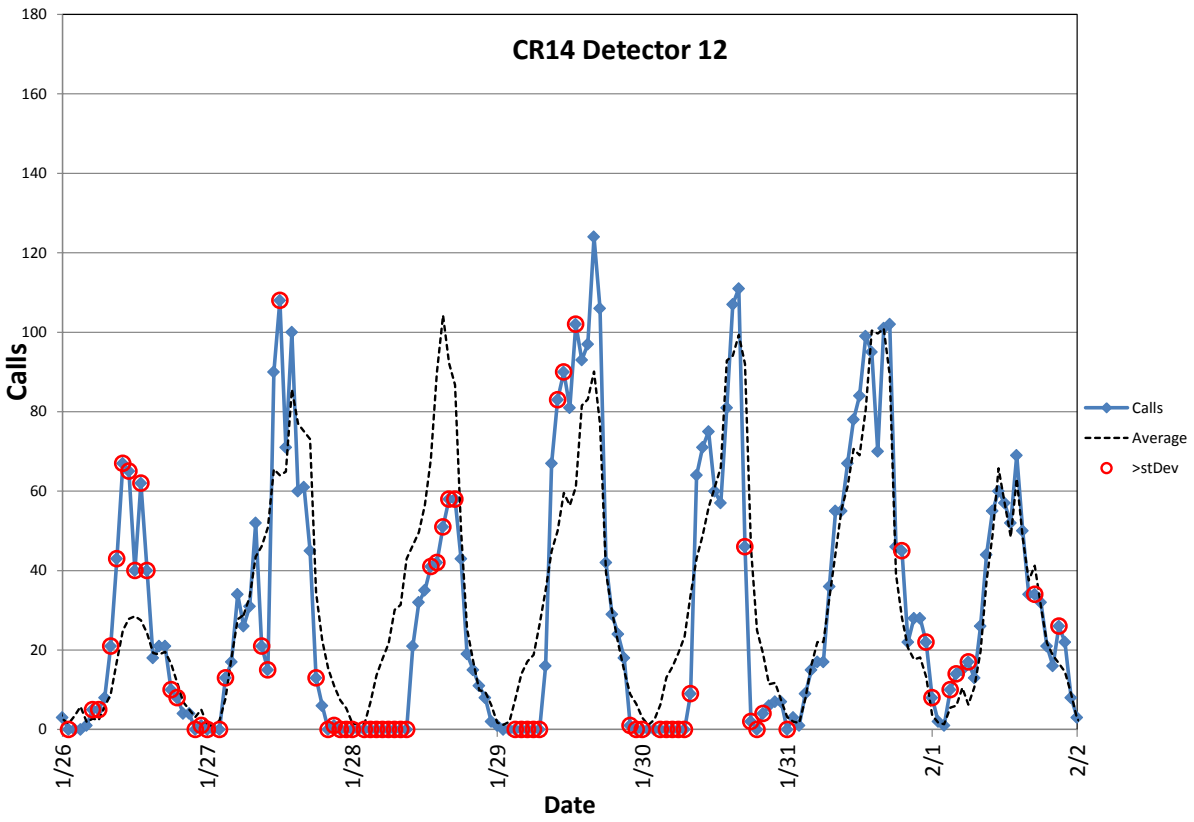


d) Number of times where Φ8 was served in the 0900-1500 timing plan on 2/3

Repair broken detection and unreliable communication. Agencies sometimes take proactive efforts to eliminate problems with equipment with a program of preventative maintenance. Field visits will be periodically undertaken to determine whether equipment such as detectors are experiencing errors, and if any are found they can either be fixed or a work order prepared when more extensive work is needed. ATSPMs can help detect errors that do are not occurring during field visits, and strengthen a preventative maintenance program.

An example of a detector error that would not have been captured by periodic field visits is shown in Figure 2-14. This diagram shows the number of hourly detector calls on a given series of dates, compared to an average value compiled from previous weeks. A statistical comparison is made of the number of calls, and the graph flags the hours where the current count was found to be significantly different from the average value with a red circle. Notice that during the three days in the middle of this week, there are a lot of times when the counts drop to zero during the overnight periods. This was due to a failure of the detector, the impact of which was to put its associated phase in recall during the overnight periods. This did not generate a public service call, but did lead to degraded performance because the signal would effectively dwell on this phase rather than on the mainline green as intended. Based on this data, a field visit was made and the error was resolved. In this case, the problem turned out to be a bad cable that, during overnight periods, was losing contact during low temperatures in the middle of winter. Other agencies have had similar experiences with video detection that fails during nighttime or under certain weather conditions.

Figure 2-14. Comparison of detector calls versus average values and errors determined by statistical analysis [31].



Adjust signal timing to improve operations. Agencies also often schedule periodic corridor retiming as part of an overall signal management program. Typical objectives of retiming include the following:

- Sync intersections to corridor TOD plans
- Adjust boundaries (start/end times) of TOD plans
- Adjust number of TOD plans
- Determine what times of day to coordinate and which intersections to coordinate
- Decide whether to combine or break up corridors running with common cycle lengths
- Allocate green time equitably between different movements (e.g., adjust splits)
- Reduce travel times and improve travel time reliability (e.g., improve offsets)
- Reduce long or residual vehicle queues
- Reduce delays caused by preemption/priority occurrences
- Reduce delays to pedestrians

In current practice, a full retiming often necessitates data collection including manual turning movement counts, software modeling to determine the new timing plan, followed by configuration and field tuning. In addition to assisting with the actual programming as mentioned earlier, ATSPMs can be used to assist retiming efforts by identifying opportunities for improvement. This can help adjust the schedule for retiming

to ensure that locations needing attention obtain it sooner, while resources are not expended on locations that do not really need them. In the case that a complete retiming is needed, it may be possible to obtain turning movement counts from the field in an automated fashion, if appropriate detection is available [32].

An example of a top-down investigation of signal retiming opportunities is presented in Figure 2-15. These charts show the number of split failures occurring in the system at various levels. First, the overall number per corridor is shown in Figure 2-15a, showing the daily count over six months. The analyst can then "drill down" to the corridor level to view the total number of split failures by intersection and movement. One corridor that features prominently in the system level view is shown in more detail in Figure 2-15b. Notably, the problems with split failures seem to be concentrated at one end of the system, so a complete corridor retiming is probably not warranted. Figure 2-15c shows a more detailed study for one of the intersections in the part of the system experiencing a heavy amount of split failures; this chart shows the hourly rate of split failures at the intersection before and after split adjustments, with a visible decrease occurring after the split adjustment.

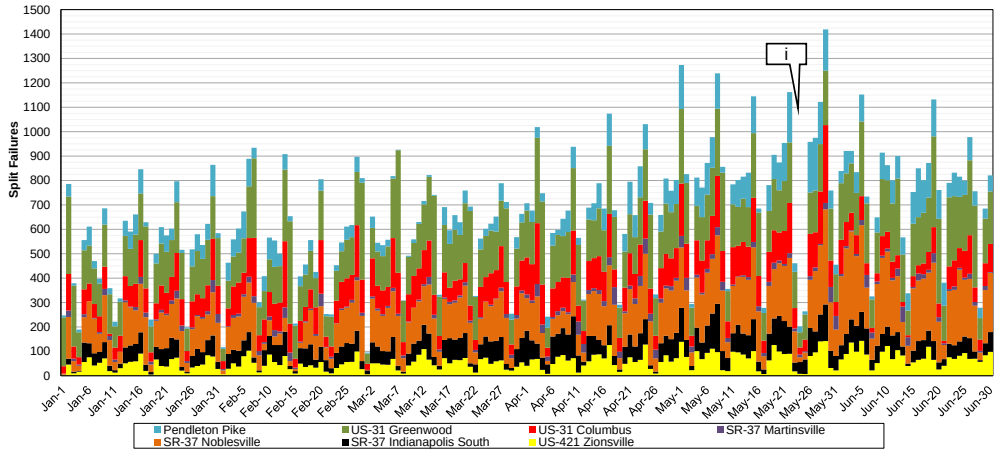
Evaluation of intersection safety. Safety might be considered as the primary objective of all traffic signal control. Timing plans are frequently adjusted, or other intersection treatments implemented, to deal with known safety issues. Safety-oriented objectives of signal timing adjustments include the following:

- Reduce conflict opportunities between vehicles, bicycles, and/or pedestrians
- Reduce red-light running occurrences
- Reduce the number of vehicles caught in the decision zone
- Identify areas of poor speed compliance

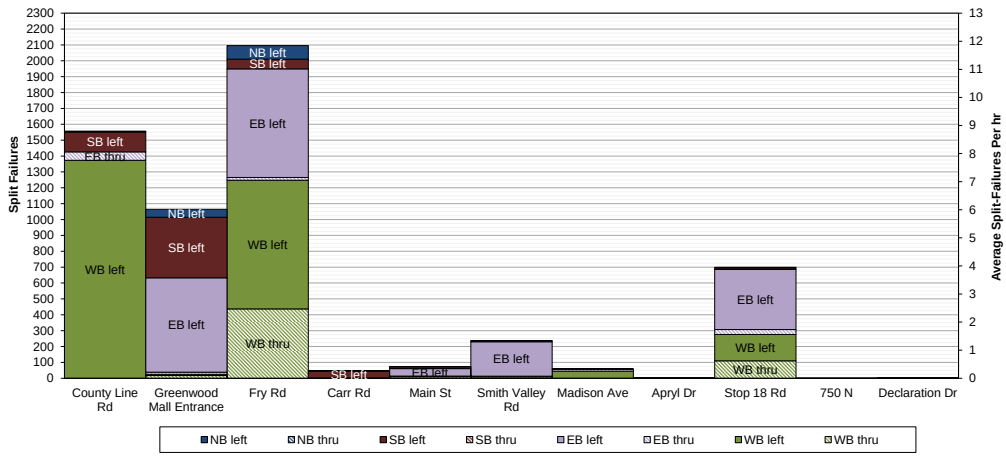
Presently, agencies rely on crash history, reports from the public, or other analysis techniques such as traffic conflict studies to identify safety needs. ATSPMs can also assist in this endeavor by enabling widespread observation of certain traffic events over all times of day.

Red light running (RLR) is a critical safety concern at signalized intersections. These can be detected automatically by analysis of detector activity relative to the signal state. Analysis of RLR activity can be used to identify locations where action should be taken, as well as to quantify the effects of those actions. Figure 2-16 shows an example of this performance measure at a location where traffic was oversaturated, and the splits were adjusted to increase the green time on the movement. The rate of detected RLR vehicles was found to decrease by about 34% when comparing the 12 weeks prior to the change against 8 weeks after the change.

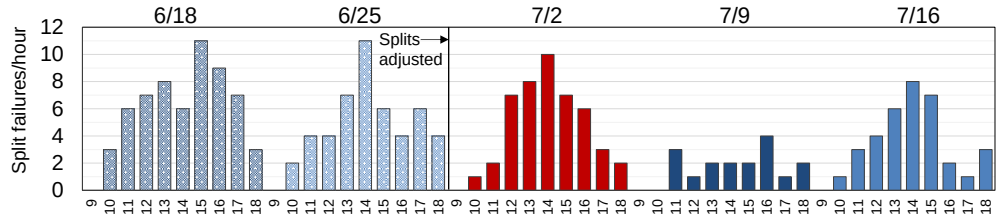
Figure 2-15. Analysis of split performance and evaluation of retiming [33,34].



(a) System level report: Split failures across nine signalized corridors.

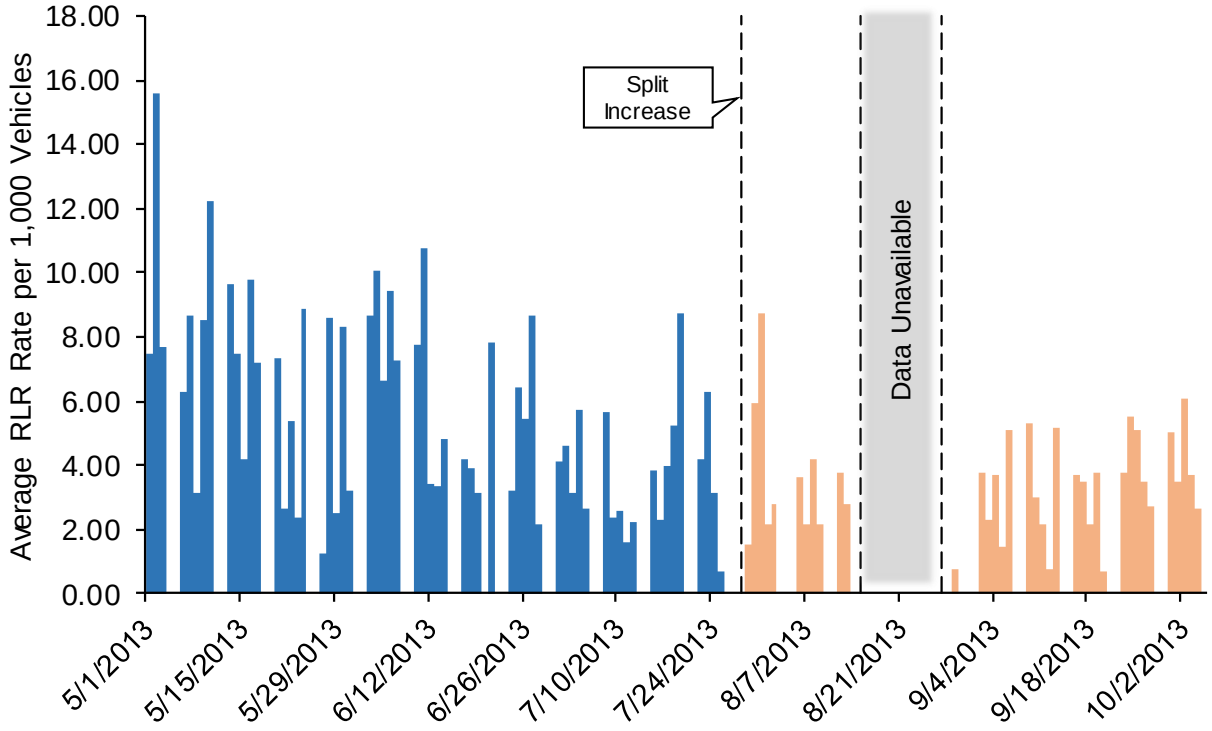


(b) Drill-down to corridor level: Split failures by intersection at US 31 Greenwood.



(c) Impact of split adjustments at US 31 and Greenwood Mall Entrance.

Figure 2-16. Impact of a split adjustment on red light running (RLR) on a signalized through movement [35]. Data is shown on a daily basis for weekdays operating under the midday timing plan (9:00–15:00) at US 31 and 126th Street in Carmel, Indiana, over a 5-month period.



2.6.2 Long-term Activities

Long-term activities of agencies include planning and administrative tasks. This includes the determination of where to invest resources for capital expenditures (such as new roadways and reconstruction), but it also involves the setting of agency policies and other standard practices, as well as performance reporting to decision makers and the public.

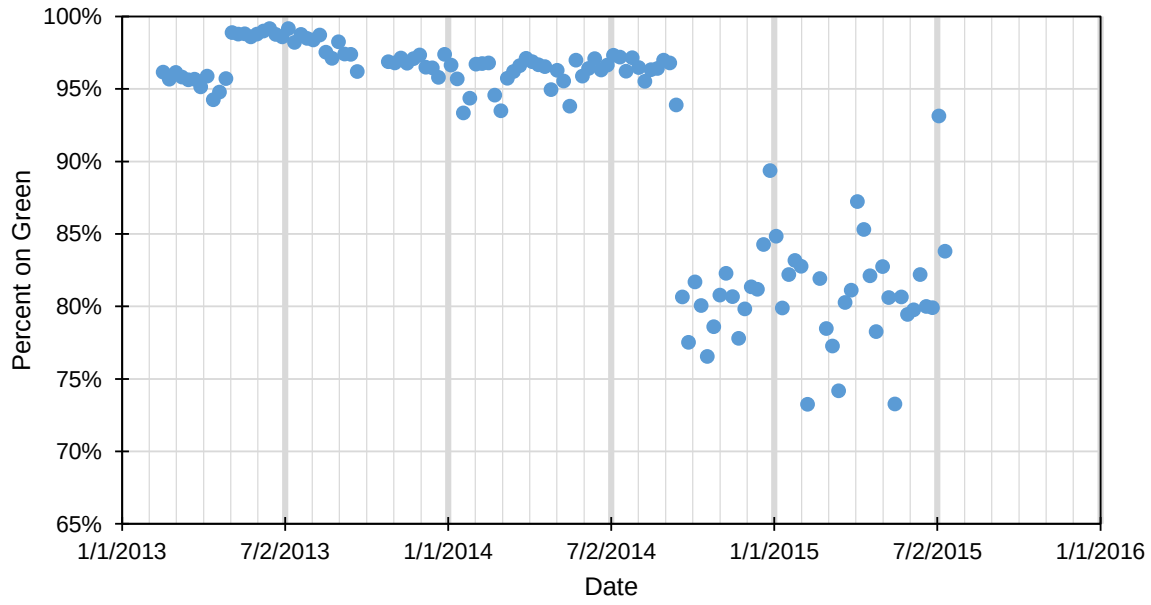
Identifying long-term trends. The planning of transportation facilities including signalized corridors involves some analysis of trends and forecasting. For example, volume forecasting is currently done in practice by extrapolating growth factors from count data which is usually available from limited time periods for individual locations. ATSPMs can help develop this sort of intelligence for signalized facilities, on a variety of aspects of operation, especially when data is continuously collected over time.

The following are examples of objectives of signal operation that are linked to the trends in traffic volumes and performance:

- Identify and implement and TOD plan adjustments
- Identify corridors that could benefit from coordination, and implement
- Help calibrate and fine-tune area-wide traffic models

Figure 2-17 shows a chart of the percent on green at a signalized approach over a 30-year period. Although data collection was not perfectly continuous across the entire time period, enough data is available to analyze the trends in the operation of this intersection. This represents data from a new intersection that was constructed along an existing highway, which provides access to anticipated retail land use. The intersection was opened in February 2013, but did not serve much traffic for the next 18 months. Because the signal was nearly always green for the mainline, very high percent on green was maintained. Suddenly, in September 2014, the percent on green decreases by about 20%, and remains at that level, after a change in land use changed traffic patterns. With traffic heading to and coming from the destination served by the intersection, demand for minor movement green increased, decreasing the mainline green and thereby lowering the percent on green.

Figure 2-17. Analysis of Percent on Green values at the approach to an intersection over a 30-month period. Each individual point represents a different day, for a Saturday timing plan.



Evaluating and informing policy and practice. Agency policies include formal material such as design manuals and approved equipment lists. It would also include initiatives that sometimes augment normal outlays for maintenance, operation, and capital programs. An example would be a statewide program or federal grant for signal system upgrades. At present, most of these things are evaluated in terms of the investments made. ATSPMs would be able to help evaluate the outcomes in a more comprehensive way than can be done using manual techniques.

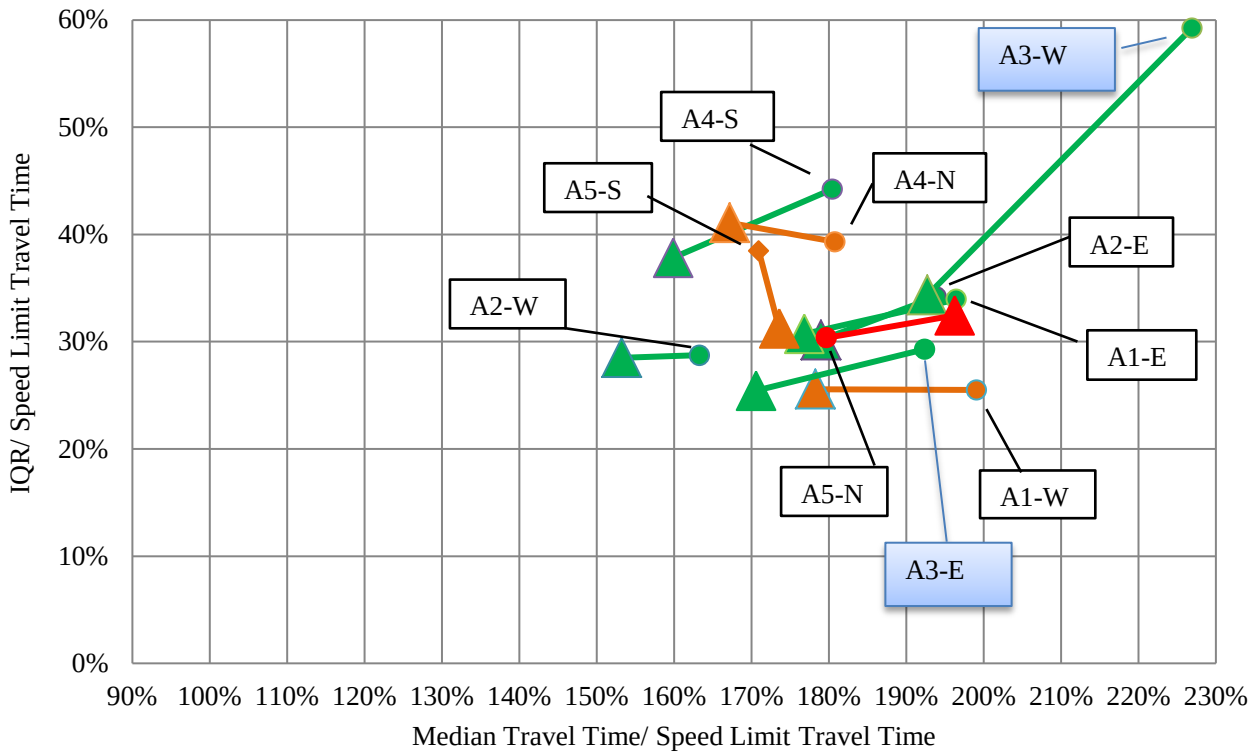
The following list identifies some potential objectives of traffic signal operation that are oriented to long-term policies:

- Connect all signals to the central system
- Add comprehensive detection at all signals
- Identify and implement adjustments to left-turn phase configurations (i.e., protected, permitted, or protected/permitted; as well as lead/lag timing)

In addition, those considered previously for understanding long-term trends could also be applied under policies. The decision of whether to coordinate signals along a corridor where new intersections have been added overtime is an example of trying to meet an objective of benefiting traffic performance through progression.

Figure 2-18 shows an example of an evaluation of transportation system investments on five signalized corridors in an urban area. Resources were invested by the state DOT for a number of intersection improvements, including retiming projects and installation of adaptive control on certain sections of the roadways. This chart shows the change in travel time metrics before and after these investments were made. Each symbol plots the variability of travel time, shown by the interquartile range (IQR), against the median travel time. Both of these are normalized to the speed limit travel time. The circle shows the "before" condition while the triangle shows the "after" condition. Green lines show where reductions were made in both dimensions of performance, while orange and red lines respectively show improvement in only one dimension, or no improvement. There are 10 lines representing two directions on each of five corridors. Six of these had improvements in both travel time and its variability, while three saw an improvement in either category, while one did not improve. This demonstrates the outcome at a system-wide level on a special investment program.

Figure 2-18. Changes in travel time and travel time reliability on five signalized corridors in the Philadelphia area after the installation of adaptive control systems [36].

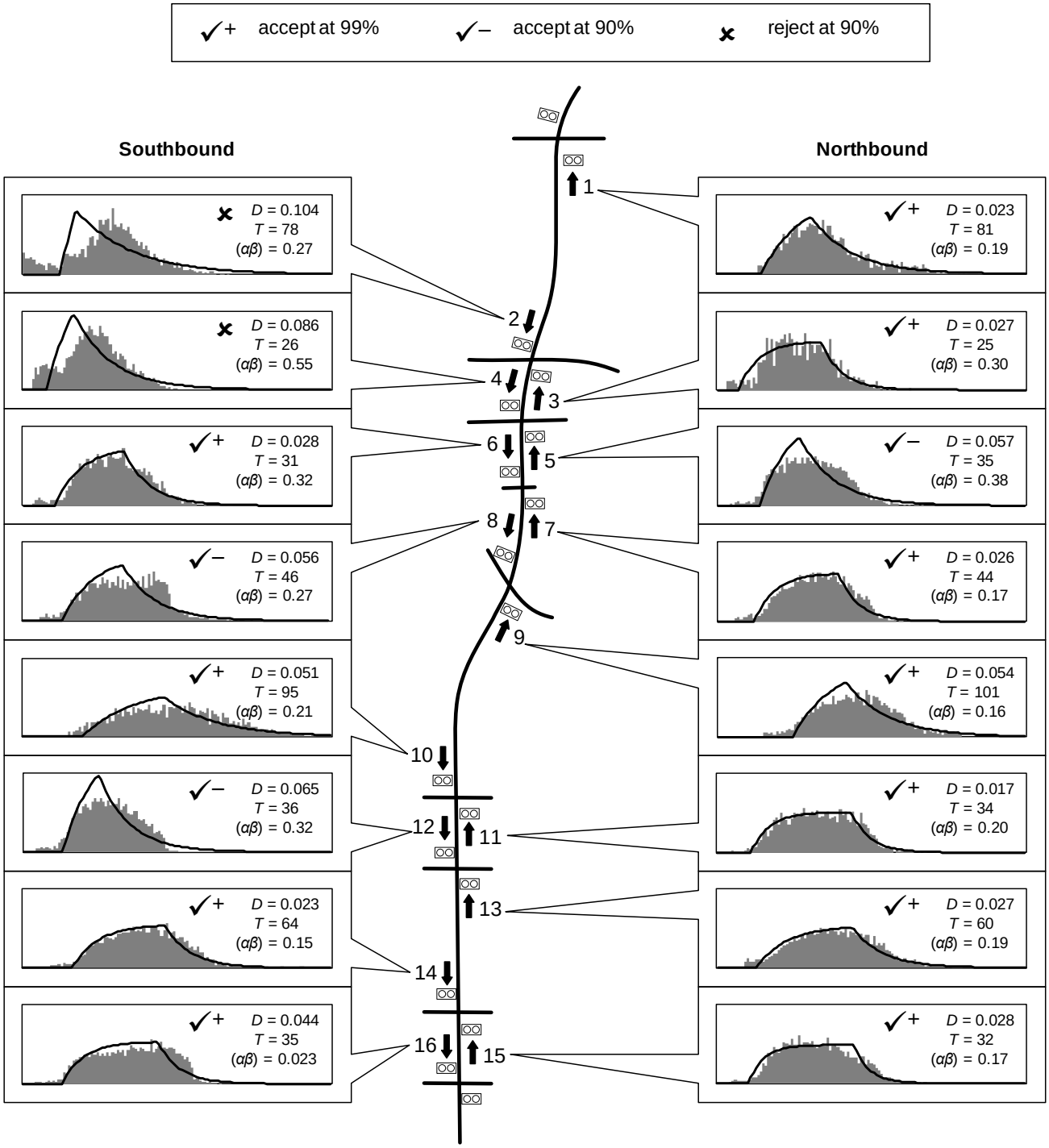


Model input and calibration. The existing set of tools for signal timing activities rely on user input such as traffic volumes to drive the model calculations, and other information for calibrating those models. In current practice, manual turning movement counts are commonly used for model inputs, while the parameters that control the model dynamics for optimization are set by the analyst largely based on site knowledge, but are also often left as the default values.

The use of detection to develop turning movement counts predates high-resolution data [32], but ATSPMs provide a more standard means to fulfill this objective. In addition to counts, the high-resolution data can examine other, more detailed traffic phenomena that are specified by optimization models. For example, a high degree of fluctuation in traffic patterns might suggest the exploration of advanced control methods such as traffic responsive or adaptive control.

Another example is the amount of platoon dispersion, which can be used to inform decisions on whether or not to coordinate neighboring intersections. Figure 2-19 shows measured versus modeled cyclic platoon profiles from a corridor, where the model parameters providing the best statistical fit to the measured data were derived. This exercise would enable more accurate models to be developed for full corridor optimization. Other important model parameters include lane utilization and residual queues, which can be measured by ATSPMs.

Figure 2-19. Calibration of a platoon dispersion model with high-resolution data [37]. Each approach shows the measured platoon profiles (bars) against the modeled profiles (lines), the degree of statistical similarity between these, and the resulting model parameters.



Reporting to the public and decision makers. Signal practitioners are sometimes asked to demonstrate accountability by executive staff, elected officials, and the public or the media. Often these encounters are preceded by some operational problem that is the focus of attention, such as road construction changing

traffic patterns in a city. At present, most practitioners are relatively limited in the amount of data that they could present to explain how the system is operating, unless they have undertaken some special effort to do so, such as travel time runs. ATSPMs would enhance their ability to give clearer answers when these situations arise. Quantitative reports can be scoped to investigate whichever objectives are prioritized for the agency.

Figure 2-20 shows an example of an executive summary that was generated by the UDOT signal performance measure system. This particular report shows the overall system performance in terms of signal progression, indicating the total amount of arrivals on red across the system wherever the data can be collected, as well as some other metrics. These are broken down into different regions in the same view, and the analyst could drill down further to individual corridors and intersections, if desired.

Figure 2-20. Example high-level executive summary from the UDOT signal performance measures system.

Executive Summary

12/2/2015 to 12/2/2015

Statewide Summary (intersections with upstream detection)

Arrival on Red		Delay		Volume	Intersections	
Percent	Platoon Ratio	Daily Average Per Approach (hrs)	Average Per Veh (sec)	Daily Average Per Approach	Total	Number Of Approaches
28.9 %	1.11	0.02	7.15	12,561	498	1,014

Region Summary

Region	Arrival on Red		Delay		Volume	Intersections	
Name	Percent	Platoon Ratio	Daily Average Per Approach (hrs)	Average Per Veh (sec)	Daily Average Per Approach	Total	Number Of Approaches
1	27.7 %	1.10	0.07	6.32	13,200	172	335
10	NaN	NaN	NaN	NaN	NaN	0	0
2	31.1 %	1.15	0.07	8.30	12,315	198	427
3	27.4 %	1.06	0.10	6.36	12,920	112	222
4	21.0 %	1.14	0.34	5.70	6,427	16	30

2.6.3 Prioritization of Activities

The previous discussion focused on various individual categories of activities at different time scales. In addition to these, the *prioritization* of those activities for allocation of engineering resources could be assisted with the use of ATSPMs to obtain better intelligence about the level of need for each individual activity. The example of the emergency detour (Figure 2-10, Figure 2-11) is one case where ordinarily a large number of resources might be invested to monitor and manage signal timing during the duration of the incident. However, in this case ATSPMs could illustrate that the system was performing reasonably well and some of those resources could be reallocated to other matters.

2.7 PERFORMANCE MEASURES

The previous section showed several examples of how performance measures can be used to support or evaluate an action by a traffic signal practitioner. Drawing from these examples and from the practitioner survey, a list of expected common objectives was compiled and is presented in Table 2-1. In the examples presented earlier, specific activities and performance measures were presented, but these are likely to differ in execution by various agencies depending on their capabilities and system characteristics. Therefore, the actions in Table 2-1 may be interpreted as *objectives*, because they have not yet been assigned a particular *strategy* (means of achieving the objective) or *tactic* (specific way of using that means).

The overall table structure is developed by considering the component levels in the system hierarchy of needs (Figure 2-4), and individual objectives are listed according to the relevant time scale (near-term or long-term).

Next, the individual objectives are mapped to specific performance measures and data types that facilitate these in Table 2-2. The list is not exhaustive, because additional performance measures are likely to be developed as more practitioners and researchers begin using the data types. For example, with passive pedestrian detection, it may become possible to evaluate whether pedestrian clearance times are sufficient by analysis of pedestrian crossing behavior relative to the timing of the flashing don't walk interval. The list reflects the types of metrics that have been introduced so far, and how these would be applied to specific objectives. A brief description of each ATSPM mentioned in Table 2-2 is presented in the following section.

Table 2-1. Objectives mapped to system components, time scales, and five common system goals.

COMPONENTS	NEAR-TERM	LONG-TERM
COMMUNICATION	- Identify and repair unreliable communications	- Connect all signals to the central system
DETECTION	- Identify and repair broken detection	- Add comprehensive detection at all intersections
LOCAL CONTROL (TIMING)	- Identify and fix intersections in flash - Identify and reduce excessive numbers of split failures and reallocate green time to correct - Identify and reduce long vehicle queues - Identify and reduce excessive vehicle, bicycle, and pedestrian delays - Identify and reduce conflict opportunities between vehicles, bicycles, and/or pedestrians - Identify and mitigate excessive occurrences of red-light running - Identify and mitigate excessive occurrences of vehicles being caught in the decision zone	- Identify and implement adjustments to TOD plan beginning and ending times - Optimize the total number of TOD plans in use within a system - Identify and implement left-turn phasing adjustments - Identify and implement adjustments to pedestrian treatments - Develop plans for special events
SYSTEM CONTROL (COORDINATION)	- Identify and correct intersections that are out of sync with corridor TOD plan, and correct - Identify locations where vehicles are frequency stopping and/or arriving on red, and reduce - Identify and reduce corridors with long travel times - Identify and improve corridors with highly variable travel times	- Identify corridors that would benefit from coordination and implement - Identify when intersections should be coordinated with neighbors and implement
OTHER	- Provide timely response to public service requests - Identify locations experiencing high numbers of preemption/priority occurrences and reduce delays	- Calibrate planning models using real volumes - Estimate economic costs and benefits - Estimate environmental impacts

Table 2-2. Objectives, performance measures, and data sources.

COMPONENTS	TIME FRAME	OBJECTIVE	PERFORMANCE MEASURES	LEGACY	HIGH RES.	AVI/ AVL
Communication	Near-Term	Identify and repair unreliable communications (i.e., intersections that are frequently offline)	- Intersection communication status - Network-wide communication status	X	X	
	Long-Term	Connect all signals to the central system	- Network-wide communication status	X	X	
Detection	Near-Term	Identify and repair broken detection	- Detector failures and outages - Network-wide detector failures		X	
	Long-Term	Add comprehensive detection at all intersections	- Network-wide detector failures		X	
Timing	Near-Term	Identify and fix intersections in flash	- Intersections in flash - Duration of flash	X	X	
		Identify and reduce excessive numbers of split failures and reallocate green time to correct	- Split monitor - Phase termination - Green and red occupancy - Volume - Volume-to-capacity ratio - Number of split failures - Flow rate during green - Wasted green time		X	
		Identify and reduce long vehicle queues	- Queue length - Delay - Effective cycle length - Flow rate during green		X	X
		Identify and reduce excessive vehicle, bicycle, and pedestrian delays	- Ped actuations - Ped/bike phase utilization - Delay - Ped arrival on walk		X	
		Identify and reduce conflict opportunities between vehicles, bicycles, and/or pedestrians	- Conflicting demand		X	
		Identify and mitigate excessive occurrences of red-light running	- Red-light running - Yellow/red actuations		X	
		Identify and mitigate poor speed compliance	- Approach speed		X	
		Identify and mitigate excessive occurrences of vehicles being caught in the decision zone	- Yellow/red actuations - Approach speed		X	

COMPONENTS	TIME FRAME	OBJECTIVE	PERFORMANCE MEASURES	LEGACY	HIGH RES.	AVI/ AVL
	Long-Term	Identify and implement adjustments to TOD plan beginning and ending times	- Volume - Effective cycle length		X	
		Optimize the total number of TOD plans in use within a system	- Volume - Effective cycle length		X	
		Identify and implement left-turn phasing adjustments	- Volume - Split monitor - Number of split failures		X	
		Identify and implement adjustments to pedestrian treatments	- Number of pedestrian actuations - Effective cycle length		X	
		Develop plans for special events	- Volume		X	
Coordination	Near-Term	Identify and correct intersections that are out of sync with corridor TOD plan, and correct	- Coordination plan status - Corridor cycle length	X	X	
		Identify locations where vehicles are frequency stopping and/or arriving on red, and reduce	- Arrivals on red/green - Platoon ratio - Coordination diagram - Cyclic flow profile - Time space diagram		X	
		Identify and reduce corridors with long travel times	- Travel times - Oversaturation metrics		X	X
		Identify and improve corridors with highly variable travel times	- Travel times			X
	Long-Term	Identify corridors that would benefit from coordination and implement	- Coordinatability index		X	
		Identify when intersections should be coordinated with neighbors and implement	- Coordinatability index		X	
Other	Near-Term	Provide timely response to public service requests	- Detector failures and outages - Event-based diagnostics - Coordination diagram - Number of split failures		X	
		Identify locations experiencing high numbers of preemption/priority occurrences and reduce delays	- Number of preemptions - Delay		X	X
	Long-Term	Calibrate planning models using real volumes	- Volume - Lane utilization - Residual queue - Saturation flow rate		X	

COMPONENTS	TIME FRAME	OBJECTIVE	PERFORMANCE MEASURES	LEGACY	HIGH RES.	AVI/ AVL
		Estimate economic costs and benefits	- Travel time - Delay - Volume		X	X
		Estimate environmental impacts	- Travel time - Delay - Volume		X	X

2.8 DESCRIPTIONS OF PERFORMANCE MEASURES

Approach speed. The speeds of individual vehicles can be measured by some detection types, such as radar. Excessive speeds, or large speed differentials, may indicate unsafe situations, while slower speeds may indicate excessive queuing or other poor performance.

Arrivals on red/green. The number of vehicles arriving during different phase states is a simple indicator of the quality of progression on a signal approach. It is more desirable to have a higher number of vehicles arriving on green, and a fewer number arriving on red. The number of vehicles arriving on red is a proxy for the number of stops.

Conflicting demand. This is the amount of traffic that crosses another movement, such as the volume of right or permissive left turn traffic crossing a pedestrian movement [40].

Coordination diagram. This chart shows the time of arrival of individual vehicles measured by setback detector actuations relative to the signal status at that moment. Traffic patterns emerge when this information is displayed for multiple cycles. The concept is similar to a disaggregate cyclic flow profile, except that the coordination diagram can also be applied in acyclic or variable-cycle operation [22,41].

Coordination plan status. The current pattern being run by individual intersections can be logged and either displayed live (as in a real-time status display) or analyzed by analysis of logs, including high-resolution data. The analysis of the pattern change times can reveal programming errors or other anomalies.

Coordinatability index. This index compares the volume to distance between intersections to determine whether neighboring intersections have a high potential for coordination. Similar metrics can be computed by measuring platoon characteristics on the links [42].

Corridor cycle length. A comparison of the effective cycle lengths at different intersections along a corridor provides a straightforward way to identify intersections that are not synchronized, or that are following a time-of-day plan that does not line up with the others [43].

Cyclic flow profile. This is a diagram that shows the time in cycle of vehicle arrivals as a distribution over a predefined analysis period [44,45,13]. It is necessary for a constant cycle length to be used over the duration of that period for the profile to be valid. It is also possible to overlay the probability of green on top of the

arrival profile. This is a common metric used in some optimization programs as well as adaptive control software [46,47], and can be developed from high-resolution data.

Degree of intersection saturation. This metric finds the overall level of demand for the capacity that is available at an intersection, by analysis of the utilization of phases in the "critical path" of the ring diagram. Comparison of the degree of utilization of individual phases with overall intersection saturation can find opportunities for split adjustments [38], while comparison of existing link performance with predicted optimized link performance can find opportunities for offset adjustment [39].

Delay. The amount of control delay is a fundamental performance measure for signalized intersections; it is used to define the Highway Capacity Manual (HCM) Level of Service (LOS). It can be estimated by a number of means, including the use of volume and phase data to calculate the HCM delay [48], or by analysis of event data by modeling queuing dynamics [53,55]; or it can potentially be measured by vehicle re-identification data, or emerging probe vehicle or connected vehicle data sets.

Detector failures and outages. This metric represents the number of detectors that are not reporting data, or whose reports are anomalous relative to an expected value.

Duration of flash. This metric measures the amount of time that an intersection is in flash, which can be used to measure the response time to correct the situation.

Duration of green. This metric is useful for documenting the amount of service that is given to individual movements, which can be helpful in a before/after analysis or to verify the outcomes of the signal timing. The green duration can be expressed in terms of individual green durations per cycle, cumulative green time over a period, or green-to-cycle length ratio.

Effective cycle length. This metric measures the total time used to serve all the phases present at an intersection. This can be defined by a variety of means but one definition that can be applied to a large majority of eight-phase intersections is subsequent crossings of the same barrier separating the mainline phases (e.g., 1,2,5,6) from the side-street phases (e.g., 3,4,7,8). This metric can be calculated regardless of whether the signal operates under a fixed cycle length (e.g., for fully-actuated or real-time adaptive control).

Event-based diagnostics. Analysis of the sequence of events in high-resolution data can be used to develop diagnostics for any traffic control feature. This can be useful to verify that complex controller operations occur as intended under the full range of conditions that occur in the field. Example applications include dynamic or adaptive changes to signal timing, preemption or priority operation, and complex phase/overlap sequencing.

Flow rate during green. The rate of vehicle discharge during green can be used in part to measure saturation flow rate (under some circumstances), as well as to identify spillback and starvation.

Green and red occupancy. The amount of time that a stop bar detector is occupied during different intervals at a traffic signal can help determine several operational characteristics. Green occupancy can be

used to determine the degree of utilization of the green interval, while occupancy shortly after the start of red can be used to determine the presence of residual demand. The combination of these metrics can be used to determine if split failures occur [49].

Intersection communication status. This amount of time that an intersection is online can be measured by a number of methods. One would be by registering the intersection response to some communication request, such as a ping command, which could be given at regular intervals. By tracking this at a system-wide level it is possible to identify intersections that have lost communication.

Intersections in flash. Intersection flash entry can be recorded by high-resolution data. Tracking this event can be helpful to find operational anomalies, in the event that unplanned flash occurs. Additional diagnostics could be used to determine the cause of the individual instances of flashing operation.

Lane utilization. Where lane-by-lane detection is used, the volume associated with a particular lane can be identified as a percent of total approach volume. This information is used by modeling methods such as that of the *Highway Capacity Manual*.

Network-wide communication status. The online status of individual intersections can be aggregated to corridor and network level views.

Network-wide detector failures. The operational status of individual detectors can be aggregated to corridor and network level views.

Number of preemptions. Tracking this data can be helpful for evaluating the impact of preemption on signal operations. This may be particularly helpful if the preemption inputs can be separated by source.

Number of split failures. A split failure is an occurrence where the amount of demand for service on a signalized movement is too great to be served within the amount of green time provided during a single instance. This means that one or more vehicles are delayed by at least one cycle length. Split failures are an indication of a shortage of capacity. These can be measured by metrics such as green and red occupancy, or the volume-to-capacity ratio. Successive split failures indicate a more protracted and systematic degree of problem than individual split failures.

Oversaturation metrics. There are several metrics for quantifying the severity and extent of oversaturation exist, including the Temporal and Spatial Oversaturation Severity Indices [50]. These measures can identify excessive queuing causing spillback between intersections.

Ped actuations. The number of pedestrian actuations can be calculated as a separate metric. Detailed information about pedestrian actuations (such as number or duration of actuations) can also be tabulated.

Ped arrival on walk. Similar to vehicle arrival on green, with passive pedestrian detection technology it would be possible to measure whether pedestrians arrive at the intersection during the walk phase.

Ped/bike phase utilization. Where pedestrians and bicycle phases are actuated, the rate of usage of those service modes can be tabulated as a proxy for the overall demand [51]. If passive pedestrian and bike detection are adopted, it would become possible to directly measure volumes as well.

Phase termination. The reason for an actuated phase to terminate can give provide some insight into the operation for the phase. For example, a phase that experiences a high number of force-off or max-out terminations could likely use more green time, whereas this would not be true for a phase that gaps out more often. This is a basic metric that can be computed in absence of information about the intersection detector layout.

Platoon ratio. This metric is equal to the percent on green (POG) divided by the green-to-cycle (g/C) length ratio. Values above 1.0 indicate good progression, while values below 1.0 indicate poor progression. Values ranging near 1.0 indicate random arrivals. This metric moderates POG by effectively giving more value to the same POG achieved with a smaller g/C ratio than with a larger g/C ratio. This can eliminate potential bias for longer cycle lengths and green times inherent in the POG metric. “Arrival Type” is a mapping of the platoon ratio to a 1–6 scale [52].

Queue length. The number of vehicles stopped at a traffic signal is a fundamental performance measure for signalized intersections. This number constantly changes dynamically as vehicles arrive and are served at the intersection. It is often helpful to measure the maximum and average queue length, or position of the back of queue, relative to each cycle, or during the course of an analysis period. Dynamic measures of queue length can also be used to derive delay estimates. There are multiple methods of estimating queue length from high-resolution data [53,55], and it may be measurable using probe or connected vehicle position data.

Red light running. Comparing stop bar detector status with phase status can identify when individual vehicles are likely to have crossed the stop bar during red [35]. This can be used to evaluate the safety performance of signal timing.

Residual queue. The length of a queue that remains after the end of a green interval can be measured by correlating queue length with phase times. This information is used by modeling methods such as that of the *Highway Capacity Manual*.

Saturation flow. The theoretical maximum flow rate of vehicles departing from an intersection during green is referred to as the *saturation flow rate*. This value varies considerably because of many different factors including location and traffic characteristics. Using ATSPMs it is possible to estimate the saturation flow rate by examining the number of vehicles passing through the intersection during green while flow is fully saturated, by examining vehicle headways when appropriate detection is available [54]. The flow rate during green is different in that there is no requirement that the movement must be fully saturated.

Split monitor. The distribution of green times on a per-phase basis can be reported by a variety of means. The UDOT performance measure system combines the individual duration of green with termination status and an indicator of pedestrian demand, with summary statistics by time of day plan.

Time-space diagram. This is a basic tool for visualizing coordinated signal timing plans. They are used in most signal timing software to show the intended design when programmed, but can also be generated by high-resolution data to show the actual field timing, which may vary because of actuation and other events [56,29].

Travel times. Travel time is a fundamental performance characteristic of roadways. It is possible to estimate travel time by a variety of means. High-resolution data can be used by itself to estimate queue lengths, which supports travel time estimates using a virtual probe vehicle concept [57]. Alternately, individual movement delay estimates can be aggregated into route travel times [15]. In addition, it is possible to directly measure travel times, by automatic vehicle identification methods [21,22,58,59,60], automatic vehicle location methods including aggregated segment speeds [61,62], or by individual trajectories.

Volume. This is a fundamental metric for traffic engineering purposes, and includes turning movement counts at intersections as well as ADT for segments and approaches. These can be automatically measured by a number of means including high-resolution data, where detection is available for counting. At present, counting is mainly used for vehicle modes, but may be possible in future for non-vehicle modes as well.

Volume-to-capacity (v/c) ratio. This metric is computed using vehicle volume data and green duration. Using assumptions to convert the green duration to estimated capacity, the amount of capacity used is determined. When the v/c ratio exceeds 1.0, it indicates that more traffic is arriving than the estimated capacity can serve, which indicates split failure [63].

Wasted green time. This metric measures the amount of time during which no vehicle service is taking place on the phases that are green, while there is demand present on another phase. This is an indicator of inefficient operation.

Yellow/Red actuations. This metric was developed as part of the UDOT performance measure system. It shows detector actuations relative to the signal state, which gives a sense of the degree to which drivers utilize the clearance times or whether they push into the next phase green.

2.9 ROADMAP FOR IMPLEMENTING SIGNAL PERFORMANCE MEASURES

To finish this discussion, a generalized implementation path for ATSPMs is presented. This is envisioned as five general steps to begin producing ATSPMs, to be adapted to the individual agency characteristics and capabilities.

- *Determine performance measures to be implemented.* Based on a review of the existing agency capabilities, the first decision would be to select the specific performance measures that are desired to be collected. The decision should consider those metrics that are currently of interest, and that are likely to be desirable in the future.

- *Select new data to be collected, and means of collection*. Based on the desired performance measures, the next step is to determine which data to collect and how to do it. Many, but not all, of the example ATSPMs in the earlier discussion make use of high-resolution data, but the decision process might consider alternative data sources that are yet to be developed. A consideration of the level of effort necessary to initiate data collection will be essential.
- *Select methods to gather, store, and process data*. To make use of the data, a means of retrieving it from the field is needed, as well as a system to warehouse the data, extract performance metrics from it, and organize these into useful reports relevant to activities at the immediate, near-term, and long-term levels discussed earlier. At present, agencies that have previously deployed ATSPMs have relied on their own server equipment to do so, and there are several software alternatives including the open source UDOT performance measure system, and several vendor software packages. The agency would need to select the approach that makes the most sense based on its capabilities and resource levels.
- *Procure any necessary components and/or services*. After the methods have been decided, the next step would be to begin acquiring the necessary elements to implement the system. New equipment, such as controller upgrades or new communication links, might be needed. For some agencies the existing field infrastructure might be sufficient, but a new server for ATSPMs might be needed. There may be additional options for deployment that appear as the technology matures.
- *Begin deployment*. Finally, the system would be deployed. This is a parallel process with some activities taking place in the field, and others where the performance measure analysis will be executed once the system is working. The first two basic milestones in deployment would be the retrieval of data from the field, and the development of the first performance measure report based on that data.

The next working paper in this series will examine the requirements for implementing ATSPMs in much more detail.

2.10 CONCLUSION

This paper presented a framework for articulating objectives for traffic signal performance measures. A brief background on signal performance measures was presented. Next, the concept of Goals, Context, Objectives, Strategies, and Tactic (G-COST) was introduced. Common goals for signal system operation were discussed. Context was then explored. System characteristics were examined by use of a structured hierarchy of system needs, which outlines various system components that would be attended to. The elements of the hierarchy begin at the communication and detection systems that allow information to be communicated from the field, and for intelligence to be gathered on site to measure traffic performance; and extend to the traffic control itself relevant to the local intersection and systems of multiple intersections. The operating environment of the signal system was then discussed, followed by consideration of agency capabilities using the Capability Maturity Model.

The activities of practitioners related to traffic signal systems were examined at time scales ranging from near-term to long-term. This was examined using an example-based discussion of several key activities

falling under each category. Near-term activities ranged from routine maintenance and response to public calls to planning of work activities to improve upon scheduled retiming and maintenance. Long-term activities included enhancements of planning and reporting to decision makers, and practical concerns such as making models more accurate.

This example-based discussion led to a mapping of objectives to a matrix of system element and time-scales, providing a preliminary menu of potential performance measures. The paper closes with a vision for implementation of performance measures leading up to the first milestones. This discussion is continued in the following working paper that more comprehensively discusses the specific requirements for implementation.

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NCHRP Project 03-122: Performance-Based Management of Traffic Signals

Working Paper No. 3
Traffic Signal Performance Measures

Prepared for the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

by

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ABSTRACT

This working paper, the third prepared for project NCHRP 3-122, covers the topic of requirements for a traffic signal performance measurement system. The paper begins by briefly investigating the physical traffic system being analyzed, yielding some understanding of the types of data that can be collected. Two main types of data are identified from this analysis: the internal data of the control system (such as the controller and detector states), and the external data that can better quantify the actual behavior of traffic. The working paper then moves to a review of data sources for signal performance measures. Twelve different data sources are discussed, and their advantages and disadvantages relative to signal performance measures are outlined. Following this, a review of the technical components of a signal performance measure system is presented. The technical components are comprised of the intersection equipment, communication systems for data transport, the architecture for data management, and the applications that can deliver the performance measures to the user. Finally, the paper briefly walks through some considerations related to agency business practices that may have consequences in the deployment and usage of signal performance measures.

3.1 INTRODUCTION

The need to improve traffic signal operations and management has been well-documented by numerous surveys of current practice [1,2]. Inefficient signal operation is often related to a lack of resources and the difficulty in assessing actual system performance. This has led to a drive for improved and automated performance measures to monitor and evaluate operations. Over the past 10 years, the results of initial research efforts [3,4,5,6,7] have transitioned into deployable technology, and there are now several transportation agencies actively using these performance measures to manage traffic signal systems. The objective of NCHRP 3-122 is to develop guidance for agencies interested in implementing these performance measures in their own systems. An essential element of that guidance is to develop an understanding of the requirements. This working paper explores those requirements.

It is helpful to begin this discussion by defining what is meant by "automated traffic signal performance measure" (ATSPM). In this paper, a traffic signal performance measure is taken to mean a numerical value or graphical arrangement of these that can be used to evaluate some aspect of the signal operation. An *automated* traffic signal performance measure is one for which the base data can be recorded and ideally collected with minimal human effort.

Historically, signal performance measures have required manual data collection. Turning movement counts would have to be collected by a human observer, and travel times would have to be recorded by floating car that was driven by the analyst. Over the years, methods of automating these *external* data collection activities have emerged. These data sets are still available today and can be quite valuable for evaluating system performance. Connected vehicle data, which is anticipated in the near future, will add to our understanding of traffic performance in response to signal systems and other control devices.

A complementary category of signal information is the *internal* data, meaning the signal state. This data has always been available, in the electrical impulses controlling the indications, and in the states of the detection inputs controlling the timing decisions. However, it was difficult to record that information. Until fairly recently, signal state information was not recorded except in a handful of research environments and internally to some adaptive systems. The development of "high-resolution data" as a means of retrieving signal state information has opened the door to a series of analysis tools that can, with an understanding of how the data is developed, reveal detailed information about different elements of the performance.

There are, therefore, essentially two categories of data that will be explored in this working paper: the *external* data sources that measure traffic performance directly, and the *internal* data sources that can capture the signal state and other decision variables. The next section looks at characteristics of these data sources in detail, and the following section describes other requirements for developing a system to manage the data and transform it into useful information.

3.2 ELEMENTS OF SIGNAL PERFORMANCE

Traffic signals assign capacity to competing movements at intersections. The primary determinant of service is the amount of delay incurred to vehicles, pedestrians, and other modes while traversing the intersection. For vehicle movements the time-space diagram is one way to visualize traffic performance. Figure 3-1 shows an example for a hypothetical signalized movement with red and green states shown, and six vehicle trajectories. This diagram also shows typical locations of detectors and points where travel time measurements might be made. These items, in combination with the signal state, represent what is measurable at an intersection:

- The signal state reflects the service state of the movement at any given time, and when reconciled against other events can be used to assess the performance.
- Stop bar detection is typically used to extend actuated phases at intersections. The occupancy of the stop bar relates to the degree of utilization of the phase.
- Setback detection is used for dilemma zone protection as well as to set added initial timing. Actuations of setback detectors can be used to identify arrival patterns (especially under coordinated operation), while the occupancy can identify when queue lengths are approaching or exceeding the setback detector location.
- Travel time measurements are made by computing the difference in vehicle detection times at two locations. This could be done with automatic vehicle identification (AVI) or automatic vehicle location (AVL) technologies. Travel time measurements can yield delay by comparison to the free flow travel time, as illustrated for the first vehicle trajectory in Figure 3-1. Travel time is also expressed in terms of the average speed from point to point.

The signal and detector states represent data that is internal to the control system. These are directly accessible by the controller and other cabinet equipment. Travel time measurement and other similar types of performance observations are external to the control system. These represent two potential data sources, “internal” and “external”, that are relevant to categorizing possible means of developing ATSPMs.

An example showing how internal and external data can be used to evaluate signal operations can be found in measuring the impacts of retiming. Figure 3-2 shows a map of an arterial with eight signalized intersections and 16 approaches on the mainline through movements. Each of these is accompanied by a chart that shows the change in the percent of vehicles arriving on green after an adjustment of the signal offsets. Most of the intersections show an increase in the percent on green (POG), while a handful show a decrease. The POG is measured using internal data, comparing arrivals measured with setback detection against the concurrent signal state.

External data (specifically vehicle re-identification data from Bluetooth MAC address matching) is used to measure the travel times, which are shown as cumulative frequency diagrams in Figure 3-3. This data shows that the median (50th percentile) travel times were reduced by about 2 minutes in the southbound direction and 1 minute in the northbound direction. Both types of data provide insights on signal operation. External

data is helpful at measuring the overall impacts on traffic, while internal data is helpful for identifying reasons why performance is better or worse.

Figure 3-1. Time-space diagram showing operations at a traffic signal and measurable elements.

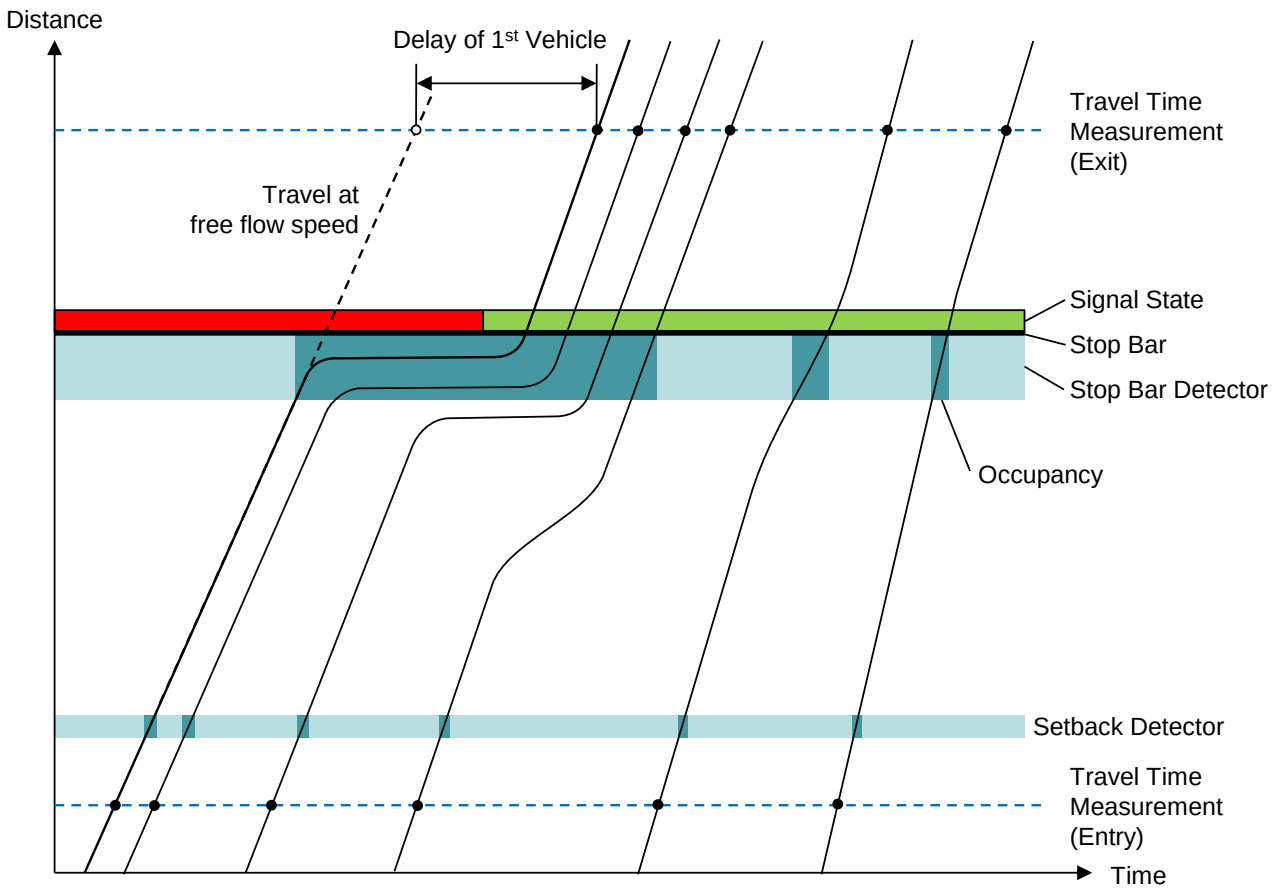


Figure 3-2. Percent on green before and after an offset change.

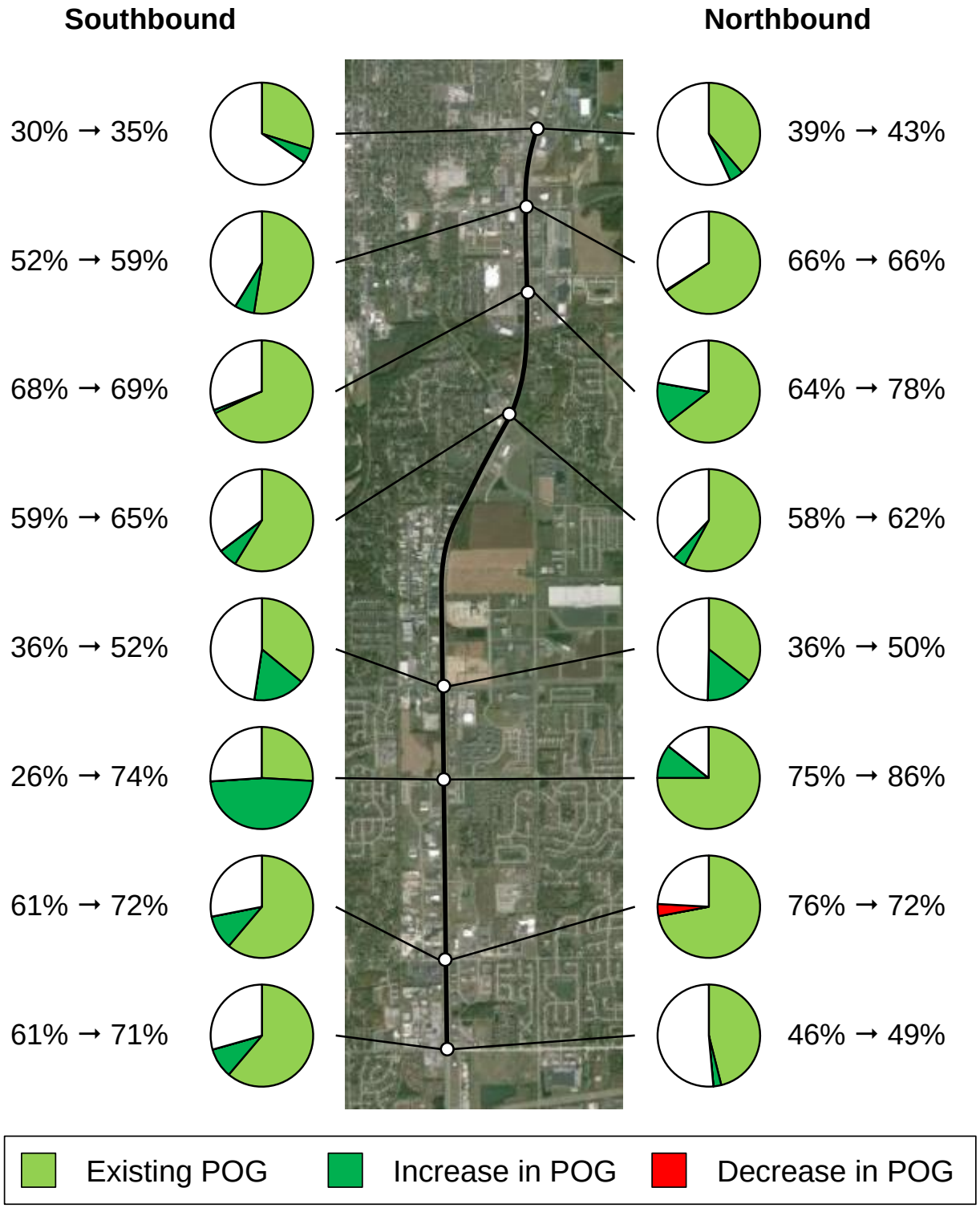
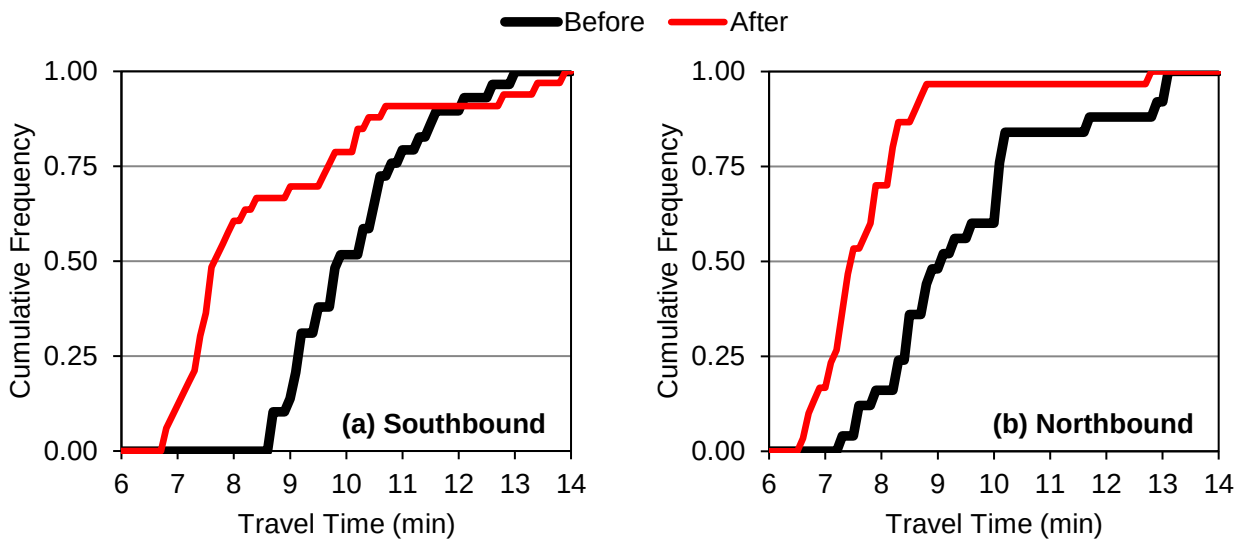


Figure 3-3. Change in travel times.



3.3 DATA SOURCES FOR SIGNAL PERFORMANCE MEASURES

Much of the current attention being given to ATSPMs is focused around high-resolution controller event data. This, however, is not the only data set available, and it is worthwhile to discuss existing and emerging data sets relative to ATSPMs, to develop a comprehensive view. Table 3-1 summarizes available and emerging sources of automatically collected data that have potential applications for evaluating signal systems. They are sorted in order of the approximate time period when the data was developed. Each data source is also identified as being "internal" or "external." In addition, some other properties of the data set are listed in additional columns, including the resolution and accuracy of the data, the method of retrieving the data, and its current availability status. Data sources that are commonly available to most agencies with standard controller and remote management software are marked as "existing" in the availability column.

Table 3-2 links each of the data sources with the objectives that were listed in the previous working paper, while Table 3-3 maps the data sources to specific metrics described in that paper.

ATSPMs require an internal source that can identify the signal state. This is essential for understanding the performance of individual movements at a detailed enough level to suggest potential problems with the control. External data is also very valuable for directly measuring the performance of traffic, including travel times and delay, but it cannot replace knowledge of the signal state in understanding the reasons for high amounts of delay where they occur. This section describes each data source and discusses advantages and disadvantages of these relative to establishing a signal performance measurement program.

Table 3-1. Data sources with potential for developing automated signal performance measures.

DATA SOURCE	TYPE	DESCRIPTION	YEAR(S) DEVELOPED	RESOLUTION AND ACCURACY OF DATA	RETRIEVAL METHOD	AVAILABILITY	PAGE
Aggregated Detector Occupancy	Internal	Percentage of time when detectors are occupied, typically aggregated in 1–15 minute bins	1960s-1970s	1–15 minutes	Traffic signal management system	Current / Existing	p. 3-15
Adaptive Control System Data	Internal	Data used in adaptive control systems to make control decisions	1980s-present	Varies by system; nearest-second in some systems; aggregated to time periods in others	Adaptive control or traffic signal management system	Current	p. 3-16
Split Monitor Data	Internal	Distribution of the durations of green time, usually over a relatively long time period	1980s	Varies by system; typically some analysis time period (several minutes)	Traffic signal management system	Current / Existing	p. 3-18
Automated Traffic Count and Classification Data	External	Vehicle volumes and classes measured using automated devices, typically aggregated to 5 or 15 minutes	1980s	Typically 5 or 15 minute counting intervals	ITS system, traffic signal management system, or third-party provider	Current / Existing	p. 3-19
ITS Sensor Data	External	Measurements of count, occupancy, speed, weight, etc. from ITS devices	1990s	Varies; data is available at some level in real time, but is rarely recorded or stored in this manner. More likely to be aggregated to 1-minute average values.	ITS system	Current	p. 3-20
Internal Detector Data	Internal	Physical responsive of a detection system to vehicles, such as inductive loop signatures or distance to intersection from radar	2000s	0.1 second or better	Vendor software	Current	p. 3-21

DATA SOURCE	TYPE	DESCRIPTION	YEAR(S) DEVELOPED	RESOLUTION AND ACCURACY OF DATA	RETRIEVAL METHOD	AVAILABILITY	PAGE
High-Resolution Controller Event Data	Internal	Record of events at a signalized intersection at the smallest controller time resolution (typically 0.1 second)	2000s	0.1 second	Traffic signal management system or vendor software	Current	p. 3-22
Real-Time Intersection Status Data	Internal	Record of events at a signalized intersection are streamed to a central system for monitoring. The data could also be recorded by the central system.	2000s	Real-time	Traffic signal management system	Current	p. 3-23
Vehicle Re-Identification Data	External	Individual vehicle travel times determined from matching vehicle IDs at different locations (Examples: Bluetooth; Wi-Fi; Toll Tags)	2008	Nearest second	Third party provider or central system data collection	Current	p. 3-24
Probe Vehicle Segment Speed Data	External	Average segment speeds based on analysis of probe vehicle movements, typically provided at 1-minute resolution	2009	Minute by minute	Third party provider	Current	p. 3-25
Probe Vehicle Location Data	External	Individual vehicle positions obtained through mobile devices with GPS capability, at varying time resolutions	2015	Position reporting may vary from every second to every minute	Third party provider	Emerging	p. 3-26
Connected Vehicle Data	Both	Individual vehicle positions and other status, delivered through DSRC communications between vehicles and infrastructure, at high time resolution	2010s-2020s (Anticipated)	To be determined, but anticipated that it will be many records per second	To be determined	Future	p. 3-27

Table 3-2. Data sources and their potential applications to objectives explored in the previous working paper.

TABLE LEGEND
✓ This data set will provide the performance measure directly.

	DATA SOURCE	Aggregated Detector Occupancy	Adaptive Control System Data	Split Monitor Data	Automated Traffic Count and Classification Data	ITS Sensor Data	Internal Detector Data	High-Resolution Controller Event Data	Real-Time Intersection Status Data	Vehicle Re-Identification Data	Probe Vehicle Segment Speed Data	Probe Vehicle Location Data	Connected Vehicle Data
Communication	Identify/Repair unreliable communication		✓					✓	✓				
	Connect all signals to central system							✓	✓				
Detection	Identify/Repair broken detection		✓				✓	✓	✓				
	Add comprehensive detection at all signals						✓	✓	✓				
Local Control (Timing)	Identify / fix intersections in flash		✓					✓	✓				
	Allocate green time equitably		✓	✓				✓	✓				✓
	Identify/reduce split failure occurrences		✓					✓	✓			✓	✓
	Identify/reduce long queues		✓				✓	✓	✓			✓	✓
	Identify/reduce high delay (for all modes)		✓				✓	✓	✓	✓	✓	✓	✓
	Identify/reduce conflicts between modes		✓				✓	✓	✓				✓
	Identify/reduce red light running occurrences							✓	✓				✓
	Identify/mitigate poor speed compliance						✓						✓
	Identify/reduce dilemma zone vehicles		✓				✓	✓	✓				✓
	Identify/implement TOD plan adjustments							✓	✓				✓
	Identify/implement left-turn phasing adjustments		✓					✓	✓				✓
System Control (Coordination)	Identify/address intersections in wrong TOD plan							✓	✓				
	Identify/reduce high number of arrivals on red		✓					✓	✓			✓	✓
	Identify/reduce high corridor travel times		✓					✓	✓	✓	✓	✓	✓
	Improve corridor travel time reliability		✓					✓	✓	✓	✓	✓	✓
	Identify opportunities to implement coordination							✓	✓			✓	✓
Other	Respond to public service requests			✓				✓	✓				
	Identify high amounts of preemption / priority requests							✓					
	Reduce delays caused by preemption/priority operation							✓	✓				
	Calibrate models with measured volumes		✓		✓	✓	✓	✓	✓				✓
	Estimate environmental impacts							✓	✓	✓	✓	✓	✓

Table 3-3. Data sources and their potential use with performance measures explored in the previous working paper.

TABLE LEGEND & NOTES

✓ This data set will provide the performance measure directly.

* This data set will provide the performance measure directly for appropriate data resolutions, which may vary among providers for this data set.

† Dependent on sample rate.

E Indicates that an estimate of the metric can be developed.

Capabilities of internal detector and connected vehicle data are shown in the case that they are provided without phase status data.

	DATA SOURCE	Aggregated Detector Occupancy	Adaptive Control System Data	Split Monitor Data	Automated Traffic Count and Classification Data	ITS Sensor Data	Internal Detector Data	High-Resolution Controller Event Data	Real-Time Intersection Status Data	Vehicle Re-Identification Data	Probe Vehicle Segment Speed Data	Probe Vehicle Location Data	Connected Vehicle Data
1	Approach Speed						✓					✓*†	✓†
2	Arrivals on Red/Green		✓*				✓	✓	✓			✓*†	✓†
3	Conflicting Demand		✓*				✓	✓	✓				✓†
4	Coordination Diagram		✓*					✓	✓				
5	Coordination Plan Status		✓*					✓	✓				
6	Coordinatability Index		✓*				✓	✓	✓				✓†
7	Corridor Cycle Length		✓*	✓				✓	✓				
8	Cyclic Flow Profile		✓*					✓	✓				
9	Degree of Intersection Saturation		✓*				✓	✓	✓				✓†
10	Delay		E*				E	E	E	✓†	✓†	✓†	✓†
11	Detector Failures and Outages		✓*				✓	✓	✓				
12	Duration of Flash		✓*					✓	✓				
13	Duration of Green		✓*					✓	✓				
14	Effective Cycle Length		✓*					✓	✓				
15	Event-Based Diagnostics		✓*				✓	✓	✓				
16	Flow Rate During Green		✓*					✓	✓				
17	Green and Red Occupancy		✓*				✓	✓	✓				
18	Intersection Communication Status		✓*					✓	✓				
19	Intersections in Flash		✓*					✓	✓				
20	Lane Utilization		✓*					✓	✓				
21	Network-wide Communication Status		✓*					✓	✓				
22	Network-wide Detector Failures		✓*				✓	✓	✓				
23	Number of Preemptions		✓*					✓	✓				
24	Number of Split Failures		✓*					✓	✓				
25	Oversaturation Metrics	E	✓*				✓	✓	✓			✓*†	✓†
26	Ped Actuations		✓*					✓	✓				
27	Ped Arrival on Walk		✓*					✓	✓				
28	Ped/Bike Phase Utilization		✓*					✓	✓				
29	Phase Termination		✓*					✓	✓				
30	Platoon Ratio		✓*					✓	✓				
31	Queue Length		E				E	E	E			✓*†	✓†
32	Red Light Running		✓*					✓	✓				
33	Residual Queue		E					⍰	⍰			✓*†	✓†

TABLE LEGEND & NOTES

✓ This data set will provide the performance measure directly.

* This data set will provide the performance measure directly for appropriate data resolutions, which may vary among providers for this data set.

† Dependent on sample rate.

E Indicates that an estimate of the metric can be developed.

Capabilities of internal detector and connected vehicle data are shown in the case that they are provided without phase status data.

	DATA SOURCE	Aggregated Detector Occupancy	Adaptive Control System Data	Split Monitor Data	Automated Traffic Count and Classification Data	ITS Sensor Data	Internal Detector Data	High-Resolution Controller Event Data	Real-Time Intersection Status Data	Vehicle Re-Identification Data	Probe Vehicle Segment Speed Data	Probe Vehicle Location Data	Connected Vehicle Data
34	Saturation Flow		✓*					✓	✓				
35	Split Monitor		✓*	✓				✓	✓				
36	Time-Space Diagram (Real-World Timeline)		✓*					✓	✓				
37	Travel Times		E*				E	E	E	✓†	✓†	✓†	✓†
38	Volume	E	✓*		✓	✓	✓	✓	✓				
39	Volume-to-Capacity Ratio		✓*					✓	✓				
40	Wasted Green Time		✓*					✓	✓				
41	Yellow/Red Actuations		✓*					✓	✓				

3.3.1 Aggregated Detector Occupancy

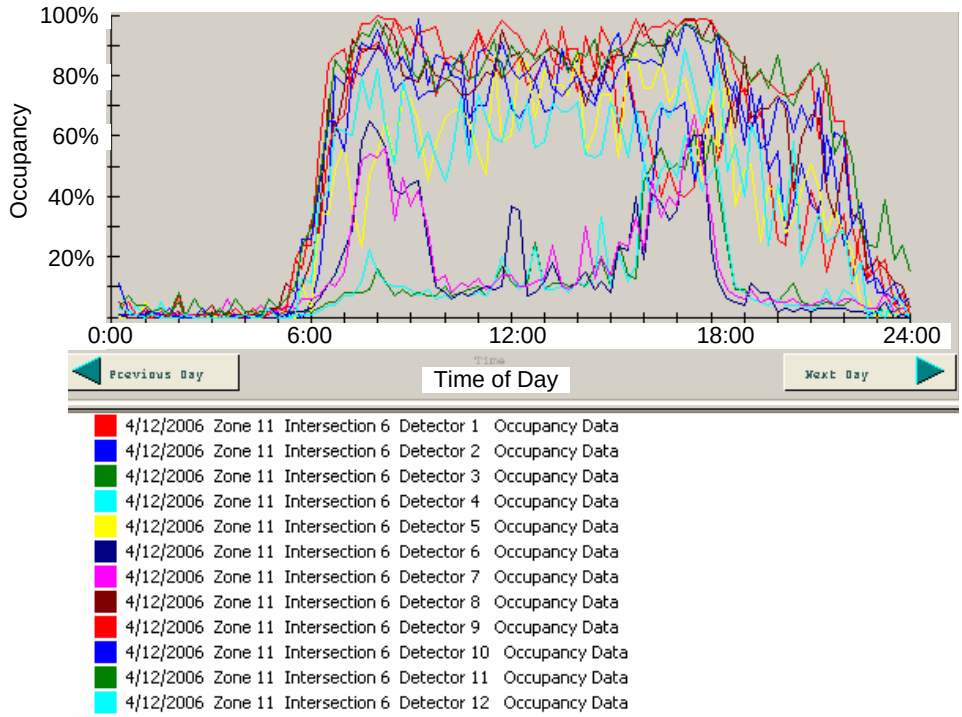
Detector occupancy is perhaps the oldest automatically obtainable performance measures in widespread use for traffic signal systems. It is used in traffic responsive systems to select patterns based on occupancy levels (in combination with volumes) sampled at various system locations. Because of its longstanding use, most signal controllers are capable of logging detector occupancy and have the ability to output that data. Typically, occupancy is stored as a percentage over some time period such as 5 or 15 minutes.

Example. Figure 3-4 shows an example from an intersection with several different detectors included in one plot. Most of the detectors have a high level of occupancy through most of the day; these are likely stop bar detectors where a vehicle is stopped while the associated signal indication is red. A few others where the occupancy takes on lower values that have peaks in the AM and PM are more likely advance detectors which are only occupied for long periods of time when queues reach back that far.

Advantages. This data type is readily available in most existing infrastructure.

Disadvantages. The data is not detailed enough to be able to provide valuable information about most signalized movements. Many agencies tie single detector leads to multiple loops in various combinations, confounding the data. In Figure 3-4, it is clear that the intersection receives demand from 6:00 through about 22:00, but other than potentially identifying queuing over advance detectors, it is not possible to distinguish between a level of demand that is being served well, versus a movement experiencing split failures. Requires stable communication from the field infrastructure.

Figure 3-4. Example aggregated detector occupancy data from several detectors (Source: J. Sturdevant).



3.3.2 Adaptive Control System Data

Adaptive control systems have been use since the late 1970s, and these necessarily involve the use of direct field measurements by detection. Every system does this in its own, proprietary manner, and this data can potentially be quite detailed, depending on the system. The raw data is not always easily extracted for analysis, but many adaptive systems can supply a series of performance measures to the user for the systems where they are installed.

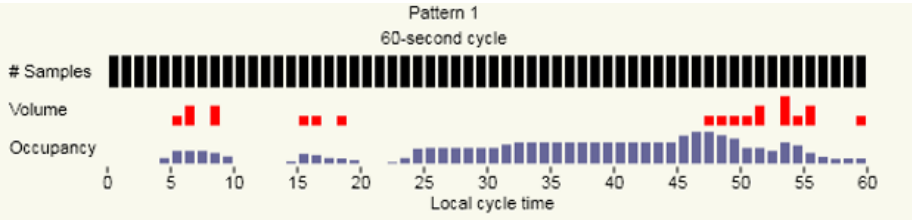
Example. Figure 3-5 shows a map view developed by an adaptive system where locations of congestions are identified using internal system measurements. Figure 3-6 shows an example of some internal data that is used for an adaptive control decision. Figure 3-6a presents a record of detector volume and occupancy output status averaged over several recent cycles, which is used to create a cyclic flow profile. The occupancy in this case is not aggregated to 1-15 minutes as in the previous examples, but is available on a second-by-second basis. Meanwhile, Figure 3-6b shows a record of recent phase states over the past several cycles. In this particular system, the flow profile data is combined with the phase state to make an adaptive adjustment of the signal offset.

Advantages. Readily available where adaptive systems are deployed. Most adaptive systems require substantial detectorization, which would provide adequate infrastructure for detailed performance measurement. Utility of the metrics will vary from one system to the next, but in general, should provide a good picture of operations.

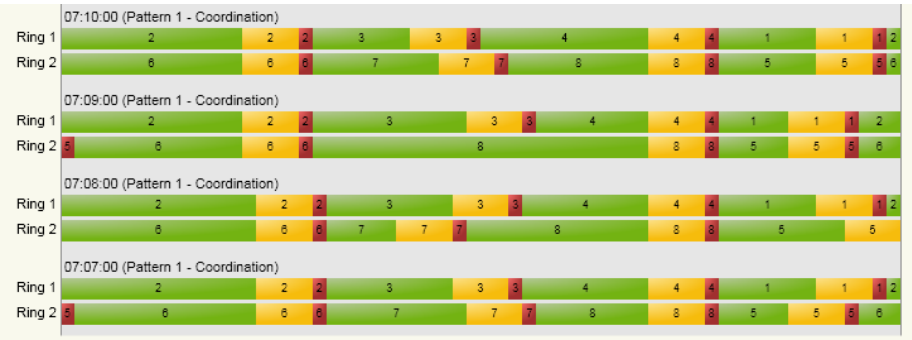
Disadvantages. Different systems are not interoperable and will differ in the metrics provided as well as the format of any raw data or high-level reports. The raw data may be not be possible to obtain. Requires stable communication from the field infrastructure.

Figure 3-5. Example graphical visualization of adaptive control system performance measures (Source: SCATS version 6 functional description [8]).

Figure 3-6. Example of internal data within an adaptive control system (Source: data used in evaluation of Centracs adaptive control [9]).



(a) Cyclic flow profile data.



(b) Phase state data.

3.3.3 Split Monitor Data

Most vendors offer some kind of management software that can remotely program signal controllers, and typically offer other features including real-time monitoring. One feature that has been available for longer than these newer features is called a “split monitor”.

Example. Figure 3-7 shows an example view of a split monitor which shows the difference between programmed and actual greens for eight phases at a signalized intersection, in addition to some other summary statistics about the phase termination. For example, most phases have somewhat less green time than their programmed value, indicating that all of the phases in this case have relatively low demand for the time period being analyzed.

Advantages. Readily available with existing infrastructure in many systems. Provides useful information about phase service times.

Disadvantages. Not all controllers will be compatible with a particular vendor’s software for doing the analysis. The data is typically aggregated and may not be available at a more detailed (cycle-by-cycle) level of analysis. The raw data may not be possible to extract. Requires stable communication from the field infrastructure.

Figure 3-7. Example of a split monitor graphic from central management system software (Source: Siemens TACTICS 3 data sheet).

3.3.4 Vehicle Count and Classification Data

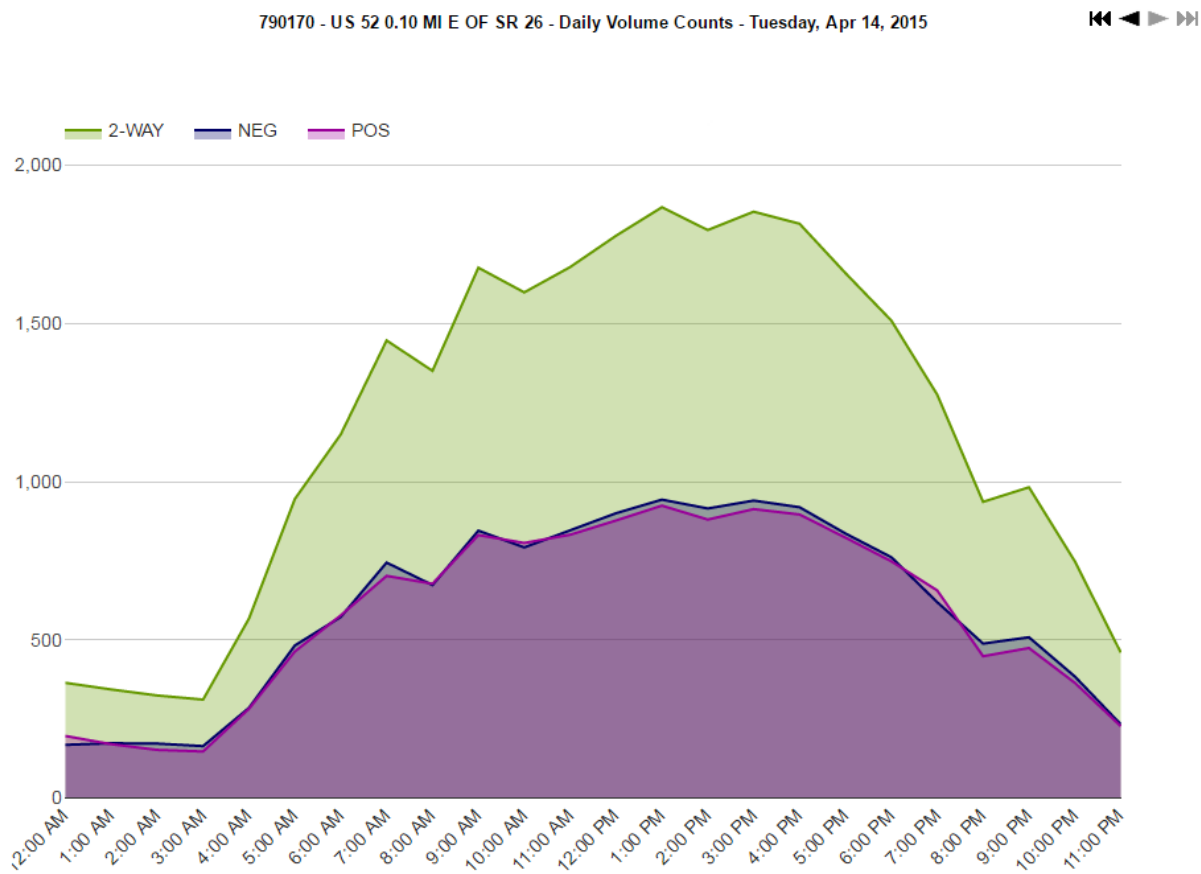
Many agencies have a program for collecting vehicle counts, in the form of average annual daily traffic (AADT) measurements, which are used for numerous traffic engineering and planning purposes. These systems can provide counts by lane and direction along a roadway, and may include vehicle classification data.

Example. Figure 3-8 shows an example traffic count taken along a signalized arterial highway, showing hourly volumes in two directions.

Advantages. Can provide some insight into the level of demand on an approach, and by movement if turning movement counts are obtained. Geospatial referencing of movements could be useful for other performance measure applications.

Disadvantages. Generally not detailed enough in the time scale to provide useful information about signal operations. Hourly or 15-minute counts can be used to model performance, but calibration is needed to successfully predict performance.

Figure 3-8. Example of vehicle count data (Source: Indiana DOT traffic counts database [10]).



3.3.5 ITS Sensor Data

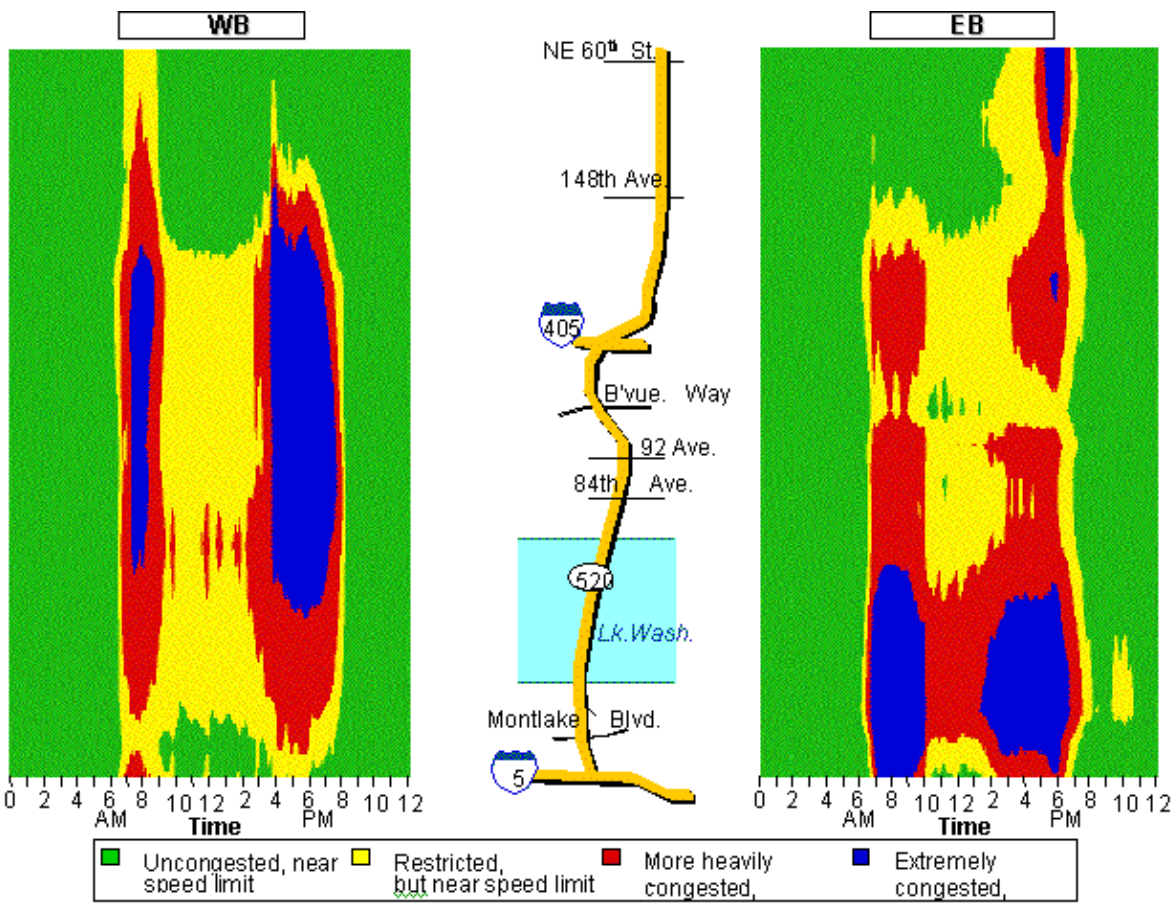
Many urban areas have a traffic management center to manage operations, more typically for freeway networks, although signalized facilities are sometimes included and may be the focus for some agencies. Monitoring infrastructure deployed to facilitate management processes fall under the category of "intelligent transportation systems" (ITS), and include cameras for video surveillance, and fixed-point sensors for measuring speeds.

Example. Figure 3-9 shows a plot of congestion, determined from speed measurements, for two directions along a freeway route, by time of day.

Advantages. Video surveillance can be valuable for monitoring current traffic conditions or for validating conditions at other times if video is recorded. Can be useful for predicting when conditions may change on signal facilities, as when traffic is detoured or likely to divert onto arterial routes.

Disadvantages. Fixed-point speed sensors are unlikely to provide useful information about traffic signal operations. Speed sensors placed along arterial segments would not capture speed fluctuations at intersections. Requires stable communication from the field infrastructure.

Figure 3-9. Example of congestion data obtained from speed sensors (Source: FHWA [11]).



3.3.6 Internal Detector Data

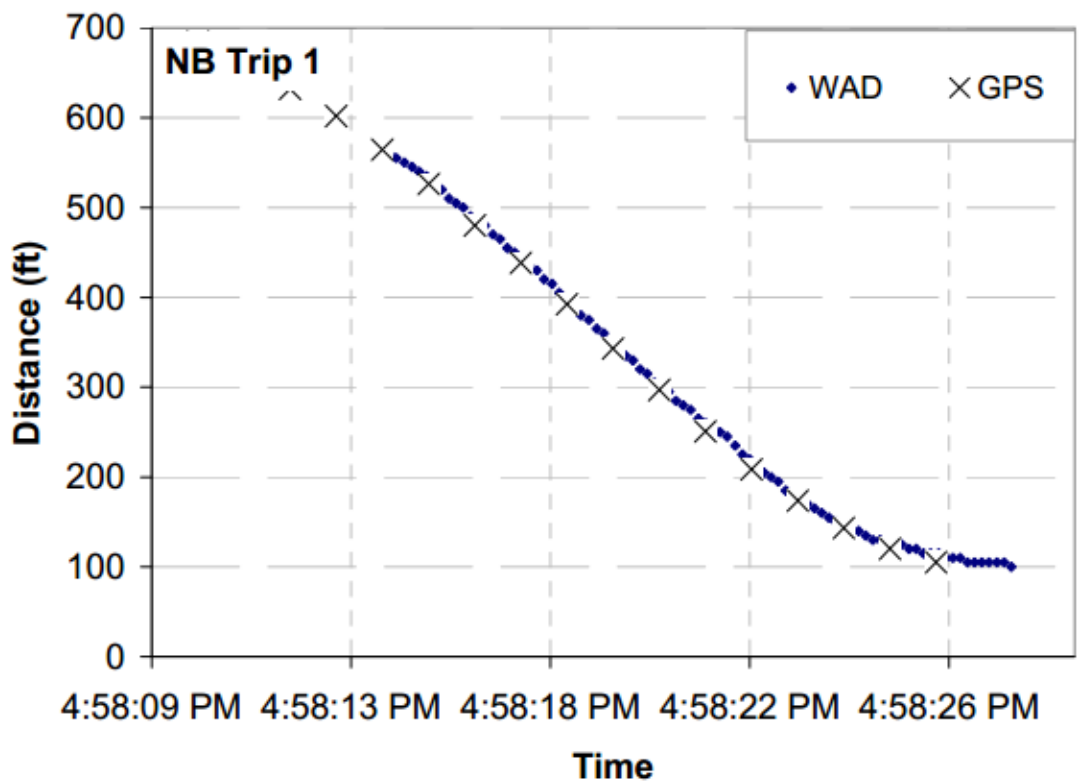
At present, detector inputs to a signal controller are a simple "contact closure", meaning that the electrical impulse is simply on or off. However, some detection systems can provide more detailed information that is only available within the detection system. Preemption and priority systems, which may provide similarly detailed information internally although they only put in a single call to the controller, would also fall within this category.

Example. Figure 3-10 shows a trace of vehicle position relative to the stop bar at an intersection, obtained from radar-based wide-area detection (WAD). In this example, the trace is validated by comparison to GPS position.

Advantages. Can provide more detailed information about traffic, varying by detector technology. May already exist in some systems.

Disadvantages. Requires a separate means of retrieval and processing, and data may differ strongly from one vendor to another. Requires stable communication from the field infrastructure.

Figure 3-10. Example of vehicle distance obtained from radar detection and compared with GPS position (Source: A. Sharma [12]).



3.3.7 High-Resolution Controller Event Data

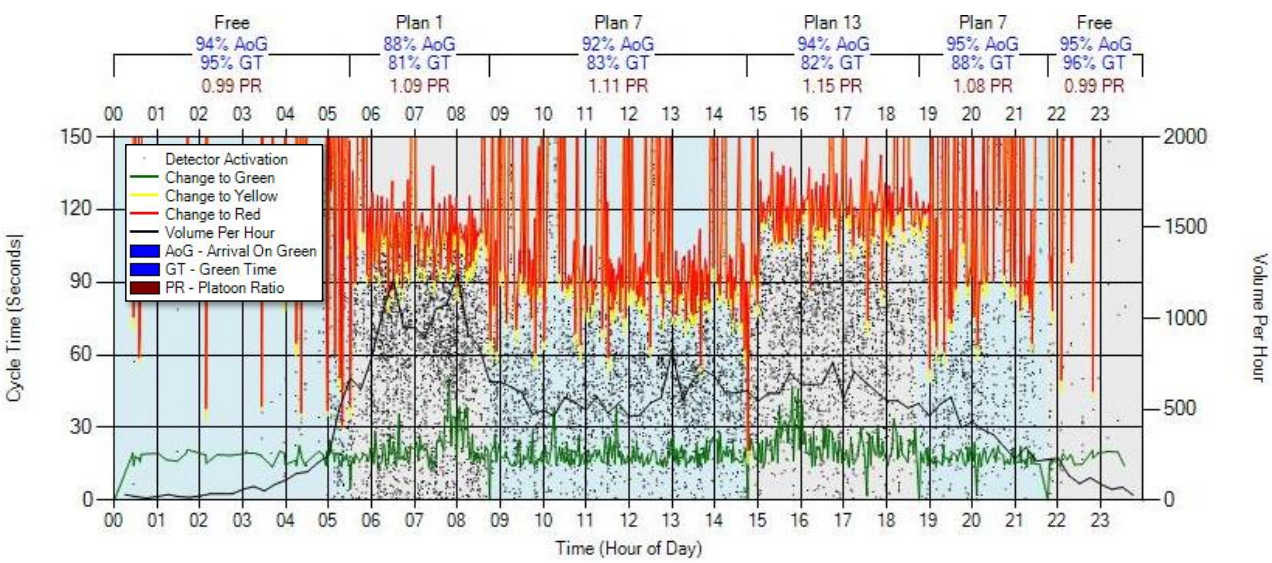
High-resolution controller event data is a means of recording the changes in the states of detectors, phases, overlaps, and other elements of signal control. These can be logged by external data collectors, or by some controller models. At the time of writing, six different vendors in the US had at least one controller model with a data logging feature. The name "high-resolution" comes from the fact that the state changes are intended to be written down in real-time as they occur. From the perspective of a signal controller this would be at the same rate at which the controller "ticks" through each decision, which is every 0.1 second at present.

Example. Figure 3-11 shows an example of a plot called the "Purdue Progression Diagram" (PCD), which exemplifies the level of detail that can be obtained from high-resolution data. This chart shows the arrival times of individual vehicles relative to the signal output on the same approach. The region below the green line represents when the signal was red, while the region between the green and red lines represents when it was green. Individual time of day periods are summarized by numerical metrics including the percent of arrivals on green (AoG) and the platoon ratio (PR).

Advantages. Can provide highly detailed and textured information about very specific aspects of signal operations. The data may be readily available in some systems, depending on existing controller types.

Disadvantages. Quality of performance measures is somewhat sensitive to the type of detection that is used. In systems with older controllers, external data collection or controller upgrades will be needed. Requires stable communication from the field infrastructure.

Figure 3-11. Example of a high-resolution data signal performance measure: the Purdue Coordination Diagram (Source: Utah DOT performance measures website [13]).



3.3.8 Real-Time Intersection Status Data

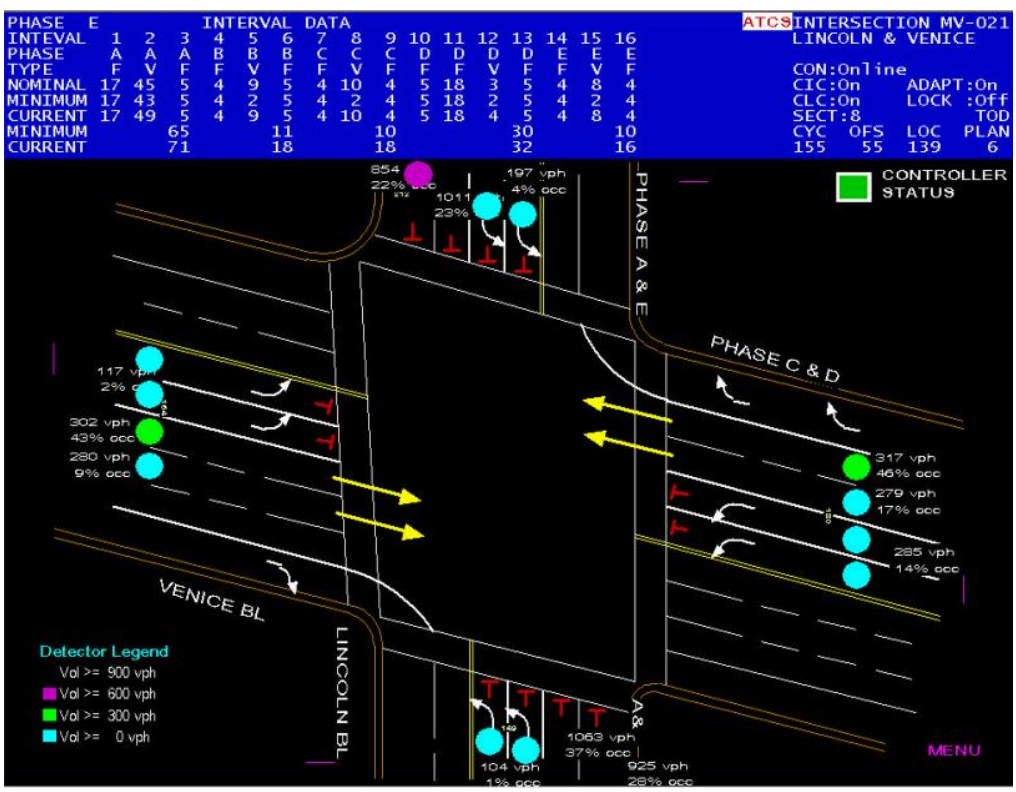
A number of systems exist for viewing intersection status in real time. These systems use some method of intersection polling to retrieve the current states of detectors, phases, and other signal timing data, which can be displayed in real time at a traffic management center, sometimes accompanied by video coverage of the intersection. One of the more well-known examples is the Los Angeles ATSAC system, but most vendors provide software that will allow their controllers to report their status so that it can be displayed in a similar fashion. If this data can be communicated and displayed on screen, it could also be logged by the software, making it a potential alternative data collection system for "high-resolution data".

Example. Figure 3-12 shows an example screen capture of an intersection status window from the ATSAC system. Detectors are shown on screen along with volume and occupancy data for each. Phase status is indicated by arrows; the controller is currently serving yellow on the east-west street.

Advantages. This type of data may provide a means of collecting the equivalent to "high-resolution data" in locations where such monitoring systems exist.

Disadvantages. The readiness of such systems to collect this type of data is likely to vary and may need to be developed. Robust, low-latency communication may be required. Without any local data buffering, any loss of communication longer than a few seconds may lead to some potential data loss. Interoperability with multiple vendors' equipment may be an issue.

Figure 3-12. Example of a real-time intersection display (Source: LA DOT [14]).



3.3.9 Vehicle Re-Identification Data

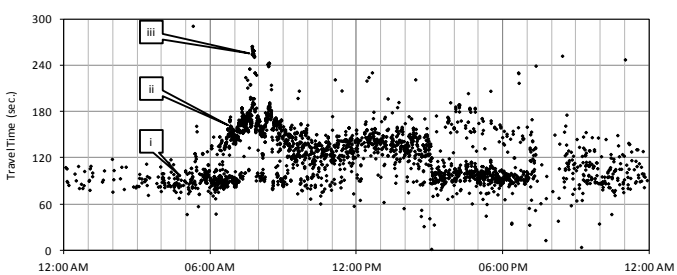
Travel time and delay are important metrics for evaluating arterial operations. One way to directly measure travel time is to observe the same vehicle at two locations; the difference in time between the observations yields the travel time. Automated methods to uniquely identify vehicles include monitoring of Bluetooth MAC addresses and WiFi identifiers broadcasted by mobile electronic devices, matching signatures of detector response to vehicle presence, and matching toll tags from vehicles equipped with transponders.

Example. Figure 3-13 provides an example of individual measured travel times through one signalized intersection, obtained from wireless magnetometer signature matching. Figure 3-13a shows the raw data, consisting of individual observations. Variations by time of day are noticeable, in particular a sharp transition around 3:00 p.m. that corresponds to a timing plan change. The AM peak shows examples of stratification, with the layers corresponding to the typical travel time (callout *i*), vehicles that made one stop (callout *ii*), and vehicles that stopped twice (callout *iii*). Figure 3-13b shows a distribution and a cumulative distribution of the travel times.

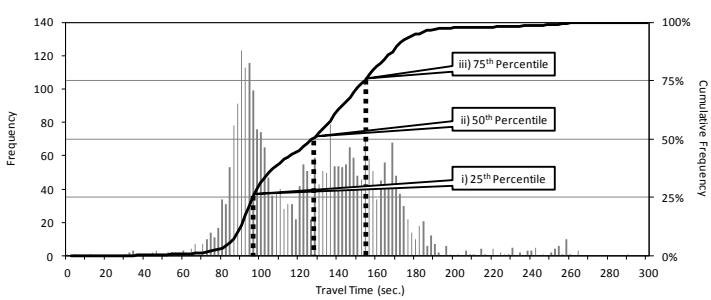
Advantages. Can provide detailed information about traffic performance.

Disadvantages. May require separate infrastructure for data retrieval and processing. Sensors located at places other than intersections may be challenging to supply power and communication to. Number of obtainable samples is sensitive to changes in mobile devices technology, and privacy concerns may be an issue in some areas. Requires stable communication from the field infrastructure.

Figure 3-13. Example of vehicle re-identification data (Source: Remias, et al. [15]).



(a) Raw travel time data.



(b) Distribution.

3.3.10 Probe Vehicle Segment Speed Data

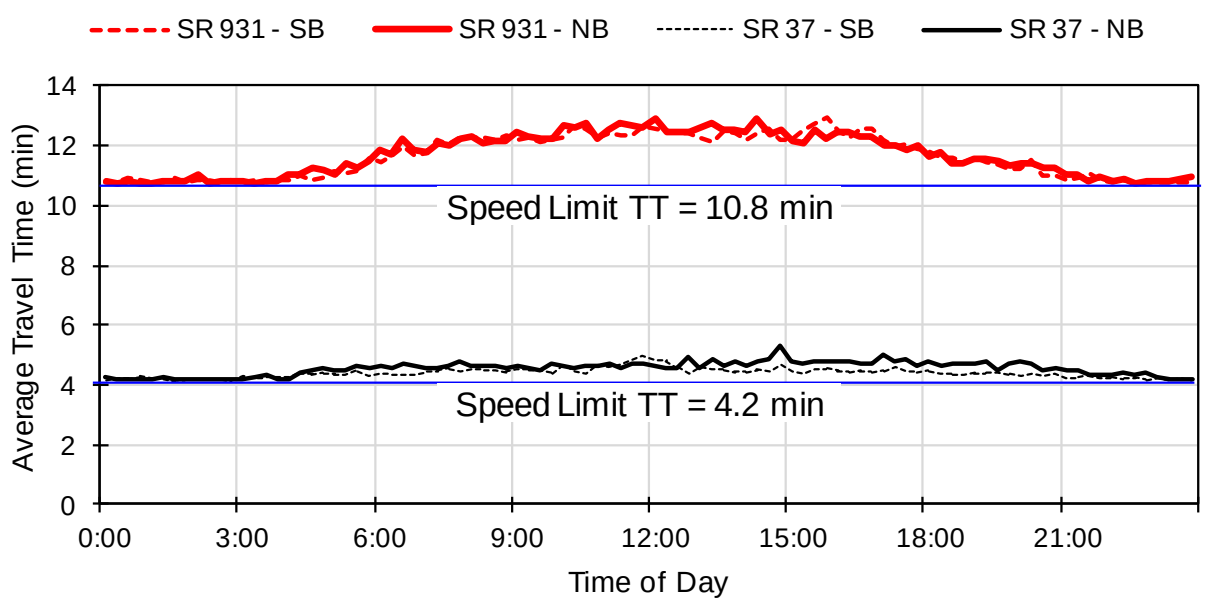
Several private sector data providers market a variety of products for traffic analytics, including segment speed data. This data set is derived from analysis of individual probe vehicles, but the data is anonymized by converting individual vehicle positions into average segment speeds. This data is typically provided on a minute-by-minute basis, with one speed record per segment per minute. The data quality is fairly reliable on freeway routes and its use on signalized arterials has been increasing [16,17].

Example. Figure 3-14 shows a plot of average travel times for two directions along two different arterial routes over a 24-hour period. The values are compared with the speed limit travel times for the two routes. Each data series is compiled from averaging over six months' data.

Advantages. No field infrastructure is needed. Data can be obtained for real-time analysis and for past performance.

Disadvantages. Segment definitions may not align with areas of interest. The data is provided as an average and may not capture the true degree of variation.

Figure 3-14. Example of segment speed data obtained from a private sector provider on two different signalized arterial routes (Source: Day et al. [18]).



3.3.11 Probe Vehicle Location Data

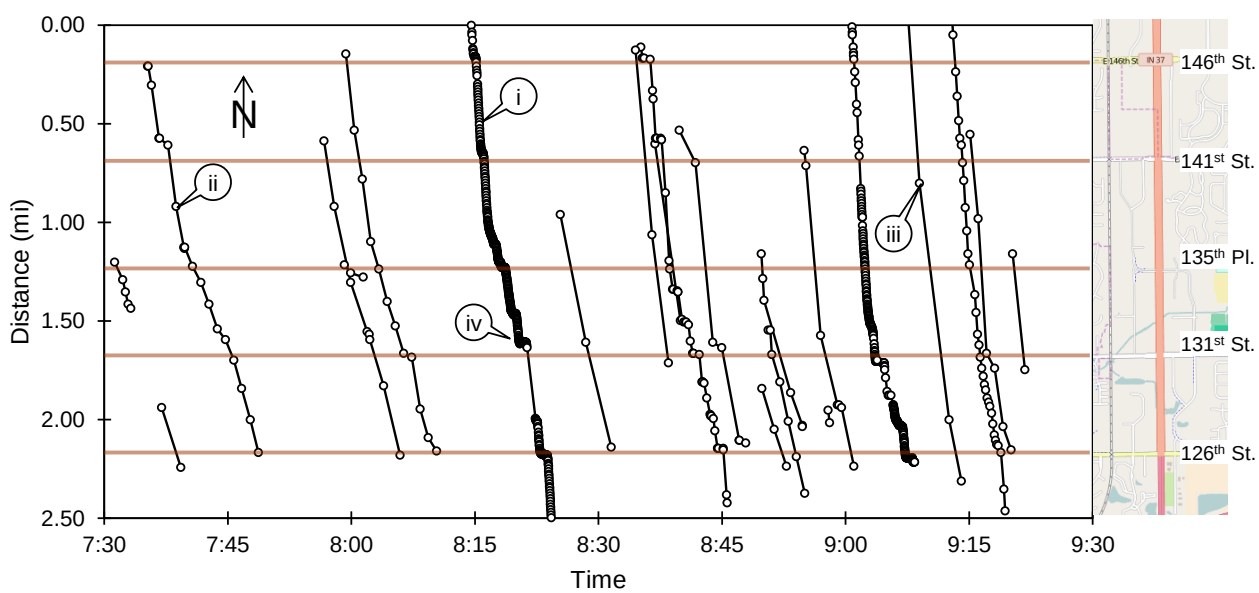
Segment speed data is based on timestamped vehicle position data. Data providers have begun to make some of the underlying raw data available for exploratory study to determine its value for more detailed analytics. Some researchers have begun to explore the use of this type of data for movement-based delay analysis [19] as well as vehicle arrival characteristics [20]. This data is still in its infancy but will likely see increasing use. Because much of this data is based on mobile devices rather than vehicle equipment, it may potentially become available faster than connected vehicle data, and also include non-vehicle modes such as bicyclists and pedestrians.

Example. Figure 3-15 shows southbound trajectories along an arterial route that were recorded in 2015 by a private sector data provider. Each point represents a particular timestamped position record. Some traces have a higher density of points than other, indicating that the reporting intervals among different vehicles differ.

Advantages. No field infrastructure is needed to collect the data. There is a potential for highly detailed analysis of individual movements.

Disadvantages. A map-matching process is needed to extract useful information about individual movement performance. Sample rates are currently quite low (about 1% or less of traffic volumes), but are likely to improve over time. Complex geometries such as where bridges occur may be difficult to analyze. Concerns about privacy remain to be negotiated for this type of data.

Figure 3-15. Example of timestamped vehicle location data obtained from a private sector provider (Source: Day et al. [7]).



3.3.12 Connected Vehicle Data

Predictions vary as to when a majority of the vehicle fleet will have onboard equipment to communicate with roadside infrastructure and other vehicles. More optimistic predictions expect to see connected vehicles appearing in the next few years and for the technology to spread quickly, while others anticipate that a few decades or longer will be needed before sufficient penetration is achieved. In the US, connected vehicle pilot programs have entered their second phase and some vehicle manufacturers have begun to include connected vehicle capabilities in new models.

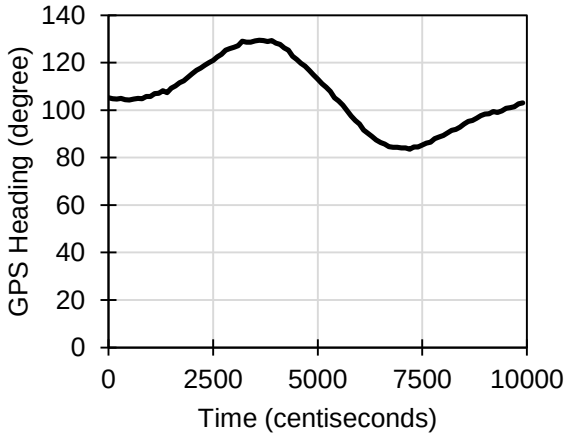
Example. Figure 3-16 presents a series of charts that are taken from the USDOT Safety Pilot Model Deployment [21]. The data shows a 100-second sample. Each chart contains 10,000 points that arise from the 0.01-second reporting interval. Detailed information about the vehicle heading and steering activity are seen in Figure 3-16a and Figure 3-16b. The vehicle position at each point is recorded by its latitude and longitude information, as reported in Figure 3-16c and Figure 3-16d. Data from vehicle sensors are also available, as shown in Figure 3-16e and Figure 3-16f, which show the measured distance from the vehicle centerline to the left and right sides of the roadway.

Another component of “connected vehicle” data relevant to signal control data would originate in the infrastructure. This includes “Signal Phase and Timing” (SPAT) data, which is intended to be broadcasted to vehicles for safety applications.

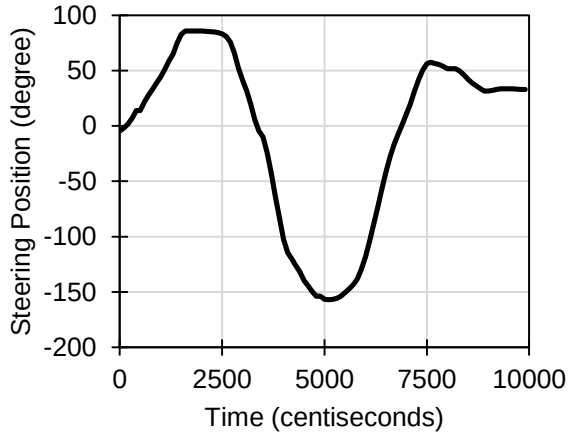
Advantages. Extremely detailed information, including a significant amount of data beyond position alone, can be extracted from the data. The data will be available in real time, potentially enabling signal control applications beyond performance measurement or off-line analysis.

Disadvantages. A significant amount of map-matching will be needed to make use of all the information available in this data set. It may be many years before enough vehicles are deployed with the necessary equipment to develop useful information. A very significant amount of infrastructure may need to be deployed to obtain this type of data. Concerns about privacy have yet to be reconciled.

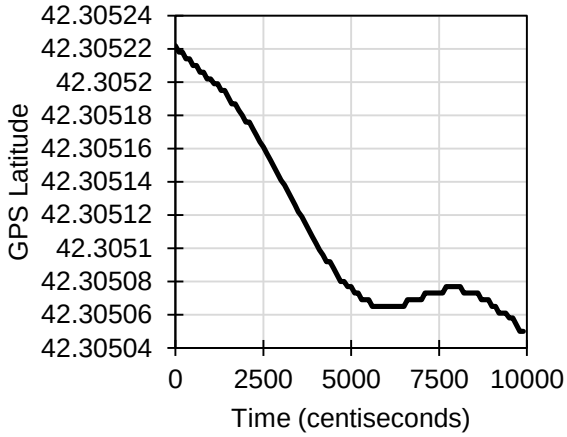
Figure 3-16. Example of a some data that may be available from connected vehicles (Source: USDOT Safety Pilot Model Development [21]).



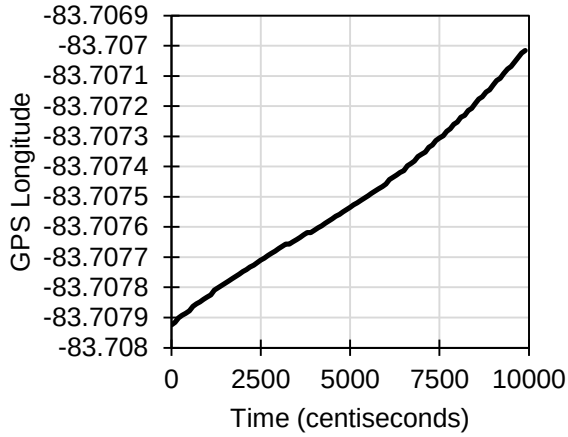
(a) Vehicle heading, from GPS.



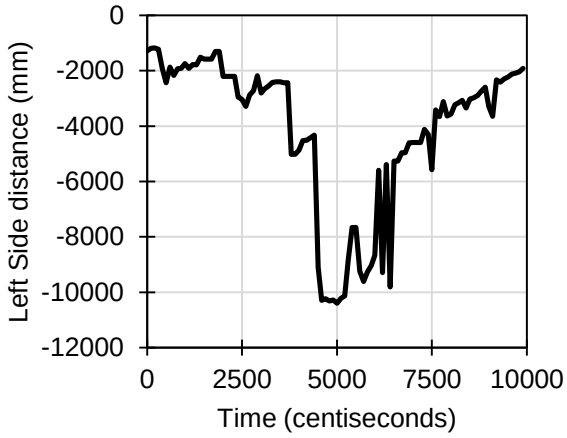
(b) Position of steering wheel.



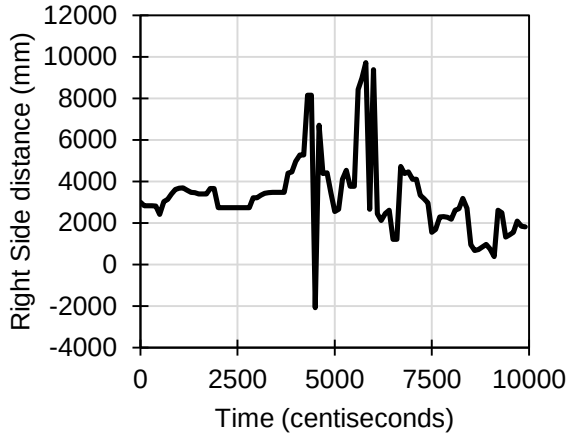
(c) Latitude, from GPS.



(d) Longitude, from GPS.



(e) Distance from vehicle centerline to left side of road.



(f) Distance from vehicle centerline to right side of road.

3.4 SELECTION OF INTERNAL AND EXTERNAL DATA TYPES

One of the aims of NCHRP 3-122 is to develop guidance for agencies to deploy performance measures in the short term, while being cognizant that emerging data sets will become available in the future. As explained in the previous section, there are a variety of data sets ranging from legacy sources that have been in use for many years, emerging sources which are currently available although not yet in widespread use, to those that are expected to become available in future, although the timeline for their availability is uncertain.

- Much of the legacy data has been developed for one particular type of product, making it challenging to achieve interoperability with multiple vendors' equipment. Although some of these tools can provide exceptionally detailed data, more often the data is only retrievable in an aggregated form that is too imprecise to be useful for detailed performance measures. This is a consequence of the limitations of data storage and communication that were present in the systems where the data was developed.
- Connected vehicle data will probably one day provide extremely detailed data about individual vehicles. Any predictions about the rapidness of adoption will be controversial. At present, all but a handful of vehicles on the roadways are *not* connected. The amount of time required to reverse the situation is unknown, but it seems likely that there will be a role for detection at signalized intersections for a long time—and hence a need for internal data to analyze operations from a complete perspective. However, connected vehicle data may quickly become a valuable external data source for measuring travel time and delay.
- Several transportation agencies have successfully implemented ATSPMs based on high-resolution data. So far, this has mostly been achieved using the *existing* detection and controllers, and often with minimal investment in communications infrastructure. It is possible to deploy high-resolution data through normal equipment upgrades and without a capital project. High-resolution data logging is currently available in at least one controller type from six vendors serving the US market, and is also available through external data collection units for older controller types. In addition, several vendors have implemented data collection and performance measurement tools in central systems software.

Because of its relative readiness for implementation, this report will focus on requirements for ATSPMs using high-resolution data as the primary means of acquiring the internal data necessary to understand signal operation in response to the control system's detection of traffic. In addition, the basic requirements for external measurements of travel time and delay are also discussed, in a technology-neutral manner that explains the basic principles of data collection that would apply to any technology used for those measurements.

3.5 TECHNICAL COMPONENTS OF A SIGNAL PERFORMANCE MEASUREMENT SYSTEM

3.5.1 Internal Data Collection

The technical components required to obtain internal data for ATSPMs can be grouped into four categories: intersection, communication, data architecture, and applications. First, the *intersection* category collects the state-change event data from the intersection using a local data collector. The *communication* category sends the event data to a management center or back office through the use of wired and/or wireless infrastructure. In some circumstances, such as limited scope or lower priority studies, "manual" data retrieval by field visits may suffice (so-called "sneaker net"). The *data architecture* category synthesizes the data into performance measure-ready structures using hardware servers and software systems. Finally, the *applications* category transforms the structured data into quantified performance measures and graphical visualizations. The components in each category are required at a minimum to develop ATSPMs (Figure 3-17).

3.5.1.1 Intersection Equipment

To collect the internal state-change data of the control system, intersections require a data collection device. This may consist of a logging-capable controller or, in the case of older controllers, some other external data collection device. An external device would have access to the same electrical outputs as the controller, although it may not be able to access variables that are internal to the controller unless they are tied to some electrical output. At present, six different vendors of traffic control equipment in the US offer at least one controller that has a data logger, and several external data collection solutions exist, so the data logger requirement is much lower than it was in the past. However, it is important to note that even if agencies already possess the appropriate controller model, it may be necessary to perform a firmware upgrade to achieve data logging capability.

In absence of detection, the data logger can record phase and overlap state change times, which can be helpful for confirming that the controller is operating as expected, but this data does not provide information about traffic behavior. For performance measures that incorporate the use of vehicle data such as occupancy and counting, detection systems are required. Detection systems are the infrastructure that can sense the physical presence of vehicles within defined detection zones on the roadway. Pedestrians and bicycles can also be "detected" by various means. This equipment is commonly deployed for actuated signal control.

Two types of detection installations are available: intrusive and non-intrusive. Intrusive detection systems include in-pavement inductive loops and magnetometers, while non-intrusive detection systems include radar and video. Connected vehicle applications may have data collection equipment internal to the traffic control system as well. These would rely on instrumentation in the vehicles to relay position data to the traffic control system through wireless transmitters and receivers, the latter of which would be non-intrusive installations.

As the detectors sense vehicles, the response of each sensor is channeled into a data collection unit that performs some processing of the raw signal before passing on data to the controller. For example, inductive loop response is monitored by a detector amplifier card that outputs a simple contact-closure state to the controller. Preemption and priority control systems also have inputs from devices that receive signals from railroad or emergency vehicles.

Figure 3-17. Components of a system to develop signal performance measures.

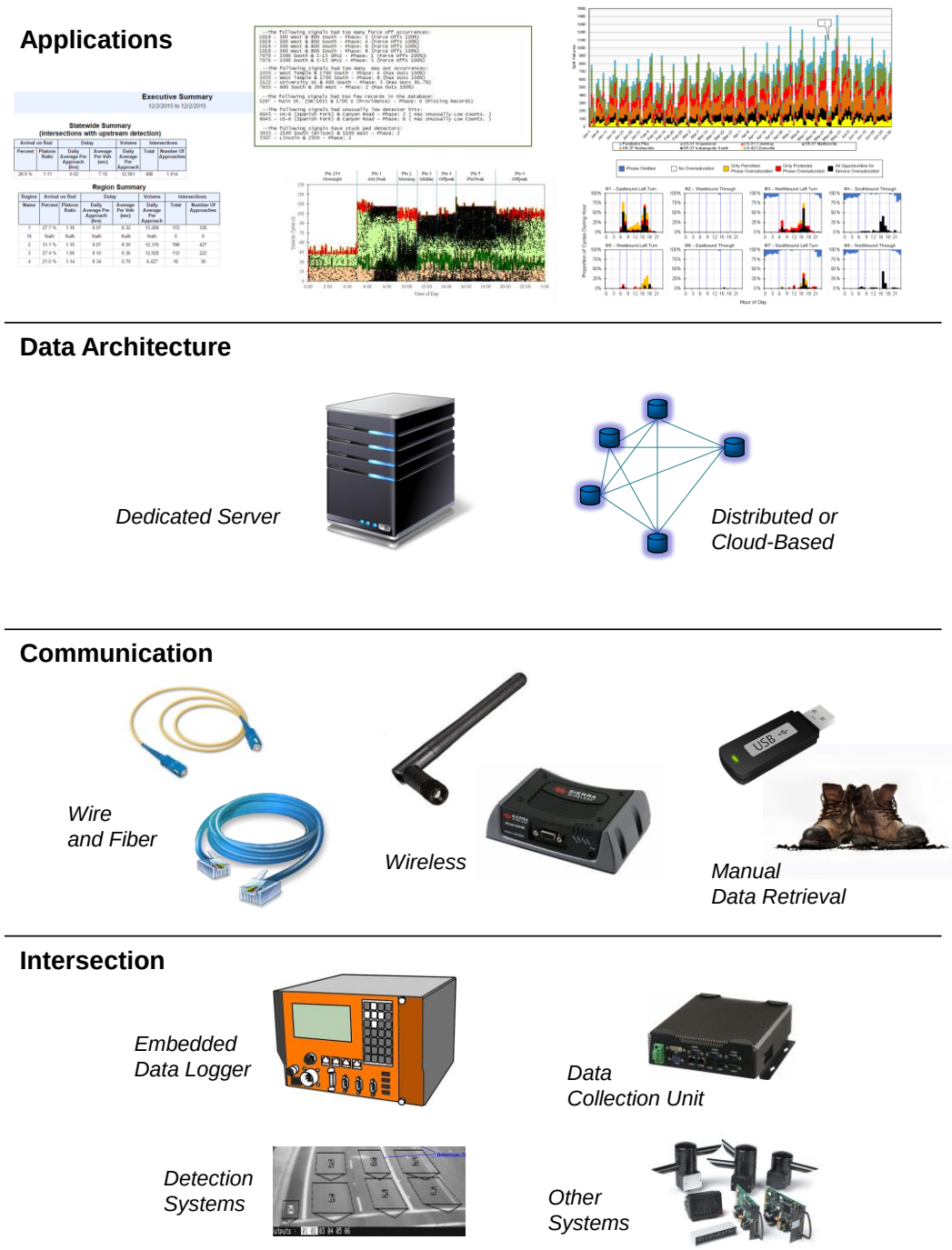
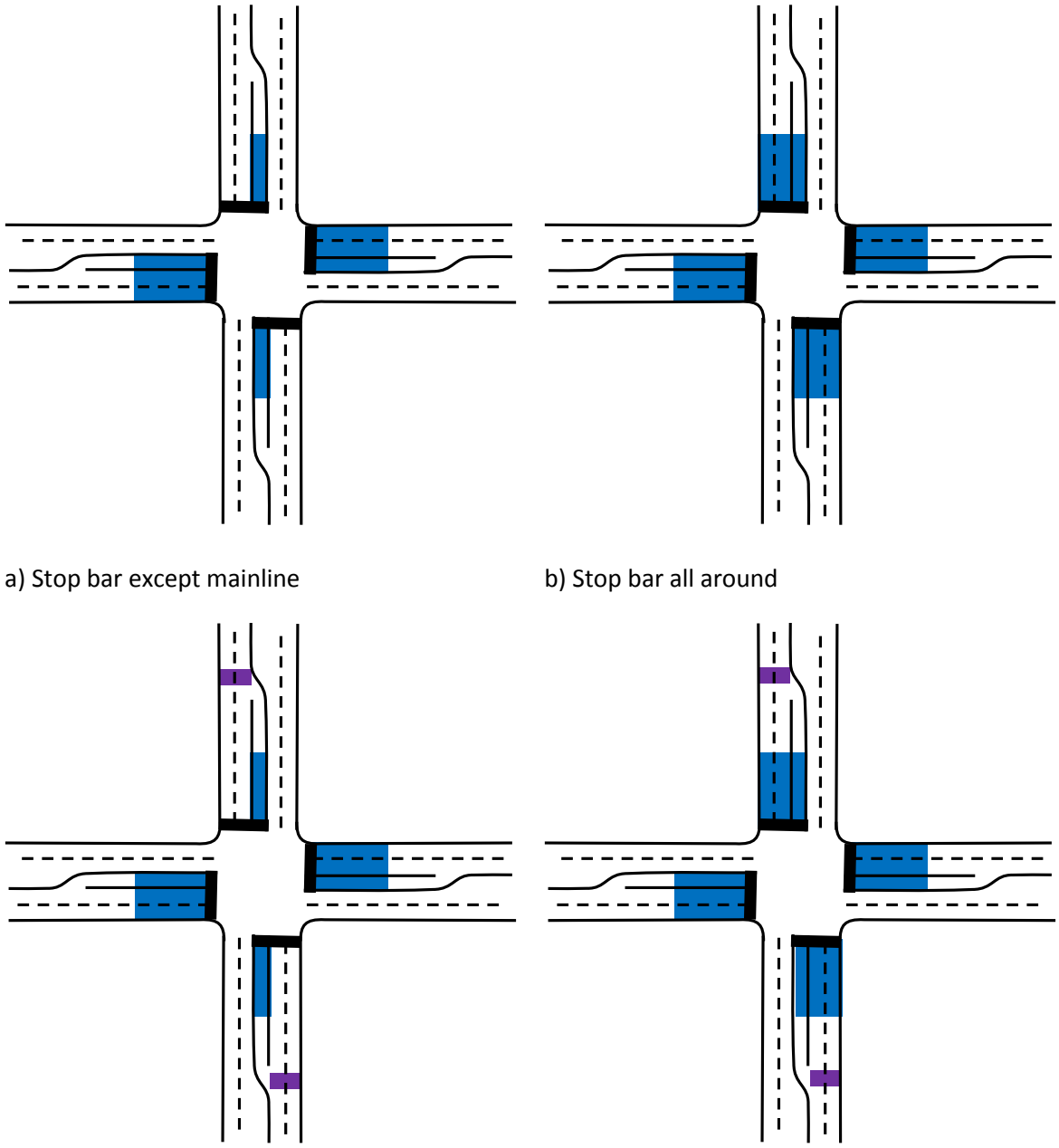


Figure 3-18. Intersection detection configurations [7].



a) Stop bar except mainline

b) Stop bar all around

c) Stop bar except mainline with mainline setback

d) Stop bar all around with mainline setback

Regardless of the technology of the detection system, the quality of the data, and any subsequently-generated performance measures, is sensitive to the physical definition of the detection zones. For detection zones that occupy a space large enough to accommodate more than one vehicle at a time, the data may be further improved when the detection system can distinguish between vehicles within the zone. This allows detection systems to accurately count the number of vehicles arriving, whereas systems that can

only output a simple occupancy state may underestimate the number. Many detection systems, including some inductive loop detector amplifiers, can provide both a presence and a count output.

Detection systems represent what is currently visible to traffic controllers. The traditional definition is that of fixed point sensors that have specific "zones" for which presence is reported, and this will likely continue to be the paradigm for traffic detector for some time. However, as technology continues to improve, it is possible that the notion of the binary contact closure for a detection zone may be replaced by more informative data. In fact, the fusion of detector data with probe and connected vehicle data may present another way to develop a more detailed picture of traffic operations. At any rate, existing detection systems are presently a vital component of a ATSPM system and must be accommodated.

The layouts in Figure 3-18 depict four common configurations of vehicle detection zones, shaded in blue, at an eight-phase intersection of a major arterial and a minor street. If an intersection operates with actuated control, all of the "minor" movements are typically instrumented with detection at the stop bar to allow vehicle presence to call and extend the associated phases. When all the vehicles have been served on the minor movements, the common default controller behavior is to return service to the major movements. Because of this, some agencies do not provide detection on the "mainline" as a cost-cutting practice. However, other agencies still provide such detection to allow for dilemma zone protection (with setback detection), fully-actuated control, or coordination with early yield.

- Configuration (a) illustrates a setup without any detection on the major through movements.
- Configuration (b) has stop bar detection at all major and minor movements.
- Configuration (c) has setback detection on the two major approaches for dilemma zone protection.
- Configuration (d) has advance detection for dilemma zone protection in addition to all stop bar detection.

Table 3-4 shows the configurations, with and without detection, and which performance measures are attainable in each configuration, for the list of performance measures that was introduced in the previous working paper. Generally, the greater the number of the detection zones and the capability of the detection technology, the more performance measures can be attained.

Another important point relevant to the detection zones is that the detector zone definitions are critical for getting useful information from the data. The physical location of the zone must be defined for each separate detection channel. In addition, it is *preferable*, although *not required*, for different lanes to be separated in the detection schema, where possible. This enables the metrics to be calculated at a higher level of detail (there is also an operational benefit to lane-by-lane detection). Some locations, for example, may be configured such that the detection system, regardless of the number of zones configured internally, only places calls on a small number of channels (e.g., channels 1–8 for eight phases). Depending on the location, this might not provide enough detail and the detection scheme might need to be revised.

Table 3-4. Detector configuration requirements matrix for performance measures (based on [7]).

		DETECTOR CONFIGURATION							
		NO COUNT				WITH COUNT			
TASK GROUP	PERFORMANCE MEASURE(S)	A	B	C	D	A	B	C	D
Control status	Coordination plan status	✓	✓	✓	✓	✓	✓	✓	✓
	Effective cycle length	✓	✓	✓	✓	✓	✓	✓	✓
	Green/yellow/red duration	✓	✓	✓	✓	✓	✓	✓	✓
	Phase termination type	✓	✓	✓	✓	✓	✓	✓	✓
	Event-based diagnostics	✓	✓	✓	✓	✓	✓	✓	✓
	Detector failures	Δ	✓	✓	✓	✓	✓	✓	✓
	Intersection in flash	✓	✓	✓	✓	✓	✓	✓	✓
	Communication status	✓	✓	✓	✓	✓	✓	✓	✓
Counting	Volume			Δ	Δ	Δ	✓	Δ	✓
	Volume/capacity (v/c) ratio			Δ	Δ	Δ	✓	Δ	✓
Monitor capacity	Time to service	✓	Δ	✓	✓	✓	✓	✓	✓
	Delay	Δ	✓	Δ	✓	Δ	✓	Δ	✓
	Green and red occupancy	Δ	✓	Δ	✓	Δ	✓	Δ	✓
	Number of split failures	Δ	✓	Δ	✓	Δ	✓	Δ	✓
	Split monitor	✓	✓	✓	✓	✓	✓	✓	✓
	Queue length			Δ	Δ	Δ	✓	✓	✓
	Degree of intersection saturation						✓	✓	✓
	Oversaturation metrics			Δ	Δ			Δ	Δ
	Conflicting demand			Δ	Δ	Δ	✓	✓	✓
	Number of preemptions*	✓	✓	✓	✓	✓	✓	✓	✓
	Ped/bike phase utilization†	✓	✓	✓	✓	✓	✓	✓	✓
Monitor progression	Arrivals on red/green			Δ	Δ			Δ	Δ
	Coordination diagram			Δ	Δ			Δ	Δ
	Coordinatability index			Δ	Δ			Δ	Δ
	Platoon ratio			Δ	Δ			Δ	Δ
	Cyclic flow profile			Δ	Δ			Δ	Δ
	Time-space diagram			Δ	Δ			Δ	Δ
	Travel times			Δ	Δ			Δ	Δ
Monitor safety	Yellow/Red actuations	Δ	✓	Δ	✓	Δ	✓	Δ	✓
	Red light running	Δ	✓	Δ	✓	Δ	✓	Δ	✓
	Approach speed*	✓	✓	✓	✓	✓	✓	✓	✓

TABLE LEGEND

✓ All movements
Δ Select movements
Gray Unsupported
* Select technologies
† Pedestrian/bike detectors required

3.5.1.2 Communication

The communication category contains infrastructure and devices used in the transferring of logged controller data from the local intersection to a centralized location, such as a traffic management center or back office, for further processing, analysis, and archival. The data transmission should be secure and should operate within a tolerable latency threshold. Communication infrastructure may be wireless or wired. Typical wired infrastructure consists of fiber cables or Digital Subscriber Lines installed in conduits, while wireless infrastructure consists of a network of transmitter and receiver devices and base stations. Both types of infrastructure can utilize pre-existing commercial communication networks through resource trading between agency and commercial owner. There is not a one-size-fits-all solution, and as such depends on the network maturity and resources that are available to each agency.

An example network consisting of a hybrid of wired and wireless technology is illustrated in Figure 3-19. The fiber conduit runs along a local arterial that provides connectivity between the signal cabinets through a set of fiber interconnects and Ethernet switches. A wireless subscriber unit then connects the arterial network to a base station via a tower, from which can access the traffic management center using a separate fiber backbone.

Data stored locally at the intersection can also be retrieved using a manual process. The “sneaker net” method for data retrieval is an alternative to wired or wireless infrastructure. Recent technologies have increased the computing power of signal controllers to allow storing large quantities of data over long periods, potentially as long as multiple years. This would allow the data to be retrieved from the field every so often as necessary, or as resources are available. For controller models that do not have a large memory, small, single-board personal computers can be utilized to cache the data through a local Ethernet connection to the signal controller.

3.5.1.3 Data Architecture

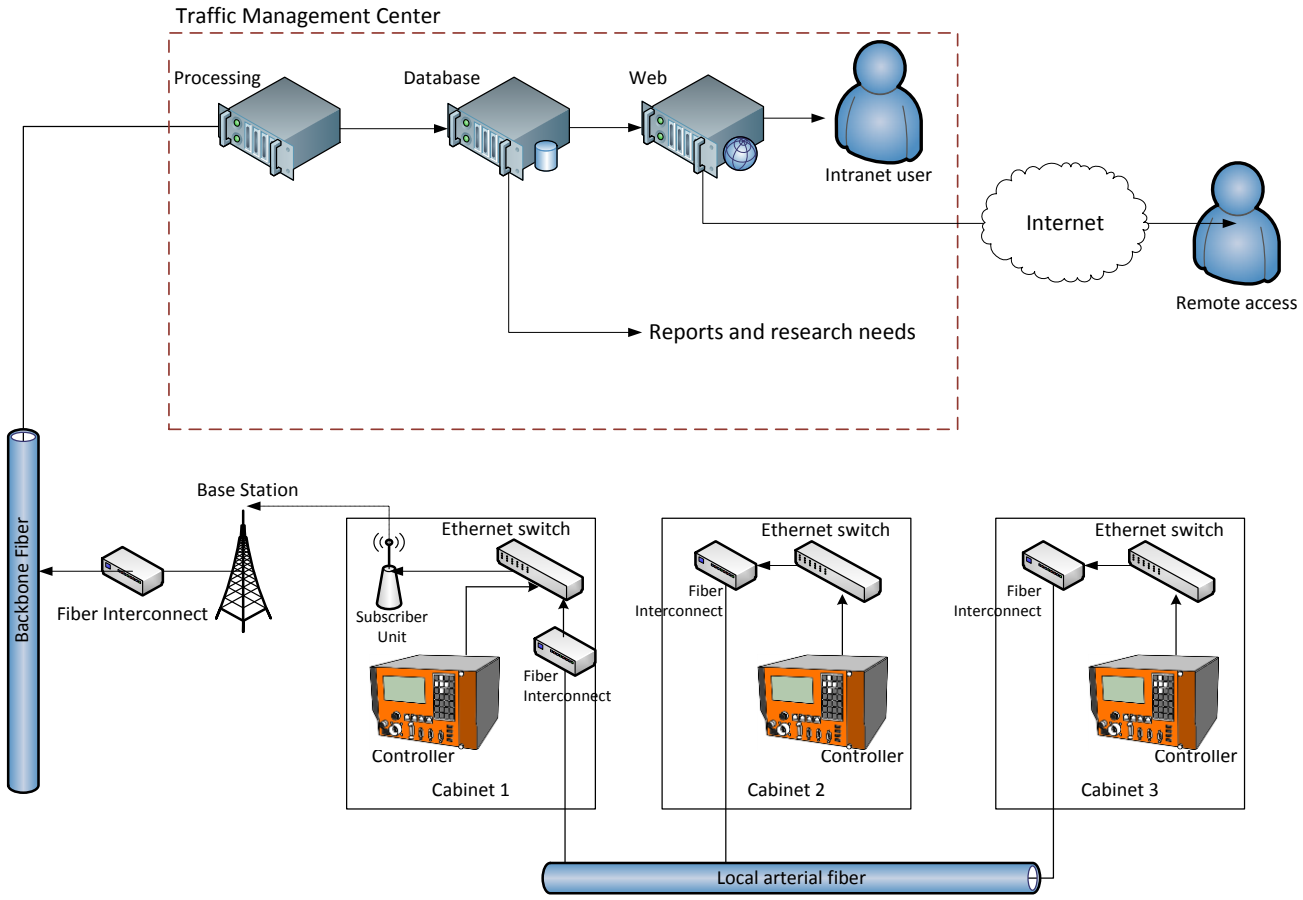
The computer hardware and software components essential for processing, analyzing, and storing data internal to the traffic control system comprise the data architecture category. There is a plethora of options in this category, with many technologies available to accommodate requirements of compatibility, scalability, cost, and ease-of-use. The *physical architecture* in which the data is managed is the computer servers, of which the processing speed, memory, and disk capacity are the most essential considerations. The “processing” and “database” components in Figure 3-19 drawn within the traffic management center box signifies the physical architecture in the data chain. The *software applications and data schemas* are deployed to the physical architecture to manage the data. Alternatively, there are many commercial vendors that offer “cloud based” computing and storage products that essentially fill the role of physical architecture. In this case, the software would be deployed to a remote physical system managed by a commercial vendor.

As a whole, the software applications and data schemas must be able to conform and integrate data logged at different intersections, potentially across vendors and formats, as part of a *data processing routine*. This typically requires specialized applications that perform the task, preferably on predefined, automated

schedules, and either require the development of customized code or are available as off-the-shelf products. The data processing routine produces normalized data that is ready for performance measure production, and is stored in a data schema, managed by database software. A widely-used database platform is the relational database management system (RDBMS) of which commercial and open-source products are available.

The design of the data schema is critical for data accessibility, scalability, and general usefulness to the practitioner. Typical unprocessed, raw data native to a traffic signal control system may contain time-stamped enumerations or codes to describe the traffic activity, but are difficult to piece together without information to decode the data. In addition, these native formats are not optimized for top-down reporting over long periods and across many intersections. As part of the data processing routine, the raw data is conformed to the data schema for greater efficiency using mapping heuristics to orient the data, and reduction techniques to compress and combine related events, such as the time a phase turns green to the time the same phase turns yellow. Moreover, summary data can be pre-calculated in advance of high-level reporting requests to further increase scalability. A study on traffic signal data scalability showed as much as a 99% data size reduction can be achieved through a data binning process.

Figure 3-19. An example communication infrastructure with blended use of fiber and wireless communication segments [7].



3.5.1.4 Applications

Finally, the applications category represents the end point where the performance measure data and graphics are delivered to the user. This involves running some tasks on the server to access the data, and arranging these into the final form for delivery. There are several different potential venues for this to take place. One would be for a particular piece of software to perform all of these tasks as a single package, potentially with some server-side data management. Some central management systems exist which include performance measurement tools. Another option is to use a web-based front end, which offers a similar interface to the user, and which would use a combination of client-side and server-side tasks. An advantage of the web-based system is that the performance measures can be accessed through the internet and no special software installation is needed. However, the advantage of a software-based system would be potential for integration with other traffic management tasks.

At present, several different options exist for agencies interested in deploying ATSPMs relevant to the applications category.

- The UDOT ATSPM system [13] is available as an open source download. It relies on some proprietary software components, but the system for running the "front end" is a web-based application for which the code is fully available. Implementation of this software requires some expertise but has been successfully carried out by several agencies at the time of writing.
- Several private sector companies offer software, either as a standalone package or as a web-based service, to produce performance measures. Several different companies have arisen to fulfill this use case, including manufacturers of controllers and detection systems, as well as software companies specifically founded for delivery of ATSPMs.
- Other agencies, such as Indiana DOT and the City of Colorado Springs, have developed their own systems in-house for handling performance measure applications.

The path taken by an individual agency would depend on its personnel and budget capabilities, IT support, and desire of control over the performance measure system.

3.5.2 External Data Collection

The previous section discussed requirements for collection of data that is internal to the traffic control system. With the possible exception of future connected vehicle data, the internal data is not typically capable of directly measuring traffic performance. It is possible to model queuing, delay, and travel time with good accuracy when the model assumptions closely match reality. However, since there are some means of measuring these phenomena it is worth discussing how this can be integrated into a performance measurement system.

Speed, travel time, stopping, queuing, and delay are the primary traffic observations that would be desirable to obtain by external measurements. The survey of data sources described various technological means of producing such measurements. Independent of the specific technology in use, the data tends to arrive in three basic ways:

- Timestamped unique vehicle identifiers may be obtained in various ways. This enables the travel time and the average speed between two locations to be measured. A network of locations can allow some routing information to be obtained as well.
- Segment-based characteristics (such as speeds) can be obtained as an average over some time interval (such as each minute).
- Individual vehicle trajectories can be measured, either as latitude, longitude, and timestamp or segment position and timestamp. The time between subsequent position records, or the reporting interval, determines the spatial and temporal resolution of the data and the level of detail that can be extracted.

The requirements for the data are generally similar to that for internal data collection, except for the category of intersection equipment. Once the data is collected, the methods of storage and retrieval could be situated in a similar manner to that of the internal data.

Some “external” data be provided by components within the traffic system but the route for data collection would not necessarily be through the signal controller. An example would be speed data collected by radar detection. This is used extensively by UDOT to measure approach speeds. These are timestamped and retrieved by the same servers that separately manage the high-resolution controller data. The radar speed data can then be overlaid onto the high resolution data.

While some equipment may be stationed at intersections, it is also possible for the data to be retrieved by other means. Data obtained from mobile devices is more likely at the present time to be obtained by private sector data providers. Connected vehicle equipment is currently envisioned as relying on “roadside units” (RSUs) to facilitate communication, which may be included in the cabinet at an intersection but could in future implementations be based on an alternative type of installation.

The location of the sensing equipment has some relevance to ATSPMs in that control delay can only be correctly measured if the impacts of delay on the vehicle performance are fully captured. In Figure 3-1, the travel time measurement locations are situated well away from the region where queuing takes place. As queues approach the entry detector, delays would start to become underestimated.

For vehicle identification based techniques, this means that ideally the entry sensor would be sufficiently upstream of the intersection such that the vehicle has not already started to slow down because of its approach to the intersection, while the exit sensor would be on the far side of the intersection. For this reason, midblock locations are desirable for these types of measurements, which can be challenging since cabinets at intersections are the more likely source of power needed for the sensors. Intersection locations are sufficient for measuring travel times on roadways spanning several intermediate intersections, but they cannot capture the delay incurred at the first and last intersection. Similarly, vehicle trajectories would need to be tracked sufficiently upstream to capture the influence of the intersection, and the reporting interval would need to be of sufficiently detailed resolution to avoid averaging out the vehicle response.

3.6 AGENCY BUSINESS PRACTICES

In addition to the technological requirements listed in the previous section, the human element is also an important one to ensure successful implementation. This is necessary both for the deployment and installation processes as well as for the usage of the data to its full potential.

The first concern in a deployment from this perspective is one of funding. Large scale traffic control system deployments are often thought of as capital procurements, and that option is indeed possible for a performance measurement system. At the same time, however, the *infrastructure requirements* for ATSPMs (controllers and detection) can be acquired without a capital procurement through regular equipment upgrades and by specifying appropriate detection into intersection layouts, thus laying the groundwork for a performance measurement system to be deployed in future. Therefore, if the agency is unable to procure specific funding for a performance measurement system, it is still possible to develop one along more "organic" lines. Given that most new controller models will likely support high resolution data logging in the near future, it might become impossible to avoid automatically building the capability whenever a controller upgrade is made.

Another potential barrier to entry is that of the organizational policies within the agency itself, particularly with regard to information technology (IT) management practices. Traditionally, traffic control systems have tended to exist within their own closed networks and would neither require the same level of management as the computers and servers used for other public services, or would they yield a potentially burdensome amount of data. The implementation of high-resolution data collection thus has the potential to create "new" use roles for some agencies—which are roles that have existed for a long time in the IT world, but which may be new to traffic control. Substantial dialog between IT practitioners and traffic management staff may be needed; in larger agencies it may be necessary to add personnel to fulfill the role rather than relying on IT who are mostly dedicated to maintaining computing equipment for day-to-day human use.

Another consideration is that of user training. In order to extract benefit from a performance measurement system, practitioners must know how to use the system and how to extract useful information from the performance measures. In the past, this has been achieved by early adopters through experience and trial-and-error experimentation. Some of the performance measures have the characteristic of being intuitive to traffic practitioners, which has facilitated this process. However, there is a learning curve and a need for training. The need for materials to facilitate that training is a likely topic for dialog and further development at a national level, such as through the Every Day Counts initiative.

One final consideration that is relevant to many agencies is that of multijurisdictional cooperation. For example, some agencies manage signal systems that coordinate with neighboring systems that other agencies manage. In this case, it is possible that only a portion of the system may be "covered" by ATSPMs, at least for some time after initial investments are made. Even if this is the case, there is still a potential to benefit from even partial coverage. It is still possible to evaluate the local performance at the included intersections, and gain some insights about coordination, particularly at those intersections on the jurisdictional boundary.

3.7 SUMMARY AND CONCLUSION

This working paper reviewed requirements for automated traffic signal performance measures. A brief description of the physical system being analyzed was presented, which gave some insights to the types of data that can be collected. These were identified as internal and external data types. Next, a review of various data sources was presented, and the advantages and disadvantages of these data sources relative to signal performance measures were discussed. Next, the required components of a signal performance measurement system were discussed. Technical components of such a system include the intersection equipment, communication systems, data architecture, and the delivery of applications to the end user. The paper closes by discussing needs relative to agency business practices relevant for deployment and usage of the performance measures.

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NCHRP Project 03-122: Performance-Based Management of Traffic Signals

Working Paper No. 4
Guidebook Outline

Prepared for the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

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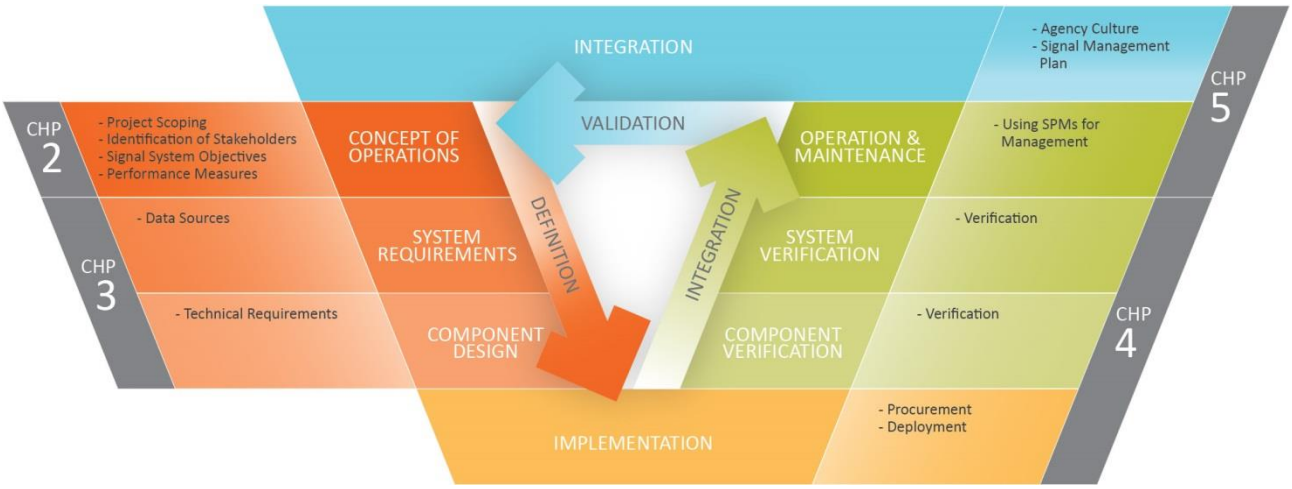
The following guidebook outline follows the systems engineering process shown in Figure 4-1. Annotations throughout describe planned section content.

Figure 4-1. Guidebook outline framework.



1. **Chapter 1: Executive Summary**

   Chapter 1 will introduce signal performance measures (ATSPMs), highlight their value, and describe the process of implementing them into traffic signal management. It will be a stand-alone document that can be given to decision-makers when requesting resources.

2. **Chapter 2: Defining the Concept of Operations**

   Chapter 2 will help an agency define a Concept of Operations for applying performance measures. Ultimately, this chapter will help an agency select ATSPMs to incorporate into the management of their traffic signal system.

   a. **Project scoping**

      The first step in defining a Concept of Operations is identifying the extent of ATSPM integration into traffic signal management. Some agencies may be ready to implement ATSPMs system-wide, while others may be starting with a limited number of signalized intersections. Multi-jurisdictional considerations will be an important element during this stage.

   b. **Identification of stakeholders**

      Different stakeholders will use ATSPMs in different ways. For example, a traffic signal engineer may use "arrivals on red" to adjust offsets for better progression, while the same ATSPM can be used to show the public how the number of stops along their commute has changed as a result of signal timing.

      i. **Traffic signal engineers/technicians**

         Traffic signal engineers/technicians can use ATSPMs to adjust signal timing and infrastructure in the field.

      ii. **Traffic signal managers**

         Traffic signal managers can use ATSPMs to help prioritize activities related to signal timing and infrastructure.

      iii. **Public**

         ATSPMs can be shared with the public to inform them about current conditions or impacts of a project.

      iv. **Policy decision-makers**

         Particularly related to funding, ATSPMs can help an agency tell a story about the performance of a traffic signal system.

c. **Establish signal system priorities**

An agency may have competing signal system priorities. For example, mainline progression could be at odds with providing pedestrians additional time to cross the mainline. Before selecting objectives and performance measures, an agency will need to establish priorities based on the operating environment and users.

d. **Select signal system objectives**

Objectives are the building blocks for an ATSPM-managed traffic signal system. They can be organized under two primary goals.

i. **Maintenance – keep equipment working effectively.**

ii. **Operations – maintain system effectiveness.**

e. **Select performance measures**

Once objectives have been defined by an agency, they must be linked to performance measures. This section will describe each of the ATSPMs, organizing them into measured performance measures, calculated performance measures, and diagnostic measures. For each ATSPM, the guidebook will include a two-page "primer" with detailed information, including how ATSPMs may be used in combination.

i. **Measured performance measures**

Measured performance measures are those that can be directly measured; they are the ATSPMs in their simplest form. They will be organized by the data source required, which relates directly to the following traffic signal components.

1. **Detection**
2. **Communication**
3. **Signal timing**
4. **Coordination**

ii. **Calculated performance measures**

Calculated performance measures are those that are calculated using the measured performance measures. For example, volume to capacity will be considered a calculated performance measure as it uses the measured performance measure of volume.

iii. **Diagnostic measures**

Diagnostic measures are those that do not measure performance directly but can be used to help diagnose traffic signal issues. For example, coordination plan status will not be used for measuring performance, but could be a useful measure to diagnose a programming error causing intersections to be out of sync along a corridor.

iv. **Primer information**

While not a section on its own, this outline bullet lists some of the information planned for the two-page primer about each ATSPM. The primers will summarize much of the information discussed in the following chapters; references to applicable sections will be included throughout.

1. **Related objectives**
2. **Required data sources**
3. **Required detection**
4. **Cost estimates**
5. **Calculation methodology (if applicable)**
6. **Visualization options**
7. **Applications (organizational, planning, design and construction, operations, maintenance)**

3. **Chapter 3: System Requirements for Performance Measures**

Chapter 3 will identify elements that need to be in place for successful ATSPM implementation as well as what is possible with existing traffic signal infrastructure.

a. Data sources

ATSPMs can be produced using a variety of data sources. This section will describe the data sources, link them to ATSPMs, and describe how they can be combined.

b. Technical requirements

Agencies may choose to implement ATSPMs that their current system can support, but many may want to use new performance measures that require equipment upgrades. This section will provide information about minimum requirements.

i. Field equipment

1. Detection

For some ATSPMs, detection is key to providing information about vehicle arrivals and correlating that to the signal state.

2. Controller

The type of controller is important for providing certain types of data.

ii. Communication network

Communication between the office and field is crucial for developing a scalable ATSPM system.

iii. Central/office equipment

1. Hardware

There are multiple ways to store ATSPM data at a central office. Depending on the data source, data may be stored in a central traffic management system or on a separate server.

2. Software

Software is required to query ATSPM data and turn it into meaningful information and visual displays.

4. Chapter 4: Implementation of Performance Measures

Chapter 4 will describe the implementation process for ATSPMs.

a. Procurement

This section will describe considerations for agencies when procuring ATSPM equipment.

i. Funding

There are multiple ways to fund ATSPM upgrades. While some agencies may choose to implement them under a capital improvements project, other agencies may prefer to start upgrading slowly using maintenance funding.

ii. Existing equipment

Agencies will need to determine how ATSPM equipment will work with existing traffic signal equipment installed both in the field and at the central office. This includes both hardware and firmware.

iii. IT coordination

Special attention should be given to coordination with the IT department, particularly for firewalls.

iv. Multi-jurisdictional relationships and information sharing

Some jurisdictions may have relationships with nearby agencies, which can be leveraged for information sharing.

v. Legal considerations

ATSPMs may be useful for reconstructing events.

b. Deployment

An agency will need to decide the best course of action for deploying new ATSPM equipment.

i. Prioritize locations and timeline for installation

ii. Mitigate risks to successful deployment

iii. Lessons learned

c. Verification

After an ATSPM system has been deployed, an agency will need a plan to verify the results being produced. An agency could consider using a secondary source (e.g., video) to confirm ATSPM reports are functioning as intended.

5. Chapter 5: Integration into Agency Practices

Chapter 5 will discuss strategies to fully integrate ATSPMs and ensure continued use by an agency.

a. Agency culture

Beyond technical requirements, there are institutional policies that should be considered. At many agencies, a culture shift will be required to fully integrate use of ATSPMs.

i. Organizational policies

ii. Training

b. Signal management plan

Sustainably using ATSPMs as part of traffic signal management requires forethought. As part of the systems engineering process, documenting objectives and performance measures in a signal management plan can help an agency focus the use of current ATSPMs and plan for future needs.

i. Complete capability maturity model (CMM) assessment

ii. Align objectives for different stakeholders/applications

iii. Link objectives and performance measures

iv. Identify how to mitigate gaps through funding, staffing, and system/technology

v. Life cycle and risk management

c. Using ATSPMs for management

This section will give examples of ATSPM applications in traffic signal management, including several case studies.

i. Goals assessment

Individual ATSPMs can inform the bigger picture when assessing whether thresholds have been met.

ii. Decision-making (near-term and long-term)

This section will include information about the types of decisions that can be informed by ATSPMs.

iii. Case studies

While case studies will be summarized in this section, particularly related to how agencies apply ATSPMs to the management of their signal systems, relevant information from the case studies will be sprinkled throughout the previous chapters.