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CONTRIBUTORS

Brandon Nevers, Tom Urbanik, Kevin Lee, Burak Cesme, Jennifer Musselman, Laura Zhao, Kittelson & Associates, Inc., Darcy Bullock, Howell Li, Purdue University, City of Portland Alison Tanaka, Iowa State University Chris Day, and Kimley-Horn & Associates Lucy Richardson; National Cooperative Highway Research Program; Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

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NCHRP RESEARCH REPORT 954

PERFORMANCE-BASED MANAGEMENT OF TRAFFIC SIGNALS

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Brandon Nevers
Tom Urbanik
Kevin Lee
Burak Cesme
Jennifer Musselman
Laura Zhao
KITTELSON & ASSOCIATES, INC.
Portland, OR

Darcy Bullock
Howell Li
PURDUE UNIVERSITY
West Lafayette, IN

Alison Tanaka
CITY OF PORTLAND
Portland, OR

Chris Day
IOWA STATE UNIVERSITY
Ames, IA

Lucy Richardson
KIMLEY-HORN & ASSOCIATES
Dallas, TX

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2020

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the FHWA. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP RESEARCH REPORT 954

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Learn more about the Transportation Research Board at **www.TRB.org**.

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By providing responses to written surveys and by participating in interviews, these individuals greatly helped the project team develop content that would be useful to a diverse array of agencies. Together, the panel and additional public agency contributors helped make this guidebook vastly more comprehensive and forward-thinking.

FOREWORD

By B. Ray Derr
Staff Officer
Transportation Research Board

NCHRP Research Report 954 compiles the best available information on automated traffic signal performance measures so that agencies can evaluate whether this performance-based approach would be cost-effective for their system and develop a plan for implementation. This guide and its accompanying data dictionary and communication materials will be useful to system managers, designers, and operators.

The performance of the surface transportation system is profoundly affected by the over 400,000 traffic signals across the United States. Ideally, traffic signals should be retimed as needed but retiming projects are often deferred because of cost. Many agencies rely primarily on user complaints to identify problems but they can be difficult to substantiate and do not always lead to a resolution of the problem. Several transportation agencies have shown that use of automated traffic signal performance measures (ATSPMs) can identify and help address the issues that contribute to poor signal operations. Many state, county, and local agencies are interested in moving toward performance-based management of their traffic signals but the financial and organizational barriers appear formidable.

In NCHRP Project 03-122, "Performance-Based Management of Traffic Signals," Kittelson & Associates was tasked with developing guidance for agencies across the spectrum of resource levels to implement a performance measurement approach to traffic signal management. The research team interviewed agencies that have implemented ATSPMs to identify factors for success and implementation approaches. They then developed use cases and reviewed potential data sources. During the second phase of the project, they developed the guide with care taken to make sure it was applicable to agencies with a wide range of capabilities. They also developed a data dictionary and communication materials.

CONTENTS

FOCUS OF THE GUIDEBOOK

Smart City technologies are changing the way agencies manage and operate transportation systems by providing access to more data than has ever been available before. One of the areas where new tools have broadened capabilities is in traffic signal systems.

Management of traffic signal systems is a critical function for every transportation agency. Yet while congestion increases and infrastructure ages, funding for equipment and staff resources often remains scarce. The result is that many traffic signals operate with poor timing and/or ill-functioning equipment, leading to unnecessary delays and costs for travelers across all modes.

Many agencies are reactive when it comes to monitoring signal performance. Highly traveled corridors experiencing poor performance are often identified only after travelers have endured frustration for an extended period. When service requests arrive, traffic signal managers and staff are often unable to validate the information.

Thanks to advancements in technology, it is now possible to collect large amounts of data at signalized intersections, which has led to the development of dozens of performance measures. Where agencies previously had little to no information about equipment health or intersection operations, they can now review cycle-by-cycle events and initiate dashboard reporting and automated alerts. Signal performance measures profoundly change all aspects of traffic signal operations from planning to design and implementation through better-informed, data-driven decisions. This guidebook provides information to help agencies invest in signal performance measures as part of a comprehensive approach to performance-based management.

CHAPTER 1 ROADMAP TO PERFORMANCE MEASURES

LIST OF EXHIBITS

CHAPTER FOCUS

Chapter 1 is a roadmap to signal performance measures, providing basic information and a summary of benefits and required investments. It also includes an introduction to the rest of the guidebook chapters, organized using the steps for installing and applying signal performance measures.

While there are many signal performance measures available, this guidebook focuses on automated traffic signal performance measures (ATSPMs) developed using high-resolution controller data. ATSPMs allow an agency to continuously monitor maintenance and operations at traffic signals with a high degree of granularity because events are recorded up to 10 times every second.

Most of the information in this document is directed at engineers and managers, but there is guidance throughout about how to share data with other agency groups, as signal performance measures can also enhance day-to-day activities for them. This document provides guidance under the assumption that a practitioner has basic knowledge of traffic signal systems. For more information about traffic signals and a glossary of terms, refer to *NCHRP Report 812: Signal Timing Manual, 2nd Ed.* (STM2) (Urbanik et al. 2015).

1.1 SIGNAL PERFORMANCE MEASURE BASICS

Signal retiming projects have traditionally been triggered when a manager assigns an intersection or corridor to an engineer for retiming based on a pre-determined schedule or public service request. The engineer collects counts and observes operations in the field, builds a model to try to reflect those conditions, and adjusts the signal timing to improve operations in the model. Staff deploy the signal timing in the field, make additional adjustments based on field observations, and potentially complete a before-and-after study to document impacts. The traditional signal retiming process limits an engineer's perspective on traffic conditions to a few days of data and field observations. While some aspects of this process will continue to be important (e.g., field observations), signal performance measures have the distinct benefit of efficiency because staff have access to comprehensive data.

EXHIBIT 1-1 illustrates the basic flow of information to produce ATSPMs. Signal state (i.e., green, yellow, red) and detector events originate at an intersection and are recorded by a data logger. The logs are transferred to data storage (either server- or cloud-based), where the data can be processed by ATSPM software into a variety of reports.

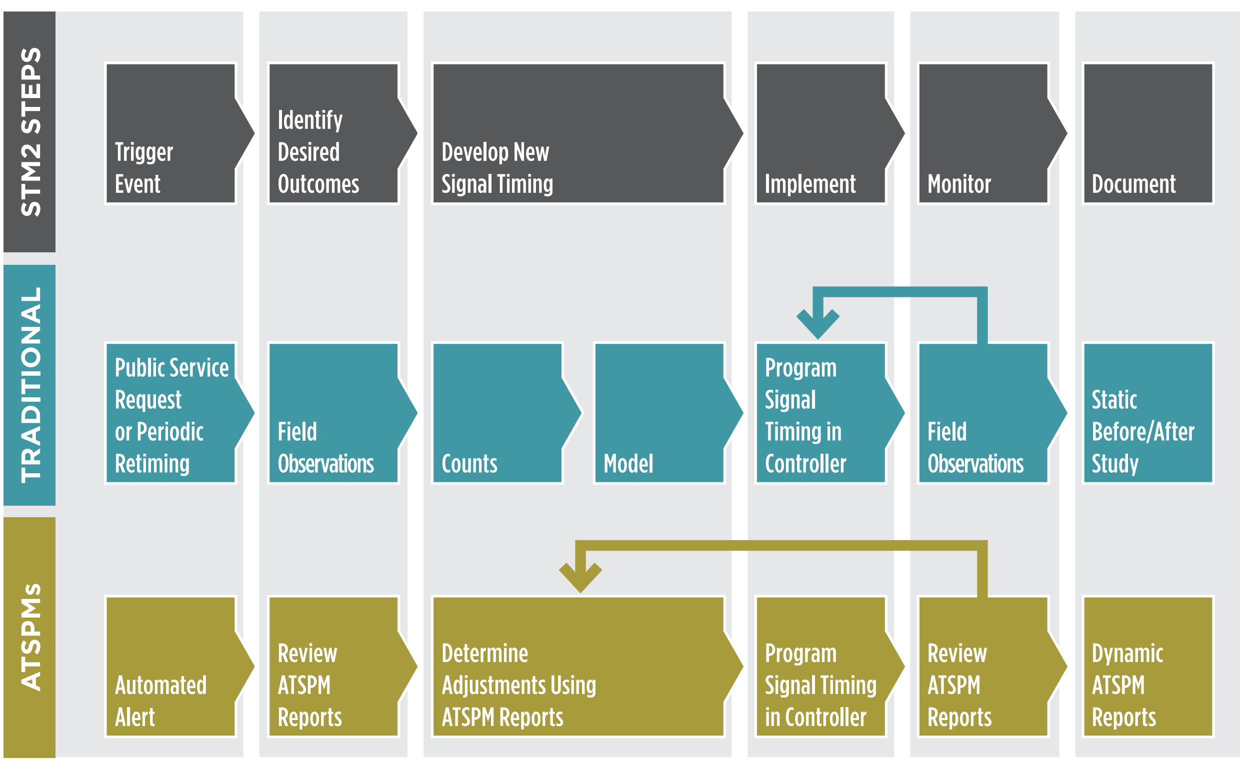
SIGNAL PERFORMANCE MEASURES report cycle-by-cycle events that can provide automated information for all aspects of traffic signal planning, design, and implementation through better-informed, data-driven decisions as part of a performance-based management approach.

AUTOMATED TRAFFIC SIGNAL PERFORMANCE MEASURES (ATSPMs) are developed using high-resolution controller data allowing for continuous monitoring of traffic flow and traffic signal operations with a high degree of granularity because events are recorded up to 10 times every second.

EXHIBIT 1-1. FLOW OF INFORMATION

ATSPM reports are an essential part of a modern retiming process because they are used at every step – identifying when changes are needed, informing which parameters need to change and by how much, verifying that the changes had a positive impact, and reporting results. **EXHIBIT 1-2** illustrates the different steps involved in traditional and ATSPM signal retiming. Performance-based management is different from traditional retiming because staff can use ATSPMs to continuously, proactively monitor the traffic signal system instead of making periodic, reactive adjustments.

EXHIBIT 1-2. TRADITIONAL VERSUS PERFORMANCE-BASED SIGNAL TIMING PROCESS



1.2 SIGNAL PERFORMANCE MEASURE BENEFITS

Using ATSPMs is a proactive approach to traffic signal system management because trends are monitored over time, allowing staff to identify issues before the public calls to report them. If public service requests are received, staff can use ATSPMs to quickly verify the information and troubleshoot issues without spending considerable time monitoring the intersection in the field. Real-time data can be used to determine impacts of signal timing changes and if additional adjustments are required. Some of the most impactful benefits are summarized in **EXHIBIT 1-3**.

EXHIBIT 1-4 summarizes the unique roles, objectives, and benefits for each stakeholder group involved in the implementation of signal performance measures.

EXHIBIT 1-3. SIGNAL PERFORMANCE MEASURE BENEFITS

EXHIBIT 1-4. STAKEHOLDER ROLES, OBJECTIVES, AND SIGNAL PERFORMANCE MEASURE BENEFITS

STAKEHOLDER(S)	ROLE(S) in the management, operation, and use of the transportation system.	OBJECTIVE(S) related to traffic signal operations.	BENEFIT(S) achieved through the use of signal performance measures over traditional methods.
Traffic Signal Engineers/ Technicians	• Identify malfunctioning equipment • Adjust signal timing • Troubleshoot, validate, and address public service requests	• Maximize functioning equipment • Minimize delay for transportation system users • Improve safety • Improve progression • Manage traffic variability	• Continuously available metrics • Less modeling required • Automated alerts for maintenance and operational issues
Traffic Signal Managers	• Prioritize project locations for infrastructure improvements and signal retiming • Set agency policies and standard practices • Report to decision-makers	• Acquire necessary staff and equipment resources • Allocate resources effectively	• Comparable metrics across intersections and corridors for prioritizing activities • Sharable reports that summarize the impacts of maintenance and operational activities
Policy Decision-Makers	• Identify funding sources and determine allocation • Report to the public	• Maximize investments	• Quantitative performance tracking • Real-time updates
IT Staff	• Procure and install equipment/software • Ensure security and backups • Manage servers and databases	• Install a system that is sustainable • Keep the technology functioning	• Potential new role in the signal system group
Other Agency Staff	• Perform transportation planning • Execute design and construction	• Program future transportation projects • Design and build functional traffic signals • Minimize delay during construction	• Continuously available metrics • Benefit/cost information
Public	• Use transportation system • Provide input on performance	• Reach destination in a safe and timely manner	• Improved mobility • Improved reliability • Improved safety

1.3 INVESTING IN SIGNAL PERFORMANCE MEASURES

The building blocks for performance-based management are people and equipment. Knowledgeable staff are needed to deploy and apply signal performance measures, and collecting and calculating signal performance measures requires specialized equipment. These are the key areas where an agency needs to invest to establish a scalable, sustainable system for measuring performance.

1.3.1 PEOPLE

Transitioning to performance-based management has many benefits, but it requires funding and staff resources. If an agency has champions in decision-making roles, they may be able to directly allocate budget and prioritize staff time. With that level of commitment to managing the traffic signal system, a program can function at a high level even when key staff depart. Champions are not always at the senior-management level, however, so **EXHIBIT 1-5** summarizes activities that staff at all levels can undertake to support the integration of signal performance measures. It is important for an agency to gain support and cultivate champions at all levels when transitioning to performance-based management.

EXHIBIT 1-5. ACTIVITIES THAT SUPPORT SIGNAL PERFORMANCE MEASURES BY STAFF LEVEL

STAFF LEVEL	RELATIONSHIP TO SIGNAL PERFORMANCE MEASURES	ACTIVITIES THAT SUPPORT SIGNAL PERFORMANCE MEASURES
Senior Management	• Define agency policies • Make data-supported decisions	• Clearly define staff roles and responsibilities when establishing a performance-based program • Promote use of performance measures to improve signal system management practices
Mid-Level Management	• Report high-level outcomes to senior management • Communicate technical details to staff	• Use projects to show staff, advisory groups, citizens, and policymakers how signal performance measures can promote the mission, goals, and objectives of the agency
Staff (i.e., Engineers, Technicians, Planners)	• Work directly with the data and outcomes from signal performance measures	• Support choices that will make signal performance measures a viable option in the future • Educate managers about the benefits of performance-based management for more effective and productive investments

1.3.2 EQUIPMENT AND SOFTWARE

Physical equipment and software are required to collect data and process signal performance measures. An important step in implementing signal performance measures is taking stock of existing equipment and determining the degree to which it is ready for ATSPMs. The main components required for signal performance measures include:

- **Communication**
- **Detection**
- **Data Logging Devices (i.e., Controllers)**
- **Data Storage (i.e., Server)**
- **Software**

Communication and detection are not required for a traffic signal to function, but they are critical to signal performance measures. Communication connects the various physical components for remote access, and detection provides information about the arrival and departure characteristics of transportation system users relative to the signal state (i.e., green, yellow, red). There are several options available for data collection devices, data storage devices, and software through vendors and open source platforms. Each system has different implementation costs, maintenance costs, features, and customization options.

1.4 IMPLEMENTING SIGNAL PERFORMANCE MEASURES

The remaining chapters in this guidebook provide a path to integrate signal performance measures into the management of a traffic signal system once an agency has decided to implement them. The eight basic steps are summarized in **EXHIBIT 1-6**. Additional details are provided throughout the chapters as shown.

EXHIBIT 1-6. ROADMAP FOR IMPLEMENTING SIGNAL PERFORMANCE MEASURES

1	SELECT PERFORMANCE MEASURES	CHAPTERS 2 + 3
2	DETERMINE IMPLEMENTATION SCALE	
3	CONDUCT SYSTEM NEEDS GAP ASSESSMENT	CHAPTER 4
4	PROCURE RESOURCES	
5	CONFIGURE SYSTEM	CHAPTER 5
6	VERIFY SYSTEM	
7	APPLY PERFORMANCE MEASURES	
8	INTEGRATE INTO AGENCY PRACTICE	CHAPTER 6

1 STEP 1: SELECT PERFORMANCE MEASURES

The first step in establishing a performance-based program is determining which signal performance measures are the most important. The answer will depend on agency goals, objectives, and methods of signal system management. Although an agency may be capable of producing many signal performance measures, it is helpful to identify the key measures for decision-making to avoid overwhelming staff with data. *Chapter 2* outlines the recommended process for selecting signal performance measures based on signal system objectives, which is similar to the outcome-based process introduced in the STM2 (Urbanik et al. 2015). Detailed descriptions of each performance measure are provided in *Chapter 3*.

2 STEP 2: DETERMINE IMPLEMENTATION SCALE

Some agencies may choose to implement signal performance measures across their entire system in a single effort. However, most agencies will use an incremental approach, deploying small-scale pilot projects or upgrading equipment as part of programmed projects or an existing maintenance program. *Chapter 2* summarizes how an agency should assess and plan the implementation scope.

3 STEP 3: CONDUCT SYSTEM NEEDS GAP ASSESSMENT

Once performance measures and intersections have been selected, an agency should conduct a gap assessment to determine if any changes to equipment, business processes, organizational structure, or resources are required. *Chapter 4* provides guidance on conducting a gap assessment and shows how the results may influence what performance measures are ultimately implemented.

4 STEP 4: PROCURE RESOURCES

The results of the gap assessment will identify additional resources necessary for a successful deployment and long-term operations and maintenance. *Chapter 4* provides guidance on acquiring equipment and staff, including coordination with other jurisdictions. ATSPMs are a critical step on the road to smart communities and connected people, so *Chapter 4* also includes procurement considerations related to future technologies.

5 STEP 5: CONFIGURE SYSTEM

Deployment involves activities at the intersection and system level. The equipment and software used to collect, store, and process data from the traffic signals will need to be configured, and information for each intersection will need to be programmed. *Chapter 5* describes the typical process an agency will use to configure hardware and software.

6 STEP 6: VERIFY SYSTEM

Once the system has been installed, a verification process should be undertaken to ensure that data is being collected consistently with an acceptable degree of precision and that performance measures are being calculated correctly. External data from separate sensor networks or special field studies may be useful in this step. *Chapter 5* provides a number of strategies to verify that performance measures match field conditions.

7 STEP 7: APPLY PERFORMANCE MEASURES

Signal performance measures can be used to inform signal timing adjustments, identify mis-programmed signal timing parameters (e.g., values that were initially programmed incorrectly), and identify equipment that is malfunctioning. *Chapter 5* uses examples to demonstrate how an agency can apply different ATSPMs for effective management of the traffic signal system.

8 STEP 8: INTEGRATE INTO AGENCY PRACTICE

By integrating signal performance measures into day-to-day practice, an agency will have continuous monitoring capabilities. Further, developing a record of performance will enable an agency to be better informed about the effectiveness of maintenance and operations practices and where to invest funding and staff resources. *Chapter 6* describes how to incorporate performance-based management into agency policies and how signal performance measures may change day-to-day practices for various stakeholders.

1.5 REFERENCE

1. Urbanik, T., et al. 2015. *NCHRP Report 812: Signal Timing Manual, 2nd Ed.* Transportation Research Board of the National Academies, Washington, DC.

CHAPTER 2 PERFORMANCE MEASURE SELECTION

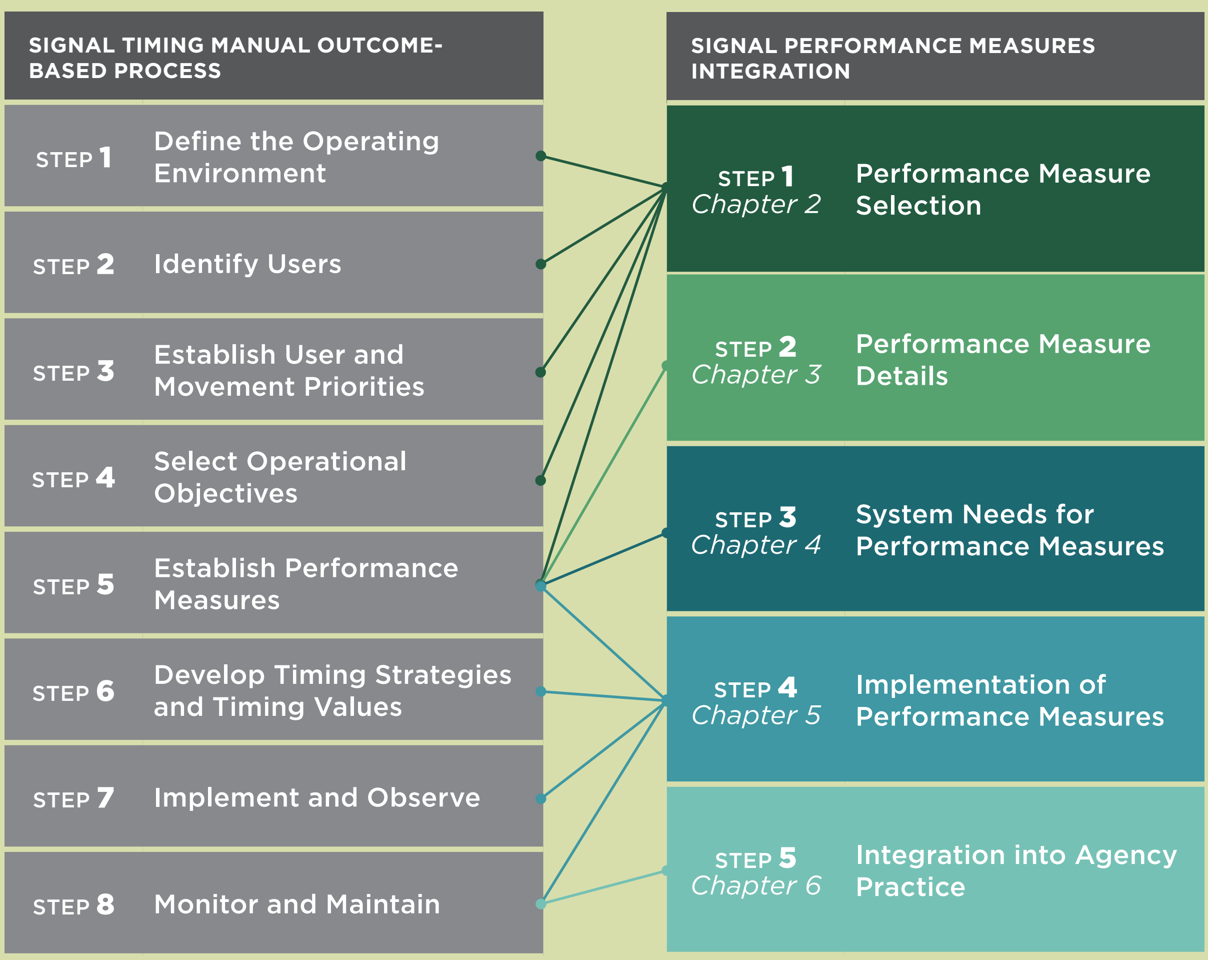
LIST OF EXHIBITS

CHAPTER FOCUS

Integrating signal performance measures into the management of a traffic signal system can follow a process that is similar to the outcome-based process introduced in *NCHRP Report 812: Signal Timing Manual* (STM2) (Urbanik et al. 2015). There are a number of ways to time a traffic signal, but the “best” way will depend significantly on what an agency is trying to accomplish. The same is true for signal performance measures.

It is important for an agency to prioritize signal performance measures that align with their desired outcomes. The number of available metrics makes it difficult to effectively monitor all of them, making a focused approach necessary. This chapter focuses on the first five steps of the outcome-based process (as illustrated in **EXHIBIT 2-1**), which lead a practitioner through selecting performance measures that will match their goals, objectives, and methods of signal system management. More details about each step of the outcome-based process can be found in STM2 Chapter 1 and STM2 Exhibit 3-1. Subsequent chapters in this guidebook describe how the steps in the STM2 relate to the use of signal performance measures.

EXHIBIT 2-1. APPLYING THE STM2 OUTCOME-BASED PROCESS TO SIGNAL PERFORMANCE MEASURES



2.1 DEFINE THE OPERATING ENVIRONMENT

The STM2 includes a comprehensive discussion of signal system operating environments (Urbanik et al. 2015). As the first step in the outcome-based process, defining the operating environment directly impacts the priorities and objectives an agency will use to select performance measures. This section summarizes different operating environment elements introduced in the STM2 and highlights considerations specific to the selection of signal performance measures. Note that in this case, the operating environment goes beyond physical characteristics and includes goals of the local operating agency and its regional stakeholders.

Multi-jurisdictional impacts. Many signalized roadway networks cross jurisdictional boundaries. As a result, multiple agencies may be interested in signal performance measures at the same intersections and along the same corridors. By sharing a signal performance measure system, multiple agencies can share the costs (e.g., equipment, software, staff time) as well as the benefits (e.g., available data, performance measure reports). Such a scheme could reduce the cost of implementation and elevate collaboration among the agencies. However, it may also require the agencies to develop new agreements.

Location and associated environment. Operational objectives (and the resulting performance measurement needs) will vary depending on whether traffic signals are located in an area that is predominately urban, suburban, or rural. For example, performance measures related to vehicles may take precedence in a rural environment, whereas performance measures that track pedestrian activity may be the primary focus in an urban area. Additionally, growth may influence the selection of performance measures. For example, if areas near a signalized corridor are developing quickly, traffic volumes may be an important performance measure to collect for planners who are modeling changing conditions.

AN OUTCOME-BASED PROCESS results in signal timing that is based on the operating environment, users, user priorities by movement, and local operational objectives.

Roadway classification. There are different user expectations on freeways, arterials, collectors, and local streets, and each type of roadway will have different operational priorities depending on the level of mobility and accessibility. For example, the priority of vehicle throughput on an arterial may lead an agency to emphasize performance measures related to progression quality, whereas the priority of pedestrians on a local street may lead to measuring pedestrian delay.

Transportation network characteristics. In addition to operational differences between isolated intersections and coordinated corridors, the degree of signal density may influence the means of implementing performance measures. For instance, an agency that maintains traffic signals concentrated in a small geographic area may be able to easily establish communication to each intersection, whereas an agency that maintains traffic signals located at greater distances might need to consider alternatives to wired communication (e.g., cellular modems or periodic field visits to collect performance measure data).

Traffic patterns. Traffic conditions change by time of day, day of week, and seasonally. Some locations may have very predictable patterns that remain consistent year after year, but others may have less predictable patterns that change as a result of special events, tourism, or regional growth. Performance measures can quantify the degree of variability in those patterns and help determine whether retiming, special timing plans, or other investments might be beneficial.

Policies and visions. Many transportation agencies have goals related to mobility, reliability, and safety, and performance measures can support the resulting policies and visions driven by those goals. Performance measures provide an agency with the opportunity to inform leadership about the health and operation of the system. For example, an agency that has a goal of improving mobility may want to measure and track the number of vehicles arriving on green, so that they can report on progress made toward a transportation system with fewer stops.

2.2 IDENTIFY USERS OF THE TRANSPORTATION SYSTEM

It is important for the roadway environment to balance the needs of all transportation system users. Agencies should select performance measures considering the mix of users at their intersections.

Pedestrians. Practitioners can use performance measures to identify intersections with high pedestrian delay, high pedestrian demand, and high conflicting demand between vehicles and pedestrians.

- High pedestrian delay can help an agency identify if cycle lengths are too long to meet pedestrian priorities.
- High pedestrian demand during peak times can indicate that an agency needs splits that can accommodate full pedestrian clearance times every cycle. A location with low pedestrian demand can operate acceptably with programmed splits that are lower than the pedestrian clearance times if allowed by the controller (resulting in a possible temporary loss of coordination when there is pedestrian demand).
- High conflicting demand can help an agency determine if a priority treatment should be considered, such as a leading pedestrian interval or exclusive pedestrian phase.

Bicycles. Signal timing parameters related to phase initiation and phase termination (i.e., minimum green, yellow change, and red clearance) are critical to bicycles. Practitioners may need to adjust parameters to account for the bicyclists' lower speeds and acceleration characteristics. Practitioners can use performance measures to make adjustments at intersections with high bicycle volumes.

Light vehicles. The number of light vehicles (i.e., passenger cars and light trucks) using an intersection will impact many signal timing parameters, including cycle length, the time allocated to each phase, and the order of the phases. Practitioners can monitor intersection- and system-level performance measures to ensure that they allocate green time appropriately and offsets are progressing traffic effectively.

Heavy vehicles. Large trucks require longer acceleration and deceleration times. This requirement impacts queue storage, discharge rates, and detector configurations. If practitioners program detection to count heavy vehicles, an agency can determine if they should consider priority treatments based on high volumes of trucks. Additionally, practitioners can track the frequency of truck priority requests and determine how often priority is serviced as well as the impacts to other users.

Transit vehicles. Transit vehicles may justify special phasing and preferential treatment through the use of priority. Similar to truck priority, performance measures can identify the frequency of priority requests, priority service, and impacts to other users.

Emergency vehicles. Emergency vehicles often use preemption to prioritize their movements at signalized intersections. Practitioners can use performance measures to monitor the number of preemption requests, preemption service, and impacts to other users during and after events.

Rail (heavy, light, or streetcars using exclusive right-of-way). Railway crossings near signalized intersections often require preemption to clear the tracks of other transportation system users prior to the arrival of trains. Practitioners can use performance measures to monitor the number of preemption requests, preemption service, and impacts to other users during and after events.

2.3 ESTABLISH USER AND MOVEMENT PRIORITIES

The operating environment and mix of intersection users may result in competing priorities. For example, in an urban setting, vehicle throughput may be at odds with providing pedestrians additional time to cross. The users and movements an agency chooses to prioritize will directly affect which performance measures are the most important to track. For example, if an agency decides that vehicle throughput is the priority, the most relevant performance measure may be arrivals on green on the major street versus tracking pedestrian delay. With the number of performance measures currently available (and more likely to be developed in the future), it is essential that an agency identify user and movement priorities to guide the selection of objectives and ultimately performance measures.

2.4 SELECT OBJECTIVES

An agency's signal system objectives should reflect the operating environment, mix of transportation system users, and priorities. Once an agency has identified what they want to accomplish with their traffic signal system, they should match the objectives to relevant signal performance measures. Throughout the remainder of this guidebook, signal performance measures will be grouped into five objective-based categories (as illustrated in **EXHIBIT 2-2**): communication, detection, intersection/uncoordinated timing, system/coordinated timing, and advanced systems and applications.

Communication is often installed to maintain coordination between signalized intersections. Although communication is not required for a traffic signal to function, it is essential for scalable, system-wide performance-based management. While data can be collected during periodic field visits, communication to a central location allows data to be collected automatically and in real-time. Performance measures can be used to determine the health of the communication system (i.e., number of intersections that are communicating).

Detection can be used to improve intersection operations, but it is not a requirement for signalized intersections. Intersections without detection operate in a pre-timed mode in which each movement receives the same amount of green every cycle. However, for signal performance measures, detection is needed to compare traffic patterns to signal events. Without robust detection, only a subset of signal performance measures will be available. Performance measures can be used to determine the health of the detection system (i.e., number of functioning detectors).

In addition to equipment health, signal performance measures can be used to report on intersection and system-wide operations. Basic intersection/uncoordinated timing is required for every traffic signal; it is programmed to serve different transportation system users efficiently and safely. Performance measures can be used to determine the delay and safety experienced by different modes at individual intersections.

If a signalized intersection is located in a system, it may be synchronized with other intersections to provide coordinated control. Performance measures can be used to determine how well the signal system is progressing traffic along the corridor and to identify impacts of high volumes, which can involve multiple intersections.

Finally, if there are modes with preferential treatment or if traffic is unpredictable, practitioners can apply advanced systems and applications to better manage the intersection and system control. For additional information on advanced systems and applications (e.g., adaptive, traffic responsive systems, transit signal priority), refer to STM2 Chapters 9 and 10. Performance measures can be used to assess the delay experienced by modes with preferential treatment as well as whether the advanced systems and applications are managing variability in traffic conditions.

EXHIBIT 2-2. OBJECTIVE-BASED CATEGORIES FOR SIGNAL PERFORMANCE MEASURES

CATEGORY	OBJECTIVE(S)
1 COMMUNICATION	• Maximize number of connected intersections
2 DETECTION	• Maximize number of functioning detectors
3 INTERSECTION / UNCOORDINATED TIMING	• Minimize delay for transportation system users (e.g., vehicles, bicycles, pedestrians) • Improve safety
4 SYSTEM /COORDINATED TIMING	• Improve priority movements (i.e., progression)
5 ADVANCED SYSTEMS AND APPLICATIONS	• Minimize delay for modes with preferential treatment (e.g., rail, emergency vehicles, transit, trucks) • Manage traffic variability

Note: Exhibit modified from *Integrating Traffic Signal Performance Measures into Agency Business Processes* (Day et al. 2015).

2.5 SELECT SIGNAL PERFORMANCE MEASURES

Practitioners can use performance measures at different levels of aggregation. Agencies should consider not only the individual performance measures they will assess, but also how they can combine those measures to provide information about their entire signal system. For example, the number of vehicles arriving on green can be reviewed for a particular phase at a particular intersection to inform an offset adjustment. At a different level of aggregation, the total arrivals on green can be calculated for the entire corridor to assess overall progression.

An agency may have an existing system that allows them to obtain many signal performance measures. However, practitioners may quickly find themselves overloaded with data if they try to evaluate all of these measures. Even if an agency is able to obtain all of the signal performance measures discussed in this guidebook, this section (along with the information in *Chapter 3*) will help an agency focus the available time on the signal performance measures that best match their needs. **EXHIBIT 2-3** groups individual performance measures into the five objective-based categories and summarizes how they can be aggregated to provide status reports. *Chapter 3* includes detailed descriptions and example applications for each performance measure.

Vendors continue to create new performance measures and new ways to visualize existing measures, and technological advances will lead to even more performance measures in the future. As connected vehicles make their way into the fleet, trajectory data will be an important data source for performance-based management. Advances in predictive tools (such as offset optimization) could lead to controllers adjusting signal timing based on high-resolution data. These developments might be accelerated with the introduction of machine learning and artificial intelligence. The signal performance measures described in this guidebook are only the beginning of performance-based management for traffic signal systems.

EXHIBIT 2-3. AGGREGATION OPTIONS FOR SIGNAL PERFORMANCE MEASURES

OBJECTIVE	AGGREGATED STATUS REPORT(S)	INDIVIDUAL SIGNAL PERFORMANCE MEASURE(S) WITH CHAPTER 3 REFERENCES
1 Communication Equipment Health	• Percent of connected signals communicating	• 3.1 Communication Status • 3.2 Flash Status • 3.3 Power Failures
2 Detection Equipment Health	• Percent of detectors fully functional by mode (e.g., vehicle, pedestrian, bicycle, rail, emergency vehicle, transit, truck)	• 3.4 Detection System Status • 3.5 Vehicle Volumes (high volumes during low-traffic times) • 3.6 Phase Termination (high number of max-outs, force-offs, and/or pedestrian calls during low-traffic times) • 3.12 Pedestrian Volumes (high volumes during low-traffic times) • 3.13 Pedestrian Phase Actuation and Service (high number of pedestrian calls during low-pedestrian times) • 3.25 Preemption Details (high number of requests) • 3.26 Priority Details (high number of requests)
3 Vehicle Delay	• Average vehicle delay • Percent of cycles with unserved vehicles • Percent of movements at or near capacity	• 3.5 Vehicle Volumes (applied to capacity analysis) • 3.6 Phase Termination • 3.7 Split Monitor • 3.8 Split Failures • 3.9 Estimated Vehicle Delay • 3.10 Estimated Queue Length • 3.11 Oversaturation Severity Index • 3.18 Effective Cycle Length (for delay estimation) • 3.24 Time-Space Diagram
Pedestrians	• Minimum, maximum, and average pedestrian delay • Percent of movements with high pedestrian activity	• 3.12 Pedestrian Volumes • 3.13 Pedestrian Phase Actuation and Service • 3.14 Estimated Pedestrian Delay • 3.15 Estimated Pedestrian Conflicts • 3.18 Effective Cycle Length (for delay estimation)
Bicycles	• Minimum, maximum, and average bicycle delay • Percent of movements with high bicycle activity	• 3.5 Vehicle Volumes (applied to capacity analysis if bicycle detection is separate) • 3.9 Estimated Vehicle Delay (if bicycle detection is separate) • 3.18 Effective Cycle Length (for delay estimation)
Safety	• Percent of movements with queues that exceed storage • Percent of vehicles entering on red • Number of conflicting movements	• 3.10 Estimated Queue Length • 3.11 Oversaturation Severity Index • 3.15 Estimated Pedestrian Conflicts • 3.16 Yellow/Red Actuations • 3.17 Red-Light-Running (RLR) Occurrences
4 Vehicle Progression	• Percent of vehicles arriving on green • Percent of vehicles arriving on red	• 3.5 Vehicle Volumes (assess TOD plans) • 3.10 Estimated Queue Length • 3.11 Oversaturation Severity Index • 3.18 Effective Cycle Length (confirm coordination) • 3.19 Progression Quality • 3.20 Purdue Coordination Diagram • 3.21 Cyclic Flow Profile • 3.22 Offset Adjustment Diagram • 3.23 Travel Time and Average Speed • 3.24 Time-Space Diagram
5 Rail	• Percent of preempt calls received at design value or no more than specified value • Percent of track clearance green intervals completed before train arrival • Average delay due to preemption	• 3.25 Preemption Details (percent of false calls as well as minimum, maximum, and average preemption times – advance and/or simultaneous)
Emergency Vehicles	• Percent of emergency vehicles arriving on green • Percent of emergency vehicles arriving on red	• 3.25 Preemption Details (delay per emergency vehicle and number of requests)
Transit	• Percent of transit vehicles arriving on green • Percent of transit vehicles arriving on red	• 3.26 Priority Details (delay per transit vehicle and number of requests)
Trucks	• Percent of trucks arriving on green • Percent of trucks arriving on red	• 3.26 Priority Details (delay per truck and number of requests)

2.6 DETERMINE IMPLEMENTATION SCALE

Once an agency has selected signal performance measures, they must decide the best approach to acquire required resources, install upgrades, and integrate signal performance measures into the management of their signal system. Agencies have taken different approaches to implementing signal performance measures, as summarized in **EXHIBIT 2-4**.

EXHIBIT 2-4. IMPLEMENTATION SCALE OPTIONS

	PILOT PROJECT	SYSTEMATIC UPGRADES	SYSTEM-WIDE IMPLEMENTATION
Description	• Test performance measures at a select number of intersections	• Upgrade equipment as other projects are completed (either to accommodate future use of performance measures or add intersections to an existing performance measure system)	• Deploy performance measures at all intersections
Potential Resources and Needs	• Equipment upgrades (e.g., controllers, detection, communication) at a select number of intersections • Central equipment or a cloud-based solution to store and process data • Training for staff	• Equipment upgrades (e.g., controllers, detection, communication) as part of other projects • Revised design standards to promote desired performance measures	• Potential equipment upgrades (e.g., controllers, detection, communication) at all intersections • Central equipment or a cloud-based solution to store and process data • Training for staff
Advantages	• Can test performance measures at intersections that already have upgraded equipment • Limited number of intersections reduces time required for setup and verification • Reduced data storage needs • Facilitates value assessment prior to a system-wide implementation	• Limited upfront investment • Allows “easing-in” of eventual ATSPM deployment and thorough assessment of gaps	• Can track performance measures across the system • Equipment and software consistency due to initial upfront procurement
Challenges	• Requires installation of central data storage • Limited number of locations with performance measures	• No performance measures until data storage and performance measure software are installed • Upgraded equipment may be inconsistent over time	• May be costly to upgrade field infrastructure at all intersections • Increased time for setup and verification • Increased data storage needs • Increased data requires a plan for effective application and funding improvements
Examples	• Oregon Department of Transportation (ODOT): Deployed ATSPMs at seven traffic signals on US 101 in Lincoln City, Oregon • Virginia Department of Transportation (VDOT): Deployed ATSPMs at 15 intersections along Route 29 near Charlottesville, Virginia • Pennsylvania Department of Transportation (PennDOT): Tested ATSPMs along a pilot corridor in Cranberry Township in the Pittsburgh area	• Indiana Department of Transportation (INDOT): Adjusted design specifications and approved materials list to facilitate incremental addition of intersections using upgrades accounted for in the maintenance budget • City of Portland, Oregon: In addition to a small pilot project, updated detection standards to accommodate future use of performance measures	• Utah Department of Transportation (UDOT) • Georgia Department of Transportation (GDOT) • Clark County, Washington • College Station, Texas

While some agencies have completed system-wide updates, most build out their systems through smaller projects, either by upgrading all required equipment at a select number of intersections to get to a fully functional pilot project or by upgrading equipment systematically in preparation for future use of performance measures. At first glance it may seem that signal performance measures require significant equipment upgrades (explained in detail in *Chapter 4*), but most investments made to facilitate signal performance measures will also improve intersection operations. For example, upgrades to communication, detection, and controllers can result in fewer equipment malfunctions and signal timing that is responsive to intersection users.

There are benefits to completing a large-scale implementation. Large implementations will likely require more equipment upgrades and staff time for installation, but they also give agencies the ability to make system-wide decisions based on performance measures. If an agency implements ATSPMs at all their intersections, they have an opportunity to identify the most-critical signalized intersections (based on their signal system objectives) and to make operations and maintenance improvements at those locations. Performance-based management applied at the system level will result in the largest benefits.

Regardless of how an agency chooses to implement signal performance measures, they should use a systematic process to identify performance measures that match their operational objectives. Different implementation scales do not negate the necessity to choose signal performance measures based on needs, capabilities, and constraints.

2.7 ADDITIONAL RESOURCES

As introduced in *Chapter 1*, most of the performance measures presented in this guidebook are automated traffic signal performance measures (ATSPMs) based on high-resolution data. There are other signal performance measures available, but the use of high-resolution data (further described in *Chapter 4*) allows for continuous monitoring of traffic signals and provides a scalable solution to signal system management. Several existing resources, listed in the next section, have previously defined many of the measures presented in *Chapter 3*. All of these reports are available for download online at no cost.

2.7.1 POOLED FUND STUDY REPORTS

From 2014 to 2017, a group of 10 state departments of transportation (DOTs) and the City of Chicago sponsored a pooled fund study on signal performance measures. This study led to the development of two reports that included extensive documentation of different performance measures based on high-resolution data and travel time data sets. The first report discussed individual performance measures in detail, compiling previous work, and the second report provided further illustrations of their use. Presentations from a January 2016 workshop on ATSPMs are also available at the link provided for the workshop.

- Day, C.M., D.M. Bullock, H. Li, S.M. Remias, A.M. Hainen, R.S. Freije, A.L. Stevens, J.R. Sturdevant, and T.M. Brennan. 2014. *Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach.* Purdue University, West Lafayette, IN. http://dx.doi.org/10.5703/1288284315333
- Day, C.M., D.M. Bullock, H. Li, S. Lavrenz, W.B. Smith, and J.R. Sturdevant. 2015. *Integrating Traffic Signal Performance Measures into Agency Business Processes.* Purdue University, West Lafayette, IN. http://dx.doi.org/10.5703/1288284316063
- January 2016 Automated Traffic Signal Performance Measures Workshop presentations. http://docs.lib.purdue.edu/atspmw/2016/Presentations/

2.7.2 HIGH-RESOLUTION DATA ENUMERATIONS

The Indiana Department of Transportation (INDOT) sponsored research into signal performance measures for several years. That research facilitated the development of the current *de facto* "standard" for high-resolution data—the "enumerations" that list the individual event codes and their meanings.

- Sturdevant, J.R., T. Overman, E. Raamot, R. Deer, D. Miller, D.M. Bullock, C.M. Day, T.M. Brennan, H. Li, A. Hainen, and S.M. Remias. 2012. *Indiana Traffic Signal Hi Resolution Data Logger Enumerations.* Indiana Department of Transportation and Purdue University, West Lafayette, IN. http://dx.doi.org/10.4231/K4RN35SH

Although this document serves as a de-facto standard, there is a need to update the enumeration list to reflect enhancements that are emerging from vendors to accommodate new features requested by agencies.

2.7.3 UTAH DOT OPEN SOURCE SOFTWARE

The Utah Department of Transportation (UDOT) developed an open source system for downloading high-resolution data, calculating ATSPMs, and publishing reports and charts online. UDOT's web page (with live field data) is publicly accessible, and the source code for the website is available at the second link in this section. The third link allows developers to track changes made to the open source code while UDOT reviews and updates the version released on the Open Source Application Development Portal (OSADP). The UDOT web page also contains links to numerous presentations on the use of ATSPMs.

- Utah Department of Transportation (UDOT). (n.d.-a). *Automated Traffic Signal Performance Measures* website. http://udottraffic.utah.gov/atspm/
- Federal Highway Administration. Open Source Application Development Portal ATSPM source code. https://www.itsforge.net/index.php/community/explore-applications#/30/133
- Utah Department of Transportation (UDOT). (n.d.-b). *ATSPM* GitHub development website. https://github.com/udotdevelopment/ATSPM

2.7.4 NCHRP PROJECT 03-90, "OPERATION OF TRAFFIC SIGNALS IN OVERSATURATED CONDITIONS"

NCHRP Project 03-90 developed guidance for agencies operating traffic signals with traffic demand above saturation levels. This project also facilitated the development of performance measures for oversaturated conditions.

- Gettman, D., M. Abbas, H. Liu, and A. Skabardonis. 2012. *NCHRP Web-Only Document 202: Operation of Traffic Signal Systems in Oversaturated Conditions, Volume 1: Practitioner Guidance.* Transportation Research Board, Washington, DC. http://dx.doi.org/10.17226/22290
- Gettman, D., G. Madrigal, S. Allen, T. Boyer, S. Walker, J. Tong, S. Phillips, H. Liu, X. Wu, H. Hu, M. Abbas, Z. Adam, and A. Skabardonis. 2012. *NCHRP Web-Only Document 202: Operation of Traffic Signal Systems in Oversaturated Conditions, Volume 2: Final Report.* Transportation Research Board, Washington, DC. http://dx.doi.org/10.17226/22289

2.7.5 AASHTO INNOVATION INITIATIVE

AASHTO selected ATSPMs as a focus technology for the Innovation Initiative in 2013. ITE produced and delivered a series of webinars in 2014; further information is available on the AASHTO website.

- Automated Traffic Signal Performance Measures webinars. http://aii.transportation.org/Pages/AutomatedTrafficSignalPerformanceMeasures.aspx

2.7.6 FHWA EVERY DAY COUNTS

In 2015, the Every Day Counts Initiative update, EDC-4, identified ATSPMs as an important tool "to support objectives and performance-based maintenance and operations strategies that improve safety and efficiency while cutting congestion and cost." Additional information is available on the FHWA EDC website.

- Federal Highway Administration. *EDC-4: Automated Traffic Signal Performance Measures (ATSPMs)* website. https://www.fhwa.dot.gov/innovation/everydaycounts/edc_4/atspm.cfm

2.8 REFERENCES

1. "Automated Traffic Signal Performance Measures" webpage. http://aii.transportation.org/Pages/AutomatedTrafficSignalPerformanceMeasures.aspx
2. Day, C.M., D.M. Bullock, H. Li, S.M. Remias, A.M. Hainen, R.S. Freije, A.L. Stevens, J.R. Sturdevant, and T.M. Brennan. 2014. *Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach.* Purdue University, West Lafayette, IN. http://dx.doi.org/10.5703/1288284315333
3. Day, C.M., D.M. Bullock, H. Li, S. Lavrenz, W.B. Smith, and J.R. Sturdevant. 2015. *Integrating Traffic Signal Performance Measures into Agency Business Processes.* Purdue University, West Lafayette, IN. http://dx.doi.org/10.5703/1288284316063
4. Federal Highway Administration. *EDC-4: Automated Traffic Signal Performance Measures (ATSPMs)* website. https://www.fhwa.dot.gov/innovation/everydaycounts/edc_4/atspm.cfm
5. Federal Highway Administration. *Open Source Application Development Portal* ATSPM source code. https://www.itsforge.net/index.php/community/explore-applications#/30/133
6. Gettman, D., M. Abbas, H. Liu, and A. Skabardonis. 2012. *NCHRP Web-Only Document 202: Operation of Traffic Signal Systems in Oversaturated Conditions, Volume 1: Practitioner Guidance*. Transportation Research Board, Washington, DC. http://dx.doi.org/10.17226/22290
7. Gettman, D., G. Madrigal, S. Allen, T. Boyer, S. Walker, J. Tong, S. Phillips, H. Liu, X. Wu, H. Hu, M. Abbas, Z. Adam, and A. Skabardonis. 2012. *NCHRP Web-Only Document 202: Operation of Traffic Signal Systems in Oversaturated Conditions, Volume 2: Final Report.* Transportation Research Board, Washington, DC. http://dx.doi.org/10.17226/22289
8. January 2016 Automated Traffic Signal Performance Measures Workshop presentations. http://docs.lib.purdue.edu/atspmw/2016/Presentations/
9. Sturdevant, J.R., T. Overman, E. Raamot, R. Deer, D. Miller, D.M. Bullock, C.M. Day, T.M. Brennan, H. Li, A. Hainen, and S.M. Remias. 2012. *Indiana Traffic Signal Hi Resolution Data Logger Enumerations.* Indiana Department of Transportation and Purdue University, West Lafayette, IN. http://dx.doi.org/10.4231/K4RN35SH

10. Urbanik, T., et al. 2015. *NCHRP Report 812: Signal Timing Manual, 2nd ed.* Transportation Research Board of the National Academies, Washington, DC.

11. Utah Department of Transportation (UDOT). (n.d.-b). *ATSPM* GitHub development website. https://github.com/udotdevelopment/ATSPM

12. Utah Department of Transportation (UDOT). (n.d.-a). *Automated Traffic Signal Performance Measures* website. http://udottraffic.utah.gov/atspm/

CHAPTER 3
PERFORMANCE MEASURE DETAILS

LIST OF EXHIBITS

CHAPTER FOCUS

Chapter 3 contains detailed information for 26 signal performance measures. After practitioners have applied the selection process introduced in *Chapter 2*, they should use the information in this chapter to learn more about the signal performance measures that have been chosen (i.e., required inputs, resulting outputs, example applications, and additional references).

This chapter organizes the signal performance measures that are listed and briefly described in **EXHIBIT 3-1** and use the objective-based categories from *Chapter 2:*

1. **Communication**
2. **Detection**
3. **Intersection/ Uncoordinated Timing**
4. **System/Coordinated Timing**
5. **Advanced Systems and Applications**

EXHIBIT 3-1 provides descriptions of the 26 signal performance measures and list example uses. **EXHIBIT 3-2** summarizes inputs and outputs for all 26 signal performance measures in a single reference table. Following **EXHIBIT 3-2,** the balance of Chapter 3 provides detailed profiles for each measure. The profiles collect key information (including, as needed, cross references to information in later guidebook chapters) as summarized here:

DESCRIPTION	
Detailed description of the performance measure and a brief overview of how it is calculated and displayed.	
APPLICATIONS	
How the performance measure can ultimately be applied (*Chapter 5*).	
STAKEHOLDERS	
Agency groups that may apply the performance measure – organizational, planning, design and construction, operations, and maintenance (*Chapter 6*).	
OBJECTIVES	
Traffic signal system objectives informed by the performance measure – equipment health, vehicle delay, vehicle progression, pedestrians, bicycles, rail, emergency vehicles, transit, trucks, and safety (*Chapter 2*).	
DATA SOURCES	
Data that can be used to produce the performance measure (*Chapter 4*).	
CONTROLLER HIGH-RESOLUTION DATA	• Timestamped "events" recorded by the controller.
CENTRAL SYSTEM LOW-RESOLUTION DATA	• Volumes, detector occupancies, green times, and phase terminations aggregated by the central system.
VENDOR-SPECIFIC DATA	• Data collected by detection systems, preemption systems, and adaptive control systems.
AUTOMATED VEHICLE IDENTIFICATION (AVI)	• Travel time, route choice, and origin-destination estimated through unique vehicle identifiers.
PROBE VEHICLE SEGMENT SPEED	• Average speeds aggregated using data from probe vehicles.
AUTOMATED VEHICLE LOCATION (AVL)	• Timestamped GPS coordinates of probe vehicles.
DETECTION NEEDS	
Type of detection needed (if any) for implementation (*Chapter 4*).	
CALIBRATION	
Some performance measures have calibration considerations; brief notes on those are included where relevant.	
REFERENCES	
Resources for further information.	
EXAMPLE USES	
Illustrative examples demonstrating how the performance measure can be used.	

EXHIBIT 3-1. SIGNAL PERFORMANCE MEASURE DESCRIPTIONS

COMMUNICATION	DETECTION	INTERSECTION/UNCOORDINATED TIMING	SYSTEM/COORDINATED TIMING	ADVANCED SYSTEMS AND APPLICATIONS	PERFORMANCE MEASURE	DESCRIPTION	EXAMPLE USE(S)
1	2	3	4	5	"3.1 COMMUNICATION STATUS"	Reports controller online/ offline status.	• Which corridor has the greatest need for communication investments? • Have maintenance efforts improved communication?
1	2	3	4	5	"3.2 FLASH STATUS"	Reports intersections that have experienced unscheduled flash events.	• Do any intersections consistently experience unscheduled flash events?
1	2	3	4	5	"3.3 POWER FAILURES"	Reports intersections that have experienced power failures.	• Are any corridors experiencing consistent power failures?
1	**2**	3	4	5	"3.4 DETECTION SYSTEM STATUS"	Reports detector failures.	• Are any corridors experiencing consistent detection issues? • Have maintenance efforts improved detection?
1	**2**	**3**	**4**	5	"3.5 VEHICLE VOLUMES"	Reports the number of vehicles (or bicycles depending on available detection) making individual movements.	• When are the peak traffic periods and what is their duration? • How were traffic volumes impacted during a special event?
1	**2**	**3**	4	5	"3.6 PHASE TERMINATION"	Reports phase termination types (i.e., max-outs, force-offs, gap-outs, skips).	• Do any phases need an adjustment to green time?
1	2	**3**	4	5	"3.7 SPLIT MONITOR"	Reports phase duration compared to programmed split (along with phase termination type).	• Are the splits programmed in a special event plan adequately serving traffic?
1	2	**3**	4	5	"3.8 SPLIT FAILURES"	Reports the number of split failures (i.e., when there were unserved vehicles).	• Are there corridors that can benefit from split adjustments? During which time periods? • Did implementation of an adaptive cycle length improve the number of split failures?
1	2	**3**	4	5	"3.9 ESTIMATED VEHICLE DELAY"	Estimates delay of vehicles (or bicycles depending on available detection).	• Did split adjustments improve vehicle delay?
1	2	**3**	**4**	5	"3.10 ESTIMATED QUEUE LENGTH"	Estimates length of vehicle queues.	• During what times of day is an approach experiencing long queues?
1	2	**3**	**4**	5	"3.11 OVERSATURATION SEVERITY INDEX"	Estimates the prevalence of temporal and spatial oversaturation.	• Did signal timing adjustments improve oversaturated conditions (i.e., downstream blockages and split failures)?
1	**2**	**3**	4	5	"3.12 PEDESTRIAN VOLUMES"	Reports the number of pedestrians making individual movements.	• What is the pedestrian demand during different times of day?
1	**2**	**3**	4	5	"3.13 PEDESTRIAN PHASE ACTUATION AND SERVICE"	Reports the number of times that pedestrian phases were actuated and served.	• What times of day have high pedestrian actuations (and resulting pedestrian phase service)? • Will an exclusive pedestrian phase impact how often pedestrians request service (using the pedestrian push button)? • Which locations (i.e., signalized intersections and corridors) have high rates of pedestrian activity?

EXHIBIT 3-1. SIGNAL PERFORMANCE MEASURE DESCRIPTIONS (CONTINUED)

COMMUNICATION	DETECTION	INTERSECTION/UNCOORDINATED TIMING	SYSTEM/COORDINATED TIMING	ADVANCED SYSTEMS AND APPLICATIONS	PERFORMANCE MEASURE	DESCRIPTION	EXAMPLE USE(S)
1	2	**3**	4	5	"3.14 ESTIMATED PEDESTRIAN DELAY"	Reports the amount of time between pedestrian phase actuation to serve.	• Are there times of day when pedestrians are experiencing long delays? • What level of service (LOS) do pedestrians experience at a signalized intersection?
1	2	**3**	4	5	"3.15 ESTIMATED PEDESTRIAN CONFLICTS"	Estimates potential for vehicle-to-pedestrian conflicts.	• What are the highest conflicting vehicular flow rates across pedestrian crossings?
1	2	**3**	4	5	"3.16 YELLOW/RED ACTUATIONS"	Reports vehicle actuations relative to the yellow and red times.	• Are there times of day with high numbers of vehicles running the red light?
1	2	**3**	4	5	"3.17 RED-LIGHT-RUNNING (RLR) OCCURRENCES"	Reports the total number of red-light-running vehicles.	• Did a split increase result in a reduced number of red-light-running vehicles?
1	2	**3**	**4**	5	"3.18 EFFECTIVE CYCLE LENGTH"	Reports the effective cycle length (amount of time used to serve all phases).	• What are the seasonal impacts on effective cycle length for a corridor utilizing an adaptive system?
1	2	3	**4**	5	"3.19 PROGRESSION QUALITY"	Reports percent on green, platoon ratio, and/or arrival type.	• Are any intersections along a corridor experiencing lower progression quality? • Did offset adjustments increase or decrease progression quality along a corridor?
1	2	3	**4**	5	"3.20 PURDUE COORDINATION DIAGRAM"	Shows individual vehicle arrival times relative to green intervals.	• Did offset adjustments improve progression for a particular approach at an intersection?
1	2	3	**4**	5	"3.21 CYCLIC FLOW PROFILE"	Reports the distribution of vehicle arrivals relative to the distribution of green.	• How much and at which locations did offset adjustments improve progression along a corridor?
1	2	3	**4**	5	"3.22 OFFSET ADJUSTMENT DIAGRAM"	Estimates potential progression quality using different offset adjustments.	• What is the potential for progression improvement along a coordinated corridor?
1	2	3	**4**	5	"3.23 TRAVEL TIME AND AVERAGE SPEED"	Measures or estimates vehicle travel times (or conversely, average speeds) on defined routes.	• Did offset adjustments impact corridor speeds? • Where are the most critical intersections based on travel times and reliability?
1	2	**3**	**4**	5	"3.24 TIME-SPACE DIAGRAM"	Can depict the actual signal timing at intersections; GPS trajectories potentially can be overlaid.	• Is the signal timing resulting in expected green bands?
1	**2**	3	4	**5**	"3.25 PREEMPTION DETAILS"	Reports timing information for individual preemption events.	• Are vehicles being consistently cleared from the railroad tracks during the track clearance green interval?
1	**2**	3	4	**5**	"3.26 PRIORITY DETAILS"	Reports timing information for individual priority events.	• How many transit signal priority requests were made, and how were they served (i.e., early green or green extend)? • How often are priority requests being made on a bus rapid transit (BRT) corridor?

EXHIBIT 3-2. SIGNAL PERFORMANCE MEASURE INPUTS AND OUTPUTS

	REQUIRED INPUTS										POTENTIAL OUTPUTS															
	DATA SOURCE				DETECTION						STAKEHOLDERS					OBJECTIVES										
PERFORMANCE MEASURE	HIGH-RESOLUTION	LOW-RESOLUTION	VENDOR-SPECIFIC	AVI/SEGMENT SPEED/AVL	NONE	UNMAPPED	STOP BAR PRESENCE	STOP BAR COUNT	ADVANCE	RADAR SPEED	ORGANIZATIONAL	PLANNING	DESIGN AND CONSTRUCTION	OPERATIONS	MAINTENANCE	EQUIPMENT HEALTH	VEHICLE DELAY	VEHICLE PROGRESSION	PEDESTRIANS	BICYCLES	RAIL	EMERGENCY VEHICLES	TRANSIT	TRUCKS	SAFETY
"3.1 COMMUNICATION STATUS"	X	X	X		X						X		X		X	X									
"3.2 FLASH STATUS"	X	X			X								X		X	X									
"3.3 POWER FAILURES"	X	X			X								X		X	X									
"3.4 DETECTION SYSTEM STATUS"	X	X	X			(1)					X		X		X	X									
"3.5 VEHICLE VOLUMES"	X	X	X					X	X			X		X	X	X	X	X		X					
"3.6 PHASE TERMINATION"	X	X				X								X	X	X	X								
"3.7 SPLIT MONITOR"	X					X								X			X								
"3.8 SPLIT FAILURES"	X						X	(2)	(2)			X		X			X								
"3.9 ESTIMATED VEHICLE DELAY"	X			X			X	(3)	(3)	(4)		X		X			X			X					
"3.10 ESTIMATED QUEUE LENGTH"	X			X			X		X	(5)			X	X			X	X							X
"3.11 OVERSATURATION SEVERITY INDEX"	X								X					X			X	X							X
"3.12 PEDESTRIAN VOLUMES"	X		X							X		X		X	X	X			X						
"3.13 PEDESTRIAN PHASE ACTUATION AND SERVICE"	X	X				X						X		X	X	X			X						
"3.14 ESTIMATED PEDESTRIAN DELAY"	X					X						X		X					X						
"3.15 ESTIMATED PEDESTRIAN CONFLICTS"	X	X	X					X		X			X	X					X						X
"3.16 YELLOW/RED ACTUATIONS"	X							X		(6)				X											X

EXHIBIT 3-2. SIGNAL PERFORMANCE MEASURE INPUTS AND OUTPUTS (CONTINUED)

	REQUIRED INPUTS										POTENTIAL OUTPUTS														
	DATA SOURCE				DETECTION						STAKEHOLDERS					OBJECTIVES									
PERFORMANCE MEASURE	HIGH-RESOLUTION	LOW-RESOLUTION	VENDOR-SPECIFIC	AVI/SEGMENT SPEED/AVL	NONE	UNMAPPED	STOP BAR PRESENCE	STOP BAR COUNT	ADVANCE	RADAR SPEED	ORGANIZATIONAL	PLANNING	DESIGN AND CONSTRUCTION	OPERATIONS	MAINTENANCE	EQUIPMENT HEALTH	VEHICLE DELAY	VEHICLE PROGRESSION	PEDESTRIANS	BICYCLES	RAIL	EMERGENCY VEHICLES	TRANSIT	TRUCKS	SAFETY
"3.17 RED-LIGHT-RUNNING (RLR) OCCURRENCES"	X						X							X											X
"3.18 EFFECTIVE CYCLE LENGTH"	X	X			(7)									X			X	X	X	X					
"3.19 PROGRESSION QUALITY"	X								X					X				X							
"3.20 PURDUE COORDINATION DIAGRAM"	X								X					X				X							
"3.21 CYCLIC FLOW PROFILE"	X								X					X				X							
"3.22 OFFSET ADJUSTMENT DIAGRAM"	X								X					X				X							
"3.23 TRAVEL TIME AND AVERAGE SPEED"	X			X			(8)	(8)	(8)	X	X			X				X							
"3.24 TIME-SPACE DIAGRAM"	X	X		X	X					(9)				X			X	X							
"3.25 PREEMPTION DETAILS"	X		X			X								X		X					X	X			
"3.26 PRIORITY DETAILS"	X		X			X								X		X							X	X	

(1) Although some detection alarms do not require detection to be mapped, the most useful metrics will report status on specific detectors.

(2) Stop bar count and advance detection can be used to calculate volume-to-capacity ratios.

(3) Stop bar count and advance detection can be used to count vehicles for use in the HCM delay equation. Advance detection can also be used in arrival and departure models and to estimate time to service (with an adjustment to account for travel time to the stop bar).

(4) AVI/AVL data can be used to estimate delay using a travel time "route" that covers only one signalized movement.

(5) AVL data can be used to measure queues if the data are available at a high enough penetration rate.

(6) Some detection technologies allow actuations to be recorded only if vehicles are traveling over a specific speed.

(7) No detection is required, but without detection, cycle lengths will remain constant.

(8) Stop bar presence, stop bar count, and advance detection can be used to calculate Estimated Vehicle Delay, which can be aggregated to estimate travel time.

(9) AVL data can be used to overlay vehicle trajectories.

3.1 COMMUNICATION STATUS

CATEGORY

1 Communication
2 Detection
3 Intersection/ Uncoordinated Timing
4 System/Coordinated Timing
5 Advanced Systems and Applications

OBJECTIVES

- EQUIPMENT HEALTH
- VEHICLE DELAY
- VEHICLE PROGRESSION
- PEDESTRIANS
- BICYCLES
- RAIL
- EMERGENCY VEHICLES
- TRANSIT
- TRUCKS
- SAFETY

APPLICATIONS

- Identify communication equipment that is malfunctioning.
- Compare different types of communication.

STAKEHOLDERS

- ORGANIZATIONAL
- PLANNING
- DESIGN AND CONSTRUCTION
- OPERATIONS
- MAINTENANCE

DATA SOURCES

- VENDOR-SPECIFIC
- CONTROLLER HIGH-RESOLUTION
- AVI/AVL/SEGMENT SPEED
- CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Communications technology can be used to connect equipment at a signalized intersection (i.e., controller, cameras, ITS equipment) both to other signalized intersections for coordination purposes and/or to a central system for monitoring. Communication is a critical element of performance-based management because it provides automatic access to real-time data.

This metric reports the online/offline status of signalized intersections connected to a central system, which can be identified through:

- An occasional (e.g., once every few minutes) "ping" of the controller. If the connection is not successful, an error message is typically recorded by the controller.
- Availability of high-resolution data in a database. Gaps in data may imply the existence of extended times during which the controller was offline.
- Vendor-specific reports.

The intersection online/offline status data can be aggregated to identify time periods (e.g., days, weeks, months), locations (e.g., individual intersections, corridors, districts, networks), or communication types experiencing communication issues.

DETECTION NEEDS

None

CALIBRATION

N/A

REFERENCES

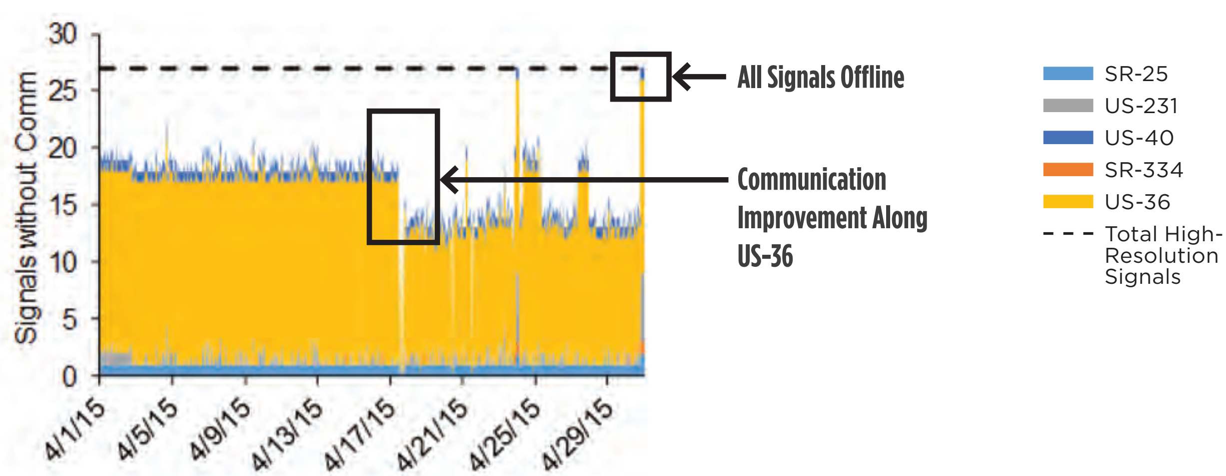
- Day et al. (2014)
- Day, Bullock et al. (2016)
- Li et al. (2013)

EXAMPLE USE

Which corridor has the greatest need for communication investments? Have maintenance efforts improved communication?

EXHIBIT 3-3 summarizes the communication status of signalized intersections connected by cell modem in an Indiana district. The total number of connected intersections is represented by the dashed line, and the bars illustrate the number of signalized intersections along each corridor (differentiated by color) for which data was *not* found on a particular day over the course of a month. This chart was used to identify which corridors should be the focus of communication upgrade efforts. An improvement made along US-36 halfway through the month resulted in additional online intersections.

EXHIBIT 3-3. COMMUNICATION SYSTEM STATUS EXAMPLE: NUMBER OF SIGNALIZED INTERSECTIONS BY CORRIDOR OFFLINE OVER 1 MONTH (DAY, BULLOCK ET AL. 2016)



3.2
FLASH STATUS

OBJECTIVES

- EQUIPMENT HEALTH
- VEHICLE DELAY
- VEHICLE PROGRESSION
- PEDESTRIANS
- BICYCLES
- RAIL
- EMERGENCY VEHICLES
- TRANSIT
- TRUCKS
- SAFETY

CATEGORY

1. Communication
2. Detection
3. Intersection/ Uncoordinated Timing
4. System/Coordinated Timing
5. Advanced Systems and Applications

APPLICATIONS

- **Identify intersections operating in flash.**
- **Determine frequency and duration of flash events to identify cause(s).**

STAKEHOLDERS

- ORGANIZATIONAL
- PLANNING
- DESIGN AND CONSTRUCTION
- OPERATIONS
- MAINTENANCE

DATA SOURCES

- VENDOR-SPECIFIC
- CONTROLLER HIGH-RESOLUTION
- AVI/AVL/SEGMENT SPEED
- CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Flash is a mode of operation that effectively turns a traffic signal into a two-way or four-way stop-controlled intersection by flashing the traffic signal displays (either yellow or red) at a constant rate. Some agencies use flash at night for low-volume intersections, but it is often applied if there is a problem at the intersection (e.g., power failure, controller malfunction, conflicting phases or indications). This metric reports how often intersections operate in flash mode based on:

- Flash status flagged as alarms by a central system.
- Flash status flagged by the controller itself and logged in the high-resolution data.

Flash status data can be aggregated to identify specific time periods (e.g., days, weeks, months) and specific locations (e.g., individual intersections, corridors, districts, networks) experiencing unscheduled flash events.

DETECTION NEEDS

None

CALIBRATION

N/A

REFERENCES

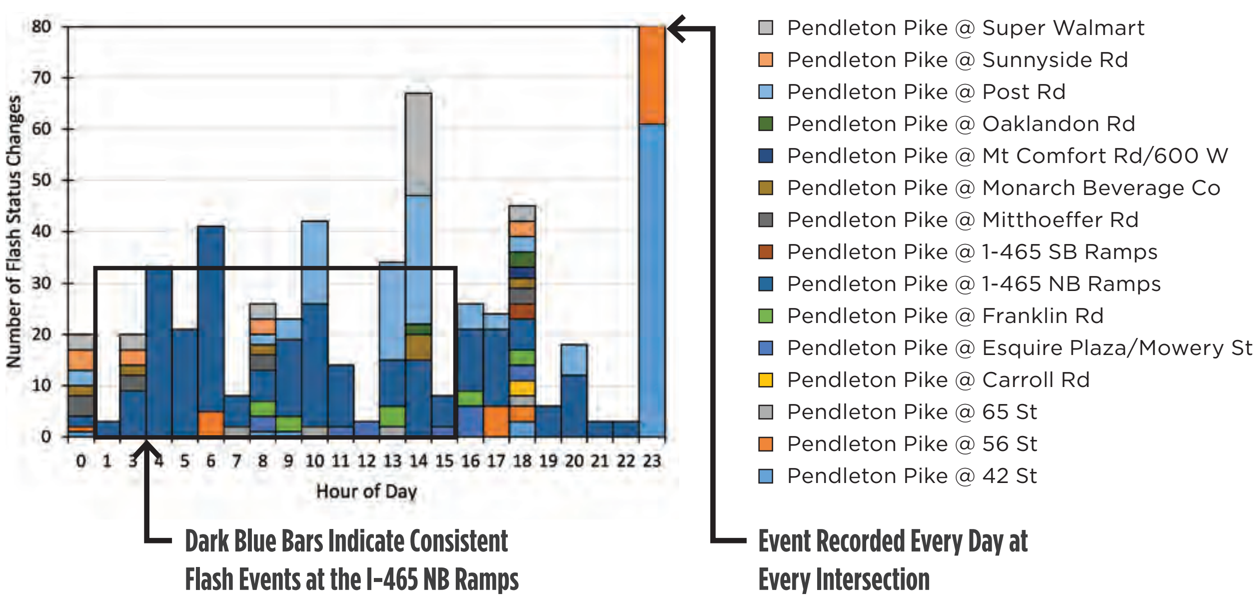
N/A

EXAMPLE USE

Do any intersections consistently experience unscheduled flash events?

EXHIBIT 3-4 shows the number of flash events recorded over 2 months using high-resolution data from a 15-intersection corridor. The data are shown by hour of the day, with each color representing a different intersection. The chart highlights that Pendleton Pike @ I-465 northbound (NB) has a number of flash events spread out over the day. A flash event is written at the “23” hour at every intersection every day, which probably does not represent an actual flash event. This chart was used to identify intersections for closer inspection and troubleshooting.

EXHIBIT 3-4. FLASH STATUS EXAMPLE: NUMBER OF FLASH EVENTS PER INTERSECTION BY HOUR OF THE DAY OVER 2 MONTHS (COURTESY PURDUE UNIVERSITY)



3.3 POWER FAILURES

CATEGORY

1. Communication
2. Detection
3. Intersection/ Uncoordinated Timing
4. System/Coordinated Timing
5. Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

APPLICATIONS

- Identify power equipment that is malfunctioning.
- Identify locations that can benefit from back-up power supply (BPS) systems.
- Identify battery life typically required for BPS systems.

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

DESIGN AND CONSTRUCTION

OPERATIONS

MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC

CONTROLLER HIGH-RESOLUTION

AVI/AVL/SEGMENT SPEED

CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Power failures can cause traffic signal outages, so agencies sometimes install back-up power supply (BPS) systems to allow traffic signal controllers to continue operating for a period of time. Information about the locations and durations of power failures can be used to determine where BPS systems should be installed as well as the typical battery life required. This metric reports how often there are power failures at an intersection based on:

- Power failures flagged as alarms by a central system.
- Power failures flagged by the controller itself and logged in the high-resolution data.

Data about power failure events can be aggregated to identify specific time periods (e.g., days, weeks, months) and specific locations (e.g., individual intersections, corridors, districts, networks) experiencing power failures.

DETECTION NEEDS

None

CALIBRATION

N/A

REFERENCES

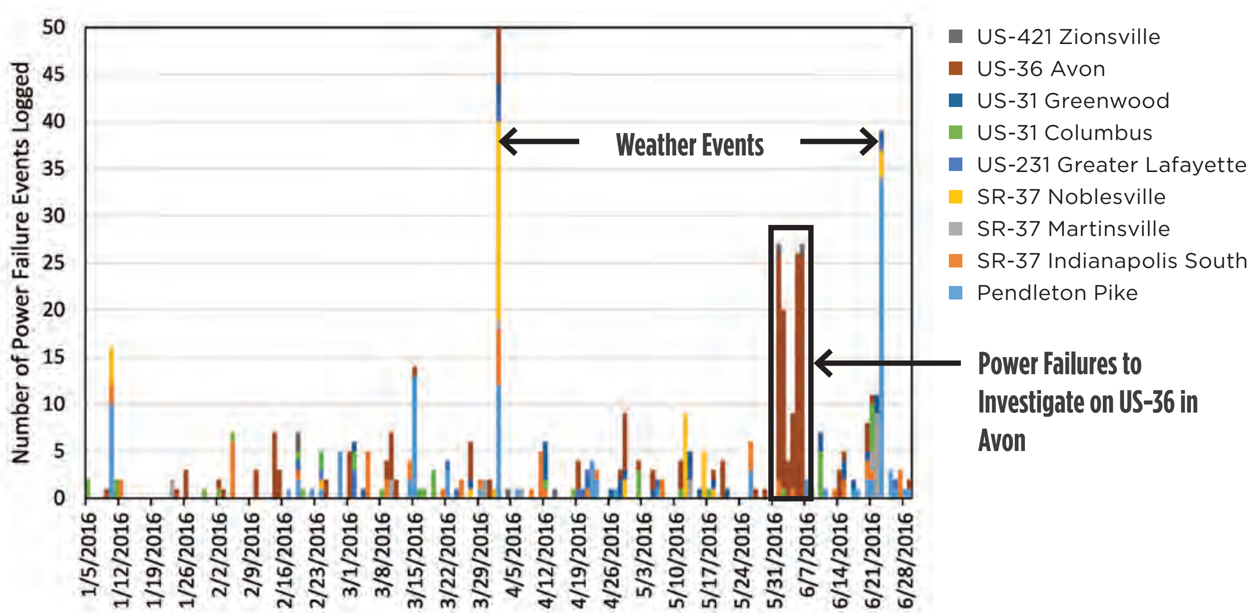
- Zhao et al. (2015)

EXAMPLE USE

Are any corridors experiencing consistent power failures?

EXHIBIT 3-5 shows the number of power failure events logged over 6 months for nine corridors in Indiana. Spikes during the weeks of 3/29/2016 and 6/21/2016 can be correlated with severe weather events that passed through those areas. However, one corridor (US-36 in Avon) experienced a number of power failures during the week of 5/29/2016 for which an explanation was not immediately available. It is possible that maintenance activity on the corridor necessitated power cycling of several intersections during the course of the day. Overall, none of the corridors experienced consistent power failures during the 6-month period.

EXHIBIT 3-5. POWER FAILURES EXAMPLE: NUMBER OF POWER FAILURE EVENTS BY CORRIDOR OVER 6 MONTHS (COURTESY PURDUE UNIVERSITY)



3.4 DETECTION SYSTEM STATUS

Communication
Detection
Intersection/ Uncoordinated Timing
System/Coordinated Timing
Advanced Systems and Applications

1 2 3 4 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- Identify detection equipment that is malfunctioning.
- Compare different types of detection.

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
DESIGN AND CONSTRUCTION
OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Detection is used at a signalized intersection to determine the presence of transportation system users, so that the traffic signal controller can allocate right-of-way safely and efficiently. Broken detection typically defaults “on” to prevent users from being skipped, but this can result in inefficiencies when a phase receives more time than needed. This metric reports the number of detector failures based on:

- Detector failures flagged as alarms by a central system or in vendor-specific reports.
- Detector failures flagged by the controller itself and logged in the high-resolution data.
- Anomalies identified through statistical analysis of the number of actuations over time (i.e., comparing the number of actuations to historical data to determine if they are “high or low”).
- Observations of a high amount of cycling during time periods when low traffic is expected (e.g., phases maxing out late at night).

DETECTION NEEDS

This metric will report on existing detection; no additional detection is necessary.

CALIBRATION

N/A

REFERENCES

- Day et al. (2014)
- Day, Bullock et al. (2016)
- Lavrenz (2015)

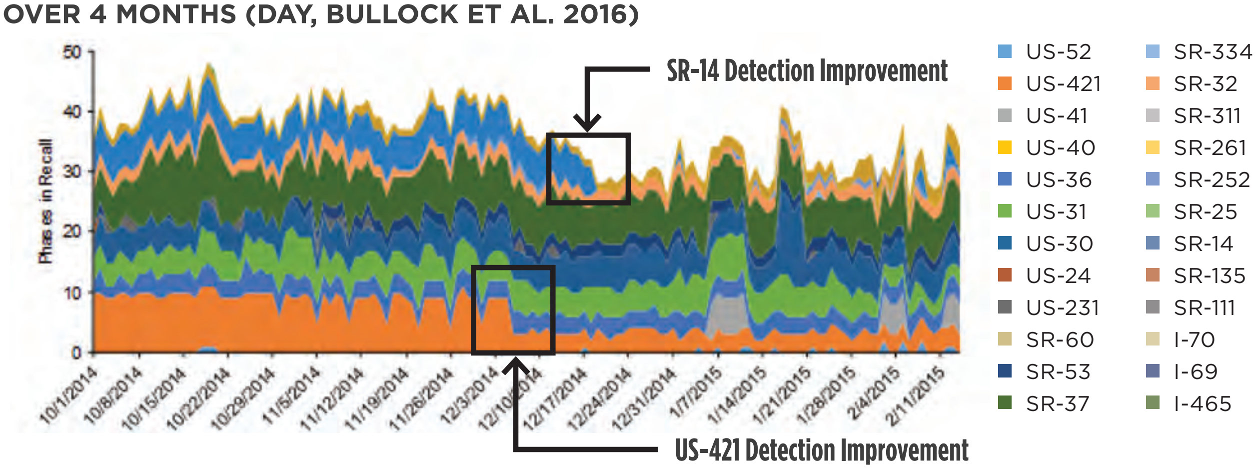
The number of failed detectors can be tracked for specific time periods (e.g., days, weeks, months) and specific locations (e.g., individual intersections, corridors, districts, networks). A list of currently broken detectors can serve as a tool for deciding where to invest maintenance efforts, while a history of broken detection can be used to evaluate the overall detection program.

EXAMPLE USE

Are any corridors experiencing consistent detection issues? Have maintenance efforts improved detection?

EXHIBIT 3-6 depicts the number of side-street phases on several corridors being served every cycle during the overnight hours. This is an indicator of detector failures, which may be causing the associated phases to max out every cycle. This chart was used to identify eight corridors consistently affected in this way during a 4-month period as well as the impact of maintenance activities. For example, numerous detector issues on US-421 were corrected the week of 12/3/2014, and detector issues on SR-14 were corrected around 12/17/2014.

EXHIBIT 3-6. DETECTION SYSTEM STATUS EXAMPLE: NUMBER OF SIDE-STREET PHASES SERVED EVERY CYCLE LATE AT NIGHT (INDICATING FAILED DETECTORS) PER CORRIDOR OVER 4 MONTHS (DAY, BULLOCK ET AL. 2016)



3.5 VEHICLE VOLUMES

Communication
Detection
Intersection/ Uncoordinated Timing
System/Coordinated Timing
Advanced Systems and Applications

1 2 3 4 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- **Identify time-of-day plan adjustments.**
- **Identify intersections with high vehicle volumes (which can be compared to capacity).**
- **Identify intersections with high bicycle volumes (depending on available detection).**
- **Identify detection equipment that is malfunctioning.**

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
DESIGN AND CONSTRUCTION
OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Volume data can be useful when programming signal timing values or troubleshooting detection issues, and is also often collected for planning purposes. This metric reports the number of vehicles (or bicycles, depending on available detection) observed in a lane or on an approach. The data may be shown as a pure count over a time interval (e.g., 15-minute counts) or on a cycle-by-cycle basis. The number of vehicles is often normalized to a flow rate (e.g., vehicles per hour). This is especially important for cycle-by-cycle counts because each (effective) cycle may not have the same duration as the others. The conversion is:

(Flow Rate, vehicles per hour) = 3,600 x (Vehicles Counted) ÷ (Counting Interval, seconds)

Signal timing adjustments. Volume profiles can be valuable for evaluating when signal timing plans should begin and end throughout the day. Lane volumes can be used to validate signal phasing and some signal timing parameters (e.g., using a critical movement analysis to assess capacity and adjust splits). If bicycle counts are available (i.e., if bicycle detection is separate from vehicle detection), signal timing parameters can be tailored to bicyclists at intersections with high bicycle volumes (e.g., extended clearance intervals and minimum green times).

Detection troubleshooting. Volumes can also be used to identify detection equipment that is malfunctioning. Because this metric often allows a disaggregated look at volumes by individual detector, individual lane, or approach, volumes that are higher or lower than historical averages can be used to identify broken detectors.

Planning. Turning movement counts can be used for microscopic models, and approach volumes can help validate macroscopic model assumptions. Although high-resolution data reduces the need to create models for signal retiming, models may be helpful for efforts such as planning for major geometric changes. Numerous secondary metrics applicable to planning studies can be determined using vehicle counts, such as peak hour factors, directional splits, and K-factors.

DETECTION NEEDS

A variety of detection schemes can be used to gather volume data. Small detection zones capable of detecting a single vehicle will provide the most accurate counts. The detectors should be placed either in advance of the intersection (upstream of typical queues) or past the stop bar. For lane-by-lane counts, detection zones located in each lane require their own input channel. When multiple detection zones across lanes report to a single channel, the total number of vehicles may be higher than the actuations recorded (e.g., if two vehicles pass over the detectors at the same time). For turning movement counts, detection zones can be set up past the stop bar as well as in the outbound lanes of the intersection.

CALIBRATION

At some locations, detectors for certain movements may not be available. It is possible to estimate the count by using a percentage of some other, related detector. For example, an advance detector may capture traffic heading to several movements on an approach. If there is no detector in place to capture a right-turn movement, it can be estimated using an assumed percentage of the advance detector count. The accuracy of this method depends on the reliability of the percentage applied.

REFERENCES

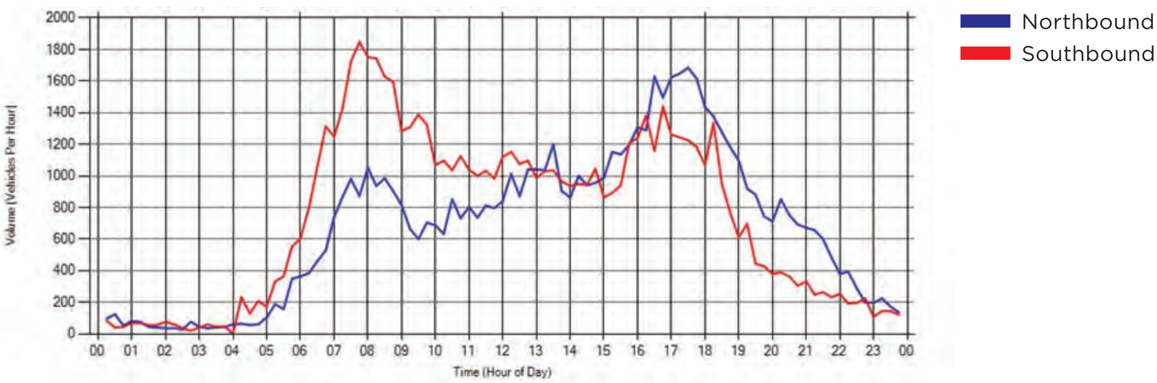
- Day et al. (2008)
- Day and Bullock (2010)
- Day et al. (2014)
- ITE (2008)
- UDOT

EXAMPLE USE 1

When are the peak traffic periods and what is their duration?

EXHIBIT 3-7 shows northbound and southbound flow rates (calculated using 15-minute volumes) that illustrate the directionality along a commuter corridor in Virginia. These volume profiles can be compared to the time-of-day plan to assess whether timing plans start and end at appropriate times. Additionally, planning-level metrics can be calculated using the same volume data, which can then be used to calibrate any models developed for the corridor.

EXHIBIT 3-7. VOLUMES EXAMPLE: VOLUME PROFILES AND PLANNING METRICS (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



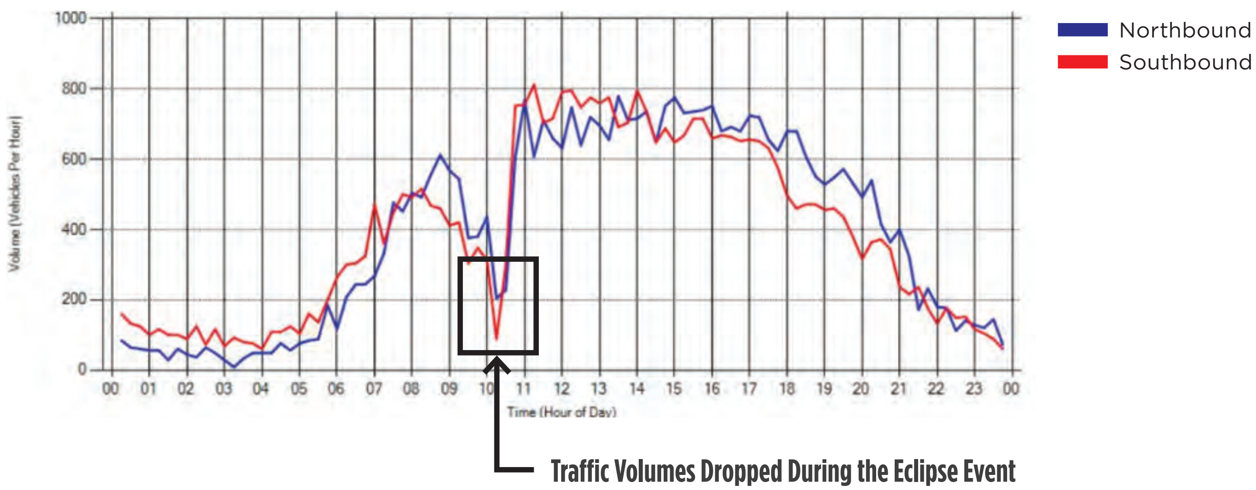
METRIC	VALUE
Peak Hour	2/12/2018 4:45:00 PM
Peak Hour Factor	0.346
Peak Hour Volume	11620
Peak Hour Factor	0.989
Total Volume	33586
Northbound Peak Hour	5:00 PM - 6:00 PM
Northbound Peak Hour D Value	0.747
Northbound Peak Hour K Value	0.407
Northbound Peak Hour Volume	6572
Northbound Peak Hour Factor	0.976
Southbound Peak Hour	7:30 AM - 8:30 AM
Southbound Peak Hour D Value	0.543
Southbound Peak Hour K Value	0.405
Southbound Peak Hour Volume	7068
Southbound Peak Hour Factor	0.956

EXAMPLE USE 2

How were traffic volumes impacted during a special event?

During the total solar eclipse on August 21, 2017, the Oregon Department of Transportation (ODOT) closely monitored traffic volumes (shown in **EXHIBIT 3-8**). Volumes dropped significantly right before and during the event but returned to normal traffic patterns relatively quickly.

EXHIBIT 3-8. VOLUMES EXAMPLE: VOLUME PROFILES DURING A SPECIAL EVENT (COURTESY OREGON DEPARTMENT OF TRANSPORTATION)



3.6 PHASE TERMINATION

CATEGORY

1 Communication
2 Detection
3 Intersection/ Uncoordinated Timing
4 System/Coordinated Timing
5 Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- Identify phases that potentially require an adjustment to green time (proxy for split failures).
- Identify detection equipment that is malfunctioning.

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
DESIGN AND CONSTRUCTION
OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Actuated phases terminate either because there is a gap in traffic or because the phase has reached its maximum programmed time. This metric reports the reason that individual phases terminated (i.e., a gap-out, max-out, force-off, or skip). This information can typically be gathered:

- For each cycle using high-resolution data from the controllers.
- As aggregated data for specified time periods from a central system (e.g., number of gap-outs, max-outs, force-offs, and skips during a 15-minute interval).

This metric is useful for determining times of day when a phase is repeatedly using all its allocated green time. While coordinated phases (except when actuated) are forced off at their programmed time to yield to other phases, non-coordinated phases that repeatedly force off are likely experiencing heavy demand or perhaps a constant call from a faulty detector.

DETECTION NEEDS

This metric is beneficial at locations with existing detection; no additional detection is necessary.

CALIBRATION

N/A

REFERENCES

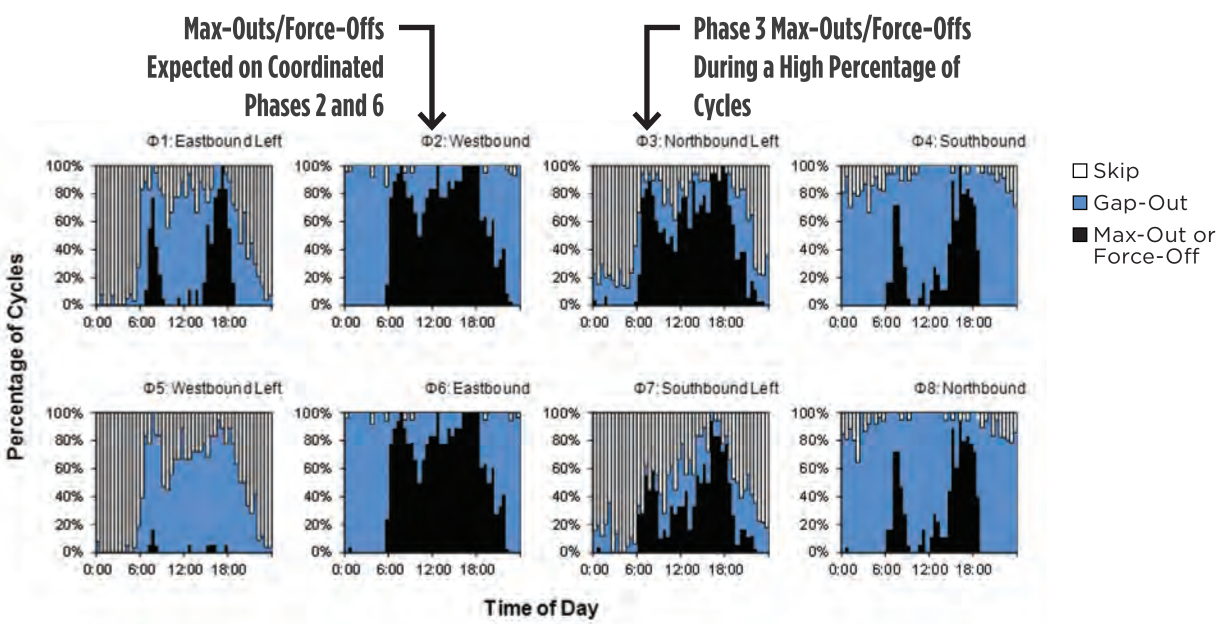
- Day et al. (2014)
- Li et al. (2013)

EXAMPLE USE

Do any phases need an adjustment to green time?

EXHIBIT 3-9 shows the distribution of phase termination types aggregated into 30-minute bins, rather than for individual cycles, for each phase at an intersection. The data includes phase skips, gap-outs, and combined max-outs and force-offs. Phases 2 and 6 are shown forcing off frequently during the day because they are coordinated; note that these phases gap out on occasion due to the use of early yield. High numbers of max-outs and force-offs can generally be correlated to heavy demand during peak periods. However, Phase 3 is a candidate for closer inspection because it forces off frequently throughout most of the day. This can indicate that the phase requires an adjustment to green time.

EXHIBIT 3-9. PHASE TERMINATION EXAMPLE: DISTRIBUTION OF TERMINATION TYPES BY PHASE (DAY ET AL. 2014)



3.7 SPLIT MONITOR

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

CATEGORY

1 Communication

2 Detection

3 Intersection/Uncoordinated Timing

4 System/Coordinated Timing

5 Advanced Systems and Applications

APPLICATIONS

- **Identify phases that potentially require an adjustment to green time (proxy for split failures).**
- **Identify amount of green time adjustment (i.e., time to add or subtract).**

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

DESIGN AND CONSTRUCTION

OPERATIONS

MAINTENANCE

DATA SOURCES

CONTROLLER HIGH-RESOLUTION

CENTRAL SYSTEM LOW-RESOLUTION

VENDOR-SPECIFIC

AVI/AVL/SEGMENT SPEED

DESCRIPTION

This metric is used to report detailed information about the performance of an individual phase. Using high-resolution data, it combines a plot of phase duration with several other pieces of information–termination type, pedestrian phase service, and programmed splits. This metric is useful for assessing whether signal timing parameters have been programmed correctly, how much of the programmed split is being used, and whether signal timing adjustments had an impact. The pattern change information can also be used to infer events such as interruption of a pattern by preemption or priority control.

DETECTION NEEDS

This metric is beneficial at locations with existing detection; no additional detection is necessary.

CALIBRATION

N/A

REFERENCES

- Mackey (2017)
- UDOT

EXAMPLE USE

Are the splits programmed in a special event plan adequately serving traffic?

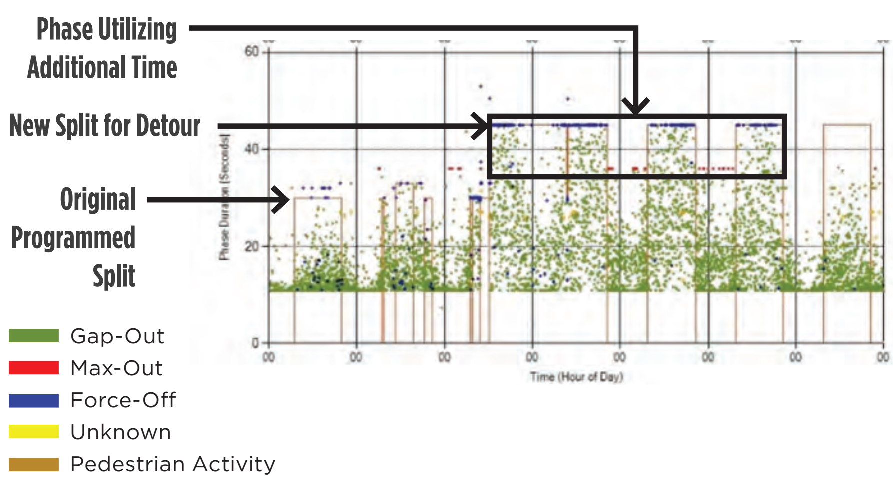
A freeway detour greatly increased northbound left-turn volumes at a signalized intersection in Cedar City, Utah. In September 2014, heavy rain in Nevada destroyed a portion of I-15, forcing the closure of the route. Traffic was diverted, and the first signalized intersection along the route was the exit ramp from I-15 (shown in **EXHIBIT 3-10**).

EXHIBIT 3-11 depicts the split monitor data for the associated northbound left-turn phase during the week of the detour. A new timing plan was implemented (with increased green time for the northbound left-turn phase) to accommodate diverted traffic. The split monitor chart does show that some force-off events occurred, but many more gap-outs were observed during the same time period.

This indicates the northbound left-turn phase typically utilized less time than the new split. Had the original programmed split been in place, the force-off events would have increased significantly, potentially causing traffic to queue onto the freeway.

EXHIBIT 3-10. SPLIT MONITOR EXAMPLE: DETOUR ROUTE

EXHIBIT 3-11. SPLIT MONITOR EXAMPLE: NORTHBOUND LEFT-TURN PHASE AFFECTED BY I-15 CLOSURE (MACKEY 2017)



3.8 SPLIT FAILURES

Communication

Detection

Intersection/ Uncoordinated Timing

System/Coordinated Timing

Advanced Systems and Applications

1 2 **3** 4 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

APPLICATIONS

- **Identify phases and/or intersections experiencing split failures (i.e., requiring adjustments to green time or detection settings).**

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

DESIGN AND CONSTRUCTION

OPERATIONS

MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC

CONTROLLER HIGH-RESOLUTION

AVI/AVL/SEGMENT SPEED

CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

A "split failure" is an occurrence when there are unserved vehicles at the end of green. A phase that has multiple consecutive split failures is very likely to have an operational problem that can potentially be fixed by increasing the split (or the max time under fully actuated control) or adjusting detection settings (i.e., passage time).

There are different ways to estimate the number of split failures depending on the type of detection available:

Occupancy ratios. Using stop bar presence detection (lane-by-lane is most effective), the green occupancy ratio (GOR) and red occupancy ratio (ROR) can be calculated. This is the percentage of the green interval or the first few seconds of the red interval during which the detector is occupied. When both GOR and ROR are above a threshold (i.e., 80%), the phase is likely to have had a split failure.

GOR = (Total Occupancy Time During Green, seconds) / (Total Green Time, seconds)

ROR = (Total Occupancy Time During the First *x* Seconds of Red, seconds) ÷ *x*

where

x = Selected amount of time for confirming a split failure, seconds (i.e., 5 seconds)

For GOR and ROR calculations, the yellow interval is not taken into consideration; however, a yellow occupancy ratio (YOR) can be calculated separately.

Volume-to-capacity ratios. Using advance detection or stop bar count detection, the volume-to-capacity (v/c) ratio can be calculated. The capacity should be estimated using the saturation flow rate, but volumes can be calculated directly through vehicle actuations. When the v/c ratio exceeds a threshold, the phase is likely to have had a split failure. Planners may also be interested in the calculated v/c ratios.

v/c ratio = (3,600 x *N*) ÷ (*s* x *g*)

where

N = Number of vehicles counted in an effective green interval and the *preceding* effective red interval (as shown in **EXHIBIT 3-12**)

s = Saturation flow rate, vehicles per hour

g = Green time, seconds

With advance detection, the vehicle actuation times should be adjusted to account for travel time from the detector to the stop bar, as discussed further in *Section 3.19: Progression Quality*. With stop bar count detection, the vehicle actuation times can be used without such an adjustment.

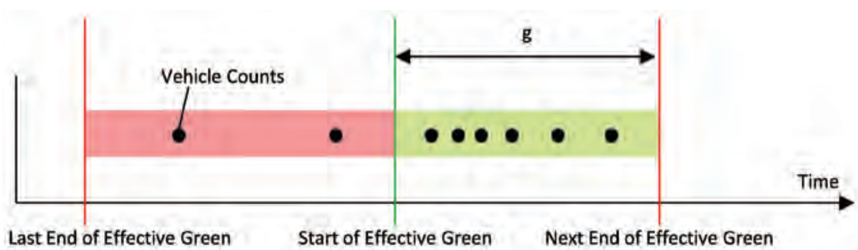
Note that the start of effective red and the start of effective green differ from the actual start of red and start of green due to start-up lost time and utilization of yellow. Historically, the *Highway Capacity Manual* (HCM) value of 2 seconds has been used (although different values may be used if warranted), yielding the following definitions:

(Start of Effective Green) = (Actual Start of Green) + 2 seconds

(Start of Effective Red) = (Actual End of Green) + 2 seconds

The number of split failures can be reviewed for individual phases, the entire intersection, or across a corridor. The underlying metric (GOR/ROR or v/c ratio) can also be examined in more detail if desired.

EXHIBIT 3-12. VOLUME-TO-CAPACITY V/C RATIO CALCULATION



DETECTION NEEDS

- For calculating GOR and ROR, stop bar presence detection is required. Lane-by-lane detection provides more accurate results than detectors tied together across lanes; multi-lane detectors may over-estimate occupancy ratios.
- For calculating volume-to-capacity ratios, either advance detection or stop bar count detection is required.

CALIBRATION

- If desired, the number of consecutive split failures may be used to identify locations requiring further investigation, but a threshold will need to be determined.
- **Occupancy ratios.** For GOR and ROR, the threshold above which to consider a phase to have a split failure is a parameter requiring calibration; previous research has used a value of 80%.

  Additionally, the amount of red time used for ROR is a parameter requiring calibration; previous research has used a value of five seconds.
- **Volume-to-capacity ratios.** For v/c ratios, both the threshold for split failures as well as the saturation flow rate require calibration. Previous research has used a threshold of 1.0 to define split failures assuming a saturation flow rate of 1,900 vehicles/hour/lane, but lower or higher values should be used to reflect site conditions. Typical saturation flow rates are between 1,800–2,100 vehicles/hour/lane with higher values usually observed in denser areas. Refer to *Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach* for more information (Day et al. 2014).

  If advance detection is used, an adjustment should be made to the vehicle detection times to estimate the time each vehicle arrives at the stop bar. This can be done by adding the travel time to the detection time. For example, if the detector is positioned 5 seconds upstream of the stop bar, 5 seconds would be added to the reported actuation times.

  The actual red and green intervals at the intersection would typically be converted into "effective red" and "effective green" times. The determination of effective red and green times should also reflect site conditions.

REFERENCES

- Day et al. (2008)
- Day et al. (2014)
- Day, Bullock et al. (2016)
- Freije et al. (2014)
- Li et al. (2017)
- Richardson et al. (2017)
- Smaglik, Sharma et al. (2007)
- Smaglik et al. (2011)

EXAMPLE USE 1

Are there corridors that can benefit from split adjustments? During which time periods?

EXHIBIT 3-13 summarizes the number of split failures per hour that occurred along seven corridors by day of the week and time of day. The values greater than 10 split failures per hour are highlighted as a way to quickly identify locations and time periods potentially requiring split adjustments. The high rates occurring during the PM peak are expected. However, US-31 Greenwood shows a high rate of split failures on Saturday when its weekday rates are generally lower. The US-31 corridor may benefit from more detailed investigation of splits programmed in the Saturday plan.

EXHIBIT 3-13. SPLIT FAILURES EXAMPLE: NUMBER OF SPLIT FAILURES PER HOUR FOR SEVEN CORRIDORS (LI ET AL. 2017)

Corridor / Day of week		SR-37 Martinsville	US-31 Greenwood	US-31 Columbus	US-421 Zionsville	Pendleton Pike	SR-37 Indianapolis South	SR-37 Noblesville
Monday - Thursday	AM	1.3	0.8	1.6	5.1	5.3	9.8	8.3
	Mid-day	1.3	2.9	4.7	5.9	2.3	5.6	7.8
	PM	2.0	8.4	8.2	8.4	8.3	13.8	19.8
Friday	AM	1.2	0.6	1.5	5.2	4.8	8.8	9.4
	Mid-day	1.9	6.3	8.1	8.5	3.5	7.4	11.0
	PM	3.6	13.2	12.4	9.7	9.9	17.1	22.2
Saturday	AM	0.9	0.1	0.1	0.3	1.5	3.1	1.3
	Mid-day	2.4	10.3	6.2	4.1	4.6	9.6	9.4
	PM	1.7	11.7	4.9	3.7	4.6	9.7	6.9
Sunday	AM	0.6	0.3	0.0	0.1	1.3	1.6	0.7
	Mid-day	1.9	4.7	2.3	2.1	2.8	5.8	3.5
	PM	1.5	4.2	1.6	2.8	2.8	6.2	4.1

High Split Failures During PM Peak Are Expected

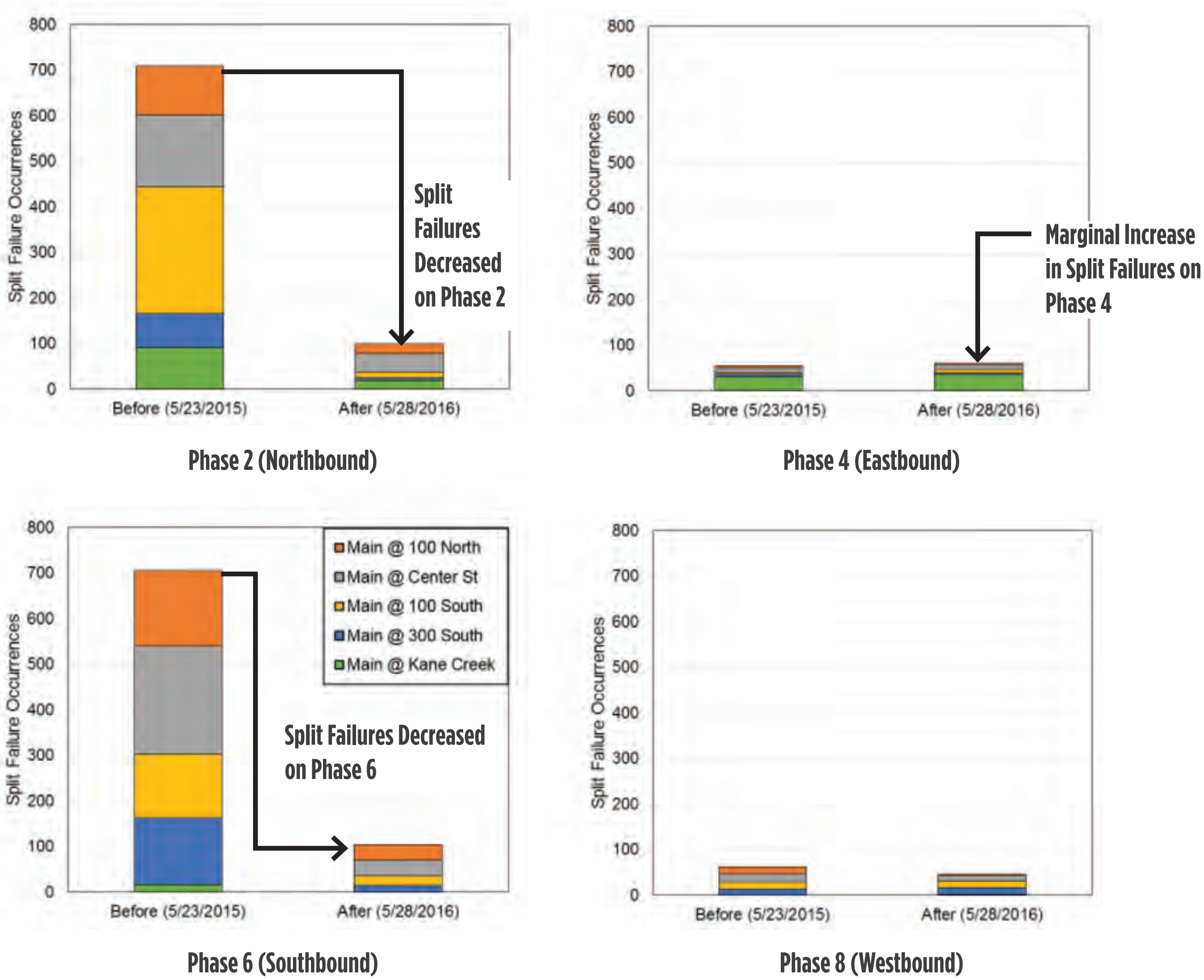
US-31 Corridor Experiencing High Split Failures on Saturday Compared to Weekdays

EXAMPLE USE 2

Did implementation of an adaptive cycle length improve the number of split failures?

EXHIBIT 3-14 depicts the number of split failures along a five-intersection corridor before and after implementation of an adaptive cycle length. Because of the corridor's proximity to national parks in Moab, Utah, traffic volumes fluctuate intensely and unpredictably, making the location ideal for an adaptive solution. **EXHIBIT 3-14** shows the number of split failures by phase with each intersection shown in a different color. The adaptive algorithm led to an overall reduction in split failures, particularly on Phases 2 and 6, without worsening the performance for any particular phase.

EXHIBIT 3-14. SPLIT FAILURES EXAMPLE: NUMBER OF SPLIT FAILURES BEFORE AND AFTER IMPLEMENTATION OF AN ADAPTIVE CYCLE LENGTH ALGORITHM (RICHARDSON ET AL. 2017)



3.9 ESTIMATED VEHICLE DELAY

Communication
Detection
Intersection/ Uncoordinated Timing
System/Coordinated Timing
Advanced Systems and Applications

1 2 **3** 4 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

APPLICATIONS

- **Identify phases/intersections with high vehicle delay.**
- **Identify phases/intersections with high bicycle delay (depending on available detection).**

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

DESIGN AND CONSTRUCTION

OPERATIONS

MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC

CONTROLLER HIGH-RESOLUTION

AVI/AVL/SEGMENT SPEED

CENTRAL SYSTEM LOW-RESOLUTION

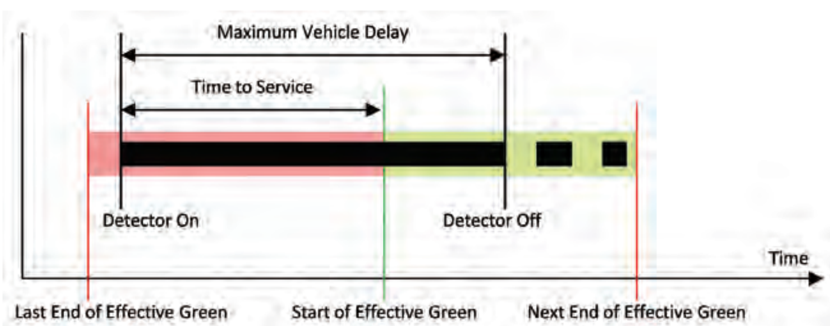
DESCRIPTION

Vehicle delay is a metric that is commonly modeled by agencies to identify whether intersection operations are acceptable. Using high-resolution data, this metric can be computed directly. For locations with high delay, particularly at uncongested locations, signal timing adjustments can help reduce wait times (e.g., through changes to cycle length, split, or phase order).

This metric is used to report the amount of delay experienced by vehicles (or bicycles depending on available detection) at signalized intersections. Delay is typically expressed as an average over a signal cycle or an interval (e.g., 5-minute, 15-minute). There are numerous ways to estimate or measure it:

- Arrival and departure model. The “input-output” method builds a queue profile by considering the measured arrival times of vehicles and their expected departure times. The “area” of the queue over time represents the delay. These methods require an advance detector to measure arrival times.
- *Highway Capacity Manual* (HCM) model based on measured traffic volumes and green times.
- “Maximum vehicle delay,” which can be estimated as the time between the first “on” time of the stop bar detector and the next time that the detector turns “off” during a green interval (illustrated in **EXHIBIT 3-15** using the phase state and stop bar detector occupancy state).
- “Time to service,” which is the time from the first call to the start of green (illustrated in **EXHIBIT 3-15**). This measure will be most accurate with stop bar detection, but an advance detector can be used to estimate time to service as long as an adjustment is made for the time to travel between the advance detector and the stop bar.
- Travel time “routes” that cover only one signalized movement (similar to travel time techniques discussed in *Section 3.23: Travel Time and Average Speed*).

EXHIBIT 3-15. MAXIMUM VEHICLE DELAY AND TIME TO SERVICE CALCULATIONS



DETECTION NEEDS

- Arrival and departure models require advance detection to measure arrival times.
- HCM model requires detection that is capable of counting volumes (refer to *Section 3.5: Vehicle Volumes*).
- Maximum vehicle delay and time to service require stop bar presence detection to estimate the time between when the first vehicle stops and is then served. Time to service can also be estimated if there is advance detection, but an adjustment must be made to account for the travel time between the advance detector and the stop bar.

CALIBRATION

Additional details are available in the references.

REFERENCES

- Day and Bullock (2010)
- Day et al. (2014)
- Lavrenz et al. (2015)
- Sharma, Bullock, and Bonneson (2007)
- Smith (2014)
- Sunkari, Charara, and Songchitruska (2012)

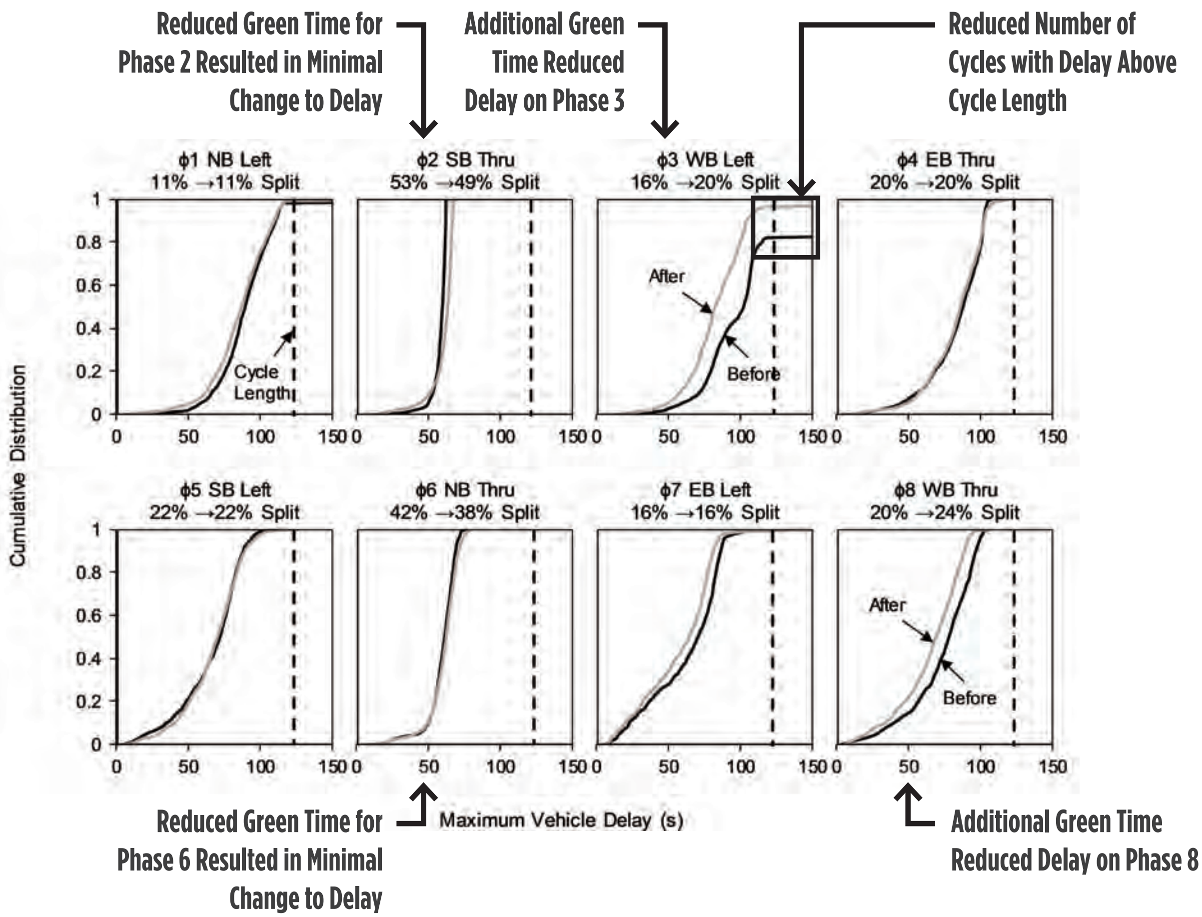
EXAMPLE USE

Did split adjustments improve vehicle delay?

EXHIBIT 3-16 shows cumulative distributions of maximum vehicle delay for eight phases before and after split adjustments. Cumulative distribution charts report the percentile of cycles for which vehicles are experiencing different durations of delay. For example, the median delay (50th percentile) before the split adjustment on Phase 3 was approximately 100 seconds, and after the split adjustment, the median delay shifted to approximately 80 seconds. In this example, green time was moved from Phases 2 and 6 to Phases 3 and 8. As a result, delay decreased on Phases 3 and 8, while Phases 2 and 6 experienced little change in delay. This chart confirmed that the split adjustment improved overall intersection delay.

Beyond median delay, the highest delays are also important to consider. When vehicles are experiencing delay above the cycle length (represented by the dashed lines), it can be an indicator of cycle failures (when there are unserved vehicles). In addition to improved median delay on Phase 3, the percentile of cycles with delay above the cycle length also improved (from approximately the 80th percentile to the 90th percentile).

EXHIBIT 3-16. ESTIMATED DELAY EXAMPLE: CUMULATIVE DISTRIBUTIONS OF MAXIMUM VEHICLE DELAY FOR EIGHT PHASES BEFORE AND AFTER SPLIT ADJUSTMENT (LAVRENZ ET AL. 2015)



3.10 ESTIMATED QUEUE LENGTH

CATEGORY

1 Communication

2 Detection

3 Intersection/Uncoordinated Timing

4 System/Coordinated Timing

5 Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

APPLICATIONS

- **Identify locations and durations of long queues.**

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

DESIGN AND CONSTRUCTION

OPERATIONS

MAINTENANCE

DATA SOURCES

CONTROLLER HIGH-RESOLUTION

CENTRAL SYSTEM LOW-RESOLUTION

VENDOR-SPECIFIC

AVI/AVL/SEGMENT SPEED

DESCRIPTION

Long queues can interfere with progression, increase vehicle delay, and cause safety issues. Queue management is particularly important at tightly spaced intersections, interchanges, and congested locations. This metric reports the queue length for signalized movements, which can be used to identify signal timing adjustments as well as inform geometric design decisions (e.g., turn bay lengths). Several methods can be used to estimate or measure queue length:

- **Arrival and departure model.** Analyzes vehicle arrival and discharge patterns using an advance detector. An "input-output" method can be developed that counts vehicle arrivals on red and estimates the size of the queue (Sharma, Bullock, and Bonneson 2007). It is then assumed that vehicles discharge at the saturation flow rate.
- **Advance detector occupancy.** Uses advance detector occupancy as empirical evidence that the queue has extended to the detector, and then combines this with a traffic model to develop a queue estimate that can be calculated even if queues reach beyond the advance detector (Liu et al. 2008).
- **Stop bar detector occupancy.** Uses the total occupancy at the stop bar presence detector combined with the count of vehicles served within the cycle (Smith 2014).
- **Directly measured using AVL data**. This method can be used if the data are available at a high enough penetration rate.

DETECTION NEEDS

- Advance detection is required for arrival and departure models but can also be used to detect queues extending to the advance detectors.
- Stop bar presence detection is required for models that use occupancy and counts to estimate queues.

CALIBRATION

N/A

REFERENCES

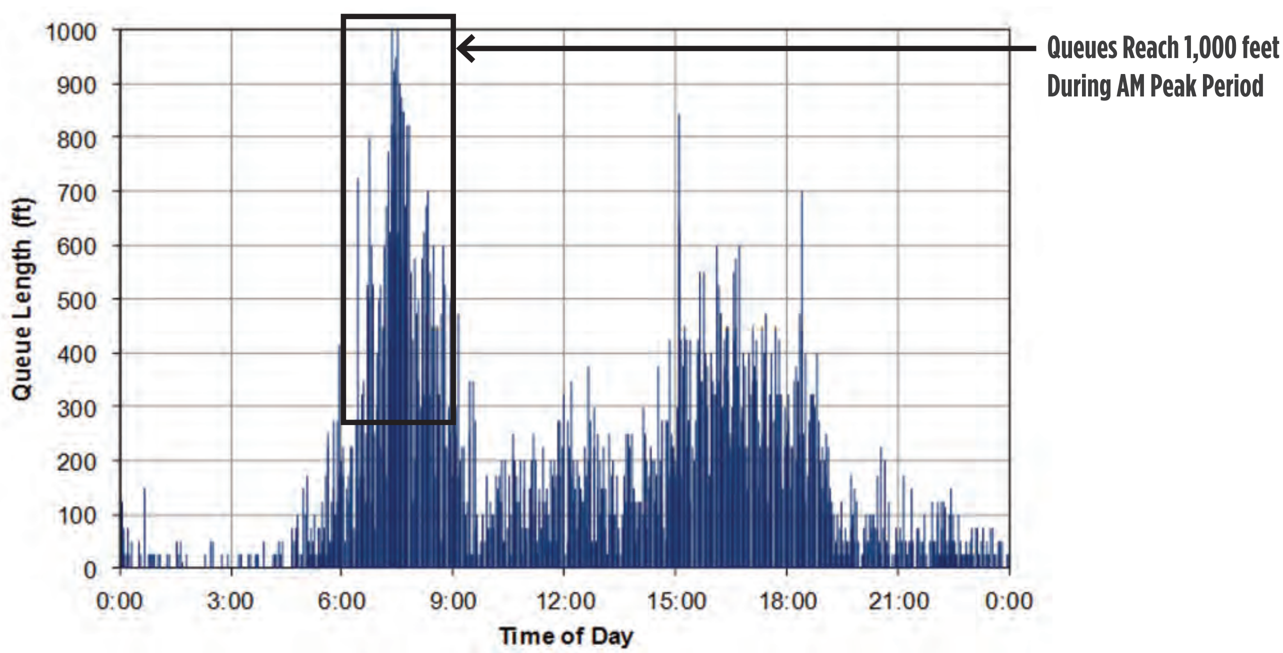
- Day, Bullock et al. (2014)
- Liu et al. (2008)
- Liu and Ma (2009)
- Sharma, Bullock, and Bonneson (2007)
- Smith (2014)

EXAMPLE USE

During what times of day is an approach experiencing long queues?

EXHIBIT 3-17 is a plot of the maximum queue lengths observed during individual cycles over a 24-hour period for a signalized approach in Indiana. The plot shows that during most of the day, queues are 300 feet or less. During the AM peak, however, queues can grow as long as 1,000 feet during certain cycles. If the approach is unable to accommodate 1,000 feet of queuing, signal timing adjustments may need to be investigated for the AM timing plan.

EXHIBIT 3-17. ESTIMATED QUEUE LENGTH EXAMPLE: CHART OF QUEUE LENGTHS ON A SIGNALIZED APPROACH IN INDIANA (DAY, BULLOCK ET AL. 2014) USING METHOD PRESENTED BY LIU AND MA (2009)



3.11 OVERSATURATION SEVERITY INDEX

Communication
Detection
Intersection/ Uncoordinated Timing
System/Coordinated Timing
Advanced Systems and Applications

1 2 3 4 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- Identify oversaturated intersections and possible mitigations.

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
DESIGN AND CONSTRUCTION
OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

The temporal oversaturation severity index (TOSI) and spatial oversaturation severity index (SOSI) measure the impact of oversaturation and inform potential mitigations.

- **Temporal oversaturation.** Refers to the impacts of split failures, when there is not sufficient green time to serve all the vehicles. Additional green time would have prevented this type of oversaturation.
- **Spatial oversaturation.** Refers to the impact of downstream congestion, when queue spillbacks at other intersections prevent the movement of traffic. Adding green time in this case is detrimental.

TOSI and SOSI are expressed as percentages. Both are ratios of the "unusable green time" and the "total available green time." A high value of TOSI implies that additional green time is needed to avoid split failures. A high value of SOSI indicates that attention should be focused on the downstream intersection to create space for traffic to enter from the upstream intersection.

$$\text{TOSI} = (L \div J \times H) \div G$$

$$\text{SOSI} = (\sum Q_i) \div G$$

In these equations, the following are computed for individual cycles:

L = Minimum residual queue length, feet

J = Headway under congested traffic conditions, feet

H = Saturation discharge headway, seconds

G = Effective green time, seconds

$\sum Q_i$ = Summation of all the durations when spillback blocked traffic, seconds (i.e., when there was a queue over an advance detector)

DETECTION NEEDS

Advance detection is required to identify queues.

CALIBRATION

Additional details are available in the references.

REFERENCES

- Gettman, Abbas et al. (2012)
- Gettman, Madrigal et al. (2012)
- Wu, Liu, and Gettman (2010)

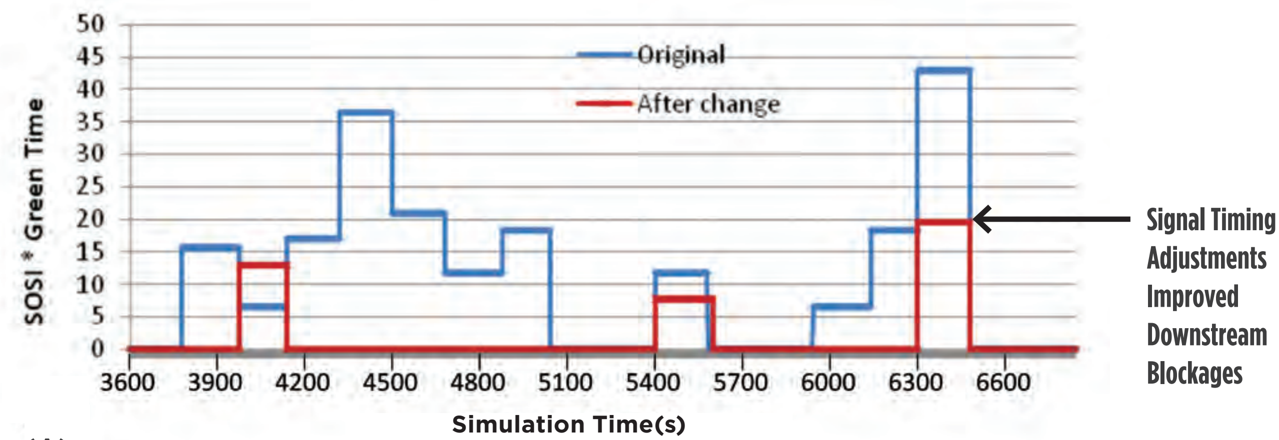
EXAMPLE USE

Did signal timing adjustments improve oversaturated conditions (i.e., downstream blockages and split failures)?

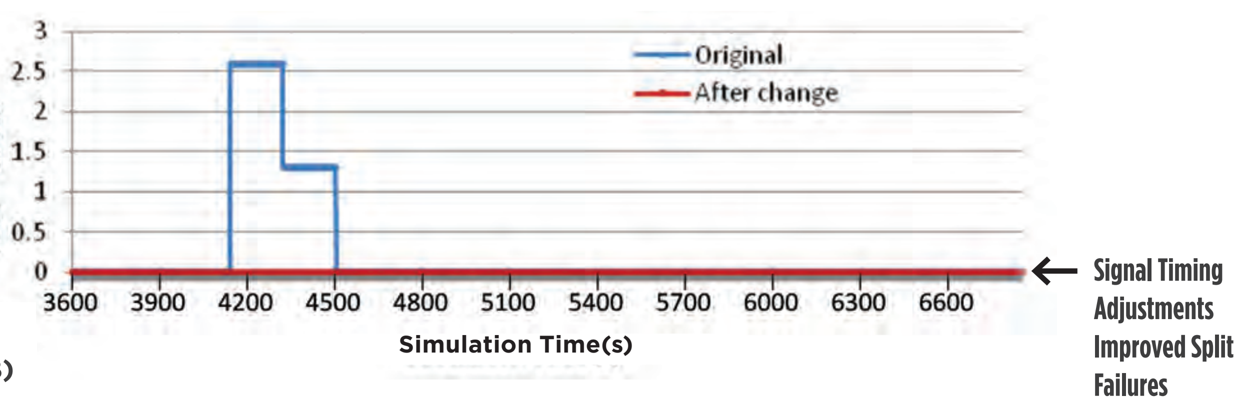
EXHIBIT 3-18 summarizes SOSI (**EXHIBIT 3-18A**) and TOSI (**EXHIBIT 3-18B**) from a simulation study of oversaturated operations. The two charts multiply the indices by green time, effectively showing the amount of unusable green time due to spatial or temporal limitations. These values are reported by cycle throughout the simulation runtime for “before” and “after” conditions.

The “after” data in each case shows a reduction in the unusable green time, indicating an improvement. Although spatial impacts are not completely eliminated in the after case (**EXHIBIT 3-18A**), they have been considerably improved, with only three cycles affected by downstream blockages. Temporal impacts (**EXHIBIT 3-18B**) were also addressed by the changes to the signal timing.

EXHIBIT 3-18. OVERSATURATION SEVERITY INDEX EXAMPLE: (A) SPATIAL (SOSI) AND (B) TEMPORAL (TOSI) INDICES FROM A SIMULATION ENVIRONMENT (GETTMAN, MADRIGAL ET AL. 2012)



(A)



(B)

3.12 PEDESTRIAN VOLUMES

OBJECTIVES

- EQUIPMENT HEALTH
- VEHICLE DELAY
- VEHICLE PROGRESSION
- PEDESTRIANS
- BICYCLES
- RAIL
- EMERGENCY VEHICLES
- TRANSIT
- TRUCKS
- SAFETY

CATEGORY

1 Communication
2 Detection
3 Intersection/Uncoordinated Timing
4 System/Coordinated Timing
5 Advanced Systems and Applications

APPLICATIONS

- **Identify time-of-day plan adjustments.**
- **Identify intersections with high pedestrian volumes.**
- **Identify pedestrian detection equipment that is malfunctioning.**

STAKEHOLDERS

- ORGANIZATIONAL
- PLANNING
- DESIGN AND CONSTRUCTION
- OPERATIONS
- MAINTENANCE

DATA SOURCES

- VENDOR-SPECIFIC
- CONTROLLER HIGH-RESOLUTION
- AVI/AVL/SEGMENT SPEED
- CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

At locations with high pedestrian demand, it may be a priority to keep the cycle length low (to prevent delay) and maintain splits that are longer than the pedestrian clearance intervals (to prevent dropped coordination) during certain times of day. High pedestrian volumes can indicate that an agency should consider priority treatments such as leading pedestrian intervals or exclusive pedestrian phases. Planners may also be interested in pedestrian volumes as pedestrian facilities are being evaluated.

Pedestrian volumes are often estimated using push button counts, but pedestrian-specific detectors can be installed for more accurate counts. The total number of pedestrians may be presented either as a raw count for a given time interval or during a given cycle, but volumes are typically expressed in units of pedestrians per hour, with the conversion being the same as for vehicle volumes (see *Section 3.5: Vehicle Volumes*). Similar to vehicle volumes, this metric can be used to identify detectors that are not working properly by comparing pedestrian counts to historical values. As pedestrian detection improves, it is likely that additional metrics will become available that will allow for enhanced pedestrian metrics (e.g., utilization of crossing time, compliance with signal indications).

DETECTION NEEDS

Special detectors are needed that can identify pedestrian presence. These are not yet commonly used in practice but are available.

CALIBRATION

N/A

REFERENCES

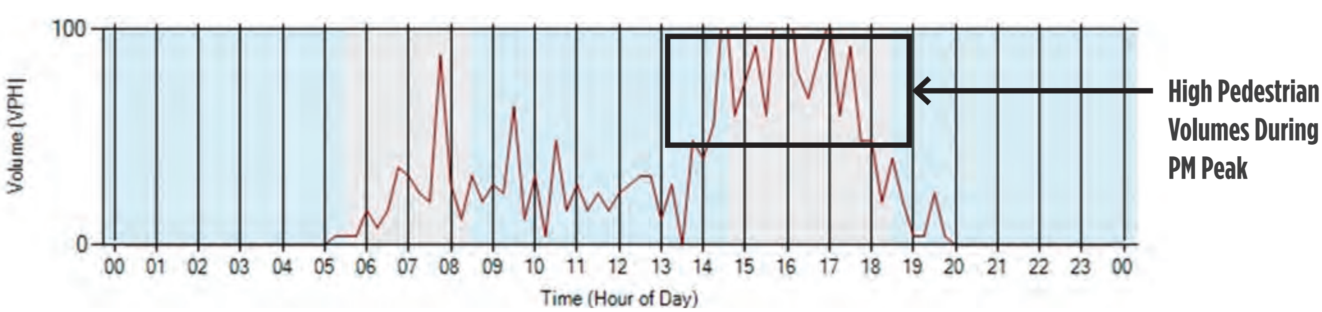
- UDOT

EXAMPLE USE

What is the pedestrian demand during different times of day?

EXHIBIT 3-19 shows pedestrian volumes collected on a trail near a signalized intersection in Ogden, Utah. The data shows the distribution of pedestrian activity throughout the day, which illustrates the high number of pedestrians using the trail during the PM peak period.

EXHIBIT 3-19. PEDESTRIAN VOLUMES EXAMPLE: PEDESTRIAN COUNT DATA FROM A TRAIL LOCATION (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



3.13 PEDESTRIAN PHASE ACTUATION AND SERVICE

CATEGORY

1. Communication
2. Detection
3. Intersection/ Uncoordinated Timing
4. System/Coordinated Timing
5. Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

APPLICATIONS

- Identify intersections with high frequencies of pedestrian phase service.
- Identify detection equipment that is malfunctioning.

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

DESIGN AND CONSTRUCTION

OPERATIONS

MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC

CONTROLLER HIGH-RESOLUTION

AVI/AVL/SEGMENT SPEED

CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Pedestrian actuations can serve as a proxy for pedestrian volumes at intersections without pedestrian-specific detection. At locations with low pedestrian actuations, a practitioner may decide to program vehicle splits that are less than the time required to serve the pedestrian clearance intervals (if allowed by the controller). While at locations with high pedestrian actuations, a practitioner may consider prioritizing pedestrians through features or modes such as Rest in Walk, leading pedestrian intervals (LPIs), or exclusive pedestrian phases.

The level of detail examined can vary from microscopic to macroscopic:

- At the microscopic level, individual button pushes can be measured or, alternatively, the earliest time in the cycle that a call for the pedestrian phase was received.
- At the macroscopic level, the rate of pedestrian phase service can be aggregated over various time periods (e.g., hours, days).

If a pedestrian phase is timing every cycle even during periods with low pedestrian volumes, it may be indicative of a faulty detector or a mis-programmed pedestrian recall.

DETECTION NEEDS

Pedestrian push buttons are required. Locations without pedestrian detection will be using pedestrian recall or omitting pedestrian phases.

CALIBRATION

N/A

REFERENCES

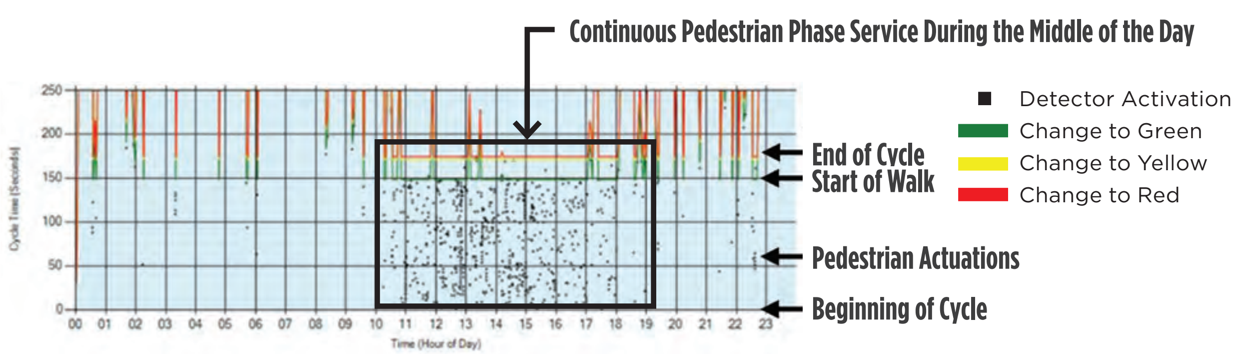
- Day et al. (2008)
- Day, Premachandra, and Bullock (2011)
- Day et al. (2014)
- Day, Taylor et al. (2016)

EXAMPLE USE 1

What times of day have high pedestrian actuations (and resulting pedestrian phase service)?

EXHIBIT 3-20 shows pedestrian actuations relative to "time in cycle" for an intersection in Las Vegas, Nevada. The concept is similar to the Purdue Coordination Diagram (see *Section 3.20: Purdue Coordination Diagram*) except that the pedestrian phase times are shown rather than vehicle phase times and the dots represent actuations of the pedestrian push button. In this case, the chart is for a pedestrian crossing near the "Welcome to Fabulous Las Vegas" sign on Las Vegas Boulevard. The graph reveals that the busiest time for the attraction was between 10:00 AM and 6:00 PM.

EXHIBIT 3-20. PEDESTRIAN PHASE ACTUATION AND SERVICE EXAMPLE: PEDESTRIAN PUSH BUTTON ACTUATIONS RELATIVE TO WALK TIMES (DAY, TAYLOR ET AL. 2016)

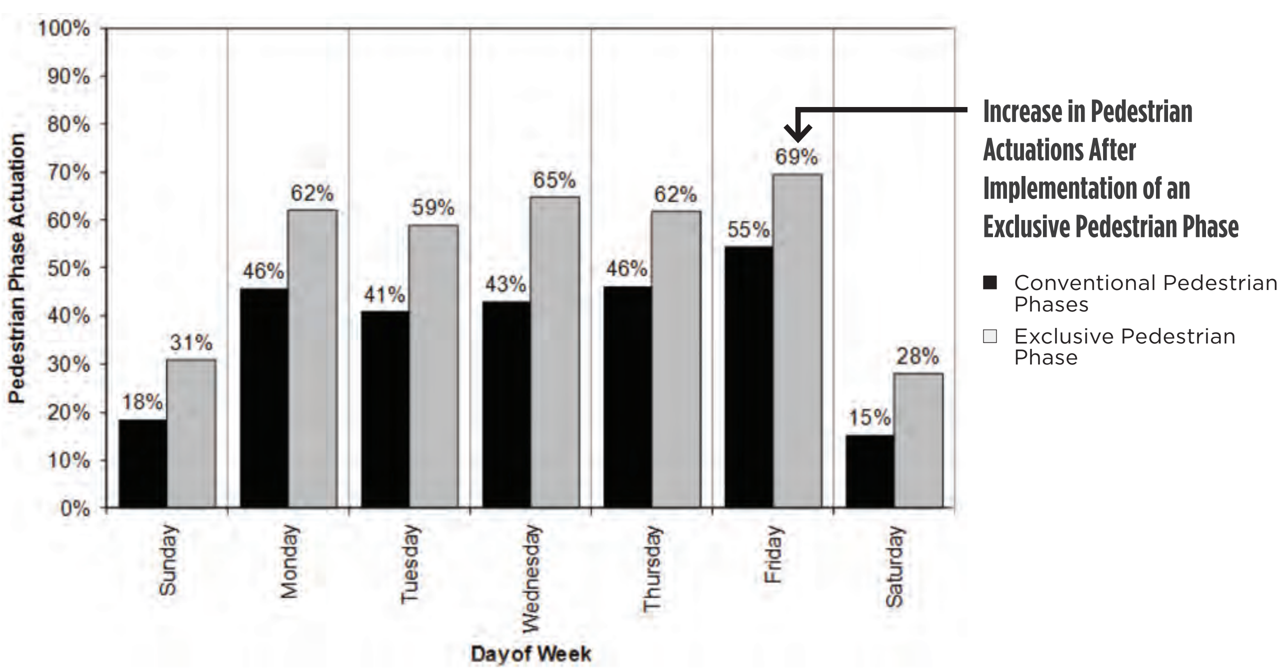


EXAMPLE USE 2

Will an exclusive pedestrian phase impact how often pedestrians request service (using the pedestrian push button)?

EXHIBIT 3-21 is a chart of pedestrian phase service at a signalized intersection on a college campus under two different control schemes: (1) with conventional pedestrian phasing and (2) after implementation of an exclusive pedestrian phase. An exclusive pedestrian phase was initially considered for this location because many pedestrians were crossing against the signal. Implementation of the exclusive phase led to an increase in pedestrian phase utilization on every day of the week, meaning that pedestrians were more likely to request service (by pushing the button). Although this does not necessarily mean they crossed with the signal, it does mean that they were actuating it more often and, consequently, receiving more opportunities to cross safely.

EXHIBIT 3-21. PEDESTRIAN PHASE ACTUATION AND SERVICE EXAMPLE: PERCENTAGE OF CYCLES WITH PEDESTRIAN PHASES BEFORE AND AFTER IMPLEMENTATION OF AN EXCLUSIVE PEDESTRIAN PHASE (DAY, PREMACHANDRA, AND BULLOCK 2011)

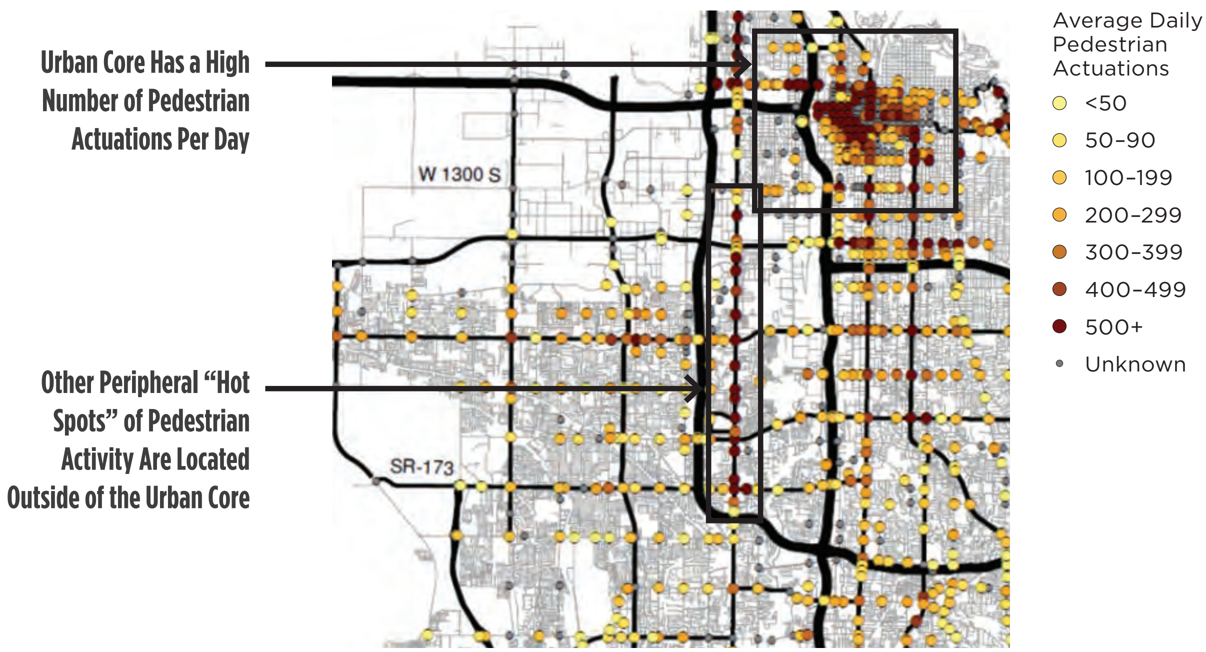


EXAMPLE USE 3

Which locations (i.e., signalized intersections and corridors) have high rates of pedestrian activity?

EXHIBIT 3-22 illustrates pedestrian actuations per day at signalized intersections in the Salt Lake City area. The total number of actuations is represented using a color scale, which can be used to identify "hot spots" of pedestrian activity. Although it is intuitive that the urban core has a high number of pedestrian actuations, there are some individual intersections and corridors in more peripheral areas that also exhibit high rates of pedestrian activity.

EXHIBIT 3-22. PEDESTRIAN PHASE ACTUATION AND SERVICE EXAMPLE: NUMBER OF PEDESTRIAN CALLS PER DAY BY INTERSECTION IN THE SALT LAKE CITY AREA (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



3.14 ESTIMATED PEDESTRIAN DELAY

CATEGORY

1 Communication

2 Detection

3 Intersection/Uncoordinated Timing

4 System/Coordinated Timing

5 Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

APPLICATIONS

- **Identify phases/intersections with high pedestrian delay.**

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

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OPERATIONS

MAINTENANCE

DATA SOURCES

CONTROLLER HIGH-RESOLUTION

VENDOR-SPECIFIC

AVI/AVL/SEGMENT SPEED

CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

If there are certain times of day or certain intersections with high levels of pedestrian delay, an agency can consider implementing measures that prioritize pedestrians. These can include pedestrian-specific treatments such as Rest in Walk, leading pedestrian intervals (LPIs), or exclusive pedestrian phases, but signal timing adjustments may be required beyond pedestrian phasing and clearance settings. A long pedestrian delay may be the result of long cycle lengths, long split times on conflicting phases, or phase order. Planners may also be interested in pedestrian delay, particularly for comparison to vehicle and bicycle delay.

This metric reports the time per cycle between the earliest call for a pedestrian phase (from a button push) until the beginning of the next Walk interval.

(Pedestrian Delay) = (Start of Walk Interval Time) – (First Button Push Time)

Although the metric does not necessarily reflect the actual time at which the pedestrian executed the crossing movement, it does reveal the amount of time elapsed between the request and when the controller provided the requested pedestrian interval. In the future, passive pedestrian detection might be used to better estimate delay.

DETECTION NEEDS

Pedestrian push buttons are required. Locations without pedestrian detection will be using pedestrian recall or omitting pedestrian phases.

CALIBRATION

N/A

REFERENCES

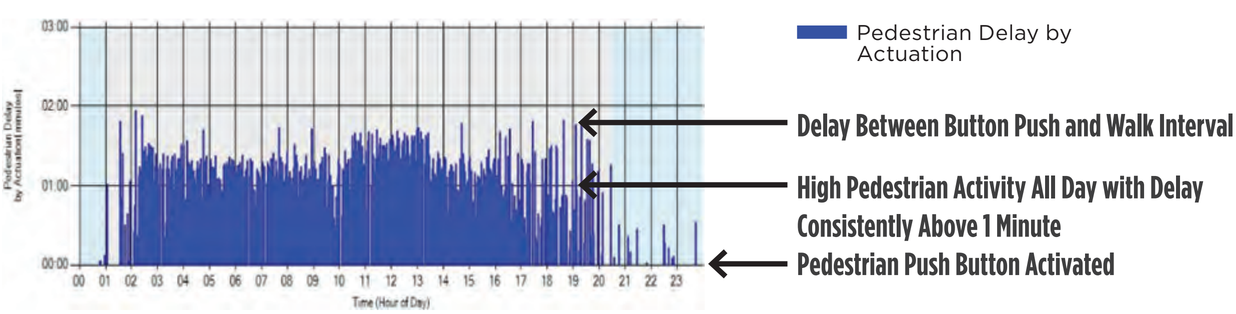
- Hubbard, Bullock, and Day (2008)

EXAMPLE USE 1

Are there times of day when pedestrians are experiencing long delays?

EXHIBIT 3-23 shows pedestrian actuations and delays for a signalized intersection on the edge of the Texas A&M campus in College Station, Texas. The chart shows a high rate of pedestrian demand from 7:00 AM through 12:00 AM. Such information can be used to demonstrate the need for potential engineering treatments such as changing left turns to protected-only, adding "No Turn on Red" signs, or implementing exclusive pedestrian phases.

EXHIBIT 3-23. PEDESTRIAN DELAY EXAMPLE: PEDESTRIAN DELAY FOR A SIGNALIZED INTERSECTION WITH A HIGH NUMBER OF PEDESTRIAN CALLS (COURTESY COLLEGE STATION, TEXAS)



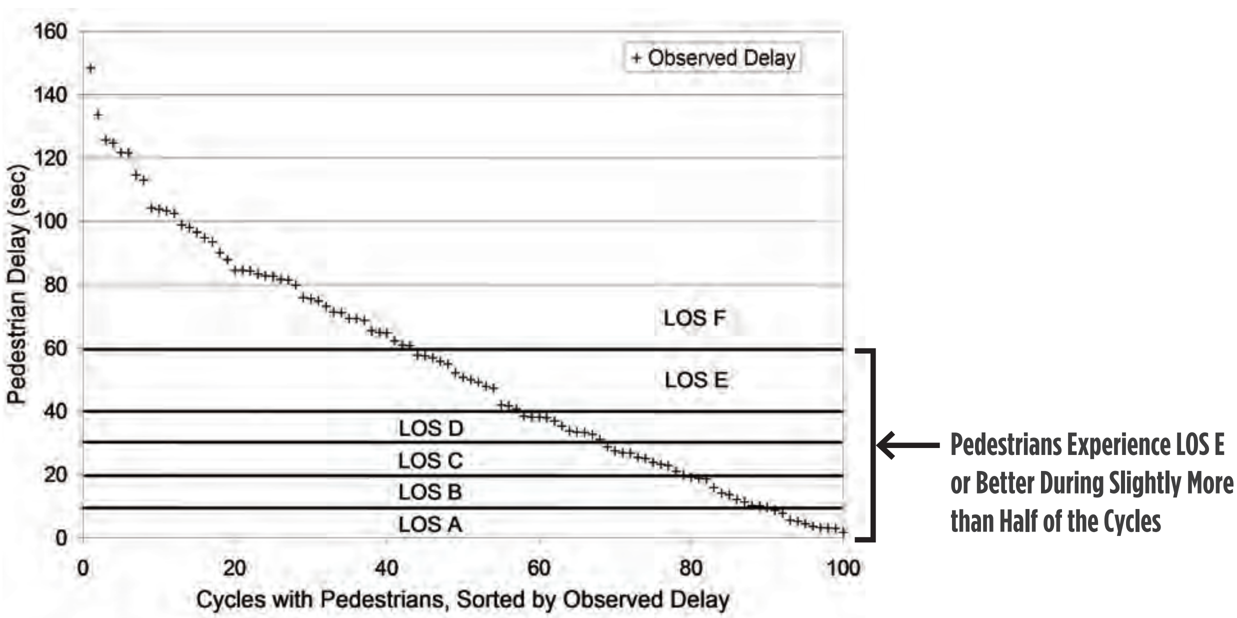
Note: Times are displayed in GMT; therefore, 2:00 AM is 7:00 AM (Central Time) and 7:00 PM is 12:00 AM.

EXAMPLE USE 2

What level of service do pedestrians experience at a signalized intersection?

EXHIBIT 3-24 is a chart of pedestrian delay at a fully actuated, non-coordinated traffic signal. The delay values have been sorted from largest to smallest and then categorized by *Highway Capacity Manual* (HCM) level of service (LOS) values. The wide range of cycle lengths at the fully actuated signal led to a wide range of pedestrian delay values (some in excess of 2 minutes). Slightly more than half of the cycles had LOS E or better (60 seconds of delay or less).

EXHIBIT 3-24. PEDESTRIAN DELAY EXAMPLE: PEDESTRIAN DELAY AT A FULLY ACTUATED, NON-COORDINATED SIGNAL (HUBBARD, BULLOCK, AND DAY 2008)



3.15 ESTIMATED PEDESTRIAN CONFLICTS

CATEGORY

1 Communication
2 Detection
3 Intersection/Uncoordinated Timing
4 System/Coordinated Timing
5 Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- Identify intersections with a high number of potential conflicts between vehicles and pedestrians.

STAKEHOLDERS

ORGANIZATIONAL
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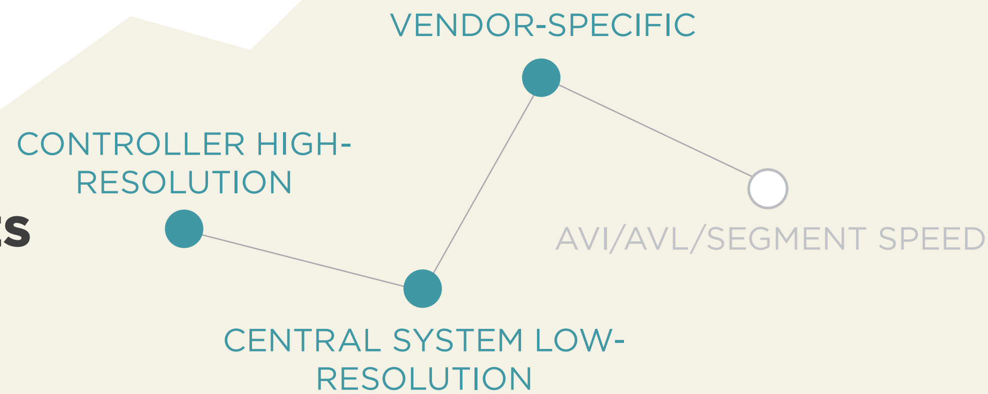
DATA SOURCES



DESCRIPTION

Pedestrians typically cross at the same time vehicles are turning, commonly including both permitted left-turn and right-turn movements. This metric reports the amount of conflicting volume, which serves as an estimate for the degree of "pressure" potentially placed on the pedestrians by the vehicles passing through the same space. The higher the number, the greater the potential for conflicts. For pedestrian crossings with a high number of potential conflicts, pedestrian-specific treatments such as Rest in Walk, leading pedestrian intervals (LPIs), or exclusive pedestrian phases may increase pedestrian safety and comfort. Alternatively, vehicle movements can be restricted by changing left turns to protected-only or adding "No Turn on Red" signs.

DETECTION NEEDS

Detectors past the stop bar are required for accurate identification of turning vehicles that conflict with the pedestrian crossings. These detection zones should be small (and lane-by-lane if possible) so they can accurately capture individual vehicles. It is also useful, though not required, to have pedestrian detection so that cycles with pedestrians present can be identified.

CALIBRATION

N/A

REFERENCES

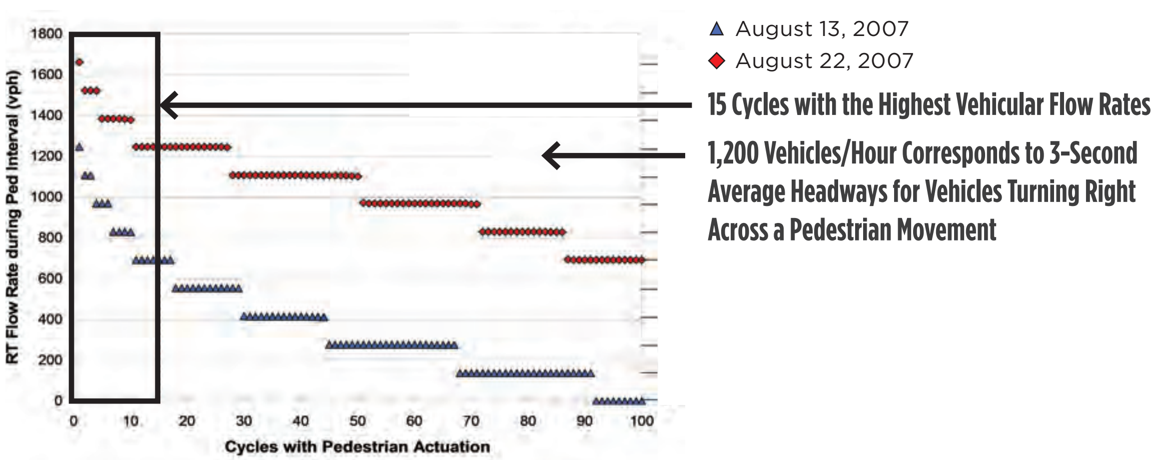
- Hubbard, Bullock, and Day (2008)

EXAMPLE USE

What are the highest conflicting vehicular flow rates across pedestrian crossings?

EXHIBIT 3-25 compares right-turn vehicular flow rates during cycles with pedestrian activity for 2 different days on a college campus. August 13, 2007 (blue) was 1 week prior to the start of classes, and August 22, 2007 (red) was during the first week of classes. The data series are sorted from largest to smallest flow rate. The increase in right-turn volume after classes began is evident with more cycles having higher flow rates, particularly the 15 cycles with the highest rates of the day. It is not uncommon to have pedestrian intervals with conflicting volumes of 1,200 vehicles/hour, which corresponds to an average headway of 3 seconds between vehicles. This particular conflict grew severe enough that an exclusive pedestrian phase was eventually implemented.

EXHIBIT 3-25. PEDESTRIAN CONFLICTS EXAMPLE: RIGHT-TURN VEHICULAR FLOW RATES DURING CYCLES WITH PEDESTRIAN ACTUATIONS (HUBBARD, BULLOCK, AND DAY 2008)



3.16 YELLOW/RED ACTUATIONS

Communication

Detection

Intersection/ Uncoordinated Timing

System/Coordinated Timing

Advanced Systems and Applications

1 2 3 4 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

APPLICATIONS

- **Identify intersections with high numbers of red-light-running vehicles and/or severe violations.**

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DATA SOURCES

VENDOR-SPECIFIC

CONTROLLER HIGH-RESOLUTION

AVI/AVL/SEGMENT SPEED

CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Red light running is a safety concern. If vehicles are frequently running the red light, an agency should consider countermeasures that will reduce the likelihood of vehicles entering the intersection on red.

This metric reports actuations (on detectors located either at or past the stop bar) relative to the phase state: yellow, red clearance, or red (after the beginning of the next phase). The actuation times can be used to estimate the number of vehicles running the red light and the amount of time into the red that the events occurred, with the most severe being those that happen after the start of green and start-up lost time for the next phase. A large amount of violations is an indicator that the intersection may benefit from a safety evaluation. There are several potential causes that can be investigated:

- Green may be too short, causing drivers to push into yellow/red. Split adjustments might be needed.
- Coordination may be poor. A large number of arrivals on red or truncation of a platoon by the end of green may be an issue.
- Detection locations and settings may result in vehicles getting caught in the decision zone (having to decide whether to stop or go). Adjusting the detection zones and passage settings can reduce the number of drivers having to make the go/no-go decision.
- Sight distance may be poor; some drivers might not be able to see the indication due to obstructions.
- Law enforcement may be needed. If deployed, this metric can help identify specific times of day for additional enforcement, as well as provide a means to evaluate impacts.

Note that some of the above items can be investigated using other performance measures, including a review of vehicle delay and progression quality (see *Section 3.9: Estimated Vehicle Delay* and *3.19: Progression Quality*). Other items may require a field visit, such as sight distance issues.

DETECTION NEEDS

Detectors at or past the stop bar are required for accurate identification of vehicles entering the intersection on yellow and/or red. These detection zones should be small, so they can accurately capture individual vehicles. Some detection technologies allow actuations to only be recorded if vehicles are traveling over a specified speed. This is beneficial for detection located at the stop bar because slow-moving vehicles coming to a stop can be omitted.

CALIBRATION

N/A

REFERENCES

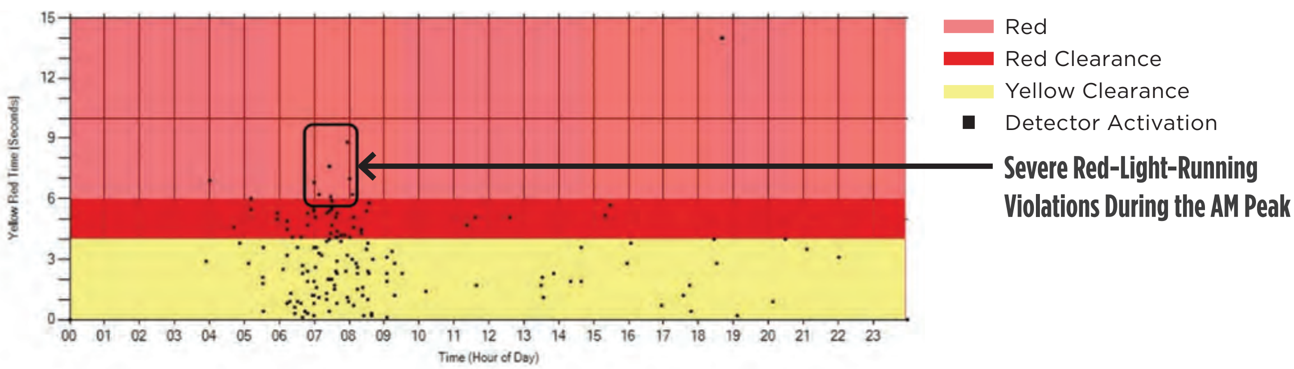
- Mackey (2017)
- Taylor (2016)
- UDOT

EXAMPLE USE

Are there times of day with high numbers of vehicles running the red light?

EXHIBIT 3-26 shows 24 hours of yellow and red actuations for a phase. In this case, there are severe violations in the AM, with vehicles entering the intersection well into the service time for the next phase.

EXHIBIT 3-26. YELLOW/RED ACTUATIONS EXAMPLE: 24-HOUR YELLOW/RED ACTUATIONS (TAYLOR 2016)



3.17 RED-LIGHT-RUNNING (RLR) OCCURRENCES

CATEGORY

1 Communication
2 Detection
3 Intersection/Uncoordinated Timing
4 System/Coordinated Timing
5 Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- Identify intersections with high numbers of red-light-running vehicles and/or severe violations.

STAKEHOLDERS

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MAINTENANCE

DATA SOURCES

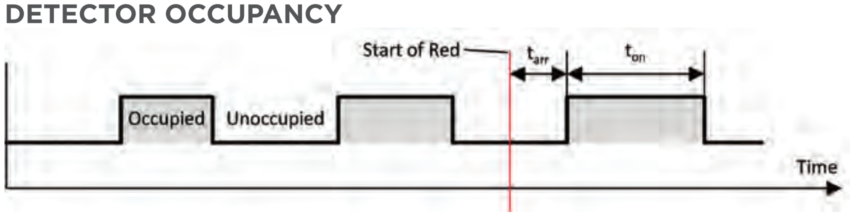
CONTROLLER HIGH-RESOLUTION
CENTRAL SYSTEM LOW-RESOLUTION
VENDOR-SPECIFIC
AVI/AVL/SEGMENT SPEED

DESCRIPTION

Red-light-running (RLR) vehicles can be detected by analyzing stop bar detector occupancy relative to the phase state. Although similar to yellow/red actuations (see *Section 3.16: Yellow/Red Actuations*), this metric uses stop bar presence detection to determine RLR. It logs RLR occurrences when a stop bar detector becomes occupied shortly after the beginning of red and then becomes unoccupied shortly later in the red interval (shown in **EXHIBIT 3-27**).

The arrival of the vehicle (detector "on" time) is marked by t_{arr}, and the duration of the subsequent occupied interval is t_{on}. Long values of t_{on} are more likely to be right turns on red (RTOR) than RLR, while very high values of t_{arr} are likely caused by left-turning vehicles on the cross street clipping the stop bar detection zone. When the number of RLR occurrences is high, it may warrant a safety evaluation at the intersection. Although not all fixes will be related to signal timing (e.g., changes to geometry), the splits, offsets, and detection locations and associated settings can play a role.

EXHIBIT 3-27. RED-LIGHT-RUNNING OCCURRENCE CALCULATION USING STOP BAR DETECTOR OCCUPANCY



DETECTION NEEDS

Requires stop bar presence detection. Lane-by-lane detection provides more accurate results than detectors tied together across lanes; multi-lane detectors may over-estimate occupancy ratios.

CALIBRATION

RLR occurrences are determined based on maximum values of t_{arr} and t_{on} (to avoid counting RTOR and left-turn clipping). A field study found values of t_{on} = 2.0 seconds and t_{arr} = 5.0 seconds to be reasonable, but these will need to be calibrated at other locations.

REFERENCES

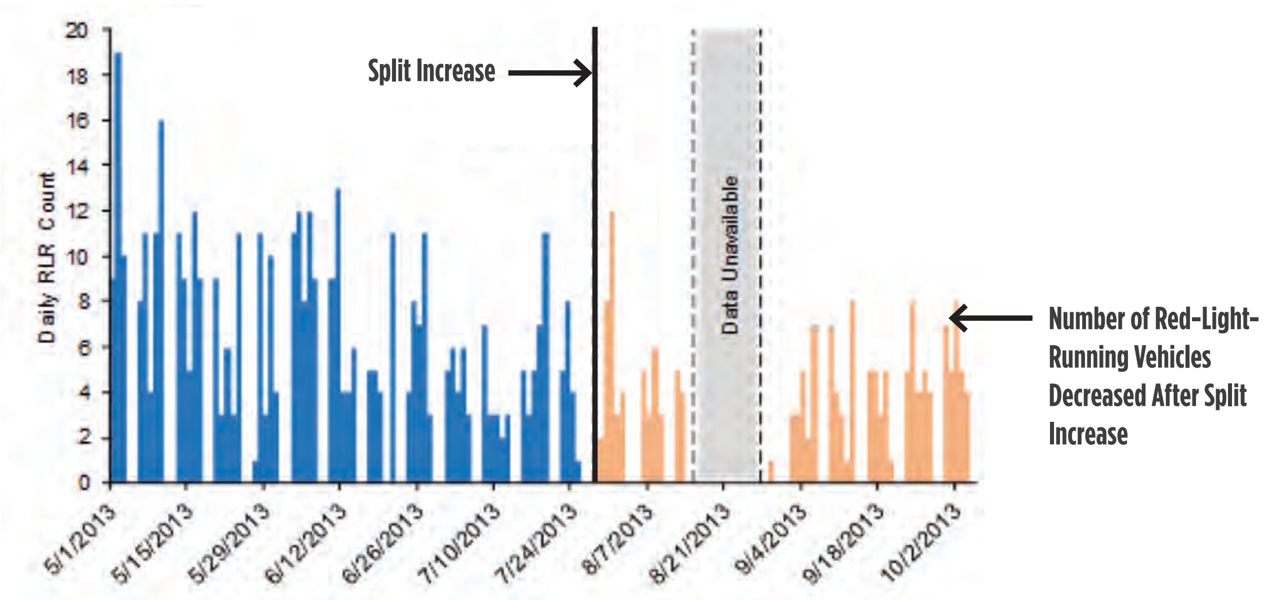
- Lavrenz et al. (2016)

EXAMPLE USE

Did a split increase result in a reduced number of red-light-running vehicles?

EXHIBIT 3-28 shows RLR as a daily count for a single phase over a 5-month period. Halfway through the study period, the split was increased, which correlates to a decrease in the number of RLR vehicles.

EXHIBIT 3-28. RED-LIGHT-RUNNING (RLR) OCCURRENCES EXAMPLE: COUNT OF RLR BEFORE AND AFTER SPLIT ADJUSTMENT (LAVRENZ ET AL. 2016)



3.18 EFFECTIVE CYCLE LENGTH

CATEGORY

1 Communication
2 Detection
3 Intersection/ Uncoordinated Timing
4 System/Coordinated Timing
5 Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- **Confirm coordinated plans are operating as intended.**
- **Confirm how adaptive systems are adjusting effective cycle lengths.**

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
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OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Effective cycle length is the amount of time used to serve all the phases at an intersection. Each phase will usually have an opportunity for service within a cycle, unless it is skipped (or omitted) by the signal controller. Effective cycle length can be measured at most intersections using one of the following:

- Comparing subsequent times of "barrier crossings" (e.g., between Phases 1, 2, 5, and 6 and Phases 3, 4, 7, and 8 in conventional eight-phase control).
- Comparing subsequent ends of green for coordinated phases, if termination of those phases is needed to serve conflicting movements.

In cases with complex phasing structures, site-specific definitions of cycle length might be needed.

Note that times between subsequent yield points or other repeating coordinated times offer a way to measure the *background* cycle length. However, the *effective* cycle length (influenced by actuations) would be unknown. In addition, those coordinated points are unavailable during free operations.

Effective cycle length can be used to confirm coordinated plans are operating as intended and is also useful for advanced applications. For example, it can be used to assess how often and by how much an adaptive system is changing the cycle length.

DETECTION NEEDS

Although high-resolution data from the controller can report this metric directly (without programming detection settings), it will be most meaningful at actuated intersections. Without detection, cycle lengths will remain constant.

CALIBRATION

The analyst must in some cases select an appropriate method for measuring cycle length.

REFERENCES

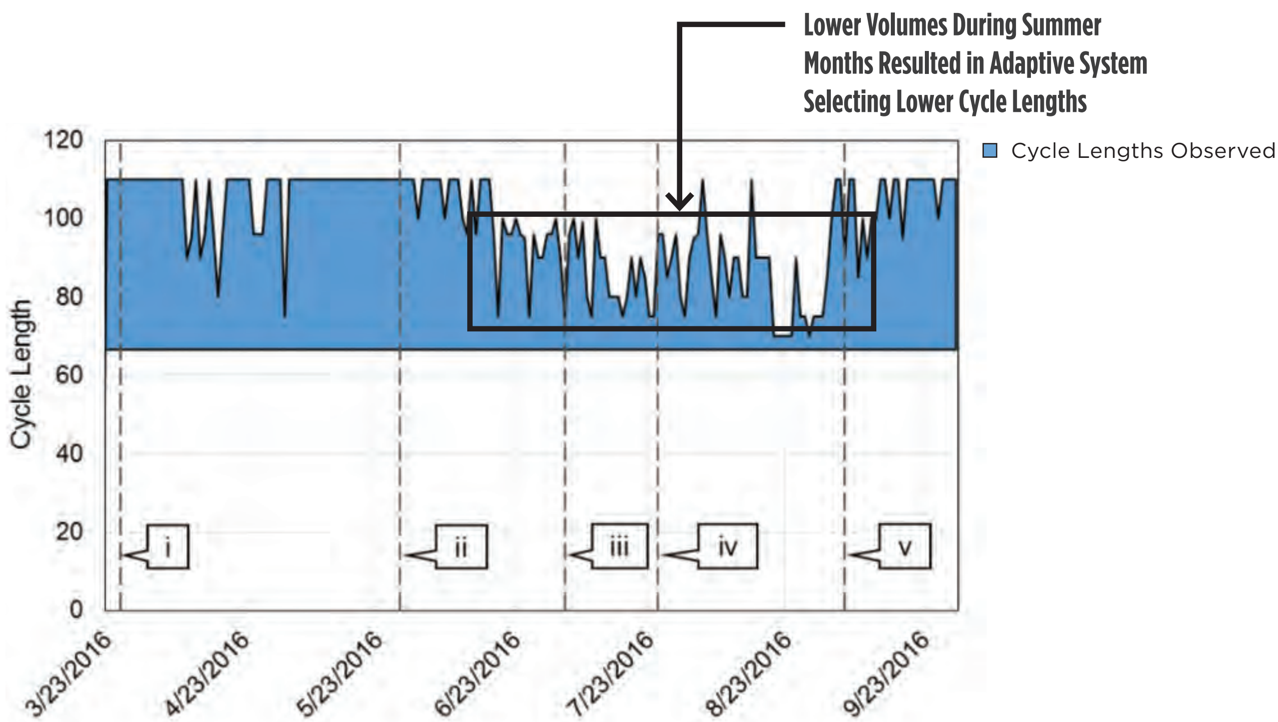
- Day et al. (2008)
- Richardson et al. (2017)

EXAMPLE USE

What are the seasonal impacts on effective cycle length for a corridor utilizing an adaptive system?

EXHIBIT 3-29 shows cycle lengths over several months for a corridor in Utah that uses an adaptive cycle length algorithm. The chart demonstrates the seasonal variation in cycle lengths due to seasonal changes in traffic volumes. During much of April and May, the maximum cycle length of 110 seconds was reached almost every day. However, in July and August, there were many days when the cycle length did not climb much higher than its minimum value. In September, the cycle lengths began to increase again.

EXHIBIT 3-29. EFFECTIVE CYCLE LENGTH EXAMPLE: EFFECTIVE CYCLE LENGTHS USING AN ADAPTIVE SYSTEM DURING A 6-MONTH PERIOD (RICHARDSON ET AL. 2017)



3.19 PROGRESSION QUALITY

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

CATEGORY

1 Communication

2 Detection

3 Intersection/ Uncoordinated Timing

4 System/Coordinated Timing

5 Advanced Systems and Applications

APPLICATIONS

- **Identify intersections/corridors with poor progression (i.e., low POG, platoon ratios, or arrival types).**

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

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OPERATIONS

MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC

CONTROLLER HIGH-RESOLUTION

AVI/AVL/SEGMENT SPEED

CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

A common reason for coordinating signalized intersections is progressing traffic platoons to reduce stops, delay, and travel time along a particular route. There are several ways to report progression quality: percent on green (POG), platoon ratio, and arrival type.

Percent on green. Reports the number of vehicles that arrive on green. An advance detector is required to compute this metric. Each vehicle actuation is associated with a time of arrival at the intersection, which is then compared to the signal state (red or green).

(Percent on Green) = (Arrivals on Green) ÷ (Total Arrivals)

Platoon ratio. A modification of POG that accounts for long green times as follows:

(Platoon Ratio) = (POG) ÷ (g/C)

where

g/C = "Green-to-cycle length" ratio. This value is computed by dividing the green time, g, by the effective cycle length, C, of the cycle in which the green interval occurred.

"Arrival type." A *Highway Capacity Manual* (HCM) metric that divides platoon ratios into a score of 1–6, with 1 representing poor progression and 6 representing excellent progression. **EXHIBIT 3-30** explains how to convert a platoon ratio into an arrival type.

Each of these metrics can be used to assess progression quality either at an intersection or along a corridor. The more vehicles arriving on green, the better the progression quality.

EXHIBIT 3-30. RELATIONSHIP BETWEEN PLATOON RATIO AND ARRIVAL TYPE (HCM 6TH EDITION)

METRIC	VALUE	PROGRESSION QUALITY
0.33	1	Very poor
0.67	2	Unfavorable
1.00	3	Random arrivals
1.33	4	Favorable
1.67	5	Highly favorable
2.00	6	Exceptionally favorable

DETECTION NEEDS

Advance detection upstream of a signalized approach is used to estimate vehicle arrivals at the stop bar. Detectors located at the beginning of the decision zone (approximately 5 seconds of travel time from the stop bar) are often available, but detectors used for this metric should be placed to avoid queuing over the advance detector.

CALIBRATION

An adjustment is made to the vehicle detection times to estimate the time each vehicle arrives at the stop bar. This can be done by adding the travel time to the detection time. For example, if the detector is positioned 5 seconds upstream of the stop bar, 5 seconds would be added to the reported actuation times.

The actual red and green intervals at the intersection would typically be converted into "effective red" and "effective green" times. This is discussed in more detail in *Section 3.8: Split Failures*.

REFERENCES

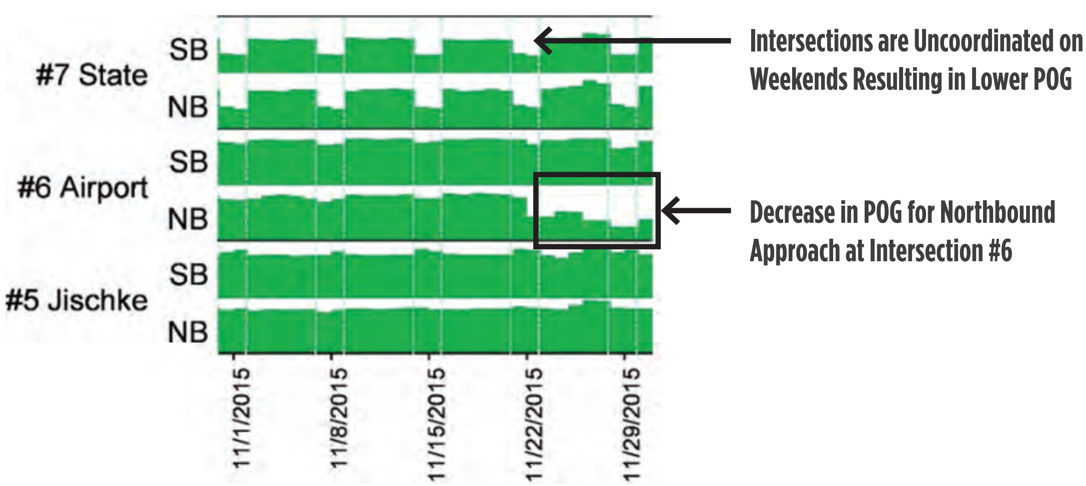
- Day et al. (2008)
- Day and Bullock (2010)
- Day et al. (2014)
- Day, Bullock et al. (2016)
- Mackey (2017)
- Smaglik, Bullock, and Sharma (2007)
- Smaglik, Sharma et al. (2007)

EXAMPLE USE 1

Are any intersections along a corridor experiencing lower progression quality?

EXHIBIT 3-31 is a plot of POG for three intersections along a corridor. Each day, the average POG is reported for the period between 6:00 AM and 10:00 PM. Weekend values tend to be lower than weekday values because the corridor is only coordinated on weekdays. This chart can be used to identify changes in progression quality. In this example, the northbound approach at Intersection #6 Airport experiences a sudden decrease in POG in late November. This indicates an offset adjustment should be investigated. This change may be the result of a permanent change in traffic patterns or a temporary condition such as construction.

EXHIBIT 3-31. PROGRESSION QUALITY EXAMPLE: PERCENT ON GREEN (POG) OVER A 1-MONTH PERIOD (DAY, BULLOCK ET AL. 2016)

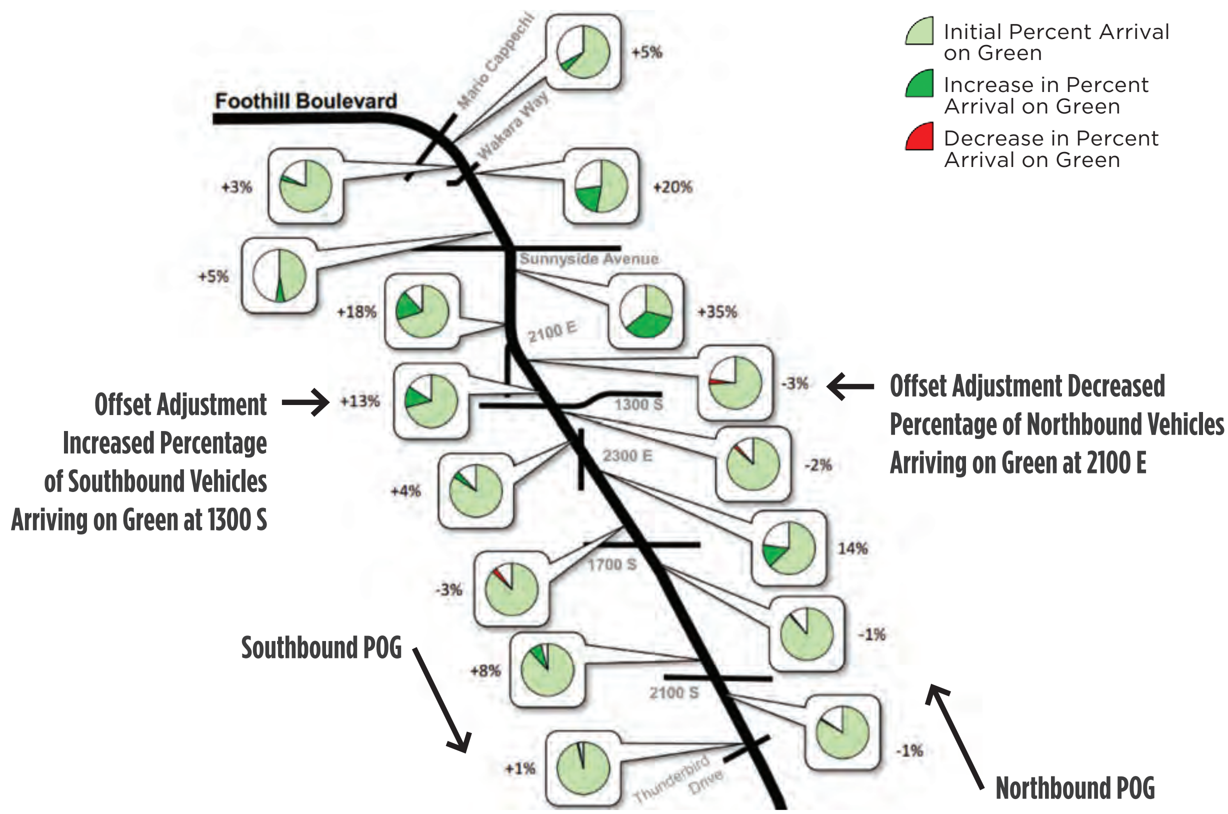


EXAMPLE USE 2

Did offset adjustments increase or decrease progression quality along a corridor?

EXHIBIT 3-32 summarizes POG before and after offset adjustments on a corridor in Utah. Each pie chart shows the existing POG as a light green series; the dark green series represents any increases in POG that occurred on each approach, and the red series represents decreases. Ideally, the change would yield mostly increases, which is the case in this situation. There are five approaches with increases in POG above 10%. Five approaches experienced POG decreases, but the decreases were between 1–3%.

EXHIBIT 3-32. PROGRESSION QUALITY EXAMPLE: OFFSET ADJUSTMENT IMPACT ON PERCENT ON GREEN (POG) (MACKEY 2017)



3.20 PURDUE COORDINATION DIAGRAM

CATEGORY

1 Communication

2 Detection

3 Intersection/ Uncoordinated Timing

4 System/Coordinated Timing

5 Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

APPLICATIONS

- **Identify when vehicles are arriving during the cycle (i.e., on green or red) for a particular phase or overlap at an intersection.**

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

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OPERATIONS

MAINTENANCE

DATA SOURCES

CONTROLLER HIGH-RESOLUTION

CENTRAL SYSTEM LOW-RESOLUTION

VENDOR-SPECIFIC

AVI/AVL/SEGMENT SPEED

DESCRIPTION

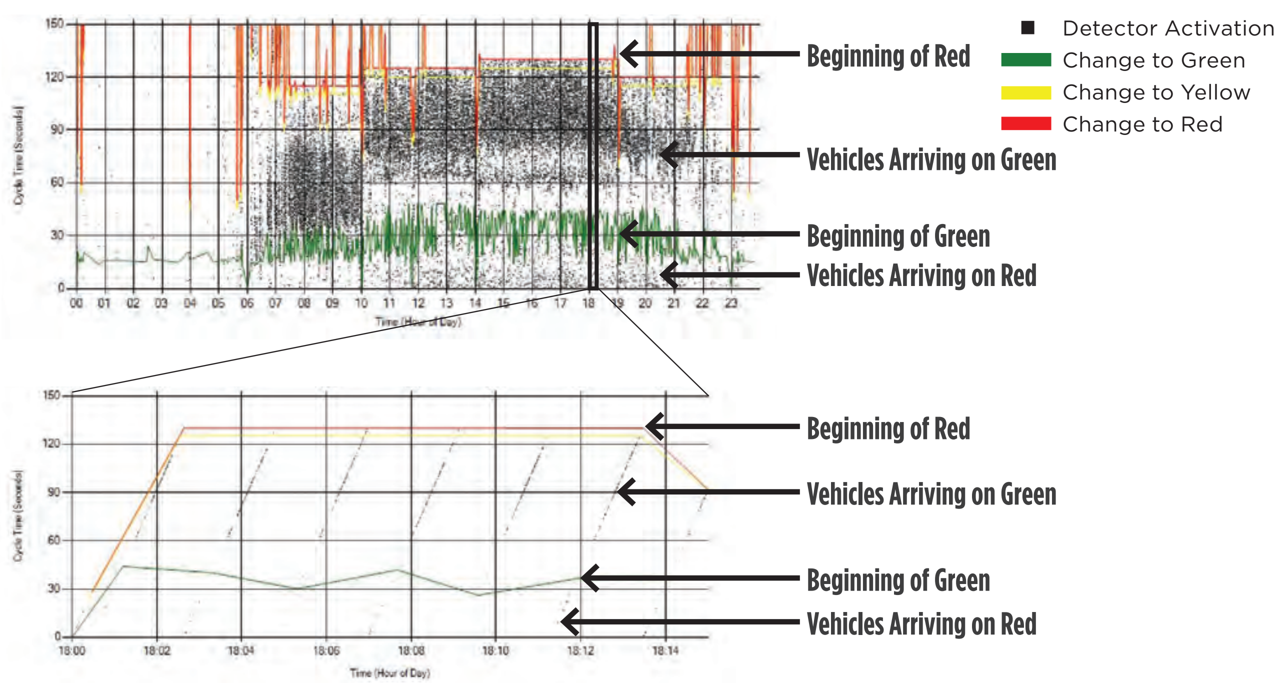
While similar to Progression Quality metrics (see *Section 3.19: Progression Quality*), the Purdue Coordination Diagram (PCD) provides additional detail on vehicle arrivals during the cycle (e.g., near the beginning of the cycle or end of the cycle). Percent on green, platoon ratio, and arrival type can help identify locations that would benefit from coordination adjustments (i.e., to cycle lengths, splits, offsets, and phase order), and the PCD can help identify the values that should be chosen for those adjustments. Additionally, the PCD can be used to monitor general intersection operations. Because the basis for the diagram is time in cycle, it can be useful for monitoring advanced applications such as traffic responsive or adaptive control.

The PCD is a graphical representation of individual vehicle arrivals at the stop bar relative to the signal state (green, yellow, or red), as illustrated in **EXHIBIT 3-33**. Each diagram depicts vehicle arrivals for one phase (or overlap) at one signalized intersection. They are most often used to depict multiple cycles (e.g., over 24 hours or several days), but can also be used to display data for a single cycle. For example, the top half of **EXHIBIT 3-33** shows a full day of data, while the bottom half of **EXHIBIT 3-33** shows a zoomed view of seven cycles that occurred over a 15-minute period on that same day.

The basic components of the PCD are three data series: (1) the beginning of green in each cycle, (2) the end of green in each cycle, and (3) the vehicle arrival times. Additional information can be overlaid such as pattern changes, approach volumes, the yellow interval, and percent arrivals on green.

The time in cycle is the basis for each individual piece of data displayed in the chart. In the PCD, this is calculated as the time since the previous beginning of red time. When the cycle length is reached (at the beginning of red), a new cycle begins at 0 (zero) seconds. A constant cycle length is not required to display the PCD. For example, **EXHIBIT 3-33** displays a fully actuated period during the middle of the night when no programmed cycle length is in effect.

EXHIBIT 3-33. PURDUE COORDINATION DIAGRAM EXPLANATION (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



DETECTION NEEDS

Advance detection upstream of a signalized approach is used to estimate vehicle arrivals at the stop bar. Detectors located at the beginning of the decision zone (approximately 5 seconds of travel time from the stop bar) are often available, but detectors used for this metric should be placed to avoid queuing over the advance detector.

CALIBRATION

An adjustment is made to the vehicle detection times to estimate the time each vehicle arrives at the stop bar. This can be done by adding the travel time to the detection time. For example, if the detector is positioned 5 seconds upstream of the stop bar, 5 seconds would be added to the reported actuation times.

The actual red and green intervals at the intersection would typically be converted into "effective red" and "effective green" times. This is discussed in more detail in *Section 3.8: Split Failures*.

REFERENCES

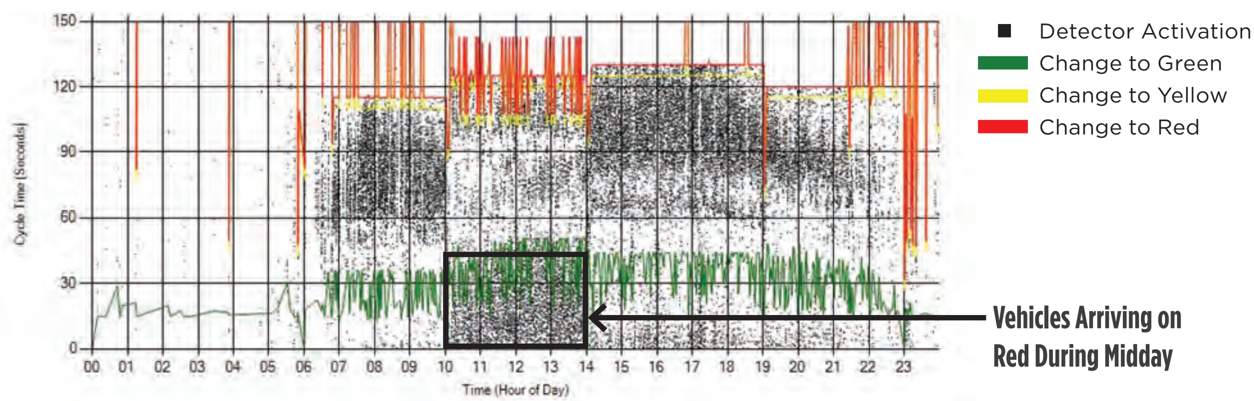
- Brennan et al. (2011)
- Day and Bullock (2009)
- Day and Bullock (2010)
- Day et al. (2010)
- Day et al. (2014)
- Day, Bullock et al. (2016)

EXAMPLE USE

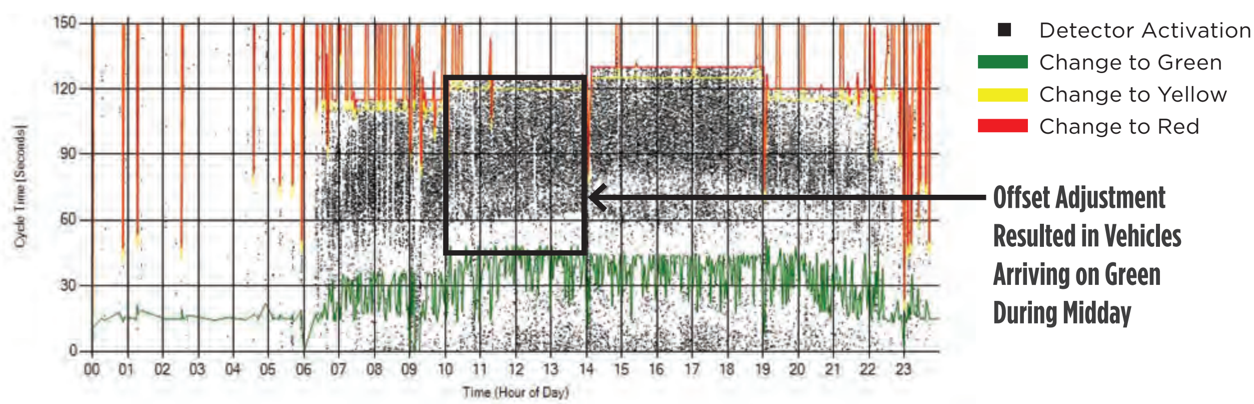
Did offset adjustments improve progression for a particular approach at an intersection?

The Virginia Department of Transportation adjusted offsets along a corridor near Charlottesville, Virginia. **EXHIBIT 3-34A** is a PCD from before the offset adjustments. Southbound vehicle arrivals at this particular intersection were arriving prior to the green interval during the midday timing plan. After the offset adjustments, a higher percentage of vehicles arrived on green, as shown in **EXHIBIT 3-34B**. A PCD chart can be used to validate that a signal timing change improved progression or, alternatively, if an additional adjustment is required.

EXHIBIT 3-34. PURDUE COORDINATION DIAGRAM EXAMPLE: OFFSET ADJUSTMENT (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



(A) Before offset adjustment



(B) After offset adjustment

3.21 CYCLIC FLOW PROFILE

Communication
Detection
Intersection/Uncoordinated Timing
System/Coordinated Timing
Advanced Systems and Applications

1 2 3 **4** 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- Identify intersections/corridors with poor progression.

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
DESIGN AND CONSTRUCTION
OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

This metric reports the distribution of green time and vehicle arrivals during an "average" cycle over some time period. The information is similar to that in the Purdue Coordination Diagram (PCD, *Section 3.20: Purdue Coordination Diagram*) except that it is aggregated over a time period rather than for individual cycles.

One advantage of this metric is being able to examine progression at many intersections at once. Although PCDs can also be used for this purpose, it can become difficult to evaluate the data if too many are presented in a single graphic. Cyclic flow profiles provide an effective summary format for determining if the highest probability of vehicle arrivals aligns with the highest probability of green.

For each cyclic flow profile, the same background cycle length (pattern) should be in effect for the chosen time period. The method of calculation relies on a time in cycle that is different from that used in other metrics. The PCD uses the last beginning of red. However, cyclic flow profiles use the time in the *system* cycle, which is referenced from a master clock zero point. No specific red and green events are used to define the cycle.

During coordination, the system cycle exists in the background of every coordinated controller; the current time in the system cycle is equal to the number of seconds since a reference time (usually midnight), modulo C, where C is the cycle length:

(Time in System Cycle) = (Seconds after Reference Time) mod C

For example, consider the timestamp 09:08:16. If the reference time is 00:00:00 (midnight), and the cycle length is 100 seconds, the time in the system cycle is:

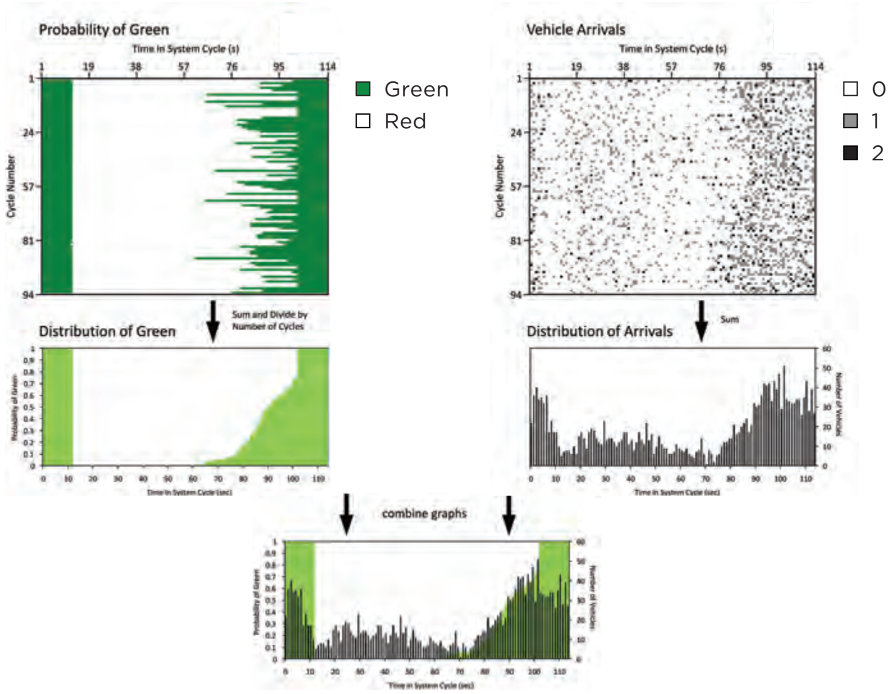
$[(9 \times 3{,}600) + (8 \times 60) + (16)] \bmod 100 = 32{,}896 \bmod 100 = 96$

This time is used to assemble the green and vehicle arrival profiles, as illustrated in **EXHIBIT 3-35**.

- For the probability of green, the state of green should be known for every 1 second interval within the time period. For each second, it is possible to look up the most recent red or green event and use that to deduce whether the signal was red or green. This yields a "matrix" of green status for each cycle in the chosen time period and time within that cycle. The probability of green can be calculated by summing all of the green events for a particular time in the cycle.
- The arrival profile is found similarly. Rather than looking up the status of green, the number of vehicles detected within every 1 second interval is known. The value for the cyclic flow profile is found by summing the number of vehicles detected at a particular time in cycle across all the cycles.

The final flow profile graphic is created by combining the two pieces of information into one chart. One option would be to represent the arrivals as bars on top of the distribution of green, as shown in **EXHIBIT 3-35**.

EXHIBIT 3-35. CYCLIC FLOW PROFILE COMPUTATION EXPLANATION (DAY AND BULLOCK 2011)



DETECTION NEEDS

Advance detection upstream of a signalized approach is used to estimate vehicle arrivals at the stop bar. Detectors located at the beginning of the decision zone (approximately 5 seconds of travel time from the stop bar) are often available, but detectors used for this metric should be placed to avoid queuing over the advance detector.

CALIBRATION

An adjustment is made to the vehicle detection times to estimate the time each vehicle arrives at the stop bar. This can be done by adding the travel time to the detection time. For example, if the detector is positioned 5 seconds upstream of the stop bar, 5 seconds would be added to the reported actuation times. The actual red and green intervals at the intersection would typically be converted into “effective red” and “effective green” times. This is discussed in more detail in *Section 3.8: Split Failures*.

REFERENCES

- Day and Bullock (2010)
- Day and Bullock (2011)
- Day, Brennan, Hainen et al. (2011)
- Day and Bullock (2014)
- Robertson (1969)
- Shelby et al. (2007)

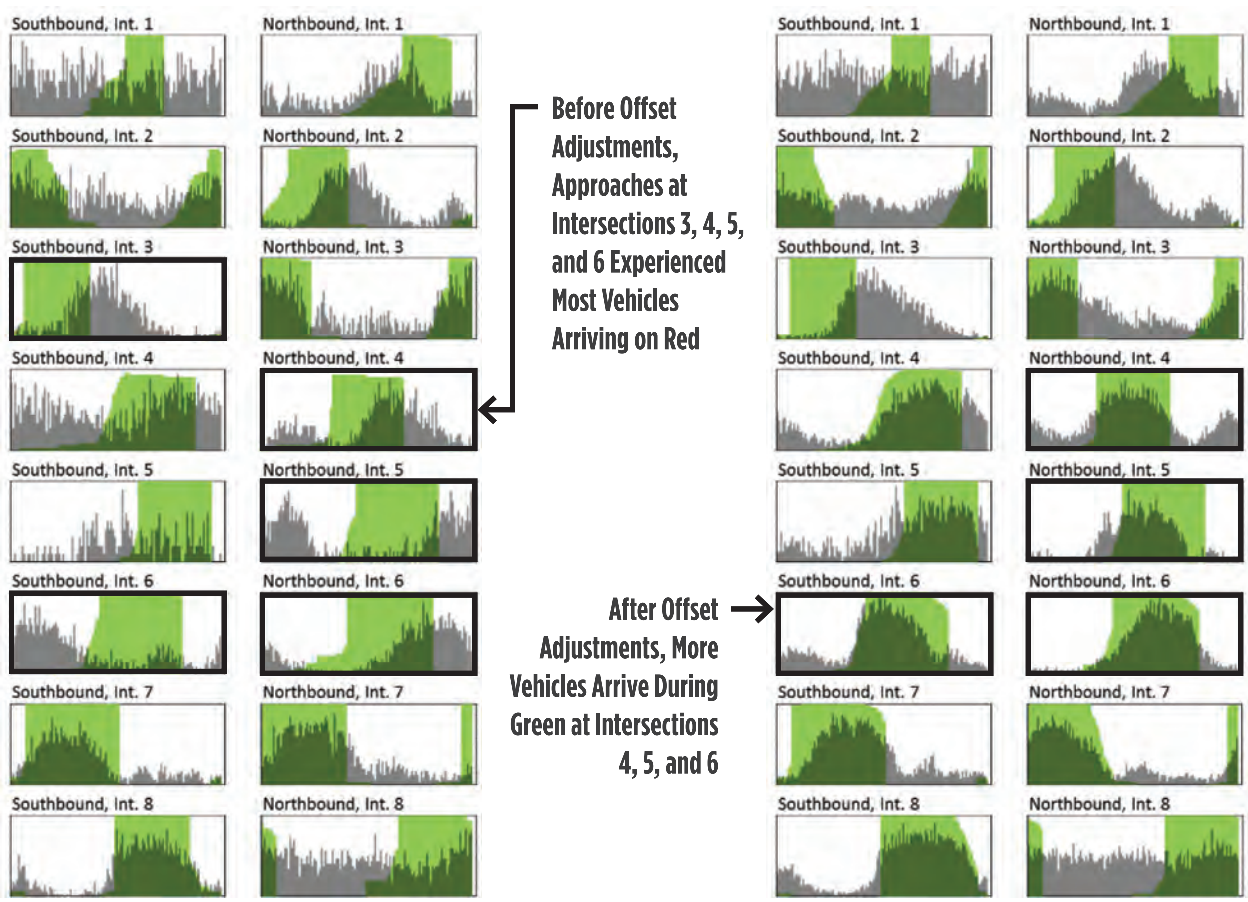
EXAMPLE USE

How much and at which locations did offset adjustments improve progression along a corridor?

EXHIBIT 3-36 shows cyclic flow profiles for an eight-intersection corridor with each intersection having its own flow profile. For simplicity, the axes are removed from the profiles and only the graphics are shown. The sixteen profiles in **EXHIBIT 3-36A** show conditions before changes were made to offsets while those in **EXHIBIT 3-36B** show conditions afterward.

Before offset adjustments, there were several approaches where most of the vehicle arrived during red or too early or too late in the green to be progressed. After offsets were adjusted, platoons at four of the five approaches arrived during the green, indicating improved progression. Progression at the southbound approach at Intersection 3 did not change; however, this is likely because any changes to the offset would have worsened conditions in the opposite direction. It is not always possible to achieve progression at every approach in both directions.

EXHIBIT 3-36. CYCLIC FLOW PROFILE EXAMPLE: CORRIDOR APPLICATION (DAY AND BULLOCK 2011)



(A) Before offset adjustments

(B) After offset adjustments

3.22 OFFSET ADJUSTMENT DIAGRAM

Communication
Detection
Intersection/ Uncoordinated Timing
System/Coordinated Timing
Advanced Systems and Applications

1 2 3 4 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- **Identify corridors with potential for progression improvement from offset adjustments.**
- **Estimate impact of proposed offset adjustments.**

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
DESIGN AND CONSTRUCTION
OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

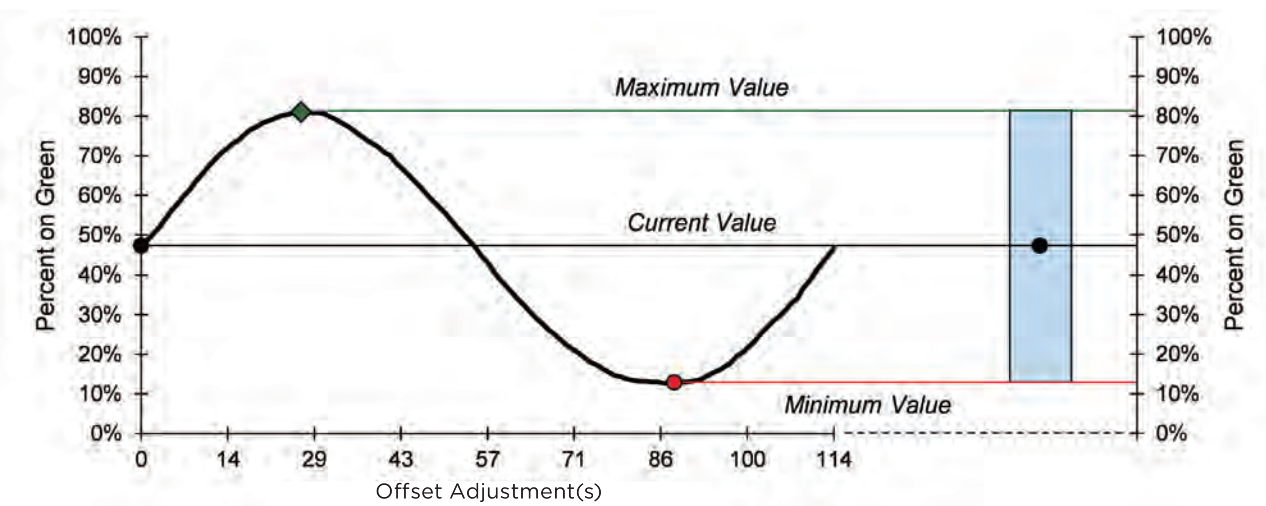
DESCRIPTION

This metric reports *potential* progression quality for individual coordinated approaches along a corridor. If calculated for approaches along several corridors, it can be used to quickly determine locations where an agency will have the greatest return on investment when adjusting offsets.

This metric is based on the Cyclic Flow Profile (*Section 3.21: Cyclic Flow Profile*). Potential progression quality of an individual approach is determined by comparing the green and vehicle arrival distributions. If the cyclic positions are shifted relative to each other by means of an offset adjustment, then the arrivals on green will change. It is possible to assess all the adjustments by shifting one of the distributions through the entire cycle and recording the performance in each case. **EXHIBIT 3-37** illustrates how the resulting sinusoidal offset performance curve can be "flattened" into a bar that describes the minimum and maximum values. The current value is plotted on top of this range. For example, in **EXHIBIT 3-37**, the current percentage of vehicles arriving on green for this approach is 48%, but with certain offset combinations it can potentially be as high as 81% or as low as 12%.

Data for multiple approaches can be combined into a composite plot with columns representing different approaches along a corridor (see example use). It is also possible to add the *predicted* progression quality resulting from a set of trial offset adjustments to such a plot. A simple, effective model for predicting optimal offset adjustments has been described in several previous studies (Day and Bullock 2011; Day and Bullock 2017).

EXHIBIT 3-37. OFFSET ADJUSTMENT DIAGRAM EXPLANATION (DAY AND BULLOCK 2017)



DETECTION NEEDS

Advance detection upstream of a signalized approach is used to estimate vehicle arrivals at the stop bar. Detectors located at the beginning of the decision zone (approximately 5 seconds of travel time from the stop bar) are often available, but detectors used for this metric should be placed to avoid queuing over the advance detector.

CALIBRATION

An adjustment is made to the vehicle detection times to estimate the time each vehicle arrives at the stop bar. This can be done by adding the travel time to the detection time. For example, if the detector is positioned 5 seconds upstream of the stop bar, 5 seconds would be added to the reported detection actuation times.

The actual red and green intervals at the intersection would typically be converted into “effective red” and “effective green” times. This is discussed in more detail in *Section 3.8: Split Failures.*

REFERENCES

- Day and Bullock (2011)
- Day, Bullock et al. (2016)
- Day and Bullock (2017)

EXAMPLE USE

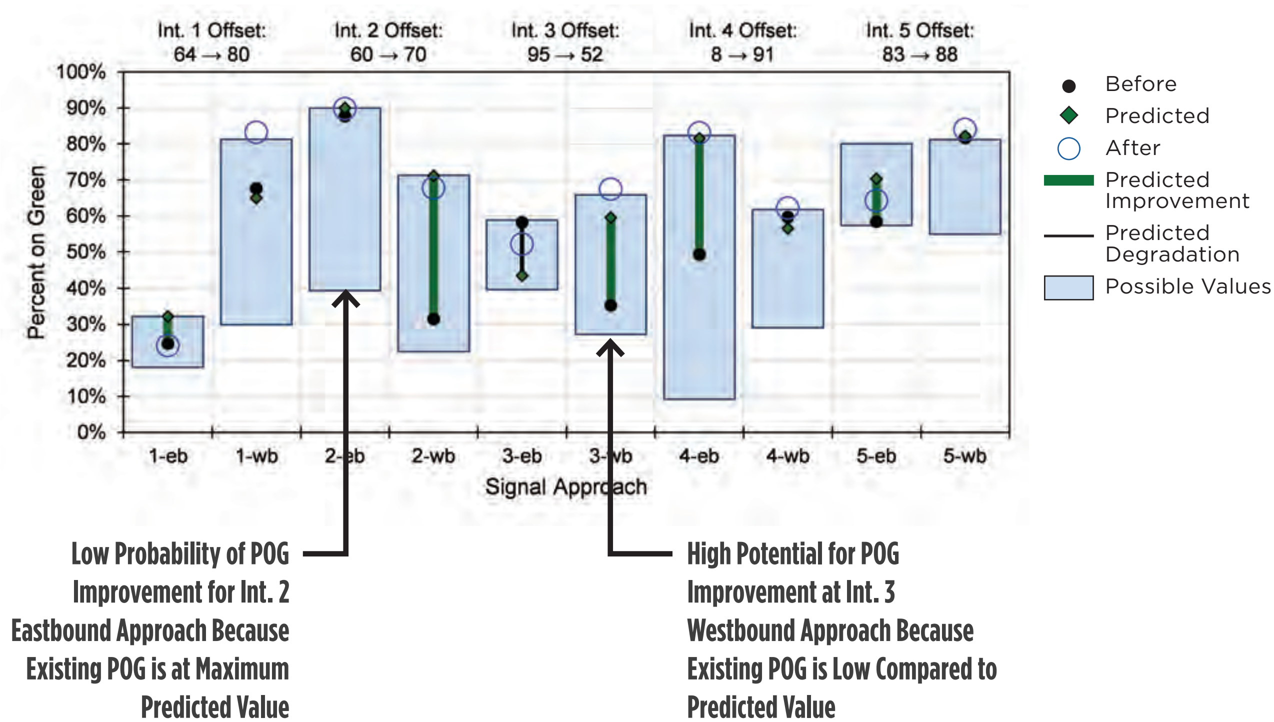
What is the potential for progression improvement along a coordinated corridor?

EXHIBIT 3-38 is an example Offset Adjustment Diagram for a corridor with five intersections: 10 approaches labeled eastbound (eb) and westbound (wb). Each blue bar represents the range of potential percent on green (POG) for each individual approach (see *Section 3.19: Progression Quality*). The black dot represents the POG before an offset adjustment. The green diamond represents the predicted value of POG using the offset adjustments shown at the top of the chart. A green line between the "before" value and the predicted value indicates a predicted improvement in POG, whereas a black line illustrates a predicted reduction in POG. This chart also shows the "after" values of POG, obtained from a different day after the new offsets were implemented.

As an example, the westbound approach at Intersection (Int.) 3 had a "before" POG of 35%. An analysis of the vehicle arrival and green distributions identified that possible POG values ranged between 28% and 65%. After offset optimization, it was predicted that the POG would increase to 60%. The "after" data shows that the actual performance was slightly better than the predicted performance.

This type of chart can be used to identify locations where POG can likely be improved because the existing value is low compared to the possible POG values. Alternatively, if most intersections have POG values that are high compared to the possible values, an agency could decide to use resources elsewhere. If these types of charts were developed for multiple corridors, they could be used to prioritize corridors for offset adjustments.

EXHIBIT 3-38. EXAMPLE OFFSET ADJUSTMENT DIAGRAM: PERCENT ON GREEN (POG) ASSESSMENT FOR FIVE-INTERSECTION CORRIDOR (DAY AND BULLOCK 2017)



3.23 TRAVEL TIME AND AVERAGE SPEED

Communication
Detection
Intersection/ Uncoordinated Timing
System/Coordinated Timing
Advanced Systems and Applications

1 2 3 **4** 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH

VEHICLE DELAY

VEHICLE PROGRESSION

PEDESTRIANS

BICYCLES

RAIL

EMERGENCY VEHICLES

TRANSIT

TRUCKS

SAFETY

APPLICATIONS

- Identify corridors with high/low travel times and speeds.

STAKEHOLDERS

ORGANIZATIONAL

PLANNING

DESIGN AND CONSTRUCTION

OPERATIONS

MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC

CONTROLLER HIGH-RESOLUTION

AVI/AVL/SEGMENT SPEED

CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Travel time and speed are metrics that can be shared with decision-makers and the public to effectively communicate signal timing impacts on vehicles, pedestrians, bicycles, and other modes of travel. They can also be used by agencies to prioritize signal timing activities; agencies can normalize the data and identify outliers where travel times and speeds are higher or lower than historical values.

Travel time is defined as the amount of time needed to traverse a route (the inverse of which is average speed). There are numerous ways to measure or estimate travel time using the following data sources:

- **AVL data.** The time spent by vehicles along a route can be deduced after map-matching the GPS positions to distances along a roadway. Travel times can be directly measured based on the path of the probe vehicle.
- **AVI data.** Travel times from point to point can be measured using the difference in time between detection at two locations. Typically, sensors are located such that there is a single route between them.
- **Segment speed data.** The average speed on individual segments that make up a route can be converted into travel times, with the total travel time on the route summed from that of the individual segments.
- **High-resolution data.** Delays on movements at individual intersections may be estimated and added together to estimate travel time. Another method is called the "virtual probe vehicle" technique, which estimates the trajectory of a virtual probe vehicle based on queue lengths at each intersection.

Some of the methods discussed give the travel times of individual vehicles, whereas others yield a representative travel time for a particular time period. The data can be visualized in numerous ways, including:

- Raw data shown in a point cloud.
- Aggregated data shown as a linear series over time (e.g., 5 minute averages over the course of a day).
    - » Speeds aggregated over a time period can be shown as profiles, which can depict the amount of time that different speed categories were observed.
    - » Travel times aggregated over a time period can be shown as histograms or cumulative frequency diagrams (which are useful for comparing two different time periods).
- Single-value numerical measures can be derived from travel time and speed data to offer a summary of performance. For example, the "planning time index" represents the 95th percentile travel time divided by the free-flow travel time.

DETECTION NEEDS

Some detection may be required depending on the type of technology being used to track vehicles.

CALIBRATION

A reference travel time can be helpful to give context to measured travel times. The desired or free-flow speed (perhaps approximated using speed limits) can be used for this comparison.

REFERENCES

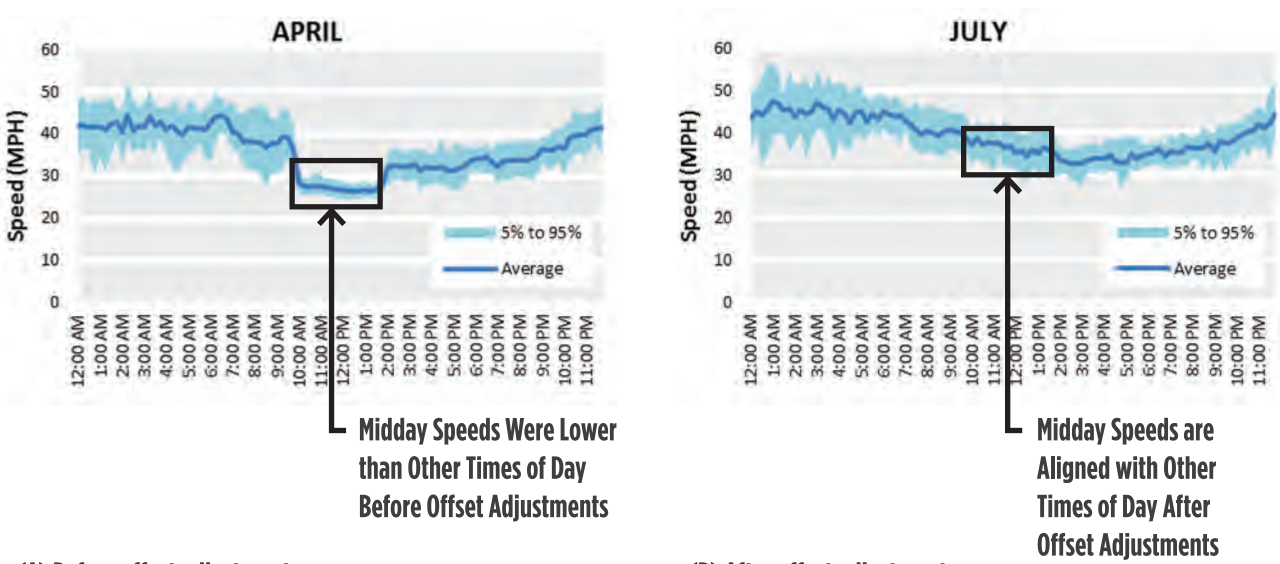
- Day et al. (2010)
- Day, Young et al. (2017)
- Hu, Fontaine, and Ma (2016)
- Krohn et al. (2017)
- Lavrenz et al. (2016)
- Liu et al. (2008)
- Mathew et al. (2017)
- Quayle et al. (2010)
- Sharifi et al. (2016)
- Talukder et al. (2017)
- Wasson, Sturdevant, and Bullock (2008)
- Young et al. (2017)

EXAMPLE USE 1

Did offset adjustments impact corridor speeds?

EXHIBIT 3-39 shows average, 5th percentile, and 95th percentile speeds for a corridor near Charlottesville, Virginia, **(A)** before and **(B)** after offset adjustments. The Virginia Department of Transportation made offset adjustments along the corridor during the midday because it was experiencing lower progression quality than during other times of day. Offset adjustments were made in June, and resulted in higher progression quality along the corridor and speeds that better aligned with other times of day.

EXHIBIT 3-39. TRAVEL TIME AND AVERAGE SPEED EXAMPLE: IMPACT OF OFFSET ADJUSTMENTS ON SPEED (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



(A) Before offset adjustments

(B) After offset adjustments

EXAMPLE USE 2

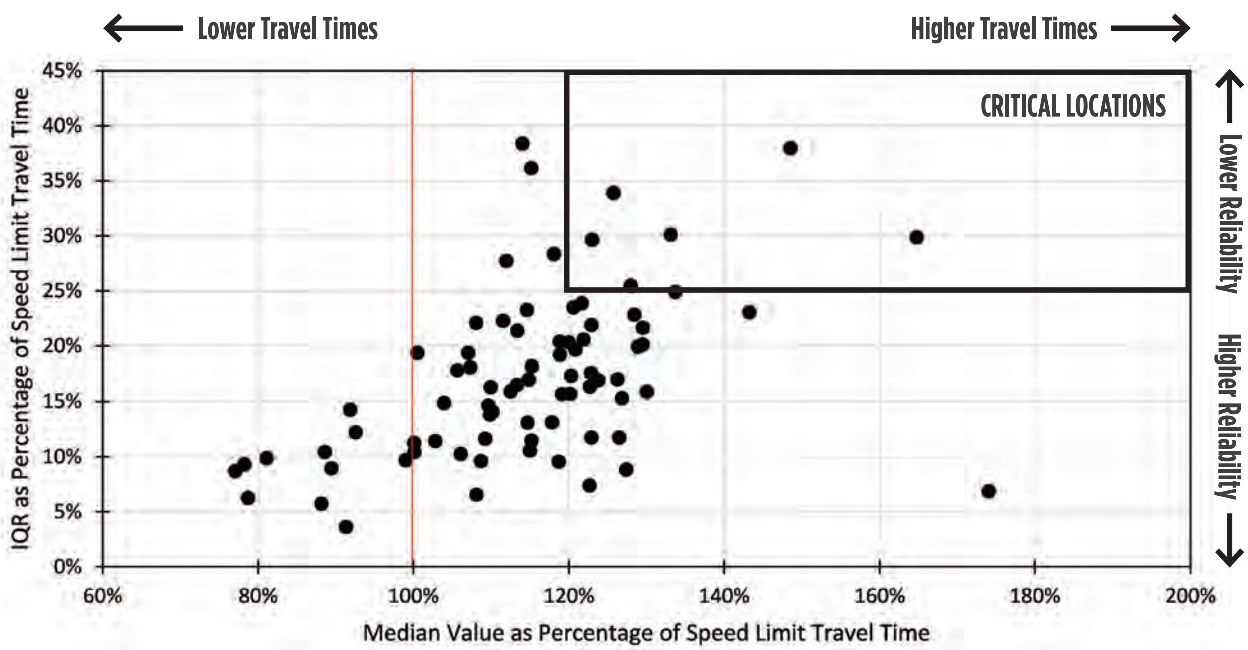
Where are the most critical intersections based on travel times and reliability?

EXHIBIT 3-40 is an example of aggregated travel time data. Values are shown for 39 corridor directional pairs in the greater Indianapolis area (for a total of 78 data points). The travel times are shown for 1 week of operation for the 6:00 AM to 9:00 AM period. The data are plotted according to the median travel time along the horizontal axis and the interquartile range (IQR) of the travel time along the vertical axis. IQR is the difference between the 75th and 25th percentiles. Both axes are normalized according to the speed limit travel time, so that data from corridors with different speed limits can be compared together.

The red line at 100% indicates where median travel times are higher than the speed limit travel time. In other words, points to the left of this line have average speeds greater than the speed limit, and points to the right have average speeds lower than the speed limit. Most of the corridors have longer travel times than the speed limit travel time.

As the median travel times increase, the IQR of the travel times also generally increase, meaning that travel times become less reliable. From such a chart, it becomes relatively easy to identify corridors that stand out from the others as candidates for further investigation. This methodology can be used on a district- or agency-wide level as a screening tool for deciding where to potentially make investments in signal operation.

EXHIBIT 3-40. TRAVEL TIME AND AVERAGE SPEED EXAMPLE: CORRIDOR RANKING USING TRAVEL TIME DATA (MATHEW ET AL. 2017)



3.24 TIME-SPACE DIAGRAM

Communication
Detection
Intersection/Uncoordinated Timing
System/Coordinated Timing
Advanced Systems and Applications

1 2 3 4 5

CATEGORY

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- Identify corridors with small green bands (i.e., poor opportunities for progression).

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
DESIGN AND CONSTRUCTION
OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

The Time-Space Diagram is a classic representation of signal coordination and a basic design tool for creating timing plans. The y-axis represents space (linear distance along a corridor) and the x-axis represents time. The signal state is represented by ring-and-barrier diagrams showing the green and red indications of the coordinated phases.

Across the signal state, individual vehicle trajectories can be represented as lines. "Green bands" (opportunities for progression) can be determined by drawing diagonal lines between the green intervals of neighboring intersections. The slope of vehicle trajectories or green bands represents speed, which can be the speed limit or some other running speed intended for progression. Additional information is available in *NCHRP Report 812: Signal Timing Manual, 2nd ed.* (Urbanik et al. 2015).

Such diagrams are often prepared in software when designing signal timing plans for implementation in the field. Actual operations may differ, in particular because of actuation. It is possible for the signal controller to record green and red times to draw a diagram of actual operations (which some central systems have been capable of for many years).

DETECTION NEEDS

None. However, AVL detection is required for overlaying vehicle trajectories.

CALIBRATION

Speeds are needed to draw bands in Time-Space Diagram

REFERENCES

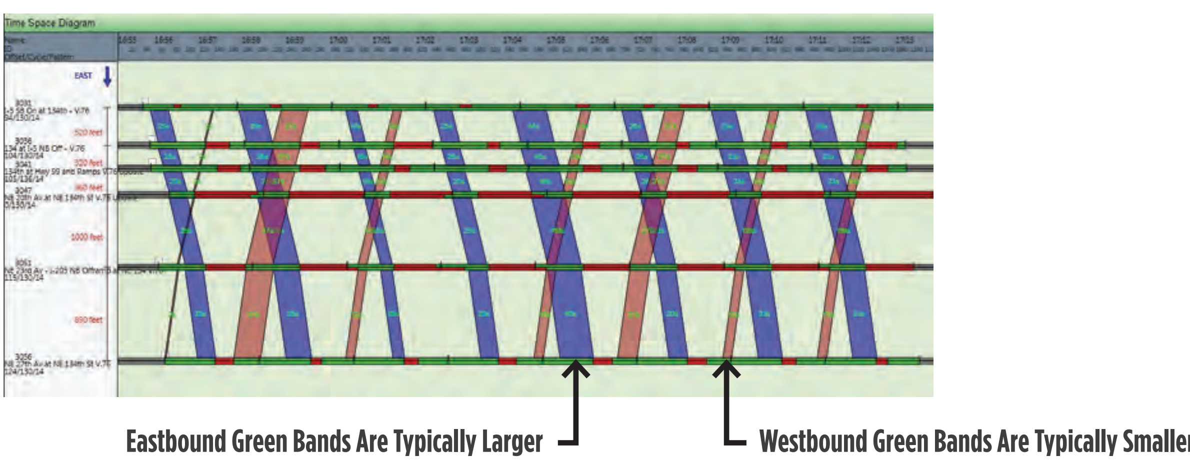
- Liu et al. (2008)
- Urbanik et al. (2015)

EXAMPLE USE

Is the signal timing resulting in expected green bands?

EXHIBIT 3-41 is a Time-Space Diagram from the Clark County, Washington, ATMS system. In addition to the red and green times, the effective arterial through bands are shown. The system provides consistent eastbound (blue) bands; westbound (red) bands are not as frequent and typically are smaller. This graphic can be used to confirm that the system is operating as intended.

EXHIBIT 3-41. TIME-SPACE DIAGRAM EXAMPLE: TIME-SPACE DIAGRAM FROM THE CLARK COUNTY, WASHINGTON, ATMS SYSTEM SHOWING ACTUAL GREEN BANDS (COURTESY CLARK COUNTY, WASHINGTON)



3.25 PREEMPTION DETAILS

CATEGORY

1 Communication
2 Detection
3 Intersection/ Uncoordinated Timing
4 System/Coordinated Timing
5 Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- Identify intersections with high numbers of preemption events.
- Identify intersections with preemption events causing high delay for other transportation system users.

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
DESIGN AND CONSTRUCTION
OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Preemption is the interruption of normal operations to serve a preferred vehicle (e.g., train, emergency vehicle). This metric can be used to determine if preemption events are occurring as intended.

- For rail preemption, the main priority is clearing track(s) of vehicles, with a secondary priority of minimizing delay for all transportation system users.
- For emergency vehicle preemption, the main priority is reducing delay for the preferred vehicle.

There are various metrics related to preemption that can be reported using high-resolution data, including the following:

- **Preempt request.** The time when preempt requests were received for each preemption channel.
- **Preempt service.** The time of service for each preemption channel.
- **Preemption details.** The duration of preemption intervals for each preemption event. The type of interval information available depends on the type of preempt (i.e., rail or emergency vehicle) and the availability of certain inputs. Some potential intervals that can be tracked include entry delay, track clearance, gate down, dwell, time to service, max-out, and preempt input on/off.

DETECTION NEEDS

Although high-resolution data from the controller can report this metric directly (without programming detection settings), specific detection equipment will be required at the intersection in order for vehicles to request preemption.

In order to evaluate rail interactions accurately, an island circuit is needed so that actual train arrival times are recorded.

CALIBRATION

N/A

REFERENCES

- Brennan et al. (2009)
- Brennan et al. (2010)
- UDOT

EXAMPLE USE

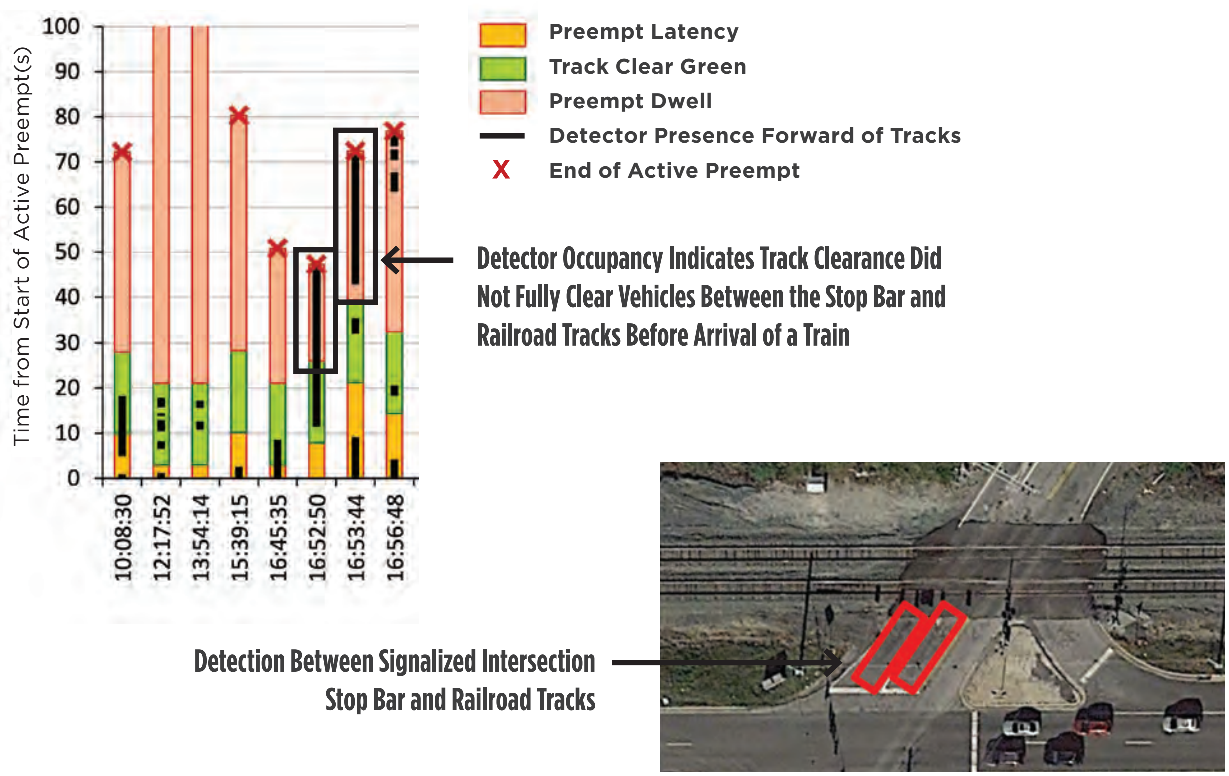
Are vehicles being consistently cleared from the railroad tracks during the track clearance green interval?

EXHIBIT 3-42 shows railroad preemption details overlaid with occupancy data for detection zones located between a signalized intersection and railroad tracks. Each column shows the following:

- **Preempt latency.** The time between the advance warning preempt and beginning of the track clearance green interval.
- **Track clear green.** When a green indication is given to the movement across the tracks, clearing vehicles from the tracks before a train arrives.
- **Preempt dwell.** The time between when the track clearance green interval ends and the preempt ends (correlating to the train being through the crossing).

During two cycles, at 16:52:50 and 16:53:44, there was a significant amount of occupancy throughout the preempt dwell interval, indicating that the track clearance green interval did not fully clear traffic between the stop bar and railroad tracks before the arrival of a train. This measure justified adding countermeasures at this particular site, including steerable signal heads and a gate-down circuit.

EXHIBIT 3-42. PREEMPTION DETAILS EXAMPLE: DETAILS WITH DETECTOR OCCUPANCY (BRENNAN ET AL. 2009)



3.26 PRIORITY DETAILS

CATEGORY

1 Communication
2 Detection
3 Intersection/ Uncoordinated Timing
4 System/Coordinated Timing
5 Advanced Systems and Applications

OBJECTIVES

EQUIPMENT HEALTH
VEHICLE DELAY
VEHICLE PROGRESSION
PEDESTRIANS
BICYCLES
RAIL
EMERGENCY VEHICLES
TRANSIT
TRUCKS
SAFETY

APPLICATIONS

- Identify intersections with high numbers of priority events.
- Identify intersections with priority events causing high delay for other transportation system users.

STAKEHOLDERS

ORGANIZATIONAL
PLANNING
DESIGN AND CONSTRUCTION
OPERATIONS
MAINTENANCE

DATA SOURCES

VENDOR-SPECIFIC
CONTROLLER HIGH-RESOLUTION
AVI/AVL/SEGMENT SPEED
CENTRAL SYSTEM LOW-RESOLUTION

DESCRIPTION

Priority is the preferential treatment of one vehicle class (e.g., transit, trucks) over another (e.g., cars) at a signalized intersection, but unlike preemption, it will not disrupt coordination. The most common application is transit signal priority (TSP). High-resolution data events related to TSP include:

- TSP check in
- TSP adjustment to early green
- TSP adjustment to extend green
- TSP check out

These data can facilitate the creation of a variety of metrics that can be used to examine the operation of priority control, including the frequency and duration of requests and the traffic signal response.

DETECTION NEEDS

Although high-resolution data from the controller can report this metric directly (without programming detection settings), specific detection equipment will be required at the intersection in order for vehicles to request priority.

CALIBRATION

N/A

REFERENCES

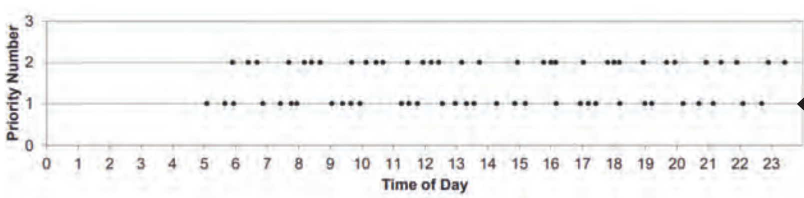
- Feng, Figliozzi, and Bertini (2015)
- Mackey (2016)
- Sajjadi, Day, and Bright (2016)

EXAMPLE USE 1

How many transit signal priority requests were made, and how were they served (i.e., early green or green extend)?

EXHIBIT 3-43A is a plot of transit signal priority requests at a signalized intersection over a 24-hour period by priority number. Priority requests were evenly distributed between 5:00 AM and 12:00 AM at this location. **EXHIBIT 3-43B** shows how (i.e., early green or green extend) and when the priority requests were served. Priority service occurred between 6:00 AM and 9:00 PM, with most requests being accommodated using early green (versus green extend).

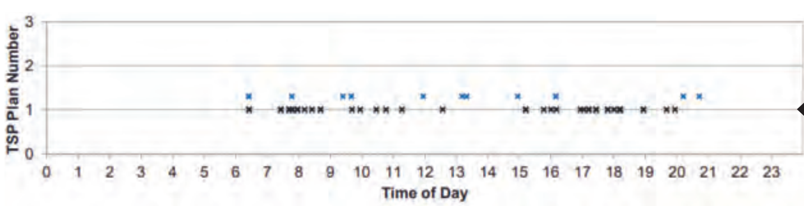
EXHIBIT 3-43. PRIORITY DETAILS EXAMPLE: TRANSIT SIGNAL PRIORITY (MACKEY 2016)



X Early Green
X Green Extended

Even Distribution of Priority Requests

(A) Priority requests



X Early Green
X Green Extended

Most Priority Requests Served with Early Green

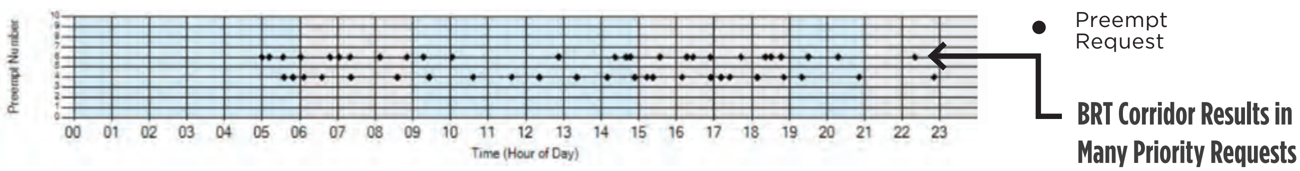
(B) Priority service

EXAMPLE USE 2

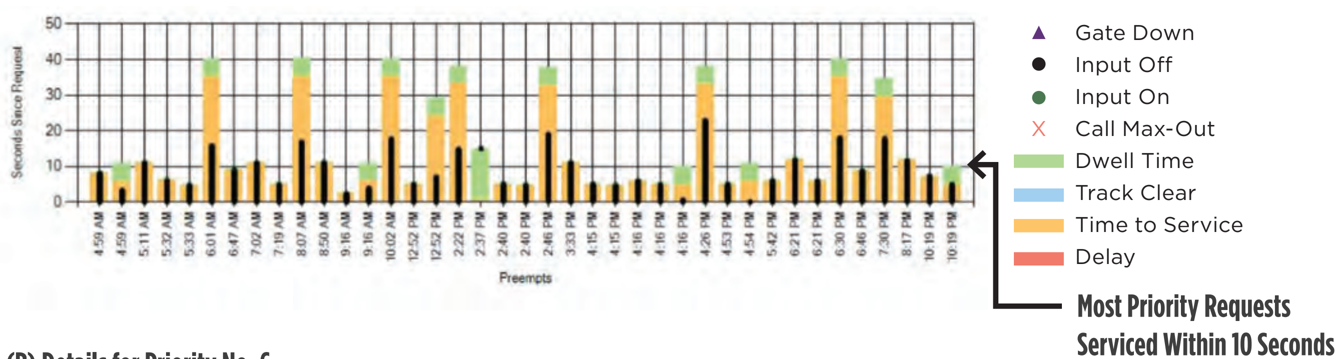
How often are priority requests being made on a bus rapid transit corridor?

EXHIBIT 3-44 summarizes priority request details for a bus rapid transit (BRT) corridor. The number of priority requests by movement can be assessed using **EXHIBIT 3-44A**. Cycle-by-cycle details are provided for one direction in **EXHIBIT 3-44B**, including the time to transition to the priority phase and the amount of time dwelling in the priority phase. In this example, most priority requests are serviced within 10 seconds.

EXHIBIT 3-44. PRIORITY DETAILS EXAMPLE: BUS RAPID TRANSIT CORRIDOR (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



(A) Priority requests



(B) Details for Priority No. 6

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CHAPTER 4 SYSTEM NEEDS FOR PERFORMANCE MEASURES

LIST OF EXHIBITS

CHAPTER FOCUS

Once an agency has identified signal performance measures to implement, staff will need to determine if their existing system can achieve those metrics or if new resources will need to be procured. *Chapter 3* introduced some of the resources required for each signal performance measure, including data sources and detection. This chapter describes those elements in more detail. Using the information in *Chapter 4*, an agency should be able to start a procurement process for required resources.

4.1 GAP ASSESSMENT

An agency should determine if additional equipment and/or staff are needed to deploy desired signal performance measures. Resource needs can generally be organized into three categories:

System components including communication, detection, data logging, data storage, and software.

Workforce resources (i.e., staff) required to apply signal performance measures.

Business processes including formal scoping, planning, programming, and budgeting processes.

EXHIBIT 4-1 is a high-level checklist that can be used to start a gap assessment. Existing capabilities may influence which signal performance measures are implemented to meet near-term goals and can also highlight needs required to meet long-term goals. For example, an agency may want to assess split failures, but the required stop bar detection may not be installed on every approach. In the near term, the agency may decide to use phase termination information to estimate the likelihood of split failures, with a long-term goal of installing additional detection.

An agency should fill out a gap assessment considering both their own resources as well as any shared resources that may be available to them. For example, local agencies may be able to share resources with the state. In Utah, many local agencies operate their own traffic signals but are able to integrate them with the Utah Department of Transportation (UDOT) Automated Traffic Signal Performance Measure (ATSPM) system (UDOT).

EXHIBIT 4-1. EXISTING RESOURCE CHECKLIST

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

4.2 DATA SOURCES

There are two categories of data that will be explored in this guidebook: the *external* data sources that measure traffic performance without using information from a traffic signal controller and the *internal* data sources that capture traffic signal controller events. **EXHIBIT 4-2** summarizes seven data sources (organized into *internal* and *external* data) that can be used to produce signal performance measures.

Historically, *external* data required manual collection methods. Turning movement counts were recorded by a human observer or travel times were collected using a "floating" car driven by an analyst. Over the years, methods of automating those data-collection activities emerged. Looking to the future, connected vehicles will continue to advance available *external* data through detailed vehicle-location information.

A complementary dataset is *internal* to the traffic signal controller. This dataset captures signal state and detection events. It has always been available through the electrical impulses sent to the signal displays and received from detectors, but the development of "high-resolution data" has allowed for the continuous collection and storage of those traffic signal events. High-resolution controller event data are considered a valuable source of signal performance measures and has been given significant attention throughout this guidebook.

EXHIBIT 4-2. DATA SOURCES

DATA SOURCE	TYPE	DESCRIPTION
Controller (High-Resolution Data)	**Internal**	Timestamped "events" (e.g., detector inputs and signal display outputs) recorded by the controller at 1/10-second resolution.
Central System (Low-Resolution Data)	**Internal**	Volumes, detector occupancies, green times, and phase terminations aggregated for a selected time period (e.g., 1, 5, or 15 minutes) by the central system.
Vendor-Specific	**Both**	Data collected by detection systems, preemption systems, and adaptive control systems.
Automated Vehicle Identification (AVI)	**External**	Travel time, route choice, and origin-destination estimated through identification of unique vehicle identifiers at multiple locations (using Bluetooth MAC addresses, Wi-Fi network IDs, physical detector signatures, or toll tag readers).
Probe Vehicle Segment Speed	**External**	Average speeds on pre-defined segments aggregated using data from individual probe vehicles.
Automated Vehicle Location (AVL)	**External**	Timestamped GPS coordinates of probe vehicles collected using external hardware or "crowd-sourced" applications. GPS coordinates for probe bicycles and pedestrians could also be obtained.
Connected Vehicle (CV)	**External**	CV data are similar to AVL data but contain more information about vehicle characteristics. CV data are defined by the SAE J2735 standard, which includes Basic Safety Messages (BSM), Signal Phase and Timing (SPaT) messages, and likely traveler information messages in the future.

The following information is provided as a "primer" for each data source.

DESCRIPTION	
Detailed description of the data source.	
REQUIREMENTS	
COMMUNICATION	Intersection and system components required to produce the data, organized using five categories.
DETECTION	
DATA LOGGING	
DATA STORAGE	
SOFTWARE	
AVAILABILITY	
Current availability of the data through agency sources or private-sector vendors.	
CAPABILITIES	
Advantages to using the data source.	
CHALLENGES	
Potential complications of using the data source.	
EXAMPLE DATA	
Example of how the data are reported.	

4.2.1 CONTROLLER HIGH-RESOLUTION DATA

DESCRIPTION

The data consist of timestamped events (and associated parameters) recorded at the nearest 1/10-second by the traffic signal controller. Events describe state changes at the intersection such as outputs to the signal displays and inputs from the detectors (Sturdevant et al. 2012), and parameters give additional details about the event such as the associated phase or detector. For example, Event Code 1 is recorded when a phase begins its green interval. If Event Code 1 is recorded along with Parameter 4, the event that occurred is Phase 4 beginning its green interval at the designated timestamp.

REQUIREMENTS

COMMUNICATION	• Communication is needed to collect the data without manual retrieval.
DETECTION	• Detection is needed to record the presence of roadway users.
DATA LOGGING	• Many different types of traffic signal controllers (i.e., ATC controllers) are now capable of logging high-resolution data. • Another option is to use a stand-alone device that is external to the traffic signal controller to record the data. These devices can typically be used alongside older traffic signal controllers. • It is also possible to develop equivalent data by central system polling (i.e., retrieving real-time status). However, this method does not tolerate any latency in the communication system.
DATA STORAGE	• Either a server or cloud-based solution is required to store the data.
SOFTWARE	• Open source software is available for data processing. • Vendors have software available through central systems and web-based platforms.

AVAILABILITY

- Most traffic signal controller manufacturers have at least one controller model that supports high-resolution data logging.
- Other vendors have external data collection units that can be used with older controllers.

CAPABILITIES

- Highly detailed records allow a wide variety of signal performance measures to be calculated.

CHALLENGES

- Because of the large amount of data, system management may be challenging for some agencies.

EXAMPLE DATA 1/10-Second Enumerations

TIMESTAMP	EVENT CODE	PARAMETER	DESCRIPTION
02/15/17 12:01:16.0	8	4	Phase 4 Begin Yellow Clearance
02/15/17 12:01:16.0	8	8	Phase 8 Begin Yellow Clearance
02/15/17 12:01:19.4	81	9	Detector 9 Off
02/15/17 12:01:19.5	10	4	Phase 4 Begin Red Clearance
02/15/17 12:01:19.5	10	8	Phase 8 Begin Red Clearance
02/15/17 12:01:20.0	1	2	Phase 2 Begin Green
02/15/17 12:01:20.0	1	6	Phase 6 Begin Green
02/15/17 12:01:25.5	82	19	Detector 19 On
02/15/17 12:01:28.0	81	19	Detector 19 Off
02/15/17 12:01:29.3	82	9	Detector 9 On

4.2.2 CENTRAL SYSTEM LOW-RESOLUTION DATA

DESCRIPTION

Volume and occupancy data have been available through central systems for many years. These data typically consist of volumes (vehicle counts) and detector occupancy measurements averaged over a time period such as 1 minute, 5 minutes, or 15 minutes. Some central systems can also provide aggregated phase information such as average green times or termination types (i.e., max-outs, force-offs, gap-outs, skips).

REQUIREMENTS

COMMUNICATION	• Communication is needed to collect the data without manual retrieval.
DETECTION	• Detection is needed to record the presence of roadway users.
DATA LOGGING / **DATA STORAGE** / **SOFTWARE**	• The data require a central system capable of polling the controllers, storing the data, and displaying or exporting it.

AVAILABILITY

- Most central systems can produce this type of data.
- Not all locations will have appropriate communication or detection in place to collect it.

CAPABILITIES

- The data are readily available to an agency using a central system. For an agency that does not have resources to collect any other type of data, low-resolution data may provide an interim solution for performance-based management.

CHALLENGES

- The level of detail in the data is typically low, so in-depth, cycle-by-cycle analysis will not be possible.
- Equipment interoperability may be an issue with some central systems.

EXAMPLE DATA 15-Minute Volumes

TIMESTAMP	NBL	NBT	NBR	EBL	EBT	WBT	WBR
03/07/18 17:00-17:15	12	21	77	78	329	258	128
03/07/18 17:15-17:30	10	20	61	92	323	265	126
03/07/18 17:30-17:45	3	21	65	107	376	273	110
03/07/18 17:45-18:00	6	27	68	92	297	275	124
03/07/18 18:00-18:15	9	27	44	92	310	248	120
03/07/18 18:15-18:30	8	22	67	91	284	199	116
03/07/18 18:30-18:45	7	25	60	92	278	184	141
03/07/18 18:45-19:00	5	20	51	94	230	181	114
03/07/18 19:00-19:15	7	22	48	90	213	156	109
03/07/18 19:15-19:30	11	20	40	105	226	162	138

4.2.3 VENDOR-SPECIFIC DATA

DESCRIPTION

Many vendors provide data directly from their equipment, which can include detection systems, preemption systems, and adaptive control systems. Most of these systems are proprietary and require specific equipment and software.

REQUIREMENTS

COMMUNICATION	• Communication is needed to collect the data without manual retrieval.
DETECTION	• This type of data requires investment in a specific system (i.e., detection, preemption, adaptive) and all the necessary components.
DATA LOGGING	
DATA STORAGE	
SOFTWARE	

AVAILABILITY

- Available through private-sector vendors.
- In general, these systems are not procured for performance measurement purposes alone but as part of a larger program of system upgrades.

CAPABILITIES

- Detailed, cycle-by-cycle metrics can be obtained from certain types of proprietary systems.

CHALLENGES

- Interoperability with equipment from other vendors is unlikely except in cases where the traffic signal cabinet and controller are modern, standards-based equipment that is compatible with other software and firmware. Intersections must be equipped with the same vendor-compatible equipment in order to obtain comparable data.

EXAMPLE DATA Adaptive Splits

	PH 1	PH 2	PH 3	PH 4	PH 5	PH 6	PH 7	PH 8
Active Split (Sec)	11	18	15	16	12	17	15	16
Utilization (%)	100	69	95	81	100	61	61	63
Next Split (Sec)	13	19	14	14	14	18	15	13

4.2.4 AUTOMATED VEHICLE IDENTIFICATION (AVI) DATA

DESCRIPTION

Automated vehicle identification (AVI) involves identifying vehicles through unique identifiers at multiple locations. Matching identifiers allow the travel time between locations to be estimated. Other network dynamics such as route choice and origin-destination patterns can also be deduced. There are several technologies that can be used to collect AVI data, including Bluetooth MAC addresses, Wi-Fi network IDs, physical detector signatures, and toll tag readers.

REQUIREMENTS

COMMUNICATION	• Communication to sensors is required for the data to be collected without manual retrieval.
DETECTION / **DATA LOGGING**	• Sensors must be procured, installed, and maintained in order to produce AVI data.
DATA STORAGE	• Either a server or cloud-based solution is required to store the data.
SOFTWARE	• Software is needed to process the relevant data into performance measures.

AVAILABILITY

- Available through private-sector vendors.

CAPABILITIES

- AVI allows corridor-level data to be collected at a much higher rate than through manual methods such as floating-car studies.

CHALLENGES

- A minimum of two sensors are required on each individual route. Developing travel times for many routes or for turning movements requires a higher number of sensors. As a result, AVI data tend to be collected only for major movements.

EXAMPLE DATA Bluetooth MAC Address Travel Times

START TIME	END TIME	IDENTIFIER	TRAVEL TIME (SEC)	SPEED (MPH)
12/01/17 13:18:29.0	12/01/17 13:20:11.0	1AC5D6	102	26.0
12/01/17 13:18:46.0	12/01/17 13:20:42.0	005FE5	116	22.8
12/01/17 13:20:14.0	12/01/17 13:22:06.0	314324	112	23.6
12/01/17 13:22:14.0	12/01/17 13:23:45.0	770FB0	91	29.1
12/01/17 13:22:58.0	12/01/17 13:25:14.0	222655	136	19.5
12/01/17 13:22:59.0	12/01/17 13:25:15.0	0055CF	136	19.5
12/01/17 13:24:16.0	12/01/17 13:25:50.0	59D7E7	94	28.2
12/01/17 13:26:26.0	12/01/17 13:28:51.0	D154A9	145	18.3
12/01/17 13:28:30.0	12/01/17 13:30:55.0	89B8A1	145	18.3
12/01/17 13:28:59.0	12/01/17 13:31:33.0	B6C049	154	17.2

4.2.5 PROBE VEHICLE SEGMENT SPEED DATA

DESCRIPTION

The data are derived from analysis of individual probe vehicles, but the data are anonymized by converting individual vehicle positions into average segment speeds. The data are provided as speed records per segment over a specified time period (e.g., 1 minute, 5 minutes, 15 minutes). This process requires that practitioners index shapefiles describing the roadway segments by route and direction. The data quality is generally reliable on freeway routes, and its use on signalized arterials has been increasing.

REQUIREMENTS

COMMUNICATION / **DETECTION**	• Requires a contract with a data provider for delivery of the data, which can be in an archived format for past data or real-time through web-based polling.
DATA LOGGING	• State agencies may also be eligible to use the National Performance Measure Research Data Set (NPMRDS) at no cost.
DATA STORAGE	• Either a server or cloud-based solution is required to store the data.
SOFTWARE	• Software is needed to process the relevant data into performance measures. • Route definitions are typically needed to make the best use of the data, which may necessitate the availability of GIS software to be able to view shapefiles and interpret the meaning of segment IDs.

AVAILABILITY

- Available through private-sector vendors.
- Available through the National Performance Measure Research Data Set.

CAPABILITIES

- The data can provide 24/7 coverage of the entire roadway network without the agency needing to install field equipment.
- Data are available both in real-time and for past performance (potentially going back several years).

CHALLENGES

- The data are constrained by the segment definitions used by the data provider, which may not align with segments of interest to the agency.
- The data are provided as averages. Although it is possible to take the average of many different time periods to develop a distribution, the full degree of variation within a small time period may not be available.

EXAMPLE DATA NPMRDS Segment Speeds

TMC	TIMESTAMP	SPEED (MPH)	AVERAGE SPEED (MPH)	REFERENCE SPEED (MPH)	TRAVEL TIME (MIN)
110N04178	09/01/14 0:00	72	57	67	0.82
110N04179	09/01/14 0:00	89	59	67	0.61
110-04175	09/01/14 0:00	61	53	65	1.51
110-04176	09/01/14 0:00	62	57	68	0.48
110-04177	09/01/14 0:00	63	59	67	1.05
110-04178	09/01/14 0:00	72	57	67	0.83
110-04179	09/01/14 0:00	89	59	67	0.24
110N04175	09/01/14 0:00	61	53	65	0.54
110N04176	09/01/14 0:00	62	57	68	0.83
110N04177	09/01/14 0:00	63	59	67	0.07

4.2.6 AUTOMATED VEHICLE LOCATION (AVL) DATA

DESCRIPTION

Automated vehicle location (AVL) data consist of timestamped GPS coordinates of probe vehicles that are recorded as they move through a roadway network. It is also possible to collect this type of data for bicycles and pedestrians. GPS data have been used for years in floating-car studies, but the number of available data points was typically low because of the cost associated with manual data collection. Over time, some agencies equipped fleet vehicles (such as buses) with GPS units, which reduced costs.

In more recent years, AVL data have become “crowd-sourced,” with participants “opting in” to provide data through the use of navigation devices or apps on cell phones. In the transportation sector, that data can yield valuable information about roadway performance, and a few private companies are beginning to make the data available after they gather, clean, and anonymize it. In the future, it is likely that similar data will be available from connected vehicles (CVs) (see *Section 4.2.7:Connected Vehicle (CV) Data*).

REQUIREMENTS

COMMUNICATION **DETECTION** **DATA LOGGING**	AVL data can be obtained through: • GPS devices installed on agency fleet vehicles. • Purchasing data from private companies. • Connected vehicles. At the time of writing, the number of CVs on the roadway remains small but is expected to increase in the future.
DATA STORAGE	• Either a server or cloud-based solution is required to store the data.
SOFTWARE	• Software is needed to process the relevant data into performance measures.

AVAILABILITY

- Available through private-sector vendors.

CAPABILITIES

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

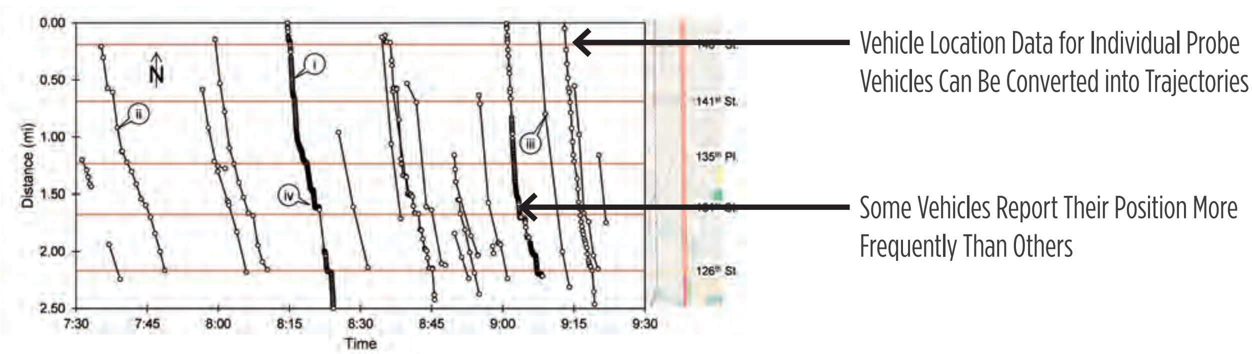
CHALLENGES

- A map-matching process is required to extract useful information about the performance of individual movements.
- Sample rates are currently low (about 1% or less of traffic volumes).
- Complex geometries, such as where bridges occur, may be difficult to analyze.
- Concerns over privacy remain to be resolved for this type of data.

EXAMPLE DATA Timestamped Position Records

EXHIBIT 4-3 shows southbound trajectories along an arterial route that were recorded in 2015 by a private-sector data provider. Each point represents a timestamped position record. Some traces have a higher density of points than others, indicating that the reporting intervals among vehicles differ.

EXHIBIT 4-3. AUTOMATED VEHICLE LOCATION (AVL) DATA EXAMPLE: TIMESTAMPED VEHICLE LOCATION DATA OBTAINED FROM A PRIVATE-SECTOR VENDOR (DAY ET AL. 2016)



4.2.7 CONNECTED VEHICLE (CV) DATA

DESCRIPTION

These data are defined by the SAE J2735 standard, which describes several data streams that will allow vehicles and infrastructure to communicate. These data streams include:

- Basic Safety Messages (BSMs) used by vehicles to communicate their position and other information about driving behavior.
- Signal Phase and Timing (SPaT) messages broadcast by infrastructure, so that nearby CVs will know the current signal state and anticipated future signal state.
- Traveler information messages are also expected to be included in the future.

CV data contain more information about vehicle characteristics than AVL data; however, it is not clear whether CV data will be traceable through multiple intersections due to privacy concerns. Predictions vary as to when a sufficient percentage of the vehicle fleet will have onboard equipment to communicate with roadside infrastructure and other vehicles. In the United States, connected vehicle pilot programs have entered their second phase and some vehicle manufacturers have begun to include connected vehicle capabilities in new models.

REQUIREMENTS

COMMUNICATION	• Dedicated short range communication (DSRC) transceivers are required for communication between infrastructure and CVs. • Other types of communication (such as cellular networks) may also be available for CV use in the future.
DETECTION	• None.
DATA LOGGING	• Additional hardware and software is typically required for signal controllers to interface with DSRC equipment for broadcasting SPaT messages and receiving BSMs.
DATA STORAGE	• Either a server or cloud-based solution is required to store the data.
SOFTWARE	• Software is needed to process the relevant data into performance measures.

AVAILABILITY

- The equipment for DSRC is readily available. At the time of writing, the “SPaT Challenge” is encouraging state DOTs to invest in this infrastructure and a few vehicle models have DSRC equipment installed.
- Other types of communication (such as cellular networks) may be available in the future for CV use.

CAPABILITIES

- Extremely detailed information (beyond vehicle position) can be extracted from connected vehicles.
- The data will be available in real time, so could potentially be used for signal control applications.

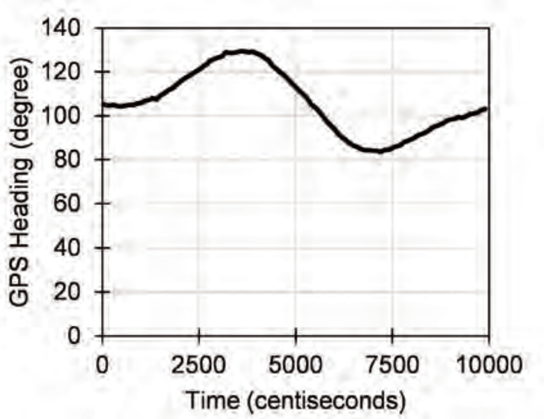
CHALLENGES

- A significant amount of map-matching is required to make use of the data.
- The number of vehicles deployed with the necessary equipment is currently low.
- A significant amount of infrastructure may need to be deployed to obtain the data.
- Concerns over privacy remain to be resolved for this type of data.

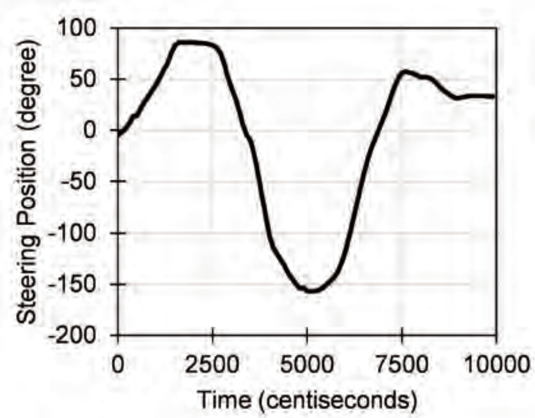
EXAMPLE DATA Connected Vehicle Data

EXHIBIT 4-4 presents charts that are taken from the U.S. DOT Safety Pilot Model Deployment. The data show a 100-second sample. Each chart contains 10,000 points that arise from the 1/10-second reporting interval. Detailed information about the vehicle heading and steering activity are seen in **EXHIBIT 4-4A** and **EXHIBIT 4-4B**. The vehicle position at each point is recorded by its latitude and longitude information, as reported in **EXHIBIT 4-4C** and **EXHIBIT 4-4D**. Data from onboard vehicle sensors are also available, as shown in **EXHIBIT 4-4E** and **EXHIBIT 4-4F**, which show the measured distance from the vehicle centerline to the left and right sides of the roadway.

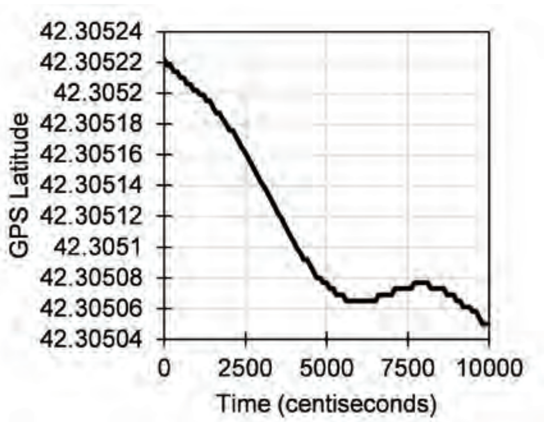
EXHIBIT 4-4. CONNECTED VEHICLE DATA EXAMPLE: VEHICLE POSITION IN THE LANE (U.S. DOT 2015)



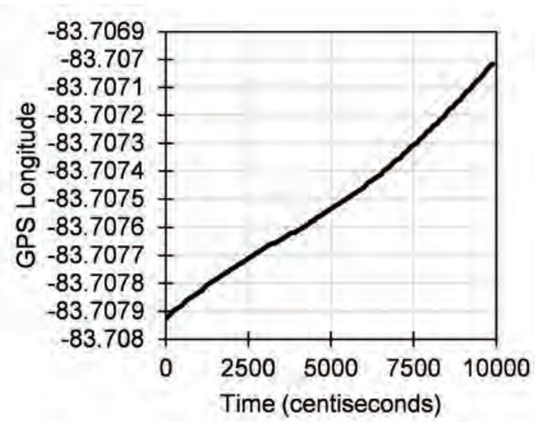
(A) Vehicle heading, from GPS



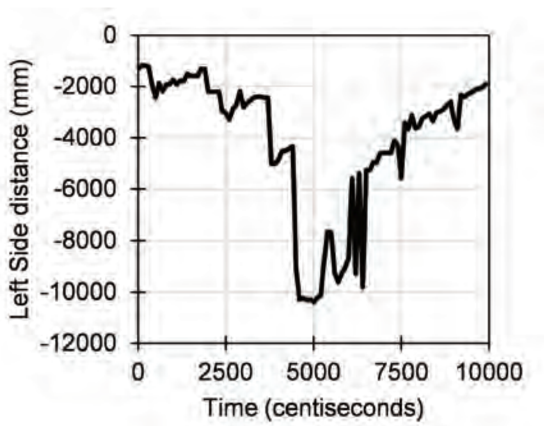
(B) Position of steering wheel



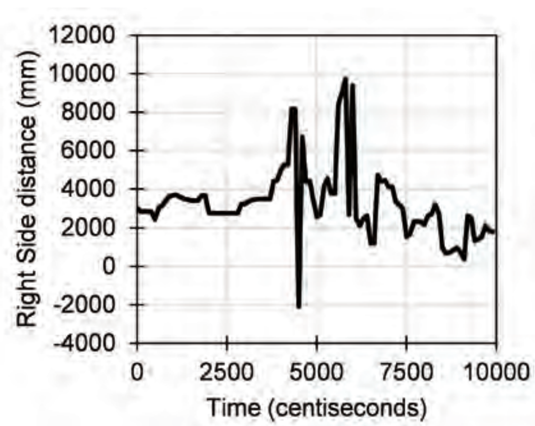
(C) Latitude, from GPS



(D) Longitude, from GPS



(E) Distance from vehicle centerline to left side of road



(F) Distance from vehicle centerline to right side of road

4.3 TECHNICAL REQUIREMENTS

This section focuses on the technical requirements for ATSPM systems, as summarized in **EXHIBIT 4-5**. In some places, the current infrastructure may already be able to support ATSPMs with marginal investments. In addition to upfront costs for intersection and system components, an agency should be aware that use of ATSPMs may result in an increased number of work orders. Malfunctioning equipment that would previously have gone unnoticed until there was a public service request will be highlighted more quickly by ATSPMs.

EXHIBIT 4-5. ATSPM SYSTEM COMPONENT DESCRIPTIONS

SYSTEM COMPONENTS & OPTIONS		DESCRIPTION
Communication		Connection between field devices and central office required for automated data collection.
Detection		Equipment used to detect presence of roadway users required for many signal performance measures.
Data Logging	**High-Resolution Data**	Traffic signal controller with onboard data logger or external data collection unit.
	Other Data Source	Vendor-specific equipment.
Data Storage	**Hardware**	Servers for hosting and workstations/laptops for accessing applications, services, and data.
	Cloud	Server hosted by private-sector vendor with cloud access.
Software	**Operating System Software**	Required for basic operation of server hardware.
	Database Software	Required for storing and managing data.
	ATSPM System Software	Required to convert data stored in a database into signal performance measures.
	Central System Software	Some vendors have ATSPM capabilities through modules that can be added onto base software.

4.3.1 LEVERAGING EXISTING EQUIPMENT

The current capabilities of existing systems vary widely from one agency to another depending on the amount of resources that have been invested over time as well as how recently those investments were made. Every agency is unique and may face challenges in procurement, operation, or maintenance of new equipment. The following list outlines opportunities to leverage existing equipment for ATSPMs.

Communication. Many existing traffic signal systems have some type of communication available for remote access. Although there are still older types of communication in use, improvements in technology and reductions in cost have made higher-bandwidth network communication (necessary for ATSPMs) more feasible for agencies to install. Alternatives to wired communication include cellular modems and point-to-point wireless bridge technology.

Detection. Detection systems are not strictly required for ATSPMs, but a large portion of the available metrics compare detector actuations to controller events. Most existing detection systems can be leveraged for high-resolution data. However, some modifications to existing configurations may be desirable (Day et al. 2017), as discussed in *Section 4.3.3: Detection Requirements*.

Cabinets. Most existing cabinets can support equipment for data collection. Cabinet upgrades are unlikely to be necessary in most cases.

Data logging. Many existing controllers can support collection of high-resolution data. Some agencies may already possess controllers with this functionality, perhaps only requiring a firmware upgrade. An alternative to a controller-based data logger is an external data collection unit.

Data storage. Agencies may be able to repurpose an old server that was previously used for another function (e.g., video camera system). Rather than decommissioning the server, it could be used for data collection.

4.3.2 COMMUNICATION REQUIREMENTS

Communication to field devices is necessary for automated data collection. The cost for communication can vary significantly depending on the desired latency and speed. The following are some considerations for an agency deciding whether to upgrade communication:

- Will the communication system be used for other purposes?
- Will data be stored locally and transmitted in batches or will it be measured in real time by polling?
- How often should data be updated?
- Is intermittent downtime acceptable?

If the communication system will be used for traffic control purposes in addition to ATSPMs, it may be desirable to make a bigger investment in the system. However, different types of signal control have different requirements. For example, clock updates for a coordinated system do not require high-speed communication, but adaptive control, traffic responsive control, and video require reliable, low-latency, high-speed communication.

Polling (particularly NTCIP-polling) can consume significant bandwidth and requires communication with little downtime. Many NTCIP “get” statements will need to be transmitted each second to every intersection. The advantage of polling is that no “new” processes necessarily need to be created; polling already exists as a central system function for retrieving real-time intersection status.

High-resolution data can also be stored in a cache locally and transmitted in packets. Data can be downloaded frequently (e.g., once every few minutes) or less frequently (e.g., once a day in the overnight hours). It is possible for different intersections to be harvested at different rates and for downloads of current data to be triggered manually during critical times.

At a minimum, each subnetwork of traffic signal controllers should have one link to the central office to facilitate data transfer (Makovejs 2012). Options for connecting between intersections and to the central office include the following communication types:

Fiber-optic communication, which typically has the lowest latency (with speeds up to 8.8 terabits per second, Tbps, of bidirectional capacity per each fiber pair). Fiber communication systems require fiber transceivers, cabling and cable deployment, and aggregation cabinets to collect and distribute the fiber.

Point-to-point wireless bridging (i.e., broadband radios), which can be used where clear lines of sight are available between connection points.

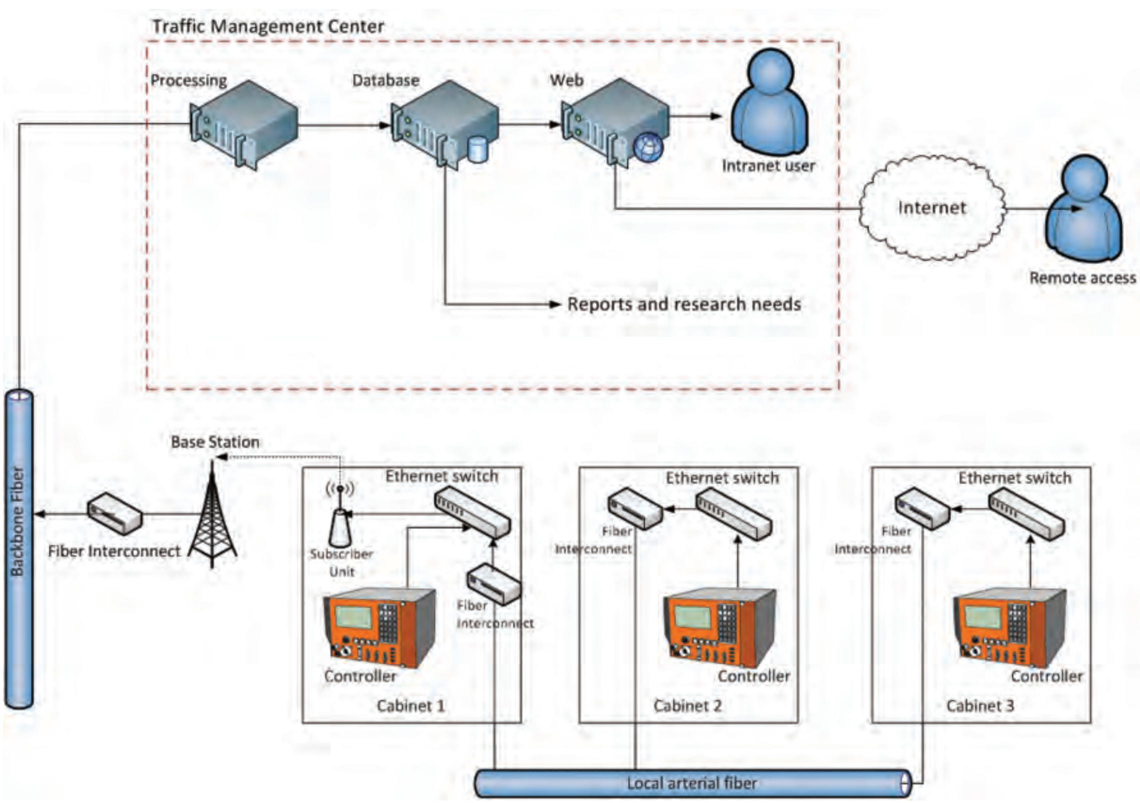
Internet-based options (i.e., Wi-Fi and serial Ethernet), which may also be used to connect intersections.

Commercial cellular communication, which can provide adequate bandwidth without extensive infrastructure.

Legacy systems, such as Digital Subscriber Lines (DSL) and dial-up via telephone, which will require investigation for available bandwidth.

For corridors or networks with a large number of intersections or intersections that are spread out over long distances, a combination of technologies may be used. For example, some architectures leverage localized fiber running along an arterial but use a cellular modem from one of the cabinets to connect to the central office. Architecture details vary by agency, but **EXHIBIT 4-6** shows one example diagram of a hybrid network that uses a combination of fiber and broadband radio communication.

EXHIBIT 4-6. EXAMPLE NETWORK ARCHITECTURE USING DIFFERENT COMMUNICATION METHODS (DAY ET AL. 2016)



If communication to a central office is not possible (and the agency wants more data than can be stored on the controller), the agency can use an embedded personal computer (PC) to cache ATSPM data. A memory capacity of a few gigabytes (GB) is capable of storing many years of raw ATSPM data for an intersection, which allows infrequent visits to the cabinet for data download. Options for data storage include flash memory cards and Raspberry Pi devices (see the example in **EXHIBIT 4-7**). There are also external processors that can serve a dual purpose, storing data and maintaining clock synchronization using GPS time sets.

4.3.3 DETECTION REQUIREMENTS

DETECTOR LAYOUT

Although detection is not an absolute requirement for signal performance measures, more metrics can be derived from high-resolution data if detection is in place. Detector configurations vary widely depending on agency practices, the type of detection technology, and site characteristics. No particular detector configuration or type is preferred for ATSPMs provided it is accurate and reliable.

- In the simplest case, a detection system might use exactly one detector channel per phase. All the detectors associated with a particular phase (regardless of which lane they are in or their position in that lane) are brought together on one channel. This task can be accomplished by splicing inductive loop wires together or extending above-ground detection zones across multiple lanes. This configuration uses the minimum number of detector channels, but all actuation information will be aggregated.
- In a moderately comprehensive configuration, a detection system may use a few different channels for each phase. For example, the advance detectors may be on their own channel, while the rest of the detectors for that phase are on another channel. This type of configuration may be employed where an agency wants more information about the presence of vehicles but has limited space in the cabinet for additional detector cards. There are two common ways agencies reduce the number of detector channels in use: (1) tying together advance and stop bar detectors in a lane and (2) tying together detectors across multiple lanes.

EXHIBIT 4-7. EXAMPLE EMBEDDED PC USED TO COLLECT ATSPM DATA (COURTESY HOWELL LI, PURDUE UNIVERSITY)

Embedded PC Storing Data Generated by Traffic Signal Controller

Advance and stop bar detectors that are tied together in a lane will not work for ATSPMs. If advance and stop bar detectors are tied together in a lane, they will need to be separated onto different detector channels to collect data for ATSPM reports.

Detectors that are tied together across multiple lanes (i.e., all advance detectors on an approach are tied together or all stop bar detectors on an approach are tied together) will work for ATSPMs without having to make adjustments. However, the data will be more aggregated than if detectors are on separate lane-by-lane channels.

- In the most comprehensive configuration, every lane has its own detectors reporting calls on their own channels. This type of configuration requires a large number of detector channels, particularly at intersections with many lanes, but it provides the most accurate data and is necessary for some metrics such as turning movement counts.

The more lanes a detection zone spans, the more aggregated the data. Data aggregation can cause occupancy to appear saturated at lower levels of traffic and vehicle arrival information to be less accurate. It is not necessary to use the most comprehensive detector configuration, but in some cases, it may be desirable to adjust the existing detector configuration to report specific ATSPMs.

Detector count data (whether collected through high-resolution data or other means) may require specific types of detection equipment to support the required number of channels. Although other types of detection can be tied together, count detection requires individual detector channels for each count detector to collect accurate counts (ITE 2008).

In addition to how detectors are tied together, their locations impact the ATSPMs that can be reported. **EXHIBIT 4-8** summarizes the metrics that can be obtained from different detector locations (illustrated in **EXHIBIT 4-9**). Note that a handful of metrics are available even if no detection is available. Without detection, an intersection will operate as a fixed-time intersection, but it is possible to identify anomalies in the programmed signal timing using ATSPMs.

If detector mapping is not readily available (i.e., unmapped detection), it is possible to examine some metrics by phase. For example, the number of gap-outs versus max-outs and force-offs can be determined without knowing which detectors belong to which lanes and phases. However, a greater number of metrics become available with detector mapping information (Smaglik, Bullock, and Urbanik 2005; Smaglik et al. 2007).

Certain types of detection allow practitioners to be selective about the vehicle actuations that are reported to the ATSPM system. For example, detection zones near (or just past) the stop bar may be used to track yellow/red actuations (see *Section 3.16: Yellow/Red Actuations*), and if a speed setting is applied, vehicles that are stopped or decelerating will not be reported. In this case, only vehicles traveling over a certain speed and likely to enter the intersection during the yellow or red intervals will be added to the Yellow/Red Actuation report.

EXHIBIT 4-8. DETECTION REQUIREMENTS FOR SIGNAL PERFORMANCE MEASURES

TYPE OF DETECTION		AVAILABLE SIGNAL PERFORMANCE MEASURES	
None		• 3.1 Communication Status • 3.2 Flash Status • 3.3 Power Failures	• 3.18 Effective Cycle Length *(7)* • 3.24 Time-Space Diagram
Unmapped Detection		• 3.4 Detection System Status *(1)* • 3.6 Phase Termination • 3.7 Split Monitor • 3.13 Pedestrian Phase Actuation and Service	• 3.14 Estimated Pedestrian Delay • 3.25 Preemption Details • 3.26 Priority Details
Mapped Detection ***Lane-by-Lane: Each Detector Mapped to Its Own Channel*** ***or*** ***Multi-Lane: Multiple Detectors Tied Together Across Lanes***	**Stop Bar Presence**	• 3.8 Split Failures • 3.9 Estimated Vehicle Delay • 3.10 Estimated Queue Length	• 3.17 Red-Light Running (RLR) Occurrences • 3.23 Travel Time and Average Speed *(8)*
	Stop Bar Count	• 3.5 Vehicle Volumes • 3.8 Split Failures *(2)* • 3.9 Estimated Vehicle Delay *(3)*	• 3.15 Estimated Pedestrian Conflicts • 3.16 Yellow/Red Actuations • 3.23 Travel Time and Average Speed *(8)*
	Advance	• 3.5 Vehicle Volumes • 3.8 Split Failures *(2)* • 3.9 Estimated Vehicle Delay *(3)* • 3.10 Estimated Queue Length • 3.11 Oversaturation Severity Index	• 3.19 Progression Quality • 3.20 Purdue Coordination Diagram • 3.21 Cyclic Flow Profile • 3.22 Offset Adjustment Diagram • 3.23 Travel Time and Average Speed *(8)*
Special Detection	**AVI / AVL**	• 3.9 Estimated Vehicle Delay *(4)* • 3.10 Estimated Queue Length *(5)*	• 3.24 Time-Space Diagram *(9)*
	Pedestrian	• 3.12 Pedestrian Volumes	• 3.15 Estimated Pedestrian Conflicts
	Speed	• 3.16 Yellow/Red Actuations *(6)*	• 3.23 Travel Time and Average Speed

(1) Although some detection alarms do not require detection to be mapped, the most useful metrics will report status on specific detectors.

(2) Stop bar count and advance detection can be used to calculate volume-to-capacity ratios.

(3) Stop bar count and advance detection can be used to count vehicles for use in the HCM delay equation. Advance detection can also be used in arrival and departure models and to estimate time to service (with an adjustment to account for travel time to the stop bar).

(4) AVI/AVL data can be used to estimate delay using a travel time "route" that covers only one signalized movement.

(5) AVL data can be used to measure queues if the data are available at a high enough penetration rate.

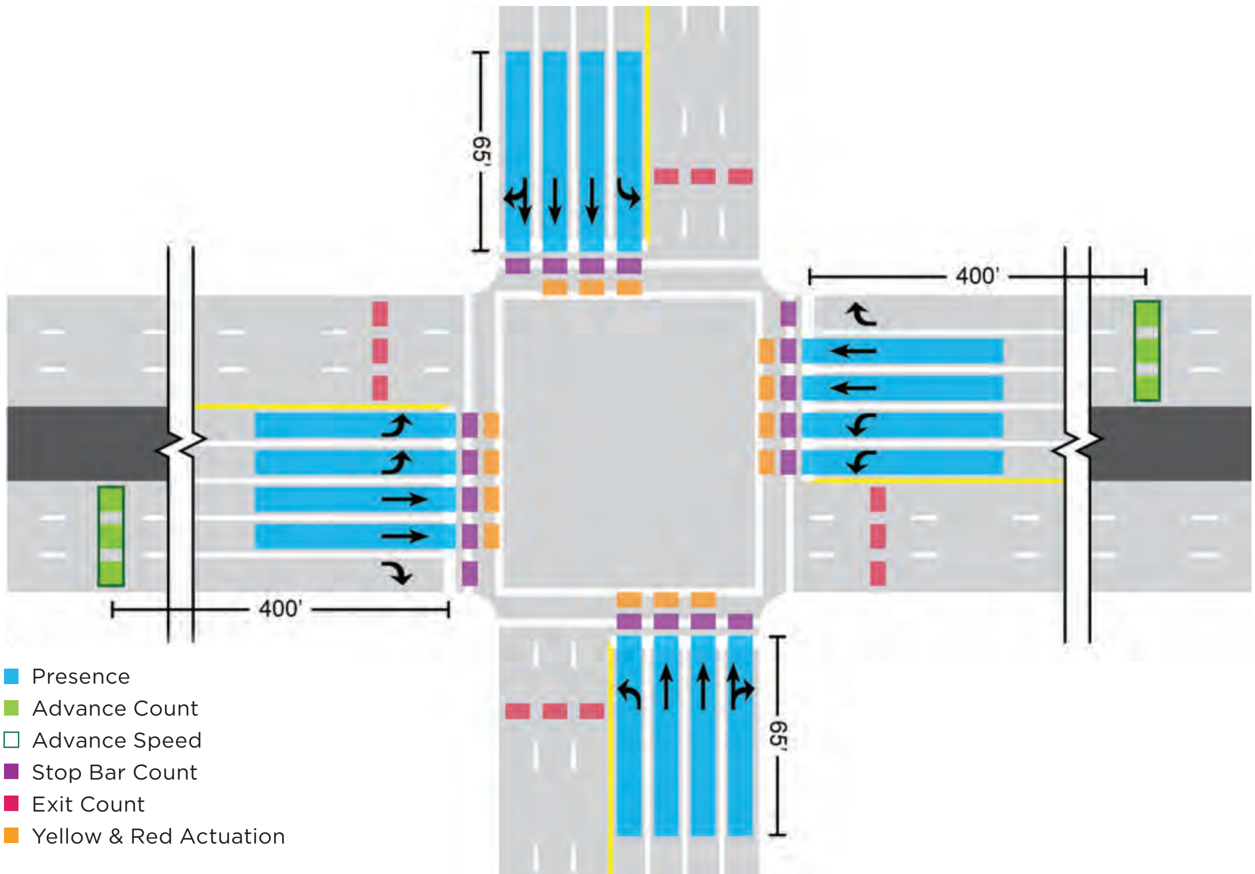
(6) Some detection technologies allow actuations to be recorded only if vehicles are traveling over a specific speed.

(7) No detection is required, but without detection, cycle lengths will remain constant.

(8) Stop bar presence, stop bar count, and advance detection can be used to calculate Estimated Vehicle Delay, which can be aggregated to estimate travel time.

(9) AVL data can be used to overlay vehicle trajectories.

EXHIBIT 4-9. EXAMPLE DETECTION LOCATIONS



Note: Adapted from "UDOT Automated Traffic Signal Performance Measures" (Mackey 2017).

DETECTOR CHANNEL MAPPING

For many signal performance measures, it is important for detection to be "mapped" so that the agency knows how detector channels are tied to lanes and phases. To fully describe an event, the following information is needed for the detection zone associated with each detector channel:

- Distance from the stop bar (i.e., advance, stop bar, past the stop bar)
- Type of wiring (i.e., lane-by-lane, multi-lane)
- Type of detection (i.e., presence, count)
- Approach (i.e., north, south, west, east)
- Lane group (i.e., left, through, right)
- Associated phase or overlap

EXHIBIT 4-10 shows example detector mapping information. The table links detector channels to lanes, movements (i.e., lane groups), and controlling phases.

EXHIBIT 4-10. EXAMPLE DETECTOR MAPPING INFORMATION

APPROACH	LANE GROUP	LANE	PHASE	CONTROL TYPE	PRESENCE CHANNEL	COUNT CHANNEL	DISTANCE FROM STOP BAR (FEET)	APPROACH SPEED (MPH)
NB	Left	-	5	Protected	17	19	0	55
NB	Thru	1 (Inside)	2	Protected	18	20	100	55
NB	Thru	1 (Inside)	2	Protected	39	-	365	55
NB	Thru	2 (Outside)	2	Protected	21	23	100	55
NB	Thru	2 (Outside)	2	Protected	40	-	365	55
NB	Right	-	2	Permitted	22	24	100	55

There are several places where detector mapping information may be available. If documentation is not readily available or no longer reflects field conditions, agencies can send staff into the field to confirm detector mapping.

- **As-built drawings.** Equipment layout and wiring diagrams are often included as part of as-built drawings (such as the example in **EXHIBIT 4-11**). A practitioner should conduct a field visit if the plans have aged and are no longer likely to represent actual conditions.
- **Signal timing sheets.** Practitioners can configure detector channels in the signal controller to call and/or extend specific phases. Although the signal timing sheets will not provide location information, they may help to clarify the phases and overlaps associated with detector channels.
- **Asset management system.** Some agencies may keep records of detection in an asset management system such as a Geographic Information Systems (GIS) database.
- **Cabinet labeling.** Detector racks in the cabinet may directly interface with physical detection; these may be “tagged” with information about the detectors (such as the example in **EXHIBIT 4-12**).
- **Detection software.** Detector rack units may provide input directly to the controller through the SDLC bus or some other interface. The detection zones (e.g., for video or radar systems) might be configured through a software interface that can provide the necessary information.

EXHIBIT 4-11. EXAMPLE AS-BUILT DRAWING (COURTESY INDIANA DEPARTMENT OF TRANSPORTATION)

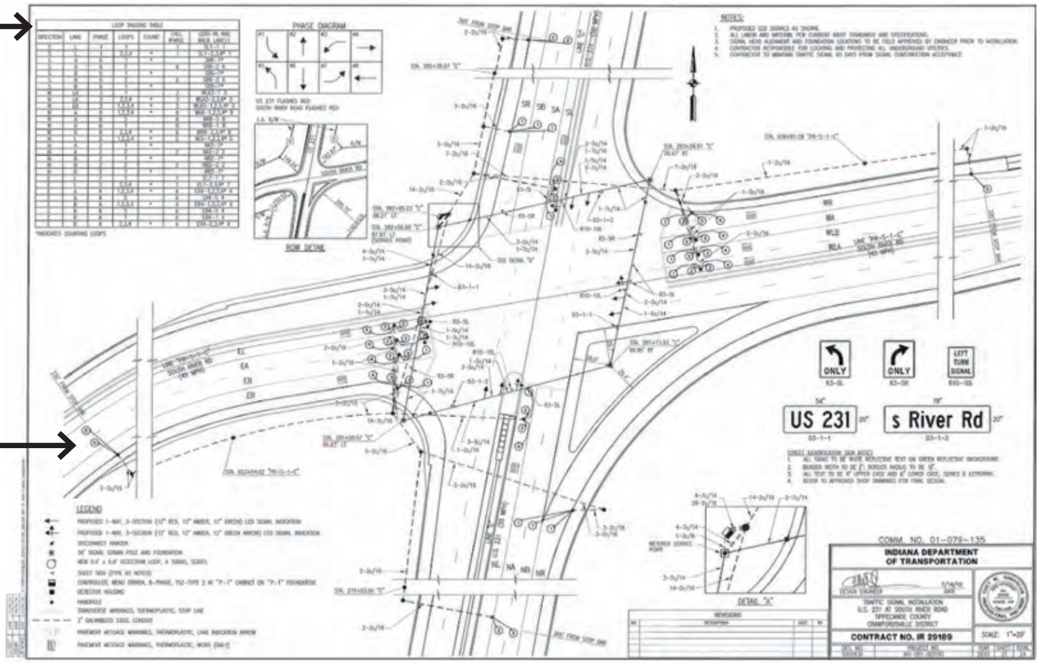


EXHIBIT 4-12. EXAMPLE DETECTOR RACK WITH LABELING FOR DETECTOR CHANNELS (COURTESY INDIANA DEPARTMENT OF TRANSPORTATION)

4.3.4 DATA LOGGING REQUIREMENTS

HIGH-RESOLUTION DATA

Several options exist for obtaining high-resolution data. All require that the IP address of the data logger be available so that data can be organized using an identifier. The most "complete" set of data will come from a data logger internal to a traffic signal controller. While external data collection units can record detection inputs and signal display outputs, a traffic signal controller can also record control parameters such as next phase decisions and phase termination types.

Several controller manufacturers have implemented the ATSPM data-logging feature in at least one controller model compatible with the NEMA TS/2 Type 1 and Type 2, ATC 170 and 2070 cabinet standards. If an agency installs new controllers to collect ATSPM data, signal timing from the old controllers will need to be converted. For more information on programming signal timing parameters, refer to *NCHRP Report 812: Signal Timing Manual, 2nd ed.* (STM2) (Urbanik et al. 2015).

It may be possible to collect high-resolution data using some older controller models through firmware upgrades or hardware upgrades (e.g., through installation of a new central processing unit, CPU). The data-logging feature may need to be enabled (through the front panel or an NTCIP setting), as this may not be the default setting. An agency should check that the data-logging feature remains active as part of regular maintenance (e.g., after a power loss).

Where controller upgrades are not feasible, an alternative would be to use an external data collection unit. There are now several vendors that have made such units commercially available. Although some events might not be captured, the data from an external unit will support most of the existing signal performance measures. Another advantage is that the controller can be separated from the ATSPM process, which may be desirable to some agencies.

Another alternative is to use NTCIP polling to obtain signal events. This method uses a central system to retrieve phase and detector states in real time. Because the event data are not cached, the events must be captured as they occur. This method requires a reliable, low-latency connection to the traffic signal controller because even 1 second of communication downtime could result in lost data.

OTHER DATA SOURCES

As discussed in *Section 4.2: Data Sources*, there are several data sources outside high-resolution data that can be used to produce ATSPMs. A few considerations relative to the field equipment required for those data sources are listed here:

- Certain data sets (such as probe data collected by private-sector vendors) do not require any agency-owned field infrastructure. However, an agency will likely need to secure server space (reference *Section 4.3.5: Data Storage Requirements*) and define the data to be provided (e.g., geographic extents and roadways).
- Vehicle identification data sources require sensors to be installed in the field with communication available to them. The sensors will need to be mapped to their geographic locations and routes in the network.
- Connected vehicle data requires a substantial investment in equipment to facilitate communication between vehicles and infrastructure. Those devices also need to have communication to a central office for full data collection capabilities.

4.3.5 DATA STORAGE REQUIREMENTS

HARDWARE

Some physical components will need to be configured at a central office if an agency decides to use in-house equipment to facilitate the retrieval, processing, presentation, access, and archiving of the ATSPM data. Agencies can use a collection of one or more servers to host applications, services, and data pertaining to an ATSPM system. The three essential considerations for a server are processing power, the size of the memory, and the disk configuration. Agencies can emphasize different components based on their needs.

- **Processing.** Agencies will need a faster processor for performing computationally intensive operations, real-time data processing, or video processing.
- **Memory.** Agencies that serve many users simultaneously, host many different applications, and perform a large amount of in-memory operations will need multiple gigabytes (GB) or terabytes (TB) of memory. Approximately one megabyte (MB) of data per intersection per day is needed (Bullock et al. 2011).
- **Disk configuration.** Agencies that store a significant amount of data may need multiple disks in a redundant array with backups. For large systems, the computational power can be distributed over multiple servers, such as with the Hadoop Distributed File System (HDFS). Depending on the server hardware, some systems may also require the additional purchase of racks and rack mounting hardware, cooling systems, power backups, and other supporting components.

In addition to servers, agencies may need to configure workstations or laptops to make use of the ATSPM platform applications and hosted services. For example, an analyst may use client software on a laptop to connect to a server database.

CLOUD

The alternative to an agency procuring their own server(s) is to use a cloud-based system with a vendor hosting the server(s). These solutions are typically subscription-based.

4.3.6 SOFTWARE REQUIREMENTS

OPERATING SYSTEM SOFTWARE

Operating system (OS) software is essential for the basic operation of server hardware. Windows and Linux-based platforms are the two most common types of server OS.

- **Windows** OS requires commercial licensing. Agencies that operate many servers can often purchase licenses in bulk.
- **Linux** OS comes in both freely available open source distributions and commercially licensed platforms.

When selecting an OS, agencies should consider ATSPM software compatibility, software dependencies, user authentication and security, and technical support options. Additionally, agencies should install anti-virus software with the OS to provide protection from viruses and malware. OS installation is typically completed by IT staff, consultants, or the server manufacturer prior to delivery of the hardware.

DATABASE SOFTWARE

There are many options available when selecting database software for storing and managing ATSPM data.

- **Relational Database Management Systems (RDBMS)** are popular for storing data in tabular formats similar to a spreadsheet organized using individual tables. Popular RDBMS software includes Microsoft SQL Server, PostgreSQL, and MySQL. Each has different features, capacities, and costs.

- **NoSQL varieties,** such as MongoDB, which store documents using dynamic schemas.
- **Cassandra**, which is highly scalable and uses a hybrid key-value and column-store architecture.

Although there are many options, it is important to consider the ATSPM software requirements as well as the workflow of the organization. Agencies can use more than one type of database software at different points in the lifecycle of the ATSPM data. For example, it may be beneficial for newer, more-frequently accessed data to operate on a highly optimized RDBMS while older data are stored as compressed flat files.

ATSPM SYSTEM SOFTWARE

ATSPM system software is used to convert data stored in a database into signal performance measures. Some software may have settings that need to be configured during initial set-up. For example, regions may need to be defined for intersection organization or user roles may need to be defined for administrative capabilities.

- **Open source software.** FHWA made an open source application developed by the Utah Department of Transportation (UDOT) available on its Open Source Application Development Portal (OSADP), and UDOT maintains a version on GitHub that allows developers to track their changes. Practitioners can download the application and install it at no cost. This option gives agencies the greatest flexibility to customize reports and features.
- **Agency-developed software.** Various research institutions and agencies, such as the University of Minnesota/Minnesota Department of Transportation (MnDOT), Purdue University/Indiana Department of Transportation (INDOT), and Colorado Springs, have developed their own ATSPM systems over the years.
- **Vendor-developed software.** More recently, vendors have incorporated ATSPM modules into their software for reporting and analytics. Available metrics and functionalities vary by vendor. There are typically annual subscription-based licensing fees, but implementation costs may be less than other options because of vendor-supplied data storage.

CENTRAL SYSTEM SOFTWARE

Central system software can potentially provide mechanisms for collecting, displaying, and archiving ATSPM data. In some cases, these implementations will need to have compatible equipment in the field to make use of the features at the central office. At present, several vendors offer central system products that include ATSPM capabilities, typically as "add-on" modules to the base software.

4.3.7 NETWORK SECURITY

There are two types of security that should be addressed in a traffic signal system (often requiring coordination with IT staff):

- **Physical** security for cabinets, server rooms, and offices where workstations and laptops reside.
- **Network** security for routers, switches, and wireless networks.

In order for the central office hardware to retrieve ATSPM data from the field, the devices must have some type of network connectivity to the intersections. Agencies with dedicated communications infrastructure (such as fiber networks out to each cabinet) have the benefit of being able to operate within the agency's intranet. Networks that rely on some type of commercially operated connection in the communications chain (such as a cellular network between the intersections and central office) typically have data transferred through the internet.

In those cases, Virtual Private Networks (VPNs) are often used for virtually incorporating networks in the field into the central office network. VPNs use encryption algorithms that are provided by dedicated VPN routers, built into a cellular modem, or configured as a software option. Common encryption protocols include:

- Point-to-Point Tunneling Protocol (PPTP)
- Layer 2 Tunneling Protocol (L2TP)
- Internet Protocol Security (IPSec)
- Secure Socket Tunneling Protocol (SSTP)
- Internet Key Exchange version 2 (IKEv2)
- OpenVPN, which employs the OpenSSL library
- Transport Layer Security (TLS) methods

Practitioners can leverage software configurations to provide further layers of security. One example is setting up or using an existing user authentication protocol to provide limited access to certain types of data or user interfaces. Other methods include further dividing the intranet into subnetworks where more sensitive devices such as controllers and signal monitors are obscured to a user with non-elevated credentials.

4.4 DATA MANAGEMENT

ATSPM data will go through the following lifecycle between initial collection and interpretation. Keeping all the raw data is not the most efficient use of storage space or processing power, so this section describes steps that can be taken to manage data between downloading it and displaying it as actionable information.

Download unprocessed data from a data logger to the central office.

Normalize unprocessed data (potentially from different sources) into a uniform, consistent, and efficient format.

Store unprocessed or normalized data in a database.

Process data using logic, algorithms, and heuristics.

Display processed data using charts, graphs, tables, maps, and text reports.

4.4.1 DATABASE STRATEGIES

Depending on the ATSPM software that is used, there may be differences in how data are stored. ATSPM databases can fill up quickly. Several basic database management strategies are suitable for large data sets.

- **Data types.** Select an appropriate data type for each data field to improve performance and reduce data size. For example, a field that contains only integers between 0 and 255 can be stored as a 1-byte integer instead of a string.
- **Compression.** Data compression reduces the amount of space needed on the server and improves query response times. Types of compression features vary amongst database software.
- **Clustering and indexing.** Queries can be faster if data are organized or "clustered" according to the most critical fields (i.e., fields consistently used for filtering clauses). Creating non-clustered indices on frequently queried columns will add further performance benefits (although at the cost of additional storage consumption).
- **Partitioning.** Large, homogeneous data sets, such as those contained in a single data table, can be subdivided or "partitioned" into separate data sets for improved performance and management flexibility. Depending on the database software, practitioners can use different partitioning methods. For example, in a relational database, practitioners can partition a single data table that spans several years into monthly partitions, back up the older partitions onto tape, and remove them from the main database.

4.4.2 DATA ARCHIVING

Moving older data to an archive (i.e., through a logical or physical separation) can limit the size and improve the efficiency of an ATSPM system. An archival process moves data from an active or "hot" system where users and programs can retrieve it quickly to an archive or "cold" system with lower priority access. In most cases, practitioners may need to process archived data to make it useful again.

- **Logical separation** keeps the data on the same physical medium (i.e., an array of hard drives) but separates the data using different software containers and pointers within the medium.
- **Physical separation** copies the data to a different medium. This can be on the same server (i.e., different array of hard drives on the same server), a different server, or in the cloud.

The amount of time to keep records "active" depends on how often and far back an agency requires access to archived data as well as storage constraints. For systems that have few intersections, it may be feasible to keep many years of data in both active and archive systems. For larger systems, practitioners may only be able to keep a few months of data active and maintain up to 2 years of archives.

4.4.3 DATA AGGREGATION

Practitioners can convert raw data into aggregated metrics for quicker queries. Aggregated metrics consume less storage space than raw data because certain temporal and spatial attributes are combined for greater efficiency. For example, practitioners might use aggregation for the following data.

- Convert detector on and off events into occupancy events, reducing the number of detection records by half.
- If there are stop bar detectors in multiple lanes, only keep the highest occupancy ratio for split failure calculations.
- Bin metrics into time intervals (e.g., 5, 10, 15 minutes) by summing the number of occurrences.

4.5 CONSIDERATIONS FOR ATSPM SYSTEM SELECTION

4.5.1 USER INTERFACES

There are three major types of user interfaces that can display ATSPM data: web-based, mobile, and desktop applications. A greater number of users can generally gain access through web-based and mobile applications than if a desktop application is used. Web-based and mobile applications can be open (for public access) or restricted (for agency-only access). Restricted access will require user accounts, but data scrubbing will not be as critical. Tools such as Google Analytics can be used to track times and pages being accessed, so that information can be tailored to the most-frequent users.

- **Desktop applications** are typically installed on a per-workstation basis and activated by licensing systems or a product key.
- **Web-based applications** are run on a server and accessed by users over the internet (or alternately within an intranet on a private network) through a web browser on a computer.
- **Mobile applications** function on a mobile device (i.e., cell phone or tablet) either through a web browser or a standalone app.

4.5.2 DATA EXPORTING

Many ATSPM systems have some capability to export data either into a flat file such as a comma-separated values (CSV) file or into tables and charts. These features typically require a small amount of configuration for the format of the exported data and which ATSPM elements will be included in the output.

4.5.3 ALERTS AND THRESHOLDS

Parameters can be defined in an ATSPM system to alert users of performance issues via email or text message. User roles can be defined so that different groups receive different types or categories of alerts; roles may be defined by staff responsibilities or geographic boundaries. For each alert, specific performance measure thresholds (discussed in *Chapter 5*) should be established to determine when alerts are sent.

4.5.4 SYSTEM REPORTS

ATSPMs can provide insights into how a system is performing for a given time period. It is important to understand how ATSPM information will ultimately be used, so that customized reports can be developed that are appropriate for different groups. For example, a field engineer may want a report for traffic signals in his or her district that contains detailed split failure information, volumes, and progression percentages, while an operations manager may only want a performance index for percentage of signals communicating.

4.5.5 INTEGRATION WITH EXISTING SYSTEMS

An ATSPM system may need to interface with multiple existing agency systems.

- Many agencies have existing user account systems to grant login and access privileges.
- Existing asset management systems and GIS can reduce some of the upfront configuration efforts for ATSPMs, such as by providing the latitude and longitude for each intersection.
- Other external systems such as weather service, automatic vehicle location, connected vehicle systems, and probe data systems can be complementary to ATSPM data.

4.5.6 COORDINATION WITH IT STAFF

Coordination with IT staff will be important, particularly for traffic signal groups that share communications infrastructure with other city services (e.g., police, fire). Managing traffic signal system components as network devices will likely be a new task for IT personnel and may require closer coordination than typical day-to-day interactions.

4.6 REFERENCES

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CHAPTER 5 IMPLEMENTATION OF PERFORMANCE MEASURES

LIST OF EXHIBITS

CHAPTER FOCUS

After an agency has procured and installed the necessary resources to deploy signal performance measures (as described in *Chapter 4*), they must program the intersections into the automated traffic signal performance measure (ATSPM) system and verify that it is reporting accurate information. This chapter describes ways to check that intersections have been configured correctly and how to use the information from the reports to make signal timing and maintenance adjustments.

5.1 CONFIGURATION

EXHIBIT 5-1 summarizes several pieces of information that must be programmed in the ATSPM system prior to producing reports: signal ID, controller type, and detection (as described in *Chapter 4*). If using a vendor-supported ATSPM system, these elements may be programmed by the vendor, but the verification techniques discussed in *Section 5.2: Configuration Verification* should be applied regardless of how initial values are programmed.

EXHIBIT 5-1. INTERSECTION CONFIGURATION REQUIREMENTS

INTERSECTION CONFIGURATION REQUIREMENTS		DESCRIPTION/EXAMPLES	
Signal ID		• Number (e.g., IP address)	
Controller Type		• Controller type and firmware version must be identified to convert the high-resolution data into a standard database format.	
Detection	**Approach**	• Northbound • Southbound	• Westbound • Eastbound
	Phase	• Number (e.g., Phases 1–8)	
	Channel	• Number (e.g., Channels 1–96)	
	Type	• Stop Bar Presence • Stop Bar Count • Advance	• AVI/AVL • Pedestrian • Speed
	Location ***(Advance Only)***	• Distance from stop bar (e.g., 400 feet)	• Speed on approach (e.g., 40 mph)
	Lane Number ***(Typically Numbered from Inside to Outside)***	• Left 1, 2, n • Left-Through 1, 2, n • Through 1, 2, n	• Through-Right 1, 2, n • Right 1, 2, n • Bicycle 1, 2, n

5.2 CONFIGURATION VERIFICATION

There are verification techniques an agency can use to confirm that data are being collected appropriately and that intersections have been configured correctly in the ATSPM system. Most of these techniques require that a practitioner compare the programmed signal timing to the ATSPM data. The comparison can reveal issues with the ATSPM system and may also highlight signal timing parameters that have been mis-programmed in the controller. For example, a practitioner may be expecting that the coordinated timing plans end at 7:00 PM, but the ATSPM reports may show them ending at 10:00 PM. There could be an issue with the ATSPM system (e.g., the wrong intersection address may have been programmed or the timestamps may not be adjusted to the correct time zone) but it is also possible that the time-of-day plan has been mis-programmed in the controller. As a practitioner uses these verification techniques, he or she should reference up-to-date signal timing plans from the controller.

5.2.1 DATA AVAILABILITY

POTENTIAL ISSUE

Data are not being reported for some or all time periods.

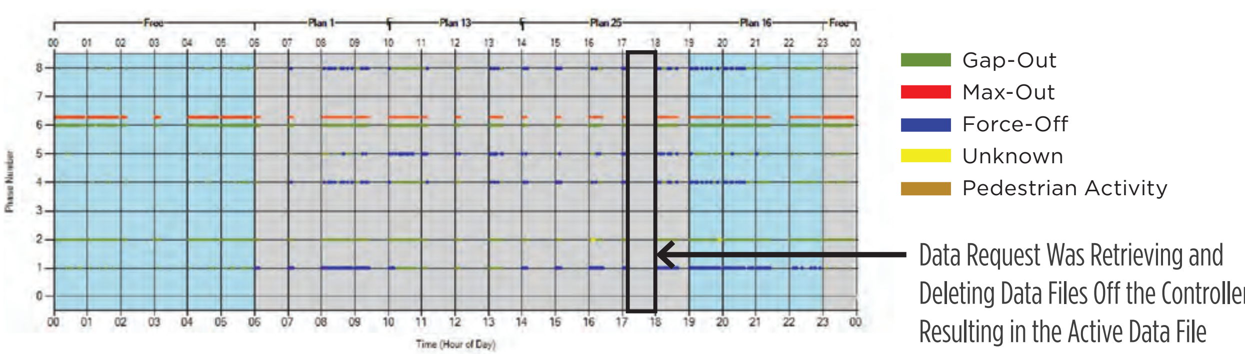
POTENTIAL CAUSE

- Data are not being recorded by the data logger. There may be a setting that is preventing the high-resolution data from being logged, the active data file may be corrupt, or the data logger may not have adequate memory.
- Data are not being downloaded from the data logger to the central office. There may be an issue with communication or the data request settings.
- Data are not being translated from the unprocessed data files into the database. There may be an issue with the code used to normalize the data.
- Data are not being aggregated correctly. There may be an issue with the functions used to calculate various metrics.
- Data are not being displayed correctly in the reports. There may be an issue with the code used to generate graphics.

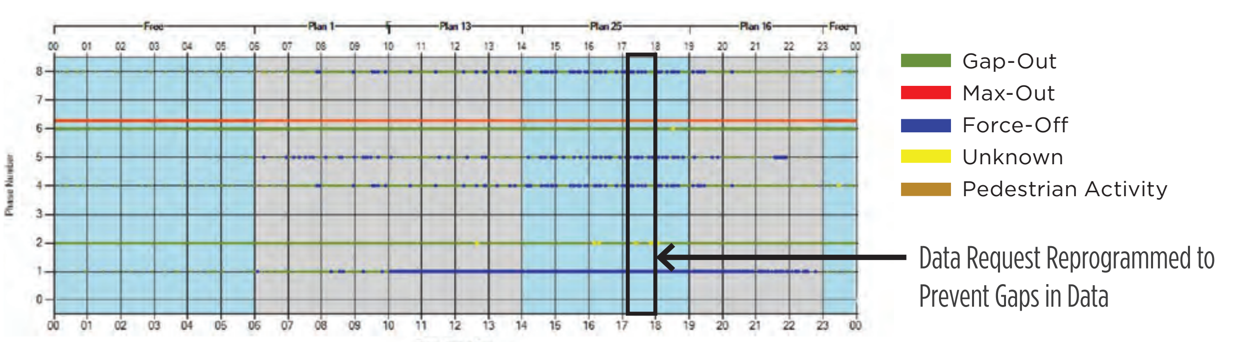
EXAMPLE CHECK Are there gaps in data?

At an intersection in Virginia, data were successfully downloaded from a traffic signal controller, but once the data set was processed, the phase termination report revealed gaps (as shown in **EXHIBIT 5-2A**). In this case, the data request was retrieving unprocessed data files and then deleting them off the controller to prevent duplication in the database. It was discovered that the active file was being retrieved and deleted in addition to the historical data files, which prevented new data from being recorded until another active data file was created at the beginning of each hour. The code used to request and transfer the data into the database was rewritten so that data did not have to be deleted from the controllers. After being collected, only the most recent data were transferred to the database, resulting in a full dataset as shown in **EXHIBIT 5-2B**.

EXHIBIT 5-2. DATA AVAILABILITY EXAMPLE (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



(A) Missing data before code updates



(B) No missing data after code updates

5.2.2 TIMESTAMPS

POTENTIAL ISSUE

Data are not being reported at the correct times.

POTENTIAL CAUSE

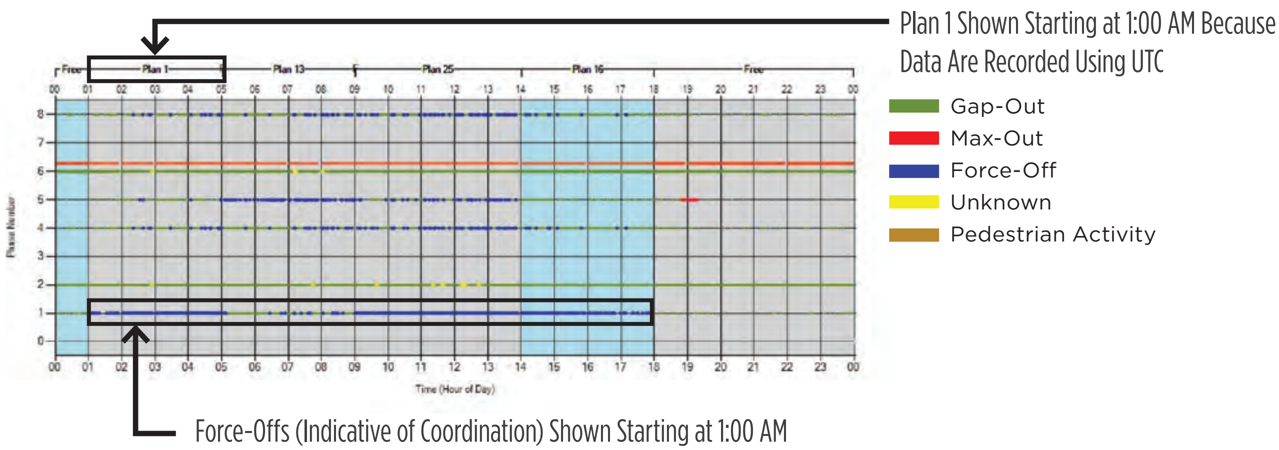
- Enumerations timestamped using Coordinated Universal Time (UTC).
- Enumerations timestamped without daylight savings time enabled.

EXAMPLE CHECK Is data being reported at the correct times?

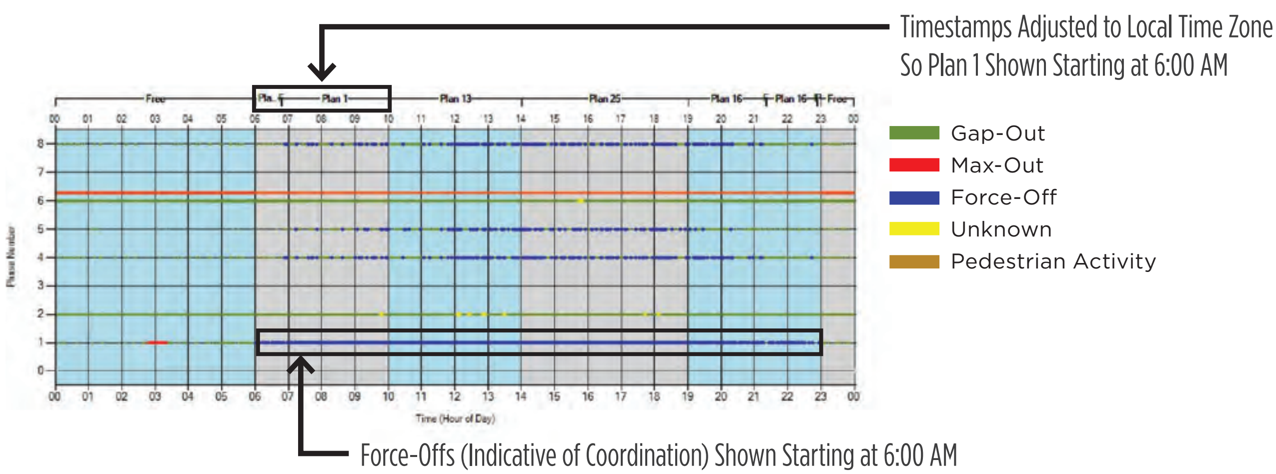
Using a phase termination report provides several indicators that data are being reported at the correct timestamps. In the example illustrated in **EXHIBIT 5-3**, the coordination plans are listed at the top of the chart, so their start and end times can be directly compared to the programmed time-of-day (TOD) plan. However, termination types can also be indicative of coordinated times of day. For example, force-offs will be recorded during coordination plans while max-outs will be recorded during uncoordinated times of day.

In this case, the first coordination plan and associated force-offs were shown starting at 1:00 AM in **EXHIBIT 5-3A**, which was several hours off from the programmed TOD plan. It was discovered that the controller was logging enumerations using UTC timestamps, so the timestamps had to be converted to the local time zone. Once the timestamps had been adjusted, the same phase termination report in **EXHIBIT 5-3B** showed the first coordination plan and associated force-offs starting at 6:00 AM.

EXHIBIT 5-3. TIMESTAMPS EXAMPLE (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



(A) Before time zone adjustment



(B) After time zone adjustment

5.2.3 INTERSECTION CONFIGURATION

POTENTIAL ISSUE

Data are being reported from a different intersection than intended. If a signal ID is mis-programmed, data from an intersection may be tied to the wrong intersection name or detector configuration.

POTENTIAL CAUSE

- Mis-programmed signal ID.

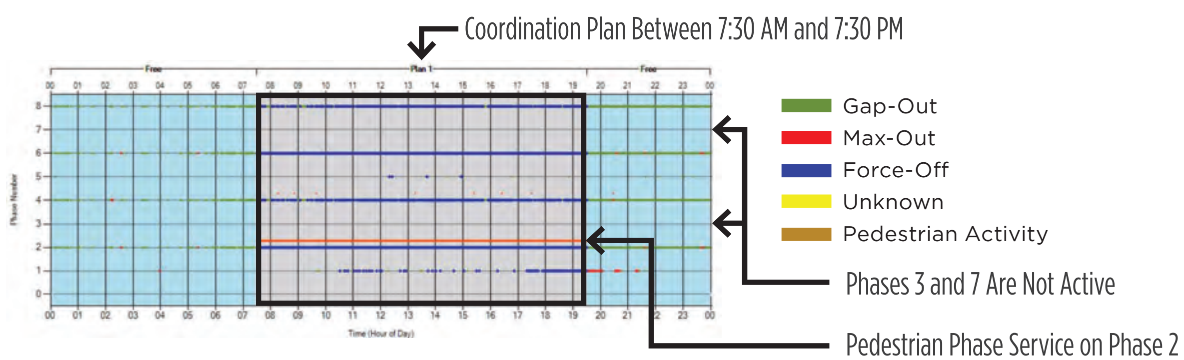
EXAMPLE CHECK 1 Do phase terminations match programmed phases?

In the example in **EXHIBIT 5-4**, the phase termination report provides several pieces of information about the operation of the intersection.

- Data are reported for Phases 1, 2, 4, 5, 6, and 8, but not for Phases 3 and 7.
- There is a pedestrian phase programmed on Phase 2 only.
- The intersection has one coordination plan that operates during the day and then runs free at night.

If a practitioner expected data on eight phases (e.g., if protected left turns were present on all approaches), pedestrian phase service on all approaches (e.g., Phases 2, 4, 6, and 8), or multiple coordination plans, this report could indicate that the data came from a different intersection than intended.

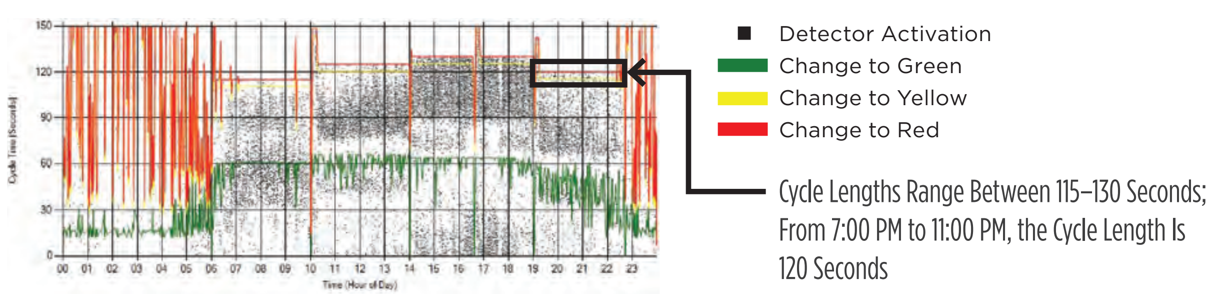
EXHIBIT 5-4. INTERSECTION CONFIGURATION EXAMPLE: PHASE TERMINATIONS (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



EXAMPLE CHECK 2 Do cycle lengths match programmed values?

Although Purdue Coordination Diagrams report a variety of progression information, they can also be used to quickly assess cycle lengths to ensure they match those programmed in the coordination plans. **EXHIBIT 5-5** is an example that illustrates cycle lengths ranging between 115 seconds and 130 seconds. If a practitioner expected cycle lengths between 90 seconds and 110 seconds, this report could indicate that the data are from a different intersection than intended. Note that there may be some variability in cycle lengths during coordination plans, depending on actuated-coordinated operations, pedestrian timing that is not accommodated within the coordinated cycle length, and preemption or priority events.

EXHIBIT 5-5. INTERSECTION CONFIGURATION EXAMPLE: CYCLE LENGTHS (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



5.2.4 DETECTOR CONFIGURATION

POTENTIAL ISSUE

Volumes are reported higher or lower than expected conditions based on directionality, peak periods, or values compared to capacity.

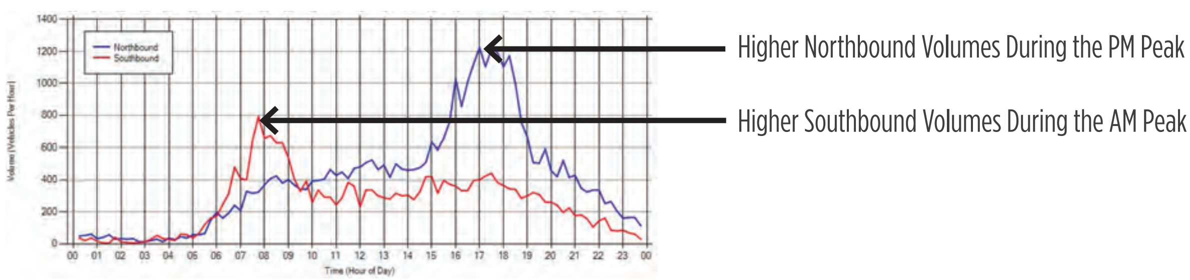
POTENTIAL CAUSE

- Mis-programmed signal ID.
- Mis-programmed detector channel (e.g., number, phase).
- Mis-programmed detector location (e.g., approach, lane, movement).
- Mis-programmed detector type (e.g., stop bar, advance, speed).
- Malfunctioning detector.

EXAMPLE CHECK 1 Do volume profiles match expected conditions?

EXHIBIT 5-6 shows 15-minute flow rates for a 24-hour period. This report can be used to verify that the correct intersection has been programmed and whether detectors have been configured correctly. In this example, there are higher southbound volumes in the morning and higher northbound volumes in the evening. If the intersection was located on a corridor with the opposite commute patterns, this report could indicate that the data are from a different intersection than intended or that the detectors have been programmed incorrectly (i.e., mis-programmed detector channel, location, or detector type).

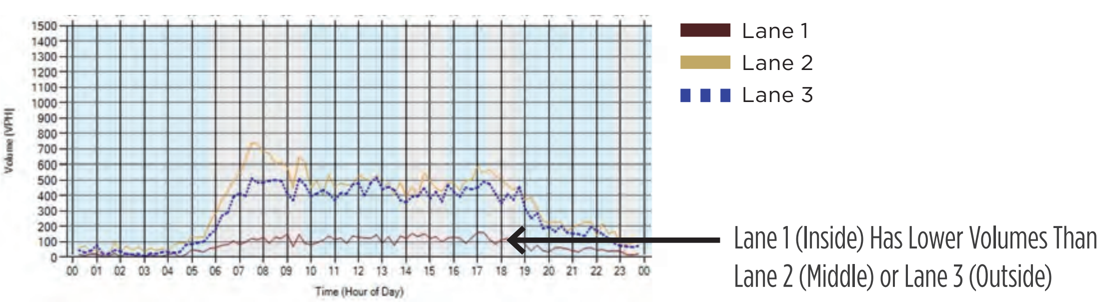
EXHIBIT 5-6. DETECTOR CONFIGURATION EXAMPLE: APPROACH VEHICLE VOLUMES (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



EXAMPLE CHECK 2 Does the lane distribution match expected conditions?

EXHIBIT 5-7 shows 15-minute flow rates for three southbound through lanes. Lanes are numbered from inside to outside, so this example shows the inside through lane has lower volumes than the middle and outside lanes. If most vehicles are making a southbound left turn downstream of the intersection, this volume distribution might indicate that the detector channels have not been configured for the correct approach or lane.

EXHIBIT 5-7. DETECTOR CONFIGURATION EXAMPLE: LANE-BY-LANE VEHICLE VOLUMES (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



5.3 DATA VERIFICATION

Although data can be verified qualitatively based on knowledge of the intersection, high-resolution data should also be verified quantitatively using a secondary source.

5.3.1 TRAFFIC COUNTS

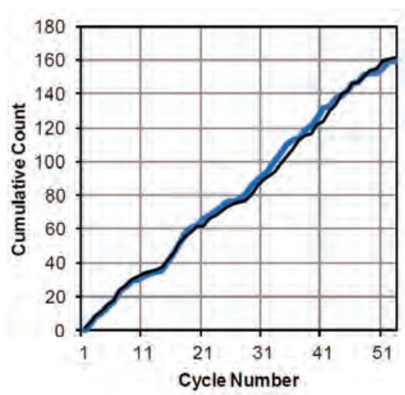
DESCRIPTION

Traffic counts can be collected using a traditional method, such as permanent count stations or manual turning movement counts, and then compared against detector actuations from high-resolution data.

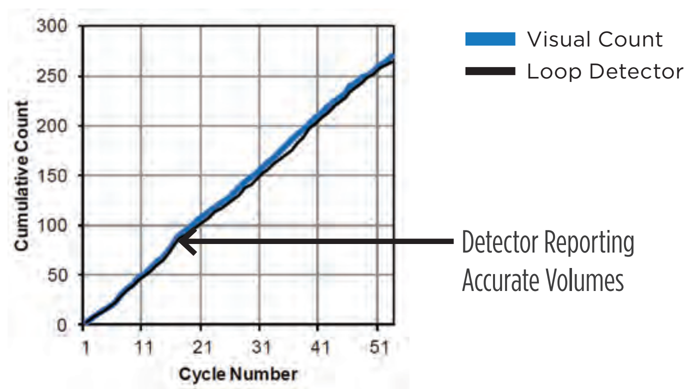
EXAMPLE CHECK

EXHIBIT 5-8 compares loop detector actuations against a visual count obtained from a video recording. **EXHIBIT 5-8A** and **EXHIBIT 5-8B** show that the westbound detectors are reporting accurate volumes, **EXHIBIT 5-8C** shows the southbound detector in the inside lane over-counts slightly, and **EXHIBIT 5-8D** shows the southbound detector in the outside lane reports twice as many vehicles as are observed. This type of analysis can help an agency determine the accuracy of volumes being reported and could be used to adjust the high-resolution data.

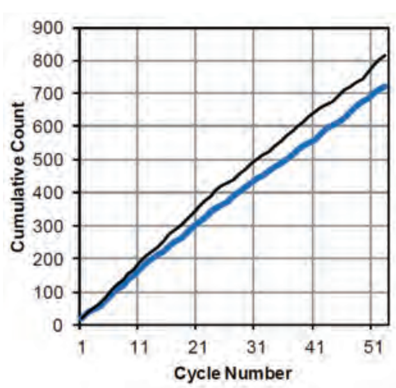
EXHIBIT 5-8. DATA VERIFICATION EXAMPLE: TRAFFIC COUNT COMPARISON OF LOOP DETECTOR ACTUATIONS VERSUS VISUAL COUNTS (DAY ET AL. 2014)



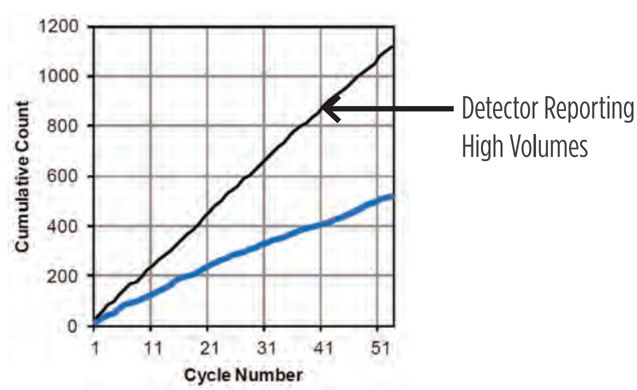
(A) Westbound left (stop bar)



(B) Westbound through (stop bar)



(C) Southbound inside lane (advance)



(D) Southbound outside lane (advance)

5.3.2 VIDEO RECORDING

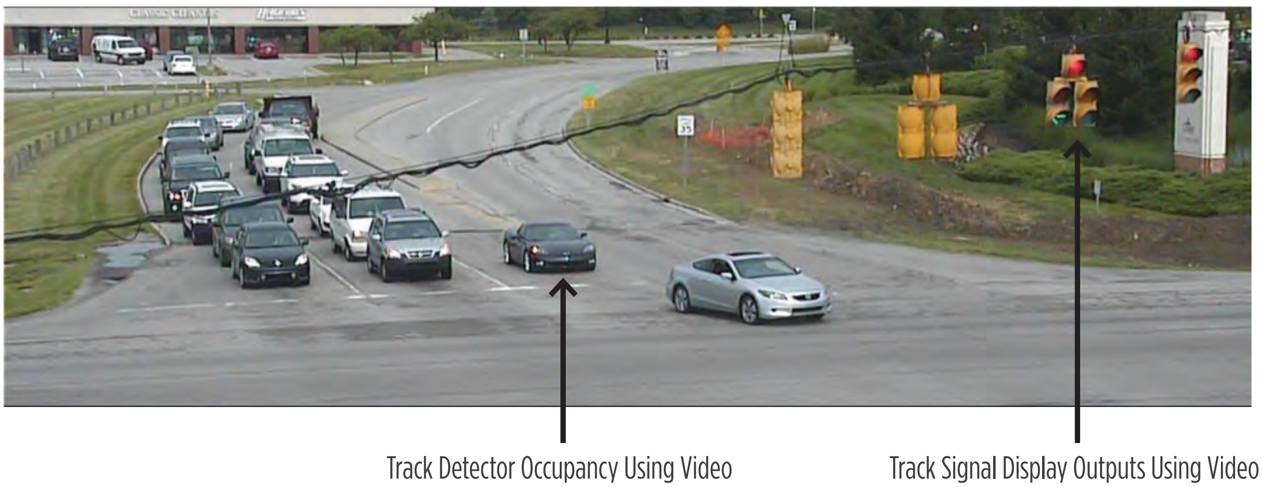
DESCRIPTION

Video recordings can be used to verify any signal performance measure. Agencies can directly compare events recorded by the controller and events seen on the video for a selected time period. This information can be used to compare the accuracy of different detection systems or ATSPM systems.

EXAMPLE CHECK

EXHIBIT 5-9 is an example of a screen capture from a video recording. In this case, the video was used to verify split failures. A practitioner used the video to observe green occupancies and red occupancies in order to identify if split failures were being reported accurately through the high-resolution data.

EXHIBIT 5-9. VIDEO RECORDING EXAMPLE (BULLOCK 2016)



5.3.3 TRAVEL TIME AND AVERAGE SPEED

DESCRIPTION

Travel times and average speeds collected by probe data can be compared to progression quality metrics. For example, intersections with poor progression (e.g., high arrivals on red along a corridor) should generally correlate to longer corridor travel times and slower speeds.

EXAMPLE CHECK

EXHIBIT 5-10 shows average, 5th percentile, and 95th percentile speeds collected using Bluetooth data on a route operated by the Virginia Department of Transportation. Prior to a midday offset adjustment, the corridor experienced lower speeds. This correlated directly to fewer arrivals on green, which could be assessed using a report such as the Purdue Coordination Diagram in **EXHIBIT 5-11**.

EXHIBIT 5-10. TRAVEL TIME AND AVERAGE SPEED EXAMPLE: AVERAGE, 5TH PERCENTILE, AND 95TH PERCENTILE SPEEDS (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)

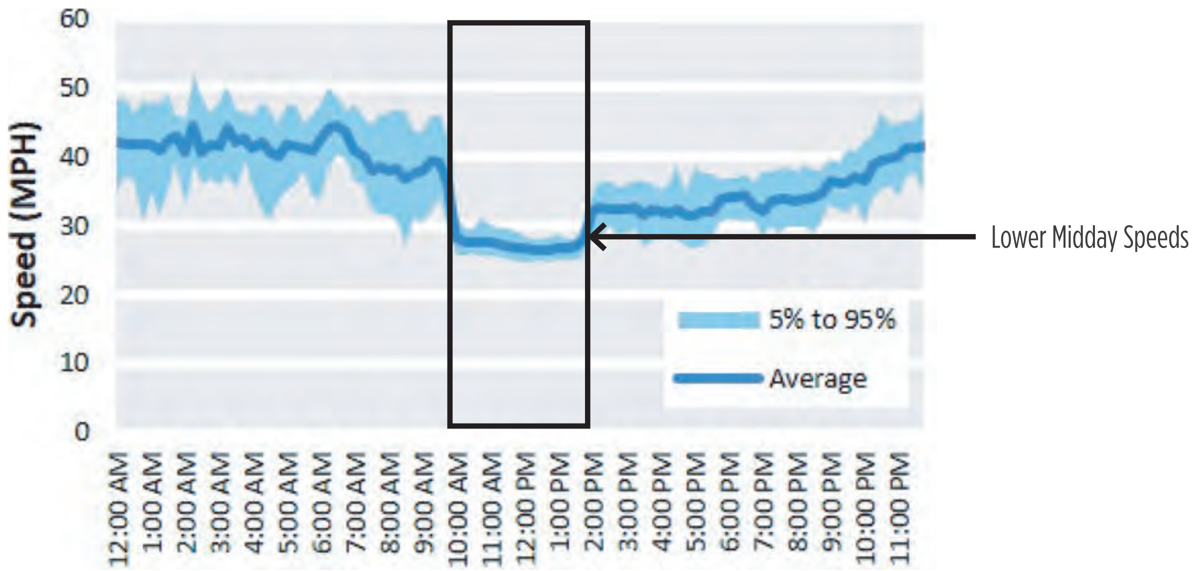
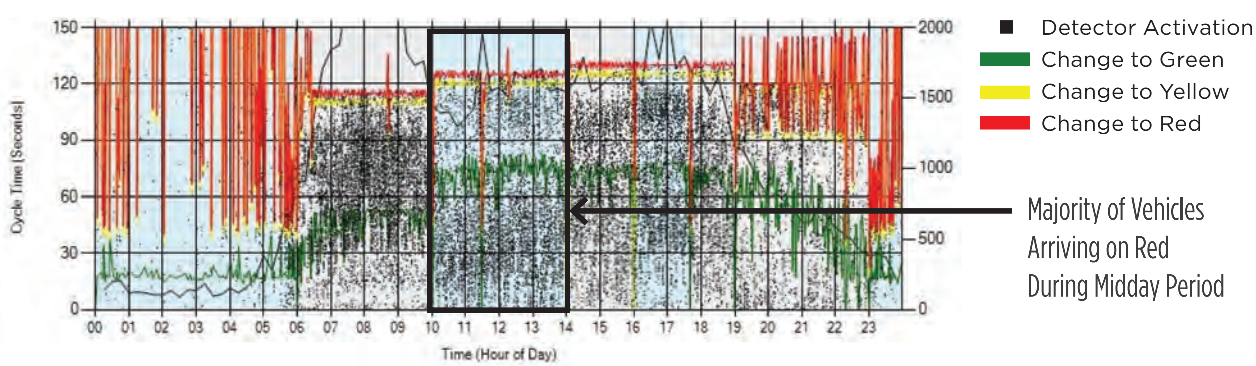


EXHIBIT 5-11. TRAVEL TIME AND AVERAGE SPEED EXAMPLE: PURDUE COORDINATION DIAGRAM (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



5.4 VALIDATION

ATSPMs allow an agency to collect robust and widespread signal performance data, which can help practitioners (1) find problems faster (e.g., mis-programmed parameters, malfunctioning equipment, and intersections that need to be retimed) and (2) quickly identify the impact of adjustments. This section discusses ways in which ATSPMs can be used by agencies for validating their signal systems, as summarized in **EXHIBIT 5-12**. The following content is organized using *NCHRP Report 812: Signal Timing Manual, 2nd ed.* (STM2) categories (Urbanik et al. 2015): (1) intersection/uncoordinated timing, (2) system/coordinated timing, (3) advanced systems and applications, and (4) equipment maintenance.

EXHIBIT 5-12. PERFORMANCE MEASURE VALIDATION APPLICATIONS

	UNCOORDINATED								COORDINATED			ADV		EQUIPMENT			
PERFORMANCE MEASURE	YELLOW CHANGE	RED CLEARANCE	MINIMUM GREEN	MAXIMUM GREEN	PASSAGE TIME	PED. INTERVALS	RECALLS	TOD PLANS	CYCLE LENGTH	SPLITS	OFFSETS	ADVANCED SYS.	PREF. TREATMENT	COMMUNICATION	SIGNAL CABINET	VEHICLE DETECTION	PED. DETECTION
3.1 COMMUNICATION STATUS														X			
3.2 FLASH STATUS															X		
3.3 POWER FAILURES															X		
3.4 DETECTION SYSTEM STATUS																X	X
3.5 VEHICLE VOLUMES			X	X			X	X	X	X		X				X	
3.6 PHASE TERMINATION				X	X		X		X	X		X				X	X
3.7 SPLIT MONITOR				X	X		X		X	X		X				X	X
3.8 SPLIT FAILURES				X	X				X	X		X					
3.9 ESTIMATED VEHICLE DELAY				X	X				X	X		X					
3.10 ESTIMATED QUEUE LENGTH			X	X					X	X	X	X					
3.11 OVERSATURATION SEVERITY INDEX				X	X				X	X	X	X					
3.12 PEDESTRIAN VOLUMES			X	X		X	X	X	X	X		X					X
3.13 PEDESTRIAN PHASE ACTUATION AND SERVICE			X	X		X	X	X	X	X		X					X
3.14 ESTIMATED PEDESTRIAN DELAY				X		X			X	X		X					X
3.15 ESTIMATED PEDESTRIAN CONFLICTS						X											
3.16 YELLOW/RED ACTUATIONS	X	X			X												
3.17 RED-LIGHT-RUNNING (RLR) OCCURRENCES	X	X			X												
3.18 EFFECTIVE CYCLE LENGTH								X	X			X					
3.19 PROGRESSION QUALITY									X		X	X					
3.20 PURDUE COORDINATION DIAGRAM								X	X		X	X					
3.21 CYCLIC FLOW PROFILE									X		X	X					
3.22 OFFSET ADJUSTMENT DIAGRAM											X	X					
3.23 TRAVEL TIME AND AVERAGE SPEED	X	X									X	X					
3.24 TIME-SPACE DIAGRAM											X	X					
3.25 PREEMPTION DETAILS													X				
3.26 PRIORITY DETAILS													X				

5.5 INTERSECTION/UNCOORDINATED TIMING VALIDATION

Intersection/uncoordinated timing parameters must be programmed at every signalized intersection.

5.5.1 YELLOW CHANGE

DESCRIPTION

The *Manual on Uniform Traffic Control Devices* (MUTCD) requires that the yellow change interval be determined using engineering practices (FHWA 2009). When determining the time for yellow change, a practitioner should consider perception-reaction time, approach speed, deceleration rate, and approach grade. These values are often estimated using defaults, but they can be adjusted based on measured data (e.g., speeds).

If there are many vehicles entering the intersection on red, the yellow change interval should be investigated. It is possible that actual speeds are higher than those used to calculate the yellow change interval. If the yellow is too short, drivers will experience a decision zone.

Note that yellow change is only one control parameter that influences whether vehicles enter an intersection on red. Detector placement and passage settings can impact the number of vehicles caught in the decision zone (i.e., forced to make a go/no-go decision) and overall signal timing can impact vehicle delay and progression quality, sometimes leading to more aggressive driving and more red-light-running occurrences.

PERFORMANCE MEASURES

- 3.16 Yellow/Red Actuations
- 3.17 Red-Light-Running (RLR) Occurrences
- 3.23 Travel Time and Average Speed

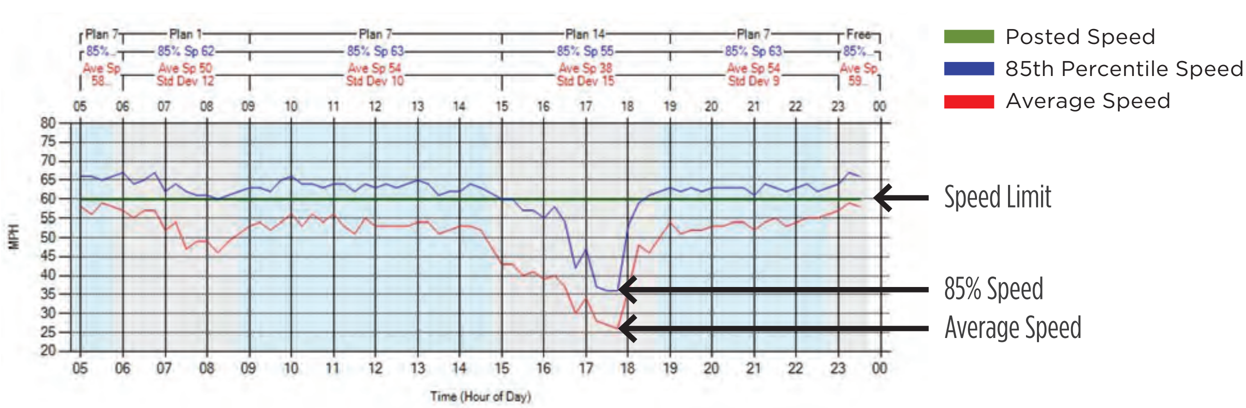
STM2 REFERENCE

- Section 6.1.1: Yellow Change

EXAMPLE

Using speed reports such as the example in **EXHIBIT 5-13**, an agency can confirm and/or adjust speeds used in yellow change calculations.

EXHIBIT 5-13. YELLOW CHANGE EXAMPLE: APPROACH SPEED (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



5.5.2 RED CLEARANCE

DESCRIPTION

Red clearance is a signal timing parameter that is applied differently across agencies. While not required, the purpose is to provide an interval when conflicting signal displays are red so that a vehicle that entered the intersection on yellow has enough time to cross the intersection without conflict.

Using signal performance measures that track vehicles entering the intersection on red can help an agency identify whether red clearance should be applied, as well as the appropriate duration.

PERFORMANCE MEASURES

- 3.16 Yellow/Red Actuations
- 3.17 Red-Light-Running (RLR) Occurrences
- 3.23 Travel Time and Average Speed

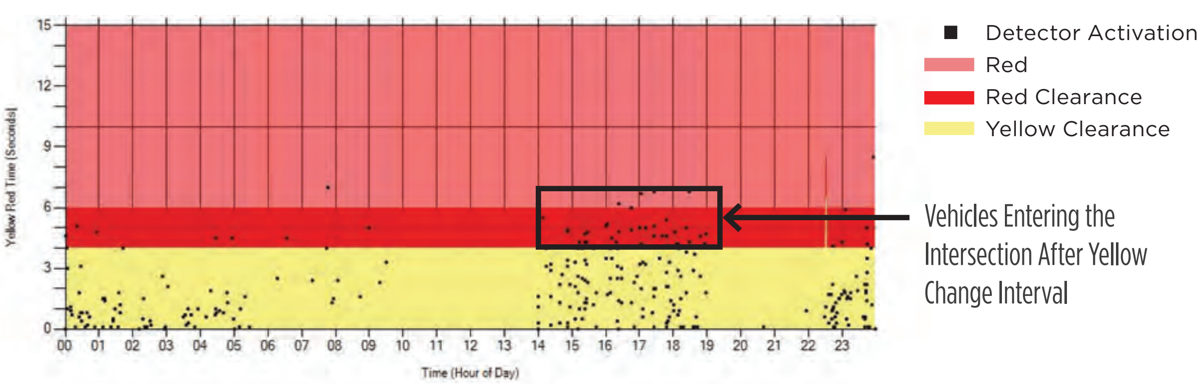
STM2 REFERENCE

- Section 6.1.2: Red Clearance

EXAMPLE

Using yellow/red actuations (as shown in **EXHIBIT 5-14**), an agency can determine the frequency of violations (i.e., vehicles that entered the intersection on red) and "severe" violations (i.e., vehicles that entered the intersection well after the end of red clearance). If the report reveals a relatively high number of vehicles entering the intersection in the first few seconds after the end of the yellow change interval, an agency may use ATSPMs to evaluate progression and determine if an adjustment to the offset or green time could reduce the frequency of violations, or if additional red clearance is necessary.

EXHIBIT 5-14. RED CLEARANCE EXAMPLE: YELLOW/RED ACTUATIONS (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



5.5.3 MINIMUM GREEN

DESCRIPTION

Minimum green values should be set based on driver expectancy and to clear vehicle queues (depending on the detector configuration), but values should also consider other intersection users including pedestrians and roadway users with longer start-up times (i.e., bicycles, trucks, and transit).

Practitioners can use volume reports to determine if there are high numbers of those users at a particular intersection or on a particular approach.

PERFORMANCE MEASURES

- 3.5 Vehicle Volumes (with classification information for bicycles, trucks, and transit)
- 3.10 Estimated Queue Length
- 3.12 Pedestrian Volumes
- 3.13 Pedestrian Phase Actuation and Service

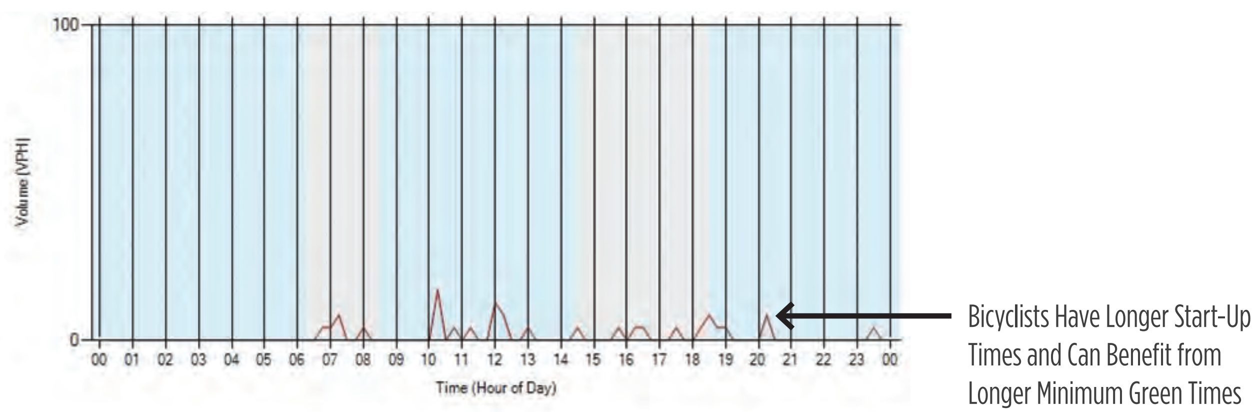
STM2 REFERENCE

- Section 6.1.3: Minimum Green

EXAMPLE

If there are high bicycle volumes, the minimum green time should accommodate cyclists' slower acceleration. **EXHIBIT 5-15** illustrates a bicycle volume report.

EXHIBIT 5-15. MINIMUM GREEN EXAMPLE: BICYCLE VOLUMES (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



5.5.4 MAXIMUM GREEN

DESCRIPTION

Maximum green is the longest duration a green signal indication can be displayed in the presence of conflicting demand. If it is too short, vehicles will remain unserved at the end of green. If it is too long, other movements will experience delay. Maximum green is typically programmed long enough to be able to accommodate pedestrian intervals.

Vehicle volumes are often used to initially distribute green time. Once maximum green values have been programmed, practitioners can use phase termination information to assess whether vehicles are unserved at the end of green. If it is found that a phase is experiencing a high number of max-outs while other competing phases are experiencing a low number of max-outs, there may be opportunity to adjust maximum green values to limit the number of occurrences of unserved vehicles. Delay and queues should also be investigated, if available, when evaluating maximum green times.

If using phase termination information to estimate split failures, a practitioner should investigate all potential causes of max-outs, which could include:

- Malfunctioning detection that is causing a continuous call for service.
- Mis-programmed maximum recall.
- Passage time that is set too high, preventing the phase from gapping out even during low flow rates.

PERFORMANCE MEASURES

- 3.5 Vehicle Volumes
- 3.6 Phase Termination
- 3.7 Split Monitor
- 3.8 Split Failures
- 3.9 Estimated Vehicle Delay
- 3.10 Estimated Queue Length
- 3.11 Oversaturation Severity Index
- 3.12 Pedestrian Volumes
- 3.13 Pedestrian Phase Actuation and Service
- 3.14 Estimated Pedestrian Delay

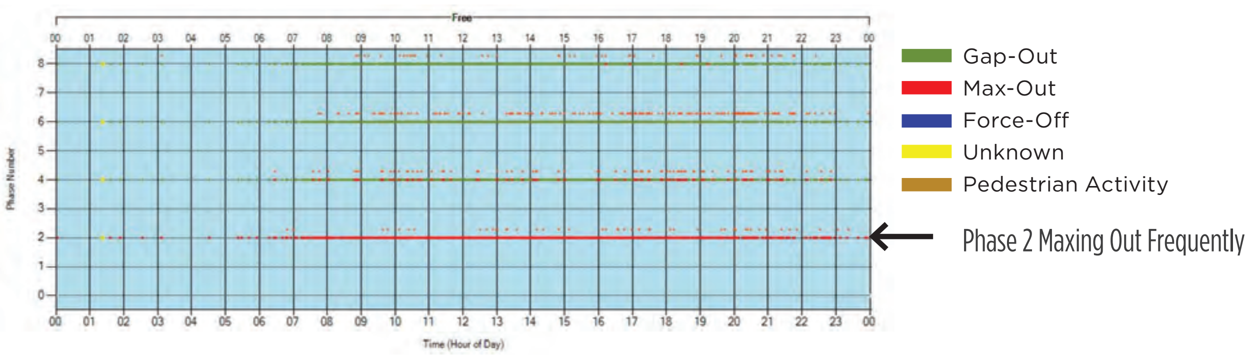
STM2 REFERENCE

- Section 6.1.4: Maximum Green

EXAMPLE

EXHIBIT 5-16 provides an example in which Phase 2 maxed out almost every cycle between 7:00 AM and 9:00 PM. These max-out occurrences indicate a potential opportunity to adjust green times.

EXHIBIT 5-16. MAXIMUM GREEN EXAMPLE: PHASE TERMINATION (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



5.5.5 PASSAGE TIME

DESCRIPTION

Passage time (also known as unit extension or gap time) is a parameter that is used to terminate the current phase when a gap in traffic is identified based on a particular flow rate. If it is too short, the green interval may end prematurely before the queue is fully served. If it is too long, the controller may extend the green unnecessarily, resulting in wasted green time and delay for conflicting phases. Similar to the maximum green assessment, a practitioner can use split failures and/or phase termination information to assess whether passage time is set appropriately. However, it is also important to understand how the size of the detection zone impacts the efficiency of phase terminations. Reference the STM2 for more information (Urbanik et al. 2015).

Passage time is also often used in combination with advance detection to limit the number of vehicles caught in the decision zone (i.e., having to make a decision whether to stop or go when the signal display turns yellow). If there are many vehicles entering the intersection on red, passage time is one parameter that should be investigated. It is possible that the phase is not being extended long enough after vehicles are detected for drivers to enter the intersection before the phase terminates.

PERFORMANCE MEASURES

- 3.6 Phase Termination
- 3.7 Split Monitor
- 3.8 Split Failures
- 3.9 Estimated Vehicle Delay
- 3.11 Oversaturation Severity Index
- 3.16 Yellow/Red Actuations
- 3.17 Red-Light-Running (RLR) Occurrences

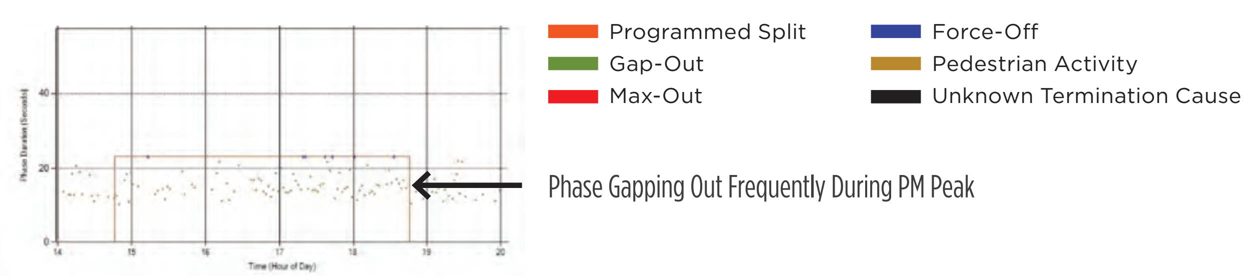
STM2 REFERENCE

- Section 6.1.5: Passage Time (Unit Extension or Gap Time)

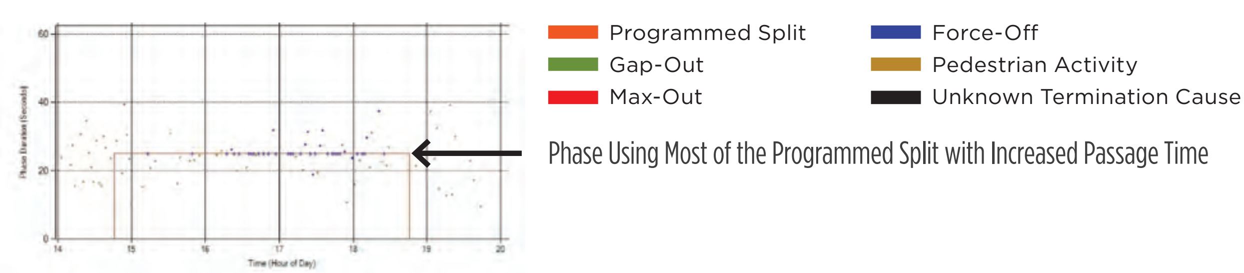
EXAMPLE

Split monitor charts can be used to assess actual phase duration compared to the programmed split. In this example, an engineer received a public service request that a particular movement was terminating before traffic was served. While an initial reaction may be to increase the green time for that movement, review of the split monitor in **EXHIBIT 5-17A** indicated that Phase 1 gapped out during nearly every cycle. The engineer identified that there was a 1-second passage time set on a 15-foot detection zone, which resulted in frequent gap-outs. After increasing the passage time, the issue was resolved with the phase utilizing most of its programmed split during the PM peak (as shown in **EXHIBIT 5-17B**).

EXHIBIT 5-17. PASSAGE TIME EXAMPLE: INCREASED PASSAGE TIME RESULTS IN PHASE UTILIZING PROGRAMMED SPLIT (MACKEY 2017)



(A) Before passage time adjustment



(B) After passage time adjustment

5.5.6 PEDESTRIAN INTERVALS

DESCRIPTION

The pedestrian phase consists of the Walk, Flashing Don't Walk, and Steady Don't Walk intervals. While the *Manual on Uniform Traffic Control Devices* (MUTCD) sets minimum requirements for the Walk and pedestrian clearance intervals based on intersection geometry (FHWA 2009), the time can be increased based on pedestrian volumes or characteristics. For example, a longer Walk interval, Rest-in-Walk mode, or Extended-Walk mode may be used at a location with high pedestrian volumes.

Using pedestrian volumes (or the number of pedestrian actuations), an agency can evaluate the level of pedestrian demand at an intersection. Other pedestrian treatments that are often considered at locations with high pedestrian demand or a high number of potential conflicts between pedestrians and other roadway users include Leading Pedestrian intervals and exclusive pedestrian phases.

Pedestrian volumes can also influence other timing parameters. For example, a practitioner may have decided not to accommodate the pedestrian time within the programmed split. This allows a shorter green to time during cycles without a pedestrian call. However, if there are pedestrian actuations most cycles, it may cause fewer disruptions to program a split time that is long enough to serve the full pedestrian time.

High levels of pedestrian delay indicate an agency should consider adopting a shorter cycle length or pedestrian re-service, which allows pedestrian calls to bring up the Walk interval after the phase has already started. Although this is not a standard feature, practitioners can use overlaps and/or specific flags in many cases.

PERFORMANCE MEASURES

- 3.12 Pedestrian Volumes
- 3.13 Pedestrian Phase Actuation and Service
- 3.14 Estimated Pedestrian Delay
- 3.15 Estimated Pedestrian Conflicts

STM2 REFERENCE

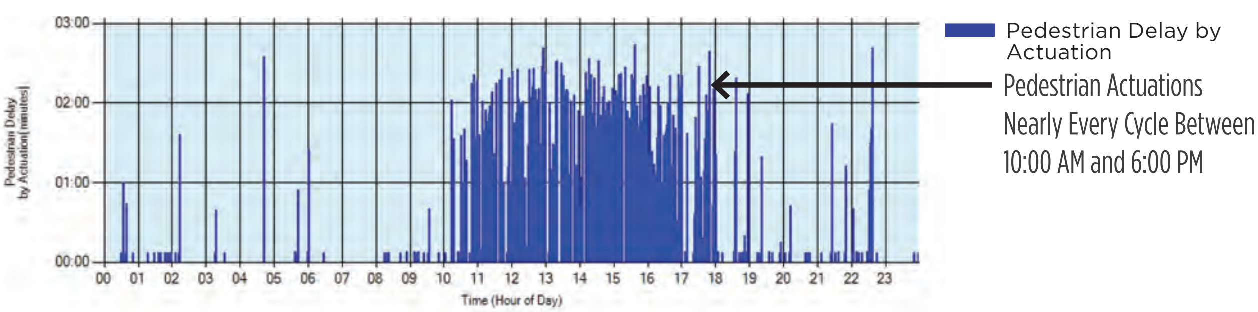
- Section 6.1.6: Pedestrian Intervals

EXAMPLE

EXHIBIT 5-18 provides an example report for pedestrian delay, which also provides information about the number of cycles with pedestrian actuations. Although this report only presents whether a pedestrian actuation was received during a cycle (and not the total number of pedestrians or the number of times the button was pushed), it does provide a snapshot of pedestrian demand.

A pedestrian call occurred during nearly every cycle between 10:00 AM and 6:00 PM, indicating heavy pedestrian activity. In this case, it may be useful to program a split that can accommodate the time required to serve pedestrians between 10:00 AM and 6:00 PM. Outside of those hours, using a shorter split may be more efficient for overall intersection operations.

EXHIBIT 5-18. PEDESTRIAN INTERVAL EXAMPLE: PEDESTRIAN DELAY (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



5.5.7 RECALLS

DESCRIPTION

Recalls place a call automatically for a specified phase regardless of any detector actuations (except for soft recall which only places a call in the absence of calls on other phases). There are four different types of recalls: minimum, maximum, soft, and pedestrian. Signal performance measures are most effective for evaluating the operation of maximum and pedestrian recalls but can also be used to determine which type of recall to apply.

Maximum recall places a continuous call, which results in the phase timing its maximum green every cycle. It is not typically used at locations with detection; if it is mis-programmed, it can result in wasted time at the intersection and long delays for conflicting movements. Using phase termination information, a practitioner can quickly identify if maximum recall is set on one or multiple phases.

Pedestrian recall places a continuous pedestrian call, which results in the pedestrian phase timing every cycle. Even at intersections with pedestrian detection, it may be programmed during times of day with heavy pedestrian demand. Similar to maximum recall, phase termination information can be used to determine times of day with pedestrian recall set on one or multiple phases.

Vehicle and pedestrian volumes can be used to determine which type of recall to program during different times of day. Minimum recall is typically applied to major movements with steady traffic, soft recall during low-traffic periods, and pedestrian recall at locations with heavy pedestrian demand.

PERFORMANCE MEASURES

- 3.5 Vehicle Volumes
- 3.6 Phase Termination
- 3.7 Split Monitor
- 3.12 Pedestrian Volumes
- 3.13 Pedestrian Phase Actuation and Service

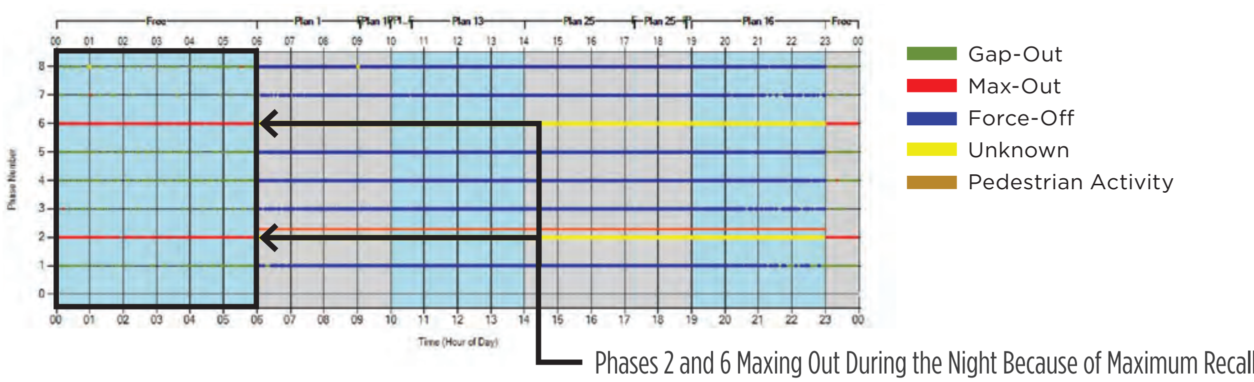
STM2 REFERENCE

- Section 6.1.8: Recalls and Memory Modes

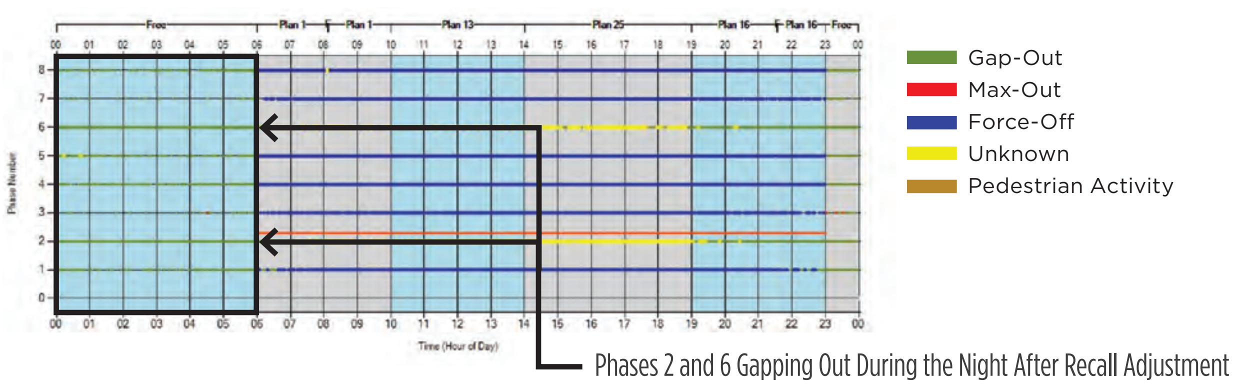
EXAMPLE

EXHIBIT 5-19 summarizes phase terminations before and after a recall adjustment. At this intersection, max-outs were being logged all night on Phases 2 and 6 (as shown in **EXHIBIT 5-19A**). After reviewing the programmed signal timing, it was discovered that a maximum recall had been set for those phases inadvertently. The maximum recall was removed, and Phases 2 and 6 were observed gapping out throughout the night (as shown in **EXHIBIT 5-19B**). This allows for more efficient transitions between Phases 2 and 6 and conflicting phases. When a vehicle arrives on a conflicting phase, it no longer has to wait the duration of maximum green if there is no demand on Phases 2 and 6.

EXHIBIT 5-19. RECALL EXAMPLE: MAXIMUM RECALL SETTING (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



(A) Before recall setting adjustment



(B) After recall setting adjustment

5.5.8 TIME-OF-DAY (TOD) PLANS

DESCRIPTION

Time-of-day plans allow a controller to apply different signal timing parameter values during different times of day or days of the week. Practitioners typically program the TOD plans to match traffic conditions, but they can also use the plans to vary operations based on the time of year or for special events.

ATSPMs provide the unique benefit of allowing agencies to track volumes over longer periods of time than traditional traffic count methods. Practitioners can use volume reports to determine how many timing plans should be programmed throughout the day, week, or year.

After TOD plans are programmed, effective cycle length reports or Purdue Coordination Diagrams can be used to confirm that TOD plan transitions are occurring as intended (i.e., correct cycle lengths are being reported for correct times of day).

PERFORMANCE MEASURES

- 3.5 Vehicle Volumes
- 3.12 Pedestrian Volumes
- 3.13 Pedestrian Phase Actuation and Service
- 3.18 Effective Cycle Length
- 3.20 Purdue Coordination Diagram

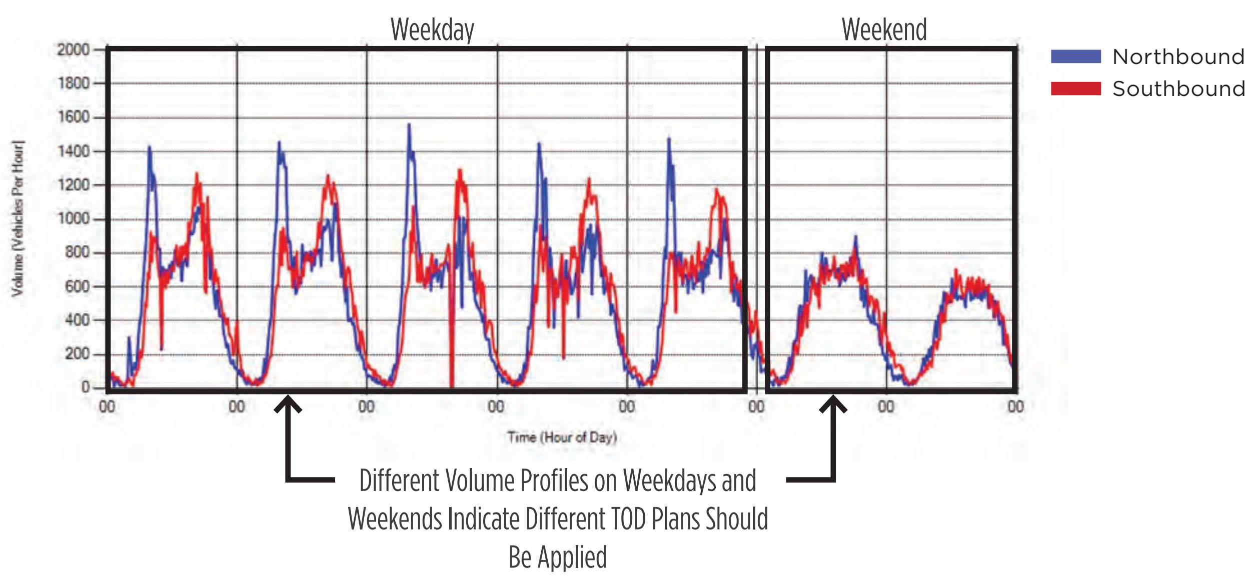
STM2 REFERENCE

- Section 6.3: Time-of-Day Plans

EXAMPLE

EXHIBIT 5-20 depicts northbound and southbound flow rates (calculated using 15-minute volumes) over 1 week. This location has different volume profiles on weekdays than on weekends, so different timing plans should likely be applied Monday through Friday versus Saturday and Sunday.

EXHIBIT 5-20. TIME-OF-DAY PLANS EXAMPLE: WEEKLY VOLUME PROFILES (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



5.6 SYSTEM/COORDINATED TIMING VALIDATION

System/coordinated signal timing parameters include cycle lengths, splits, and offsets that are used to progress vehicles.

5.6.1 CYCLE LENGTH

DESCRIPTION

Cycle length is the time required for a complete sequence of signal phases at an intersection. Along a coordinated corridor, all the intersections should have the same cycle length to maintain synchronization. One exception is "double cycling," when an intersection has half the cycle length used at other intersections and serves phases twice as often.

Cycle length is often determined based on the critical (or highest volume) intersection in a group of coordinated signals. To initially select a cycle length that meets demand, a practitioner can use vehicle volumes for a critical movement analysis (CMA) or similar approach (Urbanik et al. 2015). Splits should also be chosen considering pedestrian volumes; if there is high pedestrian demand, splits should generally be higher than the time required to serve pedestrians.

For cycle lengths already programmed in the field, practitioners can use split failures and/or phase termination information at the critical (or highest-volume) intersection to assess whether splits are long enough to accommodate demand. If all phases are experiencing a high number of split failures, it may be beneficial to increase the cycle length.

However, long cycle lengths may not provide optimal operations for all roadway users. If there is high pedestrian demand, a practitioner should consider keeping cycle lengths low to reduce pedestrian delay. Queues should also play a critical role in cycle length selection. Longer cycle lengths can result in increased congestion if there are oversaturated movements.

Vehicle volumes and arrival-on-green information can also be used to determine if free operations should be considered at an intersection, particularly during low-volume periods.

PERFORMANCE MEASURES

- 3.5 Vehicle Volumes
- 3.6 Phase Termination
- 3.7 Split Monitor
- 3.8 Split Failures
- 3.9 Estimated Vehicle Delay
- 3.10 Estimated Queue Length
- 3.11 Oversaturation Severity Index
- 3.12 Pedestrian Volumes
- 3.13 Pedestrian Phase Actuation and Service
- 3.14 Estimated Pedestrian Delay
- 3.18 Effective Cycle Length
- 3.19 Progression Quality
- 3.20 Purdue Coordination Diagram
- 3.21 Cyclic Flow Profile

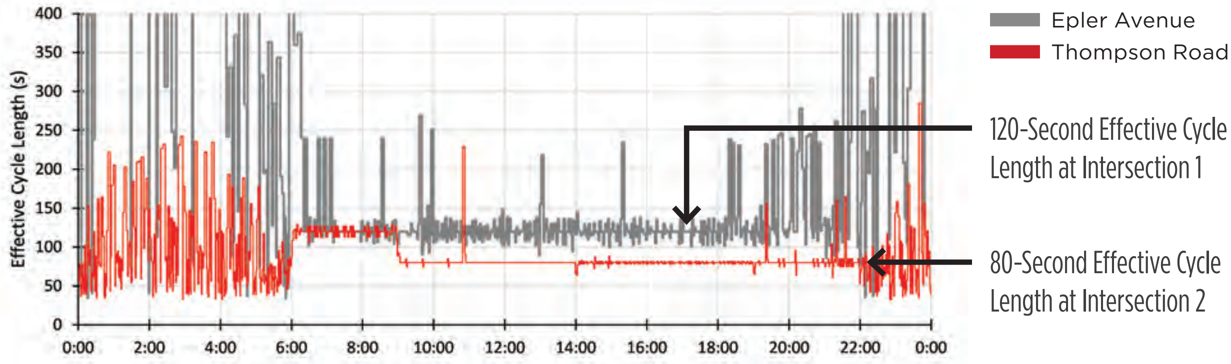
STM2 REFERENCE

- Section 7.3.2: Cycle Length
- Section 7.4.2: Cycle Length Guidance
- Section 7.6.5: Critical Intersection Control
- Section 12.3.1.2: Cycle Length Increase (*Chapter 12: Oversaturated Conditions*)

EXAMPLE

EXHIBIT 5-21 shows effective cycle lengths for two neighboring intersections on a corridor in Indiana. From 6:00 AM to 9:00 AM, the two intersections both operate with a 120-second cycle length. After 9:00 AM, Intersection 2 drops down to an 80-second cycle length for the rest of the day. In this case, the difference in cycle lengths is by design, but the example demonstrates the potential of such a graphic to identify anomalies that may be related to programmed values or a detection malfunction.

EXHIBIT 5-21. CYCLE LENGTH EXAMPLE: DIFFERENT EFFECTIVE CYCLE LENGTHS AT NEIGHBORING INTERSECTIONS (COURTESY CHRIS DAY, PURDUE UNIVERSITY)



5.6.2 SPLITS

DESCRIPTION

Splits are the portion of the coordinated cycle allocated to each phase (including the green, yellow change, and red clearance intervals). Practitioners often select splits by distributing available green time in proportion to estimated demand. When initially programming splits, practitioners can use vehicle volumes to estimate demand and the time required to serve it. Pedestrian volumes will also impact the time allocated to splits. If there is high pedestrian demand, splits should generally be programmed to accommodate the time required to serve pedestrians. During periods with fewer pedestrians, shorter splits may be more efficient for overall intersection operations.

If a practitioner has already programmed splits in the field, he or she can use phase termination information and split failures to determine how much of the programmed split the phase used and whether there were vehicles left unserved. If some phases are experiencing high split failures while others are not (or a high number of force-offs while others are gapping out), there may be an opportunity to reallocate green time between phases. Delay and queues should also be investigated, if available, when evaluating splits.

If using phase termination information to estimate split failures, a practitioner should investigate all potential causes of force-offs, which could include:

- Malfunctioning detection that is causing a continuous call for service.
- Mis-programmed coordinated phases causing them to be shown as force-offs every cycle.
- Passage time that is set too high, preventing the phase from gapping out even during low flow rates.

PERFORMANCE MEASURES

- 3.5 Vehicle Volumes
- 3.6 Phase Termination
- 3.7 Split Monitor
- 3.8 Split Failures
- 3.9 Estimated Vehicle Delay
- 3.10 Estimated Queue Length
- 3.11 Oversaturation Severity Index
- 3.12 Pedestrian Volumes
- 3.13 Pedestrian Phase Actuation and Service
- 3.14 Estimated Pedestrian Delay

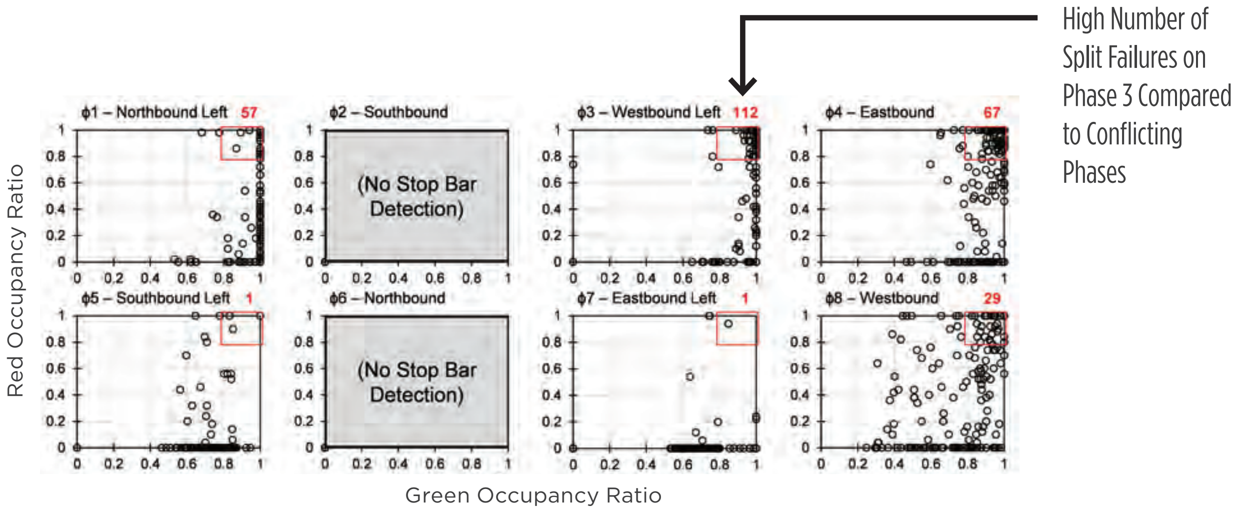
STM2 REFERENCE

- Section 7.3.3: Splits
- Section 7.4.3: Splits Guidance
- Section 12.3.1.1: Split Reallocation (*Chapter 12: Oversaturated Conditions*)

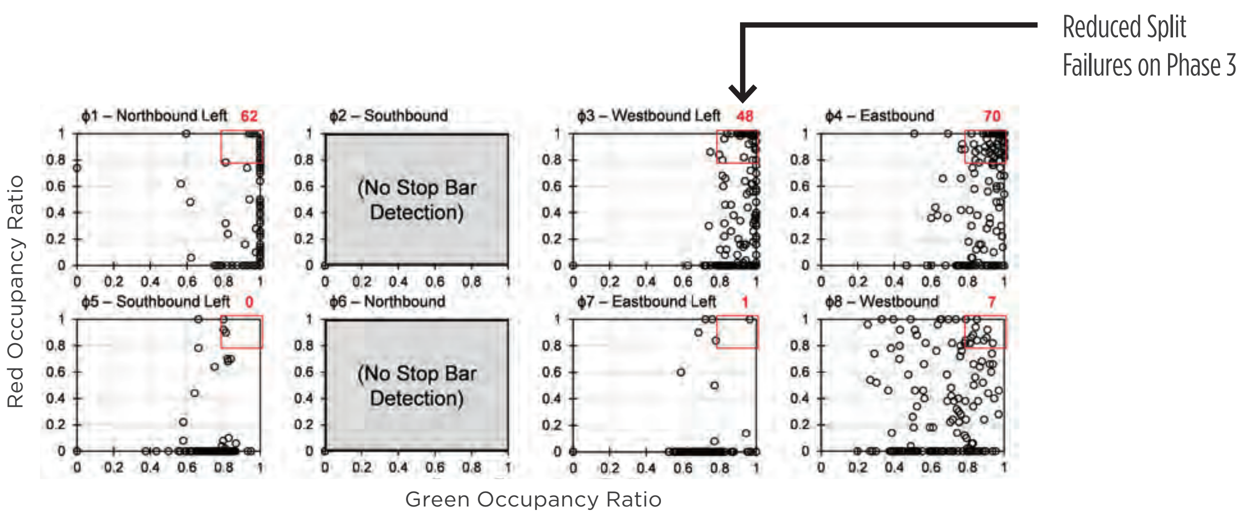
EXAMPLE

EXHIBIT 5-22 shows green and red occupancy ratios at an intersection before and after split adjustments. If the green and red occupancy ratios are both above 80%, the cycle is logged as having a split failure. The example shows a high number of split failures occurring on Phase 3 compared to the other conflicting phases in **EXHIBIT 5-22A**. A split adjustment resulted in reduced split failures on Phase 3 and for the intersection overall (as shown in **EXHIBIT 5-22B**), although split failures increased slightly on some of the conflicting phases.

EXHIBIT 5-22. SPLITS EXAMPLE: SPLIT FAILURES BEFORE AND AFTER SPLIT ADJUSTMENT (DAY ET AL. 2015)



(A) Before split adjustment



(B) After split adjustment

5.6.3 OFFSETS

DESCRIPTION

Offsets define the time relationship between the "system" clock and the "local" clock at individual intersections, thereby controlling the time relationship between intersections based on the actual or desired travel speed. Ideally, they allow platoons of vehicles to arrive on green (i.e., leave an upstream intersection at the start of green and arrive at a downstream intersection at the start of green).

There are some complexities with progression that can be investigated using ATSPMs including:

- Phase sequence.
- Early return to green.
- Heavy minor street volumes.
- Queues on oversaturated movements.

Practitioners have used high-resolution data to automatically identify offset adjustments by applying a simple prediction model to the underlying data (Day and Bullock 2011). In most cases, practitioners can predict the impacts of an offset adjustment by a linear adjustment of the arrival times at the approaches of the local intersection and at neighboring intersections. This process yields predicted metrics such as arrivals on green. One method of systematically adjusting intersections along an arterial corridor is the "Link Pivot" algorithm (Day et al. 2011).

PERFORMANCE MEASURES

- 3.10 Estimated Queue Length
- 3.11 Oversaturation Severity Index
- 3.19 Progression Quality
- 3.20 Purdue Coordination Diagram
- 3.21 Cyclic Flow Profile
- 3.22 Offset Adjustment Diagram
- 3.23 Travel Time and Average Speed
- 3.24 Time-Space Diagram

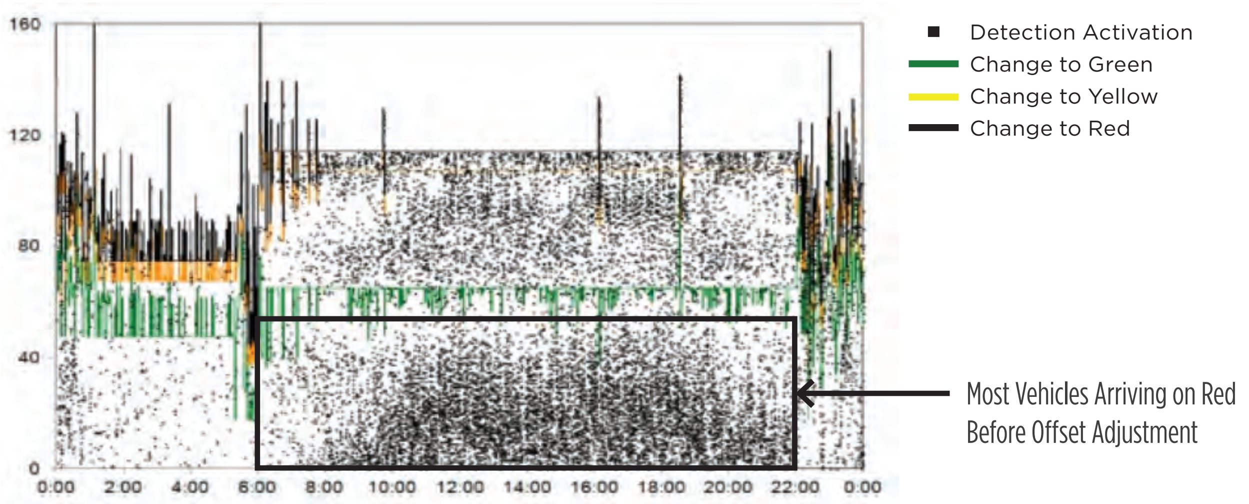
STM2 REFERENCE

- Section 7.3.9: Offsets
- Section 7.4.9: Offsets Guidance
- Section 7.6: Complexities
- Section 12.3.2.3 Offset Strategies (*Chapter 12: Oversaturated Conditions*)

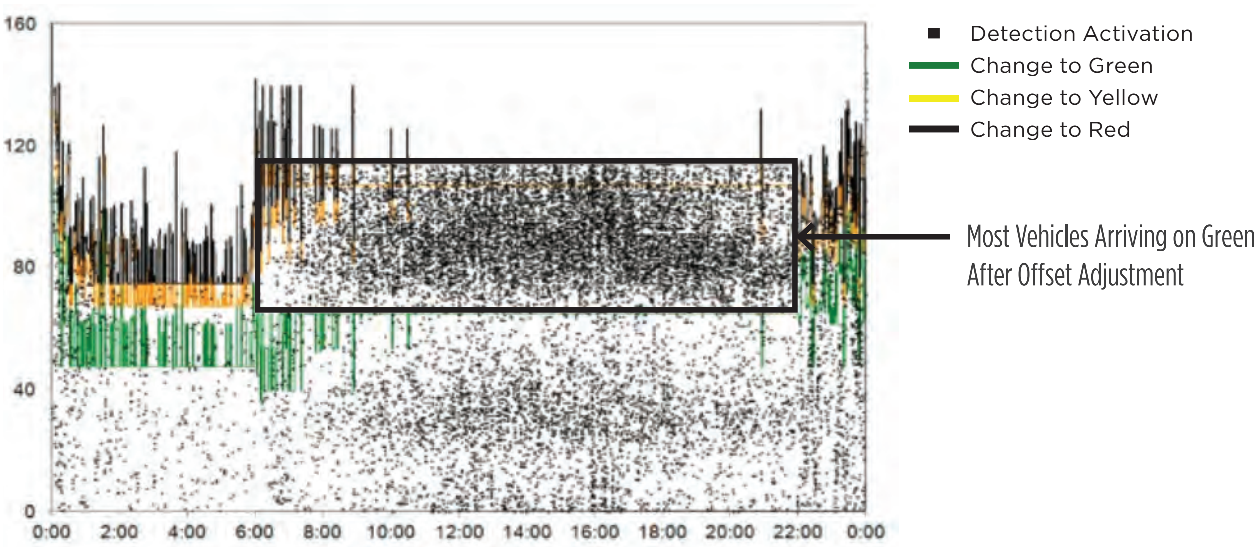
EXAMPLE

A practitioner can use the Purdue Coordination Diagram to assess when vehicles are arriving during the cycle. Although other progression metrics are better for assessing offsets corridor-wide, this type of report can help confirm the value and direction of an offset adjustment. **EXHIBIT 5-23** shows Purdue Coordination Diagrams **(A)** before and **(B)** after an offset adjustment. In this case, the adjustment resulted in vehicle platoons arriving on green much more frequently throughout the day.

EXHIBIT 5-23. OFFSETS EXAMPLE: PURDUE COORDINATION DIAGRAM BEFORE AND AFTER OFFSET OPTIMIZATION (DAY ET AL. 2010)



(A) Before offset optimization



(B) After offset optimization

5.7 ADVANCED SYSTEMS AND APPLICATIONS VALIDATION

Advanced systems are often implemented to address unpredictable traffic conditions. Objectives for these systems will vary based on agency needs.

5.7.1 ADVANCED SIGNAL SYSTEMS (TRAFFIC RESPONSIVE AND ADAPTIVE SYSTEMS)

DESCRIPTION

Traffic responsive and adaptive systems adjust signal timing parameters (often cycle lengths, splits, and offsets) in response to traffic demand. A practitioner can apply the reports discussed in *Section 5.6: System/ Coordinated Timing Validation* to assess how often traffic responsive and adaptive systems are making adjustments and whether the adjustments are improving operations.

PERFORMANCE MEASURES

- 3.5 Vehicle Volumes
- 3.6 Phase Termination
- 3.7 Split Monitor
- 3.8 Split Failures
- 3.9 Estimated Vehicle Delay
- 3.10 Estimated Queue Length
- 3.11 Oversaturation Severity Index
- 3.12 Pedestrian Volumes
- 3.13 Pedestrian Phase Actuation and Service
- 3.14 Estimated Pedestrian Delay
- 3.18 Effective Cycle Length
- 3.19 Progression Quality
- 3.20 Purdue Coordination Diagram
- 3.21 Cyclic Flow Profile
- 3.22 Offset Adjustment Diagram
- 3.23 Travel Time and Average Speed
- 3.24 Time-Space Diagram

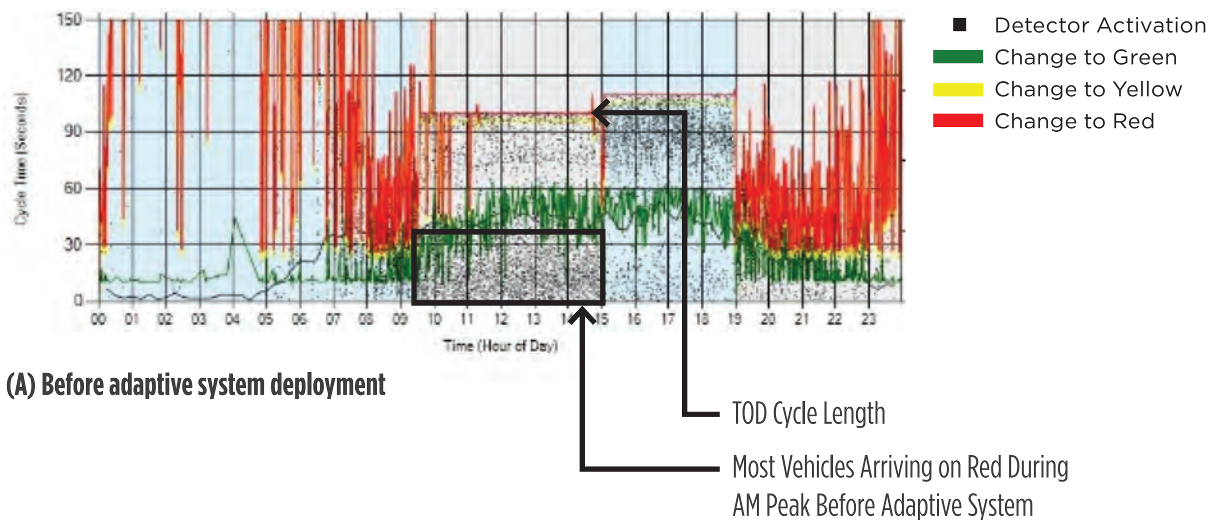
STM2 REFERENCE

- Chapter 9: Advanced Signal Systems

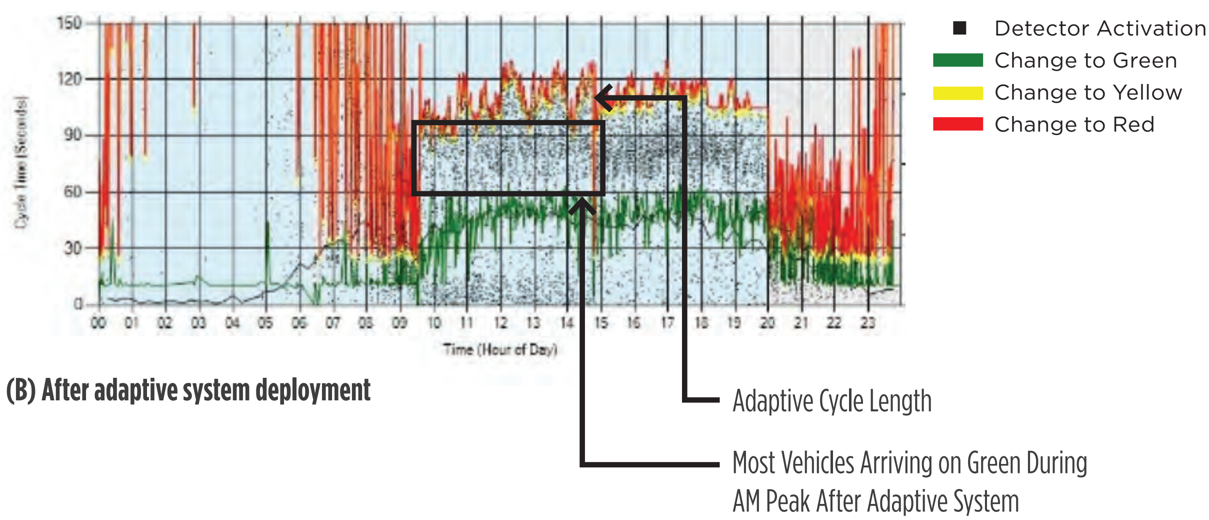
EXAMPLE

An adaptive traffic signal control (ATSC) system was deployed along a corridor in Oregon. The system adjusted cycle lengths, splits, and offsets. As shown in **EXHIBIT 5-24**, one method for validating the system was reviewing arrivals on green **(A)** before and **(B)** after deployment using Purdue Coordination Diagrams. After implementation of the adaptive system, offset adjustments improved vehicle arrivals on green during the AM peak. Cycle length adjustments could also be evaluated using this report to confirm that the minimum and maximum values were within the intended range.

EXHIBIT 5-24. ADVANCED SIGNAL SYSTEMS EXAMPLE: PURDUE COORDINATION DIAGRAMS BEFORE AND AFTER DEPLOYMENT OF AN ADAPTIVE SYSTEM (COURTESY CLACKAMAS COUNTY, OR)



(A) Before adaptive system deployment



(B) After adaptive system deployment

5.7.2 PREFERENTIAL TREATMENT (PREEMPTION AND PRIORITY)

DESCRIPTION

Practitioners can use preferential treatment to alter normal operations for a preferred vehicle. If a signalized intersection is located near a rail crossing, preemption is used to clear the space between the traffic signal and the tracks before the arrival of a train. Emergency vehicles typically use preemption to terminate normal operations and serve the approach with the emergency vehicle. Transit and truck priority differs slightly because it gives preference to transit vehicles and trucks without interrupting coordination.

ATSPMs can provide information about when a preempt or priority call was received, when it was serviced, and how the intersection operated during the event. For preemption, those metrics can include entry delay, track clearance, gate down, dwell, time to service, max-out, and preempt input on/off. For rail preemption, an island circuit is required for the most meaningful signal performance measures because it provides information about when the train arrived at the crossing. For priority, ATSPMs can record TSP check in, adjustment to early green, adjustment to extend green, and TSP check out.

A practitioner can identify how often preemption and priority events are occurring and whether they are operating as anticipated. This can help troubleshoot mis-programmed signal timing parameters and preferential-treatment-specific equipment that is malfunctioning. Using a combination of signal performance measures, a practitioner can also identify the experience of other intersection users during a preferential treatment event and may be able to adjust phasing or signal timing to reduce delay for other users.

PERFORMANCE MEASURES

- 3.25 Preemption Details
- 3.26 Priority Details

STM2 REFERENCE

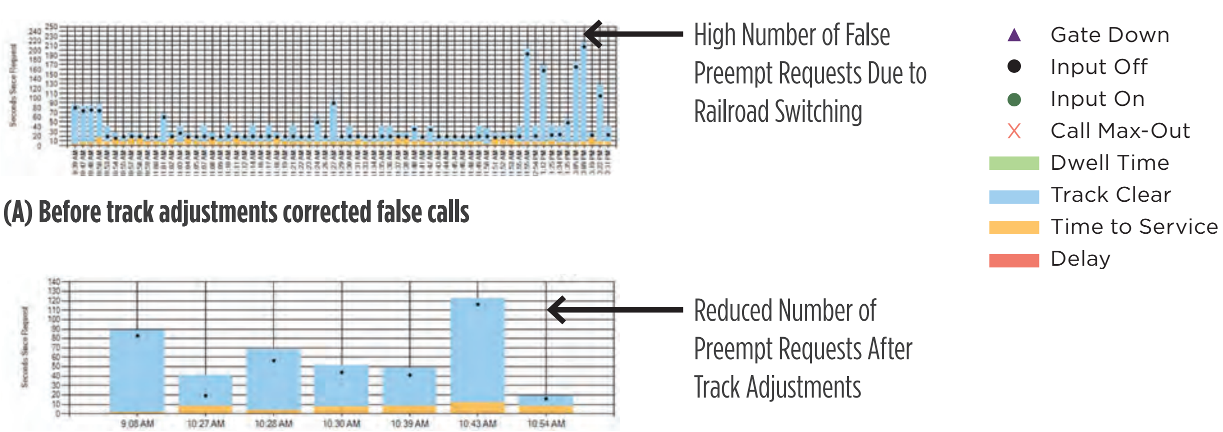
- Chapter 10: Preferential Treatment

EXAMPLE

EXHIBIT 5-25 shows preemption details for a signalized intersection near an at-grade railroad crossing with a relatively low frequency of trains (typically two trains per day, 3 days per week). Over several years, there were a number of public service requests at this location. Before any adjustments were made, **EXHIBIT 5-25A** revealed that the signalized intersection was experiencing a high number of short preemption events.

The problem was due to false inputs caused by railroad switching operations occurring on nearby tracks, which did not ultimately result in a train using the at-grade crossing. Documentation of the frequency of false calls was helpful during discussions with the railroad. The railroad confirmed the problem and isolated the tracks at the at-grade crossing from the tracks that were generating the false calls. **EXHIBIT 5-25B** shows that the number of preemption calls was reduced dramatically after adjustments were made to the tracks.

EXHIBIT 5-25. PREEMPTION DETAILS EXAMPLE: PREEMPT SERVICE (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)



(A) Before track adjustments corrected false calls

(B) After track adjustments corrected false calls

5.8 EQUIPMENT MAINTENANCE VALIDATION

This section discusses performance measures related to the maintenance of traffic signal equipment.

5.8.1 COMMUNICATION

DESCRIPTION

Communication is critical to a scalable monitoring system as well as keeping intersections coordinated. If an intersection is missing data or the central system is unable to communicate with a controller (i.e., "ping"), the communication infrastructure may be malfunctioning. Practitioners can track communication outages by location, type of communication equipment, or age of communication equipment, so they can identify the highest priority locations for future communication equipment upgrades.

PERFORMANCE MEASURES

- 3.1 Communication Status

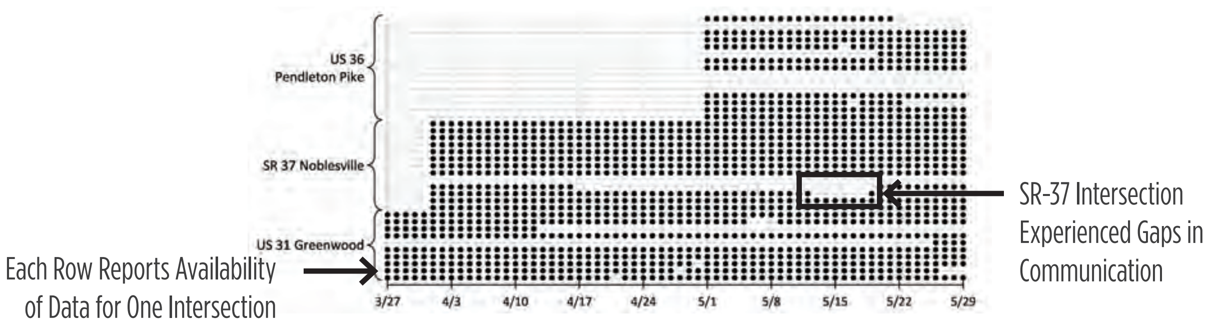
STM2 REFERENCE

- Section 4.4: Signalized System Design

EXAMPLE

EXHIBIT 5-26 shows the availability of data by intersection along three corridors. Each dot represents a day when data was present; each row represents an individual intersection. Over time, communication to the US-36 and SR-37 corridors was restored, but along all three corridors there remained some individual intersections with sporadic communication. This chart was used to validate communication upgrades.

EXHIBIT 5-26. COMMUNICATION SYSTEM STATUS EXAMPLE: DAY-TO-DAY DATA AVAILABILITY BY INTERSECTION OVER 2 MONTHS (COURTESY LUCY RICHARDSON, PURDUE UNIVERSITY)



5.8.2 SIGNAL CABINET EQUIPMENT

DESCRIPTION

Practitioners can track flash status and power failures to ensure the signal cabinet equipment is functional. By assessing the frequency of outages by location, equipment type, and equipment age, an agency can identify high-priority intersections for maintenance upgrades. In addition, those metrics can help identify locations where agencies should consider back-up power supply (BPS) systems.

PERFORMANCE MEASURES

- 3.2 Flash Status
- 3.3 Power Failures

STM2 REFERENCE

- Section 4.2: Signal Cabinet Equipment

5.8.3 VEHICLE DETECTION

DESCRIPTION

Although controllers sometimes log detector failures as alarms, practitioners can also use phase termination information and vehicle volumes to identify detector failures. If phases are consistently maxing out during low-volume periods (e.g., late at night), it may be an indication that a detector is not functioning properly and placing a constant call. When this occurs, particularly during free operations, phases may time that otherwise would not, and vehicles on conflicting approaches may be experiencing unnecessary delays.

PERFORMANCE MEASURES

- 3.4 Detection System Status
- 3.5 Vehicle Volumes
- 3.6 Phase Termination
- 3.7 Split Monitor

STM2 REFERENCE

- Section 4.1: Detection

EXAMPLE

At an intersection in Virginia, phase termination reports revealed a high number of max-outs on Phase 6 during the night, as shown in **EXHIBIT 5-27**. After reviewing lane-by-lane vehicle flow rates (calculated using 15-minute volumes), as shown in **EXHIBIT 5-28**, it was discovered that one of the southbound detectors associated with Phase 6 was not reporting any volumes. The detector had a bad splice and was defaulting to a constant call. After the splice was fixed, the detector began reporting volumes that were consistent with the other lanes on the southbound approach, and Phase 6 (and Phase 2 by association) was able to gap-out during the night.

EXHIBIT 5-27. VEHICLE DETECTION EXAMPLE: PHASE TERMINATIONS OVER 3 DAYS BEFORE AND AFTER A DETECTOR SPLICE FIX (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)

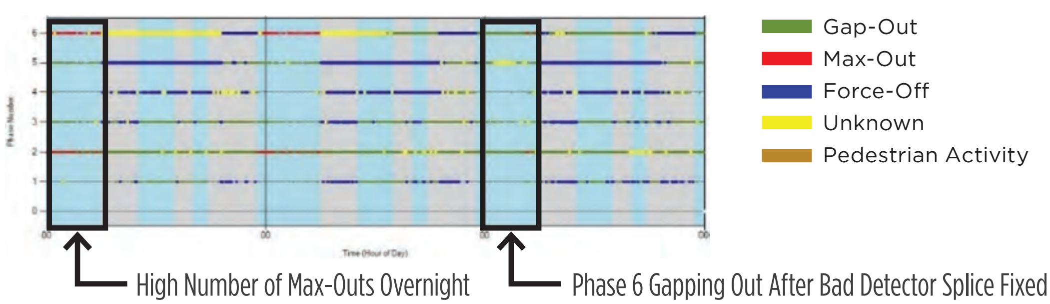
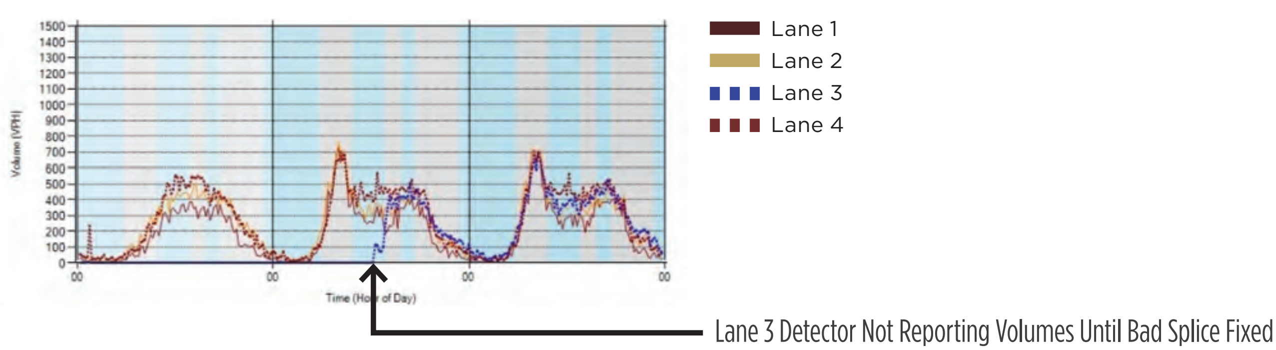


EXHIBIT 5-28. VEHICLE DETECTION EXAMPLE: VEHICLE VOLUMES OVER 3 DAYS BEFORE AND AFTER A DETECTOR SPLICE FIX (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)



5.8.4 PEDESTRIAN DETECTION

DESCRIPTION

Practitioners can use performance measures to identify locations with malfunctioning pedestrian detection. The phase termination and pedestrian delay metrics report pedestrian actuations. Like vehicle detectors, broken pedestrian push buttons default to a constant call, which can cause pedestrian phases to time when there are no pedestrians present, resulting in delays for other intersection users.

PERFORMANCE MEASURES

- 3.4 Detection System Status
- 3.6 Phase Termination
- 3.7 Split Monitor
- 3.12 Pedestrian Volumes
- 3.13 Pedestrian Phase Actuation and Service
- 3.14 Estimated Pedestrian Delay

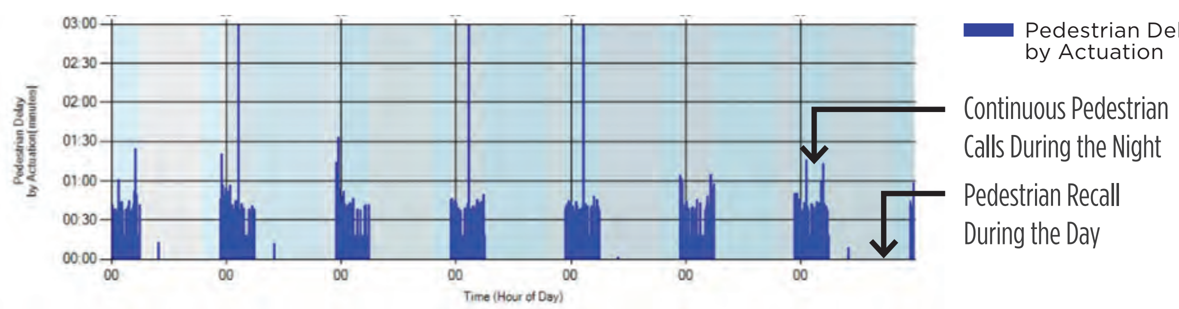
STM2 REFERENCE

- Section 4.1: Detection

EXAMPLE

EXHIBIT 5-29 highlights a high number of pedestrian actuations (i.e., calls every cycle) during a low-volume period (i.e., late at night) over the course of several days. In such cases, agencies should check the pedestrian detection for failure.

EXHIBIT 5-29. PEDESTRIAN DETECTION EXAMPLE (COURTESY VIRGINIA DEPARTMENT OF TRANSPORTATION)

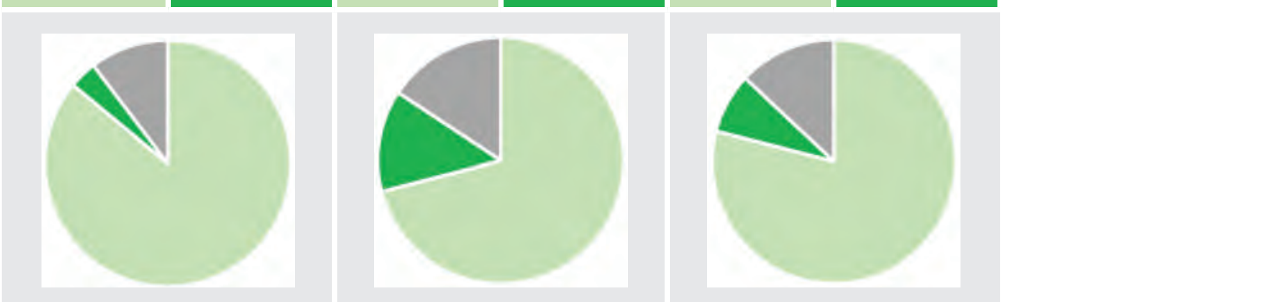


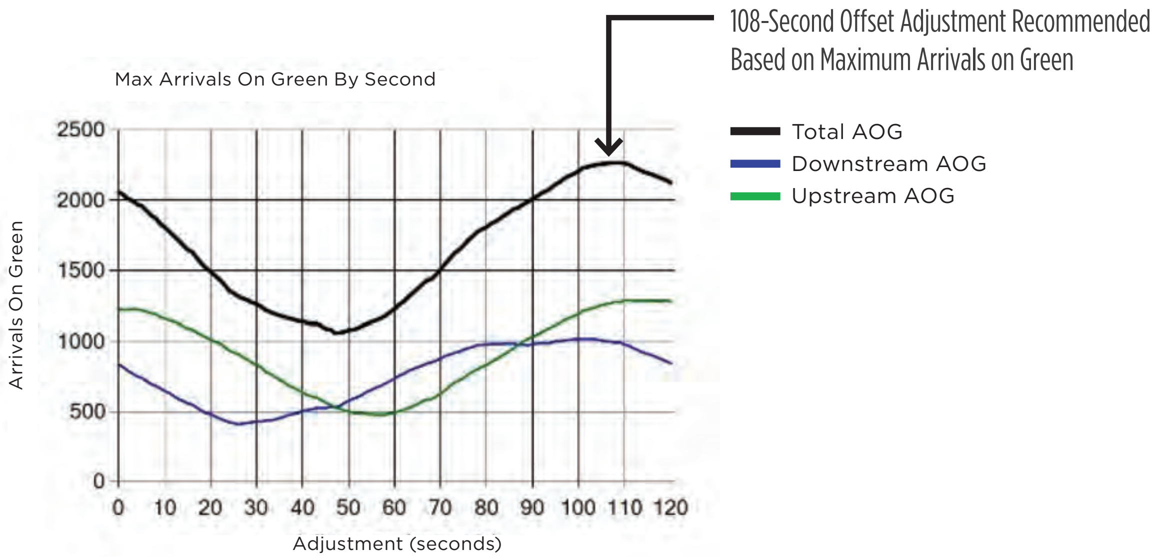
5.9 PREDICTIVE TOOLS

There are some tools available that use high-resolution data to develop predictive models. A practitioner can use these tools to predict improvements to signal timing settings based on the desired objective. One example of this type of tool is Purdue Link Pivot Analysis, which predicts offset adjustments that will improve arrivals on green. This methodology assesses whether arrivals on green would likely increase or decrease if the offset at an intersection shifted. Once the tool identifies recommended offset adjustments for all of the intersections along a specified route, it calculates programmable offset values based on the existing offset relationships between intersections (Day et al. 2011). See **EXHIBIT 5-30** for an example of existing and predicted arrivals on green for one link based on Purdue Link Pivot Analysis.

EXHIBIT 5-30. PURDUE LINK PIVOT RESULTS FOR ONE LINK (COURTESY UTAH DEPARTMENT OF TRANSPORTATION)

UPSTREAM INTERSECTION		DOWNSTREAM INTERSECTION		TOTAL LINK	
Existing AOG (#, %)	Predicted AOG (#, %)	Existing AOG (#, %)	Predicted AOG (#, %)	Existing AOG (#, %)	Predicted AOG (#, %)
1225 (86%)	1277 (90%)	833 (71%)	989 (84%)	2058 (79%)	2266 (87%)





5.10 MONITORING THROUGH AUTOMATED ALERTS

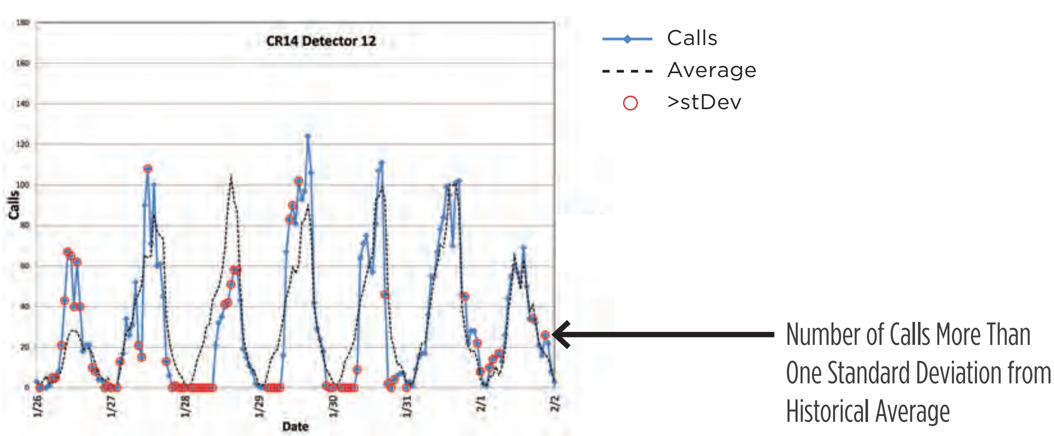
Agencies can program reports and dashboards to automatically flag issues and alert technicians of issues or inefficiencies in the system. This can help agencies identify problems faster and validate operations noted by the public in service requests. In order to develop a robust program that limits "false alerts," agencies need to determine the appropriate ATSPM thresholds for their system. The Utah Department of Transportation (UDOT) uses ATSPM automated alerts regularly to create system-wide email notifications; **EXHIBIT 5-31** summarizes their available alerts and typical thresholds.

EXHIBIT 5-31. UDOT ALERTS AND THRESHOLDS (MACKEY 2017)

CATEGORY	ALERT	DESCRIPTION	THRESHOLD	TIME PERIOD
Communication	**Data Entry**	Intersections with a low number of records in the database	Less than 500 records	12:00 AM to 11:59 PM
Detection	**Max-Out**	Phases with a high number of max-outs during low-volume periods	90% or more max-outs in at least 50 activations	1:00 AM to 5:00 AM
Detection	**Pedestrian Call**	Phases with a high number of pedestrian actuations during low-volume periods	More than 200 actuations	1:00 AM to 5:00 AM
Detection	**Detector Count**	Advance detectors reporting low volumes during high-volume periods	Less than 100 actuations	5:00 PM to 6:00 PM
System / Coordinated Timing	**Force-Off**	Phases with a high number of force-offs during low-volume periods	90% or more force-offs in at least 50 activations	1:00 AM to 5:00 AM

Agencies can also program automated alerts based on how current conditions compare to historical data. For example, **EXHIBIT 5-32** shows hourly detector calls compared to a historical average compiled from previous weeks. A statistical comparison between the current and historical data revealed hours when the current count was more than one standard deviation away from the historical average (highlighted with red circles). Note that during the 3 days in the middle of the week, there were many times when the counts dropped to zero during overnight periods. The cold overnight January temperatures caused a cable to contract and ultimately disconnected the detector. As a result, the system placed a constant call on the associated phase overnight, although it operated normally during the day. Technicians corrected the problem before a citizen made a public service request.

EXHIBIT 5-32. COMPARISON OF DETECTOR CALLS VERSUS HISTORICAL AVERAGE WITH ERRORS DETERMINED THROUGH STATISTICAL ANALYSIS (GROSSMAN 2017)



5.11 AGGREGATED REPORTS

As of writing, aggregated reports are being incorporated into the open source code and several vendor products. Aggregated reports provide several benefits for signal timers and other stakeholders. They can:

Identify "hot spots" either amongst intersections or the movements at an intersection.

Compare to historical data for trend analysis and quantitative performance tracking.

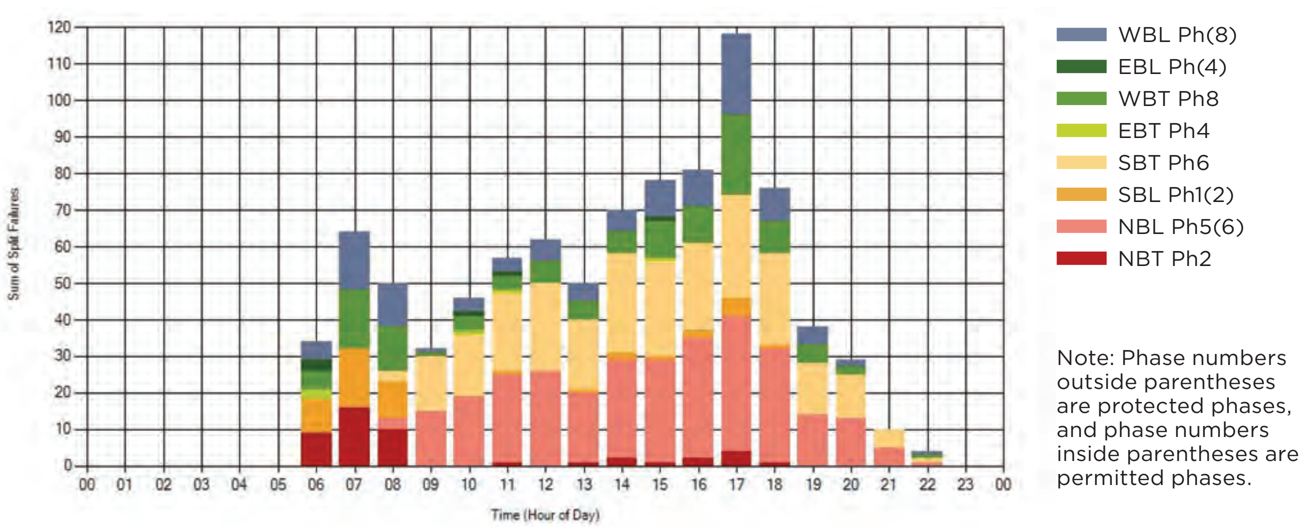
Produce shareable reports (i.e., summary tables) that can be given to the public and decision-makers.

The following example reports aggregate data at different levels for different audiences.

5.11.1 AGGREGATED CHARTS

Aggregated charts sum (or average) performance measures by intersection and time of day for various intervals (e.g., 15-minute intervals, 30-minute intervals, etc.). These are useful for signal timers trying to identify intersections or movements that require signal timing and maintenance adjustments. The example in **EXHIBIT 5-33** illustrates the number of split failures by hour of the day for different movements at an intersection. In this case, the northbound left-turn phase is experiencing the highest number of split failures throughout the day.

EXHIBIT 5-33. AGGREGATED REPORT FOR SPLIT FAILURES (MACKEY 2018)

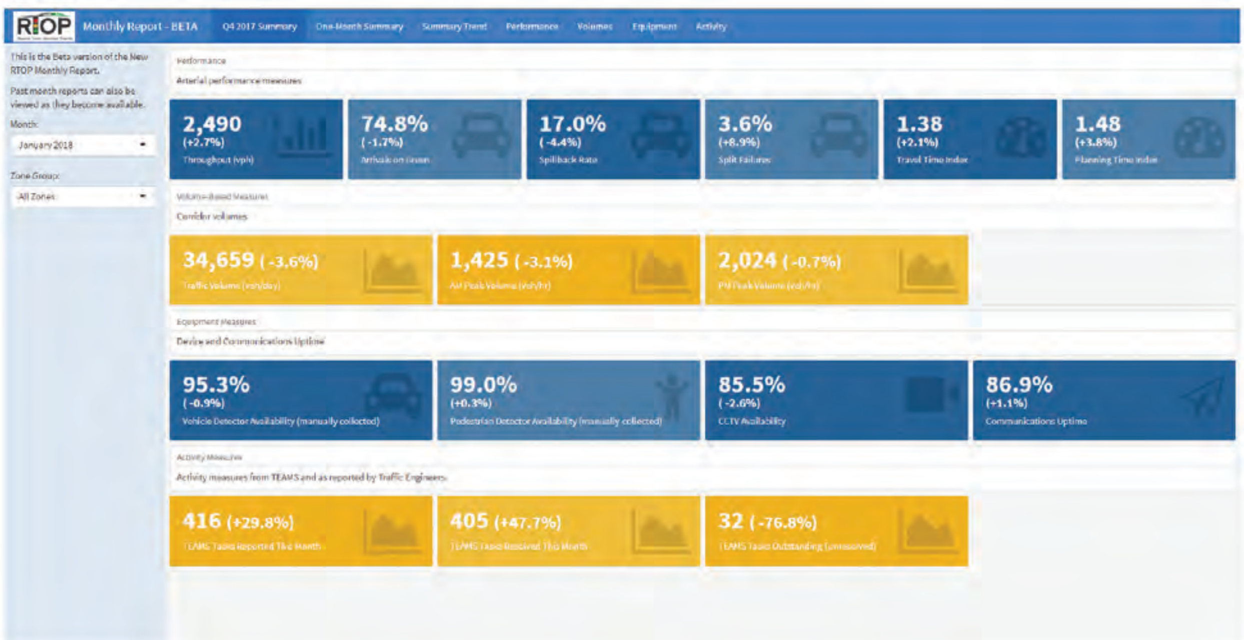


Note: Phase numbers outside parentheses are protected phases, and phase numbers inside parentheses are permitted phases.

5.11.2 DASHBOARDS

Dashboards can be used to compare current conditions to historical data. This type of summary is useful for both signal timers and decision-makers to track progress. The example in **EXHIBIT 5-34** shows the status of various performance measures along with the percent change from the previous month.

EXHIBIT 5-34. MONTHLY DASHBOARD (DAVIS AND HARRIS 2018)



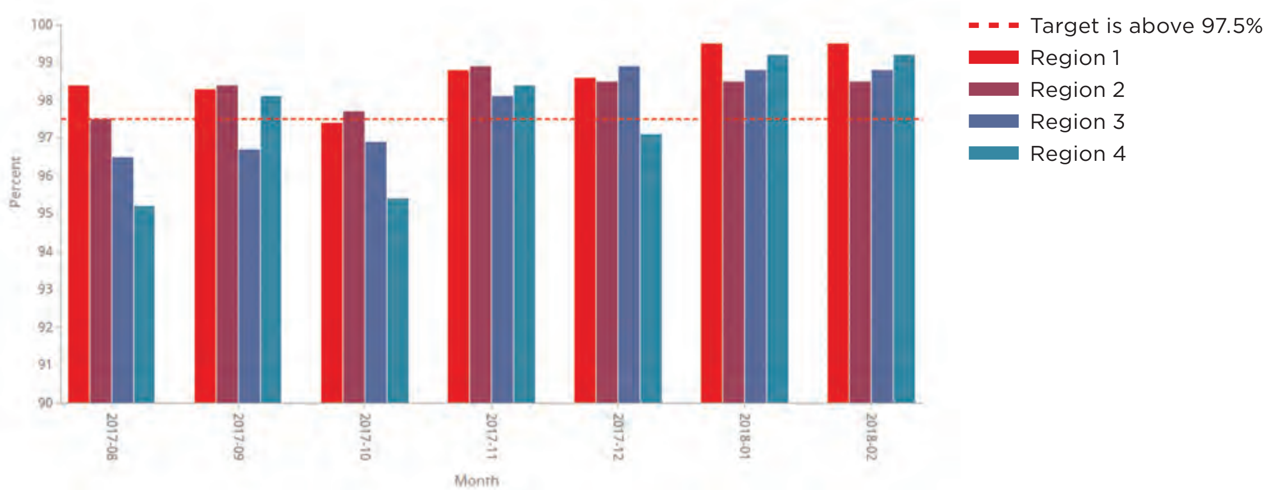
5.11.3 SUMMARY TABLES AND CHARTS

Summary tables and charts aggregate data up to a high level so that performance measures can be shared with the public and decision-makers. It is most useful to report performance measures against targets. **EXHIBIT 5-35** is a summary table of performance measure targets used by UDOT, and **EXHIBIT 5-36** is a summary chart that illustrates communication status over several years compared to the targets. On a public website, UDOT provides similar summary charts for each performance measure listed in **EXHIBIT 5-35**.

EXHIBIT 5-35. SUMMARY TABLE FOR PERFORMANCE MEASURE TARGETS (UDOT 2018)

Measure	Target
Number of traffic signals	-
Maintenance funding/traffic signal	$3400/year
Connected signals that are communicating	97.5%
Average time to close signal maintenance work order	5 days or less
Signals with preventative maintenance performed	100%
Traffic signals/ signal technician	50 maximum
Traffic signals/ signal engineer	100 maximum
Crash clearance times for PDO, injury and fatal crashes	
Ramp meters using CRM algorithm	100%
UDOT Traffic app downloads	10% increase/year
Construction projects reporting lane closures	90% key routes reporting
Lane closures activated changed or cancelled	85% by June 2018
Planned events managed	90% Level 1 events by June 2018
RWIS devices operational	95%

EXHIBIT 5-36. PERCENT CONNECTED SIGNALS THAT ARE COMMUNICATING COMPARED TO TARGET (UDOT 2018)



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CHAPTER 6 INTEGRATION INTO AGENCY PRACTICE

CHAPTER FOCUS

Chapter 6 provides strategies to fully integrate signal performance measures into agency management practices. Across an agency, there are many potential users of signal performance measures, including traffic signal operators and maintenance staff, senior managers, planners, designers, and construction staff. Information gained from signal performance measures can create opportunities to collaborate between groups, share resources, and communicate benefits to executive staff, elected officials, and the public.

6.1 TRAFFIC SIGNAL MANAGEMENT PLAN

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

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

Without a clear definition for "basic service," it can be difficult for managers to communicate the value of their program and the impacts of resource allocation and budget cuts (Denney and Olsen 2013). This section builds off that idea and provides additional guidance for creating a TSMP.

6.1.1 CAPABILITY MATURITY MODEL (CMM) ASSESSMENT

The Capability Maturity Model (CMM) is an organizational framework used in a wide range of industries from software development to transportation to describe the level of management formality and optimization. The FHWA utilizes CMM to identify opportunities and challenges in improving transportation system management and operations (TSMO). CMM can help an agency identify its current capabilities on a spectrum from ad-hoc actions to managed, optimized procedures. It uses four categories to describe varying levels of maturity in four dimensions. Once an agency identifies its current level, they can determine the actions they need to take to reach the next one. In order to reach a fully managed and optimized level of capability, an agency needs to incorporate regular performance measurement (Parsons Brinckerhoff et al. 2012).

As it relates to signal performance measurement, at Level 3, an agency is setting up and collecting performance information. The goal of a performance-based program is for the agency to operate at Level 4, where they are not only measuring performance but also making decisions based on that information in a way that does not rely on an individual but is integrated into agency practice.

CAPABILITY DIMENSIONS

Business Processes.
Approach to systematically carrying out tasks or activities in order to attain objectives and goals.

Systems & Technology.
Systems engineering, systems architecture standards, interoperability, and standardization.

Performance Measurement.
Measures definition, data acquisition, and data utilization.

Management & Administration.
Technical understanding, staff recruitment and retention, organizational structure, relationships with external partners, and program legal authority.

MATURITY LEVELS

Level 1 – Ad Hoc.
Activities and relationships largely ad-hoc, informal, and champion-driven; substantially outside the mainstream of other agency activities. Business processes depend on the actions of individual staff.

Level 2 – Documented.
Basic strategy applications understood. Key processes support identified requirements, and key technology and core capacities under development. Business processes documented. Limited internal accountability and uneven alignment with external partners.

Level 3 – Measured.
Standardized strategy applications implemented in priority contexts and managed for performance. Technical and business processes developed, documented, and integrated into agency. Partnerships aligned. Efficiency and quality of activities evaluated through measures.

Level 4 – Managed.
Full, sustainable core agency program priorities established on the basis of continuous improvement with top-level management status and formal partnerships. Activities optimized based on performance data. Performance assessed relative to objectives and goals of the agency.

PERFORMANCE MEASURE IMPACTS ON CMM DIMENSIONS

The use of signal performance measures affects all aspects of CMM, not just the performance measurement dimension. This section summarizes how signal performance measures relate to the other three dimensions.

- **Business Processes.** Business processes are the foundation for traffic signal program activities. The service that an agency is able to provide will improve as they move closer to performance-based decision-making. At the highest level of maturity, agencies will use signal performance measures to assess goals, prioritize projects, and distribute funding to attain their goals and objectives.
- **Systems & Technology.** Agencies need to invest some resources into systems and technology to begin using signal performance measures. To function at the highest level of capability, the agency needs a system that allows consistent monitoring and supports a dynamic response to changing conditions. The technology will no longer be experimental but an integrated part of system management.
- **Management & Administration.** To successfully implement signal performance measures, agencies need to identify champion(s) and have staff all working toward the same goals and objectives. The capability of an agency depends on the availability of staff resources, including staff time and technical knowledge about signal performance measures. There will be an increased role for IT staff, which may be a new approach for some agencies. Workforce maturity relies on an agency's ability to retain talent and provide adequate compensation to mitigate risks of attrition. Maturity depends on internal and external relationships, including the extent of data and information sharing. At the highest level, an agency will routinely collaborate with stakeholders and use signal performance measures to support regional activities.

CMM LEVEL ASSESSMENT

An agency can start to assess its current capabilities in several ways. One of the most effective methods for gathering information is conducting a self-assessment that includes surveys and workshops with staff, partner agencies, and other stakeholders to assess activities and collaboration. Agencies can also review manuals, guides, policies, and other documents to see how well they have documented their capabilities. Agencies can incorporate current capability maturity information into a TSMP as a first step in planning for program management.

6.1.2 DOCUMENT GAP ASSESSMENT AND POTENTIAL MITIGATIONS

After an agency assesses its current capabilities and maturity levels, it can document gaps and, more importantly, mitigation options in the TSMP. Common gaps include deficiencies in funding, resources/staffing, and infrastructure. Actions included in the TSMP should help the agency improve capabilities in those areas and reduce overall agency risk. FHWA has created a framework to help agencies assess their strengths and weaknesses related to CMM, as well as develop targeted action plans for improvement (https://ops.fhwa.dot.gov/tsmoframeworktool/).

FUNDING

Agencies should identify projects that can aid the implementation of signal performance measures as part of the TSMP. As described in *Chapter 2*, agencies may be able to implement signal performance measures by building on ongoing projects. For example, the only upfront cost for the Regional Transportation Commission of Southern Nevada (RTC) during implementation was a server, procured by the IT department. They built the equipment costs for new controllers and detection systems into other, planned projects. In Texas, the City of College Station was similarly able to deploy signal performance measures at the same time as a central system procurement that already had funding.

RESOURCES/STAFFING

As an agency is developing a TSMP, it should identify and document regional and/or national resources. Agencies may be able to share resources as they deploy signal performance measures, including technical knowledge, lessons learned, and pooled funds to supplement low staff resources. For example, multiple agencies could hire a vendor or consultant to deploy a signal performance measure system.

In addition to staff time required to set up a system, an agency should consider whether they have enough staff to monitor the traffic signal system proactively once it is operational. In order to extract benefit from a performance measure system, practitioners must know how to use the system and how to develop useful information from the performance measures. Ongoing training may be required to increase knowledge region-wide. Training topics can be identified in the TSMP.

INFRASTRUCTURE

An agency should conduct a thorough review of existing equipment and identify gaps between the existing system and a system that is capable of reporting signal performance measures. *Chapter 4* includes a detailed discussion of system needs, which an agency should document in the TSMP. If significant equipment upgrades are required, the plan may involve prioritizing locations or pieces of equipment. For example, an agency may decide that communications investments are a lower priority in one region than another. For the lower-priority region, the agency may plan to collect performance measure data manually on a periodic basis until they can install additional equipment.

6.1.3 MONITOR PROGRESS AND RISK MANAGEMENT

The ability to collect performance data and make decisions based on it is a hallmark of highly capable agencies. As part of the TSMP, an agency should create an action plan that details short, mid-term, and long-term improvements related to signal performance measures. This plan should be a living document, and agencies should regularly update it with new activities that seek to improve agency capabilities and reduce overall agency risk.

6.2 IMPACT ON AGENCY ACTIVITIES

As introduced in *Chapter 1*, signal performance measures can benefit traffic signal operators, but the measures can also be shared with other agency groups. This section summarizes how signal performance measures impact daily activities for all stakeholders as well as considerations for applying them as part of a performance-based management program.

6.2.1 ORGANIZATIONAL

CULTURE SHIFT TO PERFORMANCE-BASED PRIORITIZATION

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

AGENCY EXAMPLE

The Utah Department of Transportation (UDOT) uses staff in their Traffic Operations Center (TOC) to check automated alerts each morning. Staff work their way through a checklist, resolving issues and writing work orders. This system helps UDOT fix problems before the public calls, and when the public does make a service request, ATSPMs help staff substantiate and resolve issues quickly.

SHAREABLE REPORTS

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

AGENCY EXAMPLE

The Pennsylvania Department of Transportation (PennDOT) found "annual hours of delay" was not easy for the public to understand. When conveying their message, they reported the average amount of time each person sits in traffic using hours per driver per year (31.5 in Pennsylvania).

QUANTITATIVE PERFORMANCE TRACKING

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

AGENCY EXAMPLE

Some agencies have moved beyond pilot projects and incorporate performance measures into long-term management of the agency. As part of its 2017 TSMO Strategic Plan, the Florida Department of Transportation (FDOT) detailed how staff can incorporate TSMO throughout the project development process. Part of this process includes selection of operational objectives and related performance measures that are feasible given agency capabilities and constraints (FDOT 2017).

AGENCY POLICIES AND STANDARD PRACTICES

The organizational structure of a transportation agency can vary greatly. Some agencies have separate ITS and signals groups, others have a signal group within the ITS department, and still others group ITS and signals under one umbrella (i.e., Traffic Signal Management & Operations, TSMO). When ITS and signals are separate, the signals group often focuses on arterials and integrated corridor management, whereas the ITS group is focused on freeway operations. Regardless of how an agency is organized, close collaboration between the signals and ITS groups will be essential. An agency can enhance inter-departmental communication by documenting standards for design, operations, and maintenance activities, such as policies for incorporating signal performance measures. Documentation that is clear and up-to-date will help individual groups or departments improve consistency across the agency.

INTER-AGENCY COLLABORATION

Agencies should proactively look for opportunities to collaborate externally with state agencies, metropolitan planning organizations (MPOs), and local agency partners. Using the gap assessment introduced in *Chapter 4*, agencies may be able to identify opportunities for resource sharing involving technical knowledge, lessons learned, and physical resources like servers. Agencies can often achieve effective external collaboration through regional groups that bring several agencies together.

AGENCY EXAMPLE

The Regional Transportation Commission (RTC) of Southern Nevada has the Freeway and Arterial System of Transportation (FAST) group, which is an integrated ITS organization administered by RTC in partnership with the Nevada Department of Transportation and the Cities of Las Vegas, North Las Vegas, Henderson, and Mesquite, along with Clark County. FAST has worked with the agencies to standardize controller and detection equipment, simplifying information sharing and the deployment of ATSPM across the region.

IT STAFF

Implementing signal performance measures will require significant collaboration between information technology (IT) practitioners and traffic management staff. Traditionally, traffic control systems have existed within their own closed networks. They did not require the same level of management as the computers and servers used for other public services, and the amount of data generated by those systems was relatively small. Although some agencies have IT staff that are highly involved with traffic signal control, managing high-resolution data creates the need for “new” roles in some agencies — roles which may exist in the IT department but which may be new to the signals group. In larger agencies, it may be necessary to add IT personnel to fill this role.

AGENCY EXAMPLE

In the City of College Station, Texas, implementation of signal performance measures required an improved relationship between the traffic control center and IT staff. IT staff had not previously worked with traffic control systems, but the amount of networking required for signal performance measures necessitated their involvement. The signals group chose to engage IT staff early in the implementation process as they were developing a master plan. This early engagement fostered a relationship that has been helpful in the maintenance of the ITS system and expansion of the fiber network for traffic system purposes.

6.2.2 TRANSPORTATION PLANNING

MODEL VALIDATION

Signal performance measures provide a way for agencies to validate planning models. While signal performance measures can reduce the number of planning models needed to replicate existing conditions, models will still be required to test certain scenarios such as new geometry or significant traffic pattern changes. Through ATSPMs and a comprehensive detection scheme, an agency can have access to volume data on a regular basis, which can be used to track traffic patterns and congestion during normal conditions as well as during special events, weather, and other incidents. If an agency has access to probe data, they can combine travel time, speed, and origin-destination information with volumes to refine a variety of models. Economic development groups can also use comprehensive volume data to track seasonal trends in traffic and growth from year to year.

EVALUATE BENEFIT/COST FOR PROGRAMS AND GRANTS

Agencies can use signal performance measures to evaluate the outcomes of investments in the transportation system. With readily available data from signal performance measures, agencies can compare conditions for all times of day and for much longer analysis periods than through manual data collection methods. Agencies can compare operational benefits to project or program costs, which the planning group can use when prioritizing locations or project types. Example metrics include:

- Red-light-running (RLR) events to evaluate safety improvements at an intersection.
- Travel time and travel time reliability to evaluate the impact of corridor signal retiming.
- Intersection delay to assess the impact of transit signal priority.

6.2.3 DESIGN AND CONSTRUCTION

COMPARE EQUIPMENT TYPES

Agencies can use signal performance measures to assess different types of communication, detection, and cabinet equipment. For example, agencies can sort the number of malfunctions over time by equipment type (i.e., vendor, model) to determine if certain equipment functions more reliably overall or under certain conditions (e.g., late at night, during weather events). The design group can use that information when designing intersections and updating guidance and standards. Additionally, agencies can coordinate with vendors to correct problems associated with a particular piece of equipment.

EVALUATE MAINTENANCE OF TRAFFIC (MOT)

Planned events (i.e., construction or special events) and unplanned events (i.e., traffic incidents or weather) often require detours, resulting in abnormal traffic patterns. Signal performance measures allow agencies to quantify the impact of MOT plans on congestion. Not only can staff potentially use the reports in real time to identify signal timing adjustments, but they can also use signal performance measures to compare different management strategies or technologies deployed as part of MOT. Note that in order to collect high-resolution data during construction events, signalized intersection equipment must remain operational (Ullman et al. 2011). However, practitioners can use probe vehicle data to supplement high-resolution data if signalized intersection equipment is offline during construction.

6.2.4 TRAFFIC OPERATIONS

CONTINUOUSLY AVAILABLE DATA FOR LESS MODELING

Engineers traditionally make traffic signal adjustments with the assistance of a model. Models are built to reflect existing conditions using traffic counts and field observations (typically from a single day), and then staff adjust existing signal timing values to improve operations in the model. The signal timing is deployed in the field, and then additional adjustments are made based on field observations.

Models will continue to be important for evaluating future conditions (e.g., geometric changes or significant traffic pattern changes), but for existing conditions, ATSPMs allow an agency to consistently measure operations over longer periods of time at more intersections than through traditional methods. Instead of looking at a single day of data, practitioners can review ATSPMs over the course of weeks or months to determine if the traffic signal is operating as expected and whether conditions are changing. If engineers make a change to the signal timing, they can quickly compare performance measures to identify the impact of the adjustment without developing an existing conditions model.

AUTOMATED ALERTS FOR OPERATIONAL ISSUES

Use of automated reports and dashboards can help agencies identify operational issues before the public calls to report them. The thresholds identified in *Chapter 5* can be used as a starting point for alerts, but some refinement will likely be required to prevent "false alarms."

AGENCY EXAMPLE

Clark County, Washington, uses an integrated video system with incident triggers. When the signal system exceeds a certain threshold, the system can send a notification and bring up the video feed on the traffic signal engineer's computer monitor.

PRIORITIZE SIGNAL RETIMING

Managers can use signal performance measures to prioritize which intersections/corridors to retime. Performance-based prioritization will ensure that staff spend time on the most-critical locations. This type of management requires that the agency establish thresholds to identify when an intersection or corridor has exceeded acceptable operational standards.

CONFIRM PUBLIC SERVICE REQUESTS

Citizens often make public service requests when they notice an issue at a signalized intersection. Staff typically spend time talking with the citizen about the issue and trying to observe the issue that was reported. Sometimes these issues are easy to observe, but at other times, an agency may send a technician to the field multiple times without a solution.

ATSPMs can help practitioners investigate publicly reported issues before sending technicians to the field. Practitioners can often isolate problems to a specific approach or specific lane, reducing the time a technician must spend in the field trying to recreate an event.

After validating a public service request, operators should decide if and how to adjust the signal timing based on the agency's objectives. If the agency's objectives are at odds with the public service request, signal performance measures can help an operator explain the rationale for current timing to the public.

6.2.5 MAINTENANCE

CONTINUOUSLY AVAILABLE DATA TO SUPPORT PREVENTATIVE MAINTENANCE

Agencies can take a proactive approach to maintenance through a preventative maintenance program, which typically involves periodic field visits undertaken to determine whether equipment is functioning properly. If practitioners identify an issue, they fix it in the field or process a work order (if more extensive work is required). Even if field visits occur semi-regularly, a technician will only be able to observe operations for a limited amount of time. ATSPMs provide continuously available data, which a technician can review prior to conducting preventative maintenance to help detect errors that may not occur during the one-day field visit.

AUTOMATED ALERTS FOR MAINTENANCE ISSUES

Automated alerts can highlight intersections with malfunctioning equipment. Practitioners can use signal performance measures to determine which equipment is failing, the time that the issue began, and when the issue was fixed. Without ATSPMs, an agency will be highly reliant on calls from the public to notify them about equipment failures.

PRIORITIZE INFRASTRUCTURE IMPROVEMENTS

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

AGENCY EXAMPLE

The City of Atlanta, Georgia, has created a system by which they incorporate ongoing maintenance and operations into their capital projects. When they contract a capital program, they ask contractors to operate, manage, and maintain the infrastructure for a set period of time, and budget this expense into the capital program. This creates a modified public-private partnership whereby the agency is outsourcing operations and maintenance activities in a way that does not require exclusive maintenance funding.

6.3 REFERENCES

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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