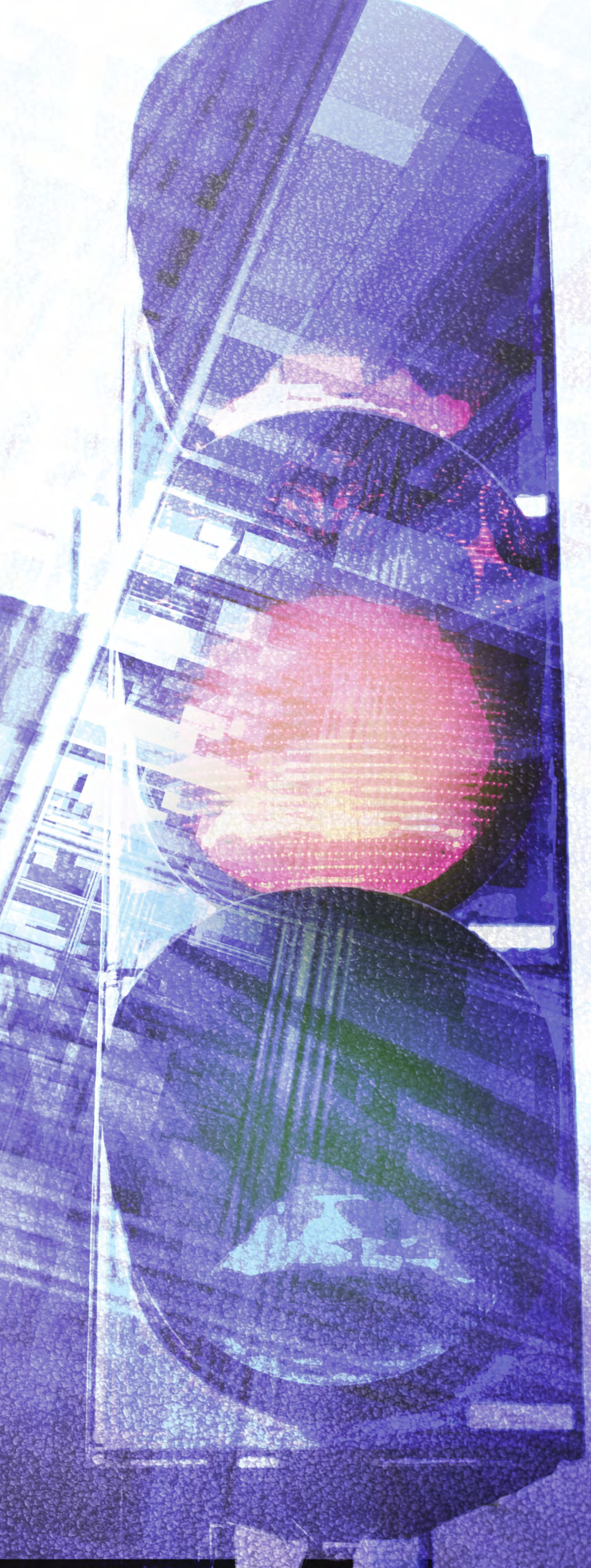

TRAFFIC SIGNAL PROGRAM HANDBOOK

Publication No. FHWA-HOP-23-041

April 2023

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Federal Highway Administration

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16. Abstract

A programmatic approach to traffic control systems management and operations strategically links business processes, workforce, systems and technology, and management decisions to objectives that are consistent with the goals of the organization. The purpose of this handbook is to advance the use of objectives and performance-based approaches to traffic signal management and to improve design, operations, and maintenance practices, resulting in increased safety, mobility, and efficiency for all users. This handbook is divided into two parts. Part I focuses on how to develop an effective traffic signal program by describing the elements of a traffic signal program (Chapter 2) and how to assess and improve the level of maturity of the program's capabilities (Chapter 3). Part II focuses on the systems and technologies associated with a traffic signal program, specifically the systems and technologies agencies may want to deploy to achieve various program objectives. The intent of part II is to provide insight and guidance to allow traffic signal program managers and operators to make decisions related to the types of systems and technologies they need to install at signalized intersections. Part II begins with a discussion of the Systems Engineering process (Chapter 4) and illustrates its roles in the identification, selection, and design of traffic signal systems and technologies. Part II next discusses the basic systems and technologies needed to achieve good basic service at the intersection level (Chapter 5), and then discusses how higher program objectives can be achieved through improved detection (Chapter 6), communications (Chapter 7), system control (Chapter 8), and, finally, advanced control (Chapter 9).

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Alternating Current
AMU	Auxiliary Monitor Unit
API	Application Programming Interface
APT	Advance Preemption Time
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASC	Adaptive Signal Control
ATC	Advanced Traffic Controller
ATCC	Advanced Traffic Controller Cabinet
ATSPM	Automated Traffic Signal Performance Measures
BBU	Battery Backup Unit
BIU	Bus Interface Unit
BSM	Basic Safety Message
BSP	Board Support Package
C	Cycle Length (sec)
C2C	Center-to-Center
C2F	Center-to-Field
CCTV	Closed-Circuit Television
CFR	Code of Federal Regulations
CIP	Capital Improvement Program
CMAQ	Congestion Mitigation and Air Quality
CMM	Capability Maturity Model
CMU	Conflict Monitor Unit
CTSS	Central Traffic Signal System
CV	Connected Vehicle
DC	Direct Current
DDI	Diverging Diamond Interchange
DLT	Displace Left Turns
DMS	Dynamic Message Sign
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communications
EPA	Environmental Protection Agency
EVP	Emergency Vehicle Preemption

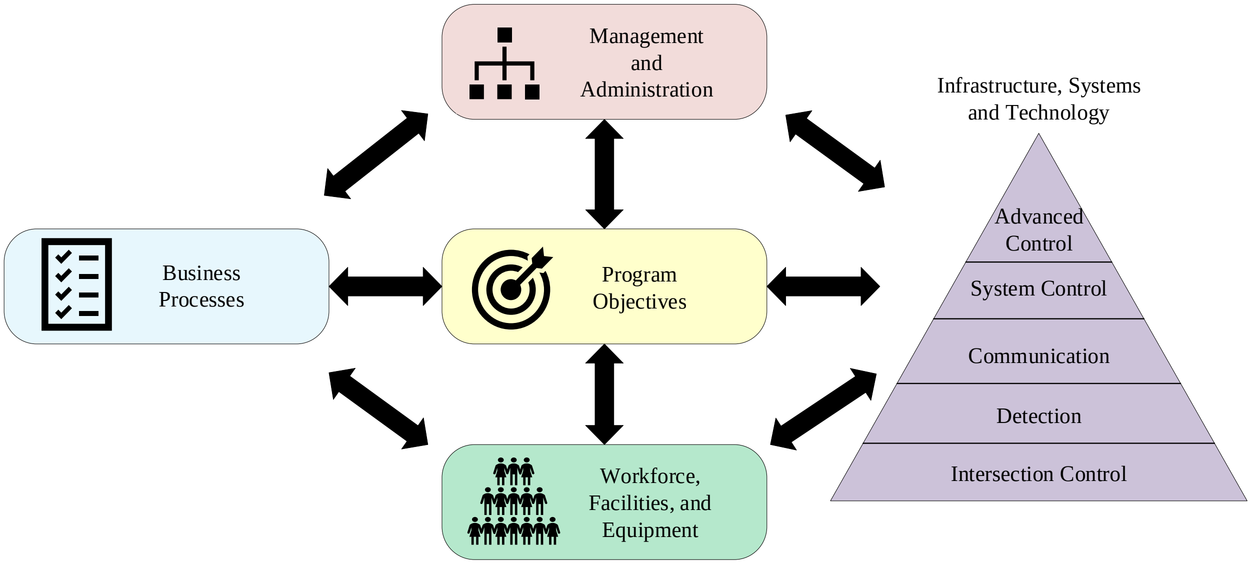
FAST	Fixing America’s Surface Transportation
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
g	Green Interval (sec)
GcOST	Goals, Context, Objectives, Strategies, Tactics
GHz	Gigahertz
GPS	Global Positioning System
HSIP	Highway Safety Improvement Program
ICE	Intersection Control Evaluation
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation System
LED	Light-Emitting Diode
LTE	Long-Term Evolution
MIB	Management Information Base
MMU	Malfunction Monitor Unit
MOU	Memorandum of Understanding
MPO	Metropolitan Planning Organization
MUT	Median U-Turn
MUTCD	Manual on Uniform Traffic Control Devices
NACTO	National Association of City Transportation Officials
NCHRP	National Cooperative Highway Research Program
NEC	National Electrical Code
NEMA	National Electronic Manufacturers Association
NHFP	National Highway Freight Program
NTCIP	National Transportation Communication for ITS Protocol
OS	Operating System
P2P	Peer-to-Peer
PCD	Purdue Coordination Diagram
RCTO	Regional Concept of Transportation Operations
ROW	Right-of-Way or Right of Way
RTSOP	Regional Traffic Signal Operations Program
SAE	Society of Automotive Engineers
SCATS	Sydney Coordinated Adaptive Traffic System
SCOOT	Split Cycle Offset Optimization Technique

SDLC	Synchronous Data Link Control
SPaT	Signal Phasing and Timing
SPUI	Single-Point Urban Interchange
SSM	Signal System Master
STIP	State Transportation Improvement Plan
TCSH	Traffic Control Systems Handbook
TMC	Traffic Management Center
TRB	Transportation Research Board
TSMO	Transportation System Management and Operations
TSMP	Traffic Signal Management Plan
TSP	Traffic Signal Priority
TSPH	Traffic Signal Program Handbook
TSS	Traffic Signal System
UPS	Uninterruptible Power Supply
USB	Universal Serial Bus
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
VME	Versa Module Eurpora

EXECUTIVE SUMMARY

The necessity of accountability and the rapid pace of technology and innovation calls for programmatic approaches to traffic control systems management and operations. A programmatic approach to traffic control systems management and operations strategically links business processes, workforce, systems and technology, and management decisions to objectives that are consistent with the goals of the organization. The purpose of this *Traffic Signal Program Handbook* (TSPH) is to advance the use of objectives and performance-based approaches to traffic signal management in order to improve design and operations and maintenance practices, thereby resulting in increased safety, mobility, and efficiency for all users.

This handbook strategically links the four areas of a traffic signal program—program management and administration; business processes; workforce, facilities, and equipment; and systems and technologies—to program objectives that guide day-to-day activities and inform decisions that improve program effectiveness. As shown in Figure 1, these primary elements support the ability of the agency to attain its program objectives.



Source: Federal Highway Administration

Figure 1. Graphic. Elements of a traffic signal management program.

This handbook focuses on the systems and technology area of the traffic signal program in particular, providing an in-depth discussion of each level of the hierarchy of investments (the triangle on the right side of figure 1) within this program area that is integral to the sustained attainment of objectives. Users of this handbook should first focus on what systems and technologies are needed to provide the foundational building blocks associated with providing good basic service for traffic signal operations. The handbook then discusses how adding detection technologies to the systems and technologies providing intersection control allows agencies to achieve different, more complex operational objectives to more reliably sustain delivery of good basic service. Adding communications then provides the necessary technology and systems to support linking multiple intersections together to accomplish corridor-level objectives. Finally, good system control technologies and systems provide the foundation upon which agencies can accomplish more advance control features, such as adaptive signal operations, priority control, and so forth.

The handbook is divided into two parts. Part I addresses the identification of strategies and tactics for establishing and improving a traffic signal program and focuses on how to develop an effective traffic signal program by describing the elements of a traffic signal program (Chapter 2), and how to assess and improve the level of maturity of the program's capabilities (Chapter 3).

Part II focuses on the systems and technologies associated with the traffic signal program, specifically the systems and technologies agencies can use to achieve various program objectives. The intent of part II is to provide insight and assist traffic signal program managers and operators with making decisions related to the types of systems and technologies to install at signalized intersections. Part II begins with a discussion of the systems engineering process (Chapter 4) and illustrates its role in the identification, selection, and design of traffic signal systems and technologies. Part II then discusses the basic systems and technologies needed to achieve good basic service at the intersection level (Chapter 5), followed by a description of how higher program objectives can be achieved through improved detection (Chapter 6), communication (Chapter 7), system control (Chapter 8), and advanced control (Chapter 9).

The TSPH extensively uses and references existing resources within the Federal Highway Administration (FHWA) Office of Operations and other FHWA offices, such as the Office of Safety, Planning Environment and Realty, Infrastructure, and Policy and Governmental Affairs. It also identifies, leverages, and references resources developed by external organizations to ensure comprehensive coverage of current guidance, policy, practices, research, standards, processes, training, strategies, and methods that contribute to effective traffic signal program management.

CHAPTER 1. INTRODUCTION

The planning, design, operation, and maintenance of signalized intersections influence and are integral to achieving safety, mobility, and reliability goals. Recent collaborations between public agencies and the Federal Highway Administration's (FHWA) Traffic Signal Management and Operations Program(1) (located within FHWA's Office of Operations) aimed at improving the effectiveness of traffic signal operations and signal timing have found that linkages between design, operations, maintenance, workforce, and management and administration functions within a transportation organization are fundamental to the attainment of good basic service. From a traffic signal operational perspective, good basic service occurs when an organization provides the best level of operational performance to attain its primary objectives within the constraints of its operational resources. An outcome of FHWA's collaborations is the recognition that agencies can organize—formally or informally—traffic signal design, operations, maintenance, workforce, and associated management and administrative components into a single cohesive program with a set of shared goals and objectives. As a result of conducting numerous traffic signal program reviews and a review of National traffic signal management and operations self-assessments, FHWA has found that effective traffic signal programs exhibit the following characteristics:(2)

- Place a high priority on providing good basic service.
- Have clear, measurable, unambiguous, documented objectives that relate to the agency's goals.
- Avoid constructing infrastructure elements that they cannot maintain and operate.
- Measure and report results and outcomes.
- Actively develop and reward capable staff.

PURPOSE OF HANDBOOK

The purpose of this handbook is to discuss traffic signal control systems and technologies in terms of how they support and are influenced by what the agency wants to accomplish, as well as how the design, operations, and maintenance of the systems and technology used by an agency influence the overall effectiveness of the traffic signal program. This handbook builds upon the fourth edition of the Tr*affic Control Systems Handbook* (TCSH).(3) Developed in 2005, the TCSH is a basic reference for planning, designing, and implementing traffic control systems. However, since its development, intelligent transportation systems (ITSs) have evolved dramatically, primarily due to rapid and substantial technological improvements in communications, computing power, software development, and, most notably, mobile devices. The need to better guide the investment of limited transportation funding necessitates clear linkages between traffic signal design, operations, and maintenance processes and the meaningful application of system architecture and systems engineering concepts. The TCSH no longer substantively covers the myriad of systems and technology necessary to manage and operate today's traffic signal systems. This handbook not only updates the systems and technologies used in today's traffic signal systems, but also how systems and technologies, combined with solid management and administrative practices; good business processes; and adequate workforce, facilities, and equipment resources function together to attain the sustained delivery of good basic service.

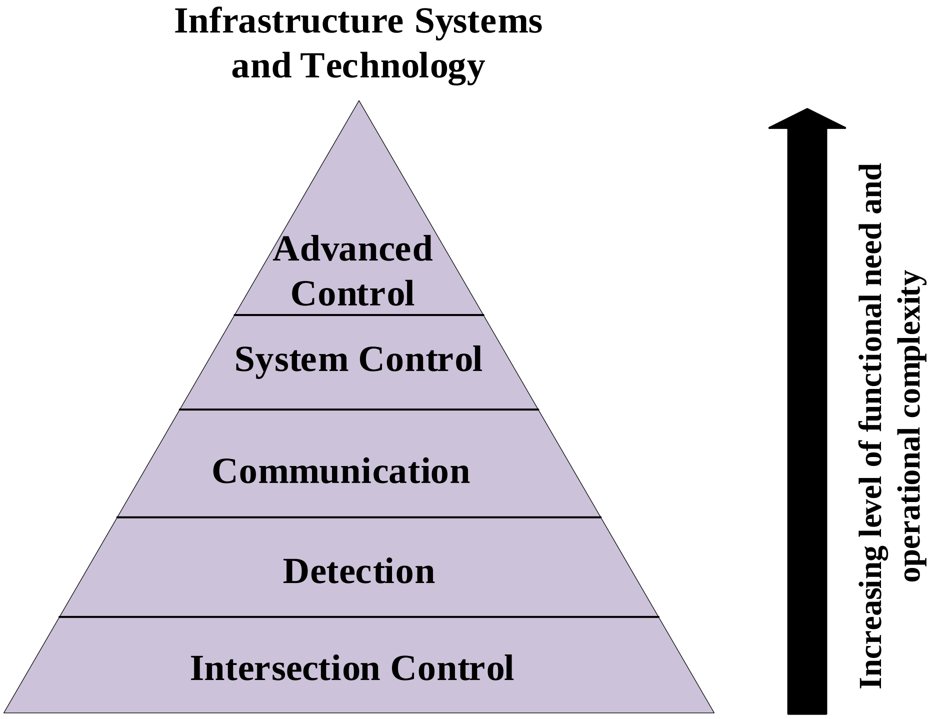
TARGET AUDIENCE

This handbook supports professionals who are involved in the planning, design, management, operation, or maintenance of traffic signal systems and who are responsible for the following activities in a traffic signal program:

- Guiding and assisting decision-makers in determining agency priorities and establishing performance objectives.
- Identifying and managing agency traffic signal resources (including technological and human assets).
- Providing fiscal oversight and management (including budgeting and expenditure control) of traffic signal management assets.
- Designing installations and procuring systems and technologies.
- Monitoring and reporting on the performance of the systems and technologies related to achieving agency program objectives.

HOW TO USE THE HANDBOOK

This handbook is part of a collection of publications designed to support the planning, management, implementation, operation, and maintenance of traffic signal systems to achieve transportation goals, such as safety, reliability, mobility, and economic vitality. A traffic signal system with minimal investment in systems and technology could still make progress toward most of the goals mentioned; however, doing so would require organizations to sustain a high level of rigor and workforce expertise that would be difficult if not impossible to sustain over a long period. By investing in systems and technology, the organization can maximize the efficiency of its workforce while also increasing system capability to consistently attain objectives. Figure 2 demonstrates the relationship between capital investment, traffic signal system capability, and program reliability. Each level in the hierarchy represents an investment in systems and technology to improve the capability, reliability, and efficiency of the program. The base of the hierarchy represents the fundamental level of intersection control required to safely assign right of way (ROW). The second level adds detection to improve the capability and reliability of attaining fair distribution of green time and minimizing delays. The next level, communications, allows agencies to perform remote monitoring and management capabilities (e.g., proactively maintaining the system in a state of good repair). Communications also becomes the foundation upon which agencies can more reliably achieve corridor and system-level operational objectives (e.g., providing smooth flow, balancing directional flows, etc.) in the fourth level. Finally, in the fifth level, system-level technologies allow agencies to achieve more advanced program objectives (e.g., traffic signal timing that adapts automatically to changes in traffic demand trends, etc.).



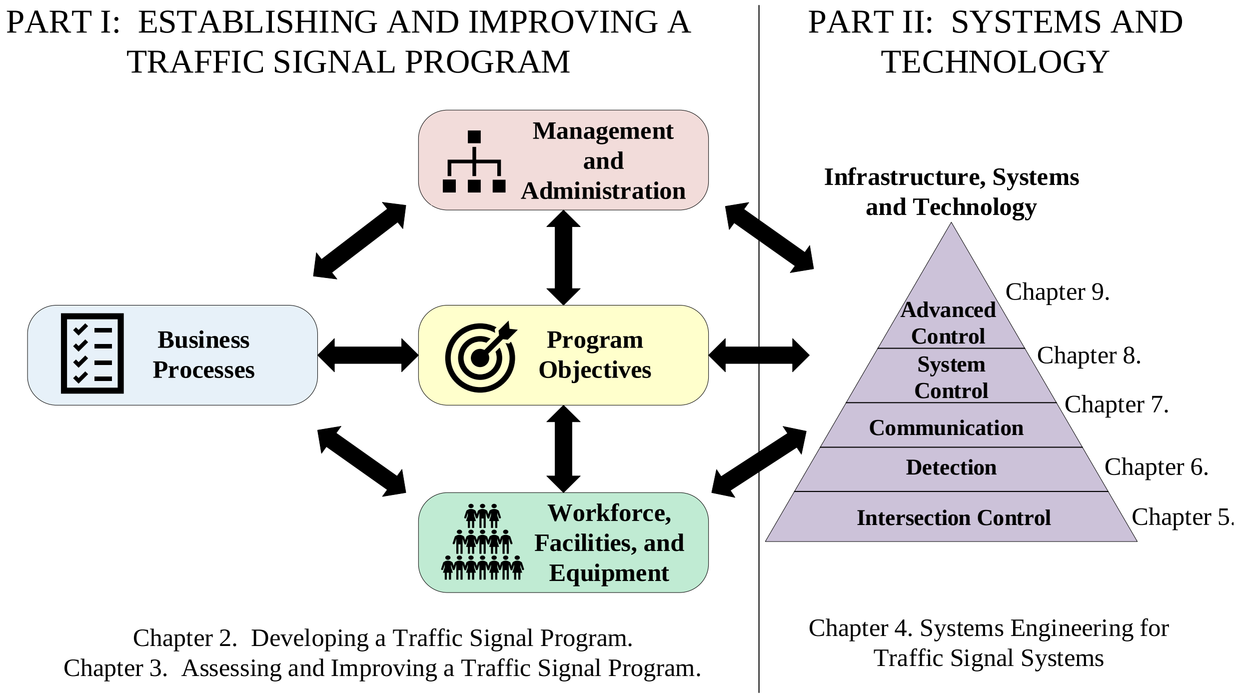
Source: Federal Highway Administration.

Figure 2. Graphic. Hierarchy of traffic signal systems and technology.

STRUCTURE OF HANDBOOK

As illustrated in figure 3, this handbook consists of two parts. Part I of this handbook identifies strategies and tactics for establishing and improving a traffic signal program and focuses on the left side of the traffic signal program diagram in the figure. Part I includes the following chapters:

- Chapter 2. Developing a Traffic Signal Program.
- Chapter 3. Assessing and Improving a Traffic Signal Program.



Source: Federal Highway Administration.

Figure 3. Graphic. Structure of handbook.

Part II discusses the advantages and disadvantages of traffic signal systems and technologies, ~~to~~ providing traffic signal program managers and operators an understanding of which systems and technologies can most benefit their agency. Part II of the handbook focuses on the right side of the traffic signal program diagram in figure 3 and includes the following chapters:

- Chapter 4. Systems Engineering for Traffic Signal Systems.
- Chapter 5. Intersection Control.
- Chapter 6. Detection.
- Chapter 7. Communications.
- Chapter 8. System Control.
- Chapter 9. Advanced Control.

TRAFFIC SIGNAL PROGRAM AND TRANSPORTATION SYSTEM MANAGEMENT AND OPERATIONS

Whether formally or implicitly, traffic signals operation is a component of the overall transportation system management and operations (TSMO) activities of many agencies. TSMO activities are a set of integrated, coordinated, and collaborative operational strategies that focus on getting the most out of the existing transportation system.(3) Often, these strategies require coordination across multiple jurisdictions, agencies, and modes so that the transportation system works as a unified whole. Typical operational strategies in a TSMO program include the following:

- Work Zone Management.
- Traffic Incident Management.
- Special Event Management.
- Road Weather Management.
- Transit Management.
- Freight Management.
- Active Transportation and Demand Management.
- Ramp Management.
- Traveler Information.
- Access Management.
- Bicycle and Pedestrian Crossing Management.
- Integrated Corridor Management.

TSMO activities emphasize the following:

- Integrating systems and components throughout the entire project life cycle, including planning, development, construction, and maintenance.
- Being proactive and predictive versus static and reactive.
- Improving the reliability of travel through the entire transportation system, not simply individual facilities or jurisdictions.
- Focusing on moving people and goods instead of just vehicles.
- Using integrated strategies as opposed to individual or isolated responses.

RELATIONSHIP TO OTHER DOCUMENTS

This handbook represents the next evolution of the TCSH.(3) It focuses on the relationships between people, processes, and technology and demonstrates how the three components work together in an integrated fashion to attain established agency goals and objectives. It shifts the focus away from isolated discussion of specific systems and devices and instead helps an agency develop its understanding of its program activities to determine what systems they might need. The handbook references guidelines, policies, and standards that support the design and implementation of the systems and technologies that can help attain an agency's documented objectives. It uses and references existing resources within the FHWA Office of Operations and other FHWA offices, such as the Office of Safety, Safety, Planning Environment and Realty, Infrastructure, and Policy and Governmental Affairs.as well as external organizations such as the Transportation Research Board (TRB), National Cooperative Highway Research Program (NCHRP), American Association of State Highway and Transportation Officials (AASHTO), Institute of Transportation Engineers (ITE), and others. Key references for this document include the following:

- *Traffic Control Systems Handbook.*(3)
- *Improving Traffic Signal Management and Operations: A Basic Service Model.*(2)
- *An Objectives- and Performance-Based Approach for Improving the Design Operations and Maintenance of Traffic Signal Systems.*(5)
- *Part 4: Highway Traffic Signals. Manual on Uniform Traffic Control Devices for Streets and Highways.*(6)
- *Signal Timing Manual, 2nd Edition.*(7)
- *Model System Engineering Documents for Adaptive Signal Control Technology (ASCT) Systems.*(8)
- *Model Systems Engineering Documents for Central Traffic Signal Systems (CTSSs).*(9)
- *Traffic Signal Benchmarking and State of the Practice Report—2019.*(10)
- *Automated Traffic Signal Performance Measures.*(11)
- *Traffic Signal System Capability Maturing Model.*(12)

Links to many of the key document are located on FHWA's Arterial Management Program website at https://ops.fhwa.dot.gov/arterial_mgmt/index.htm.

This handbook is not intended to replace local standards, policies, or procedures, but does provide summaries of the best practices established in the literature.

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CHAPTER 2. GOOD BASIC SERVICE

Improving Traffic Signal Management and Operations: A Basic Service Model (1) introduces the concept of good basic service for traffic signal operations. The report identified five archetype programs based on observations of high-performing programs, each with different resource combinations in the program areas of workforce, business process, and systems and technology. These traffic signal programs produced varying outcomes over a sustained period based on how they invested constrained operating and capital resources to overcome limitations in one or more program areas. Effective traffic signal programs focus on doing their most important objectives first, within the constraints of the resources they have. According to *Improving Traffic Signal Management and Operations: A Basic Service Model*, (1) highly effective traffic signal programs exhibit the following traits:

- Have a clear understanding of their program objectives.
- Routinely conduct meaningful evaluations of performance.
- Communicate priorities throughout the organization.
- Coordinate design, operations, and maintenance activities to attain specific objectives.
- Commit to the professional development of staff.

In contrast to the practices that produced high-performing traffic signal programs, program reviews conducted in over 20 regional areas between 2006 and 2015 and the outcomes of three iterations of the National Traffic Signal Report Card suggest that agencies that struggled to provide good basic service typically exhibited the following traits:

- Treating traffic signal systems and technologies as commodities rather than resources.
- Having no established or documented management philosophy to guide operations and maintenance activities.
- Using complaints as the primary measure of performance to determine the effectiveness of operations.

OBJECTIVES DRIVEN APPROACH TO MANAGING TRAFFIC SIGNALS

The concept of good basic service was honed further and presented in FHWA's *Traffic Signal Management Plan—An Objectives- and Performance-Based Approach for Improving the Design Operations and Maintenance of Traffic Signal Systems.*(2) That document provided a procedural approach to documenting the relationship between objectives and the program activities of design, operations, maintenance, and management and administration. What is most important to an organization is generally captured in the mission, vision, and goal statements developed by the organization and encapsulated in strategic plans, such as long-range or regional metropolitan plans. A process of identifying goals and examining the range of physical and operational contexts present at a signalized intersection and within the transportation network can inform the development of a set of objectives. The objectives guide the way that agencies program activities (i.e., strategies) and engage specific methods (i.e., tactics) to ensure that they attain their objectives. FHWA has dubbed this process of identifying goals, evaluating context, formulating objectives, and developing strategies and tactics as the Goal, Context, Objectives, Strategies, and Tactics (GcOST) process. Figure 4 illustrates the GcOST process.

Source: Federal Highway Administration

Figure 4. Graphic. Goals, context, objectives, strategies, and tactics (GcOST) pyramid.(2)

The GcOST process supports the application of the concept of good basic service by providing a method to develop clear objectives. FHWA recommends agencies develop a Traffic Signal Management Plan (TSMP) to document the management philosophy of a traffic signal program, identify gaps in capabilities, and create an action plan to address how to sustain the delivery of good basic service. Agencies can find support for the development of TSMPs in *Traffic Signal Management Plans—An Objectives and Performance-Based Approach for Improving the Design Operations and Maintenance of Traffic Signal Systems*.(2) That document also discusses the GcOST process and its elements in detail.

The sections that follow provide a brief overview of goals, context, objectives, strategies, tactics, and performance measures.

Goals

Goals define what is most important to an organization. Goals are the expressed end states of elected officials and policy makers. They are usually expressed in high-level documents, such as long-range planning documents or agency policy statements. Table 1 lists some of the more common agency goals, expressed in a single word or phrase in the left column, and interpreted at a high level in the context of a traffic signal system in the right column.

Context

Context is the set of physical, operational, and organizational constraints that influence the prioritization of goals and the selection of objectives, strategies, and tactics. The most important thing to note about context is that it changes based on location, time, seasons, and organizational preferences and policies. Operational contexts include factors that influence how an agency might operate a signal. Operational contexts might change by time of day, by operating modes, or because of external events (e.g., planned and unplanned events and incidents). Physical context includes items such as land use, network configuration, and weather. Organizational context includes the infrastructure and workforce capabilities, and agency preferences. All contexts must be adequately considered to support the selection of appropriate objectives, strategies, and tactics. The identification and analysis of context is arguably the most important capability of an effective program. Effective identification and evaluation of context is pivotal to the identification and selection of attainable objectives, as well as the supporting strategies and tactics. As context changes, so should objectives, strategies, and tactics to ensure that progress toward goals is sustained.

Objectives

Objectives describe what must be attained to achieve the goals of the organization. A complete set of objectives must be developed based on a comprehensive evaluation of all goals and contexts. For any given context, a clearly stated objective should be available to direct the development, selection, and execution of a program of activities (strategies) and specific methods and actions (tactics). Clearly stated objectives also support the selection of meaningful performance measures that validate and demonstrate the effectiveness of strategies and tactics.

Strategies

Strategies are the activities and solutions that programs undertake to attain one or more specific objectives. The four program areas described in the traffic signal program model (systems and technology, business processes, management and administration, and workforce) encapsulate strategic programs of activities that agencies apply to attain objectives. For example, an agency might implement a preventative maintenance program of activities to improve the reliability of its infrastructure. The preventative maintenance program represents the strategy, while sustaining systems and technology reliability represents the objective. Strategies reside within program areas and may have dependencies that cut across multiple program areas. To effectively execute strategies, agencies provide resources (i.e., people, equipment, system, and processes).

Table 1. Examples of common transportation goals.

Goal Category	Description
Safety	Actions to reduce fatalities and serious injuries. (3)
Mobility	The ability of people to move easily from place to pace how, and when they want. (4)
Accessibility	The ease of reaching valued destinations, such as jobs, shops, schools, entertainment, and recreation. (3)
Reliability	Reliable transportation systems offer some assurance of attaining a given destination within a reasonable range of an expected time. (3)
Livability	Using the quality, location, and type of transportation facilities and services available to help achieve broader community goals, directly benefiting people who live in, work in, or visit an area. (3)
Resilience	The ability to prepare for changing conditions and withstand, respond to, and recover rapidly from disruptions. (5)
Economic Vitality	Manages transportation systems and infrastructure in a manner that maximizes the relationship between customers, workers, viable businesses, and/or profitable investments.
Reduce Congestion	Efforts to reduce travel time or delay in excess of that normally incurred under light or free-flow travel conditions. (4)
State of Good Repair	The condition in which capital assets operate at a full level of performance, meeting designed function, not posing a safety risk, and life-cycle investments have been met or recovered.
Quality Customer Service	Providing efficient, quick, and friendly service to customers as well as building strong relationships with them and resolving issues swiftly.
Sustainability	Sustainability is the satisfaction of present and future basic social and economic needs, while responsibly use natural resources, while maintaining or improving the well-being of the environment and ecology on which life depends. (3)
Fiscal Responsibility	Manage resources in a cost-effective, strategic and systematic manner.
Regional Coordination	Balancing regional and local travel needs by integrating transportation facilities and systems to enhance the experience of all users.

Source: Federal Highway Administration.

Tactics

Tactics are the specific actions or methods that operationalize one or more strategies. For example, developing inspection procedures, implementing inspection checklists, and conducting regular inspections are all examples of tactics that an agency might implement in support of a preventative maintenance program. Tactics can also include implementing supporting technologies and infrastructure that enable agencies to execute strategies to attain system objectives. For example, an agency might consider deploying an automated traffic signal performance measurement system to provide data for assessing the effectiveness of different operational and maintenance strategies.

Performance Measures

Meaningful performance measurement is a key tenet of achieving good basic service and is imperative for evaluating the achievement of objectives, appropriateness of strategies, and optimization of tactics. Performance measures are central to implementing performance-based planning and management processes. This topic will be discussed in more detail from a systems and technology perspective later in this document. The selection of performance measures significantly affects the types of strategies and tactics implemented, as well as the capital projects advanced to achieve them. Moreover, performance results inform agencies on whether projects and strategies they have implemented are helping them achieve their program objectives.

PROGRAM OBJECTIVES

Program objectives are at the center of a traffic signal program. Program objectives describe what (not how) the program must attain to meet a particular set of agency goals. Program objectives guide the development, selection, and execution of the activities performed in the surrounding program areas (business processes; management and administration; systems and technologies; and workforce, facilities, and equipment).

Regardless of size, location, or complexity, traffic signal programs generally pursue a common and finite set of maintenance, organizational, and operational objectives. Organizational objectives focus on what, as an organization, the agency is trying to achieve. Organizational objectives influence (and are influenced by) organizational context, such as scale, agency preference, and organizational capabilities. Common organizational objectives include the following:

- Ensure responsiveness to stakeholder needs.
- Comply with National, State, and local policies and standards.
- Minimize life-cycle costs.

Maintenance objectives focus on sustaining the infrastructure in a state that is consistent with its design. Maintenance objectives influence (and are influenced by) the physical context of the intersection, such as land use, network configuration, roadway classification, and so forth. Common maintenance objectives include the following:

- Maintain intersection infrastructure (poles, foundations, cabinets, etc.) in a good state of repair.
- Sustain the reliability of the control systems and technologies (detection systems, communications, controller firmware, central management system software, etc.).

Operational objectives describe desired outcomes that an agency is trying to attain using its traffic signal systems and technologies. Operational objectives focus on how the traffic signal systems and technologies should operate within the context of individual intersections and a network of roadways.

Table 2 shows the relationship between program objectives and agency and community goals. The following sections provide brief definitions of these operational objectives. Agencies can tailor these operational objectives to fit their specific traffic signal programs.

Assign ROW Safely

At in individual intersection level, ROW assignment is "the permitting of vehicles and/or pedestrians to proceed in a lawful manner in preference to other vehicles or pedestrians by the display of a sign or signal indications."(6) This objective focuses on managing conflicts between intersection users (vehicles, pedestrians, bicyclists, transit vehicles, etc.). This objective also focuses on minimizing or eliminating potential conflicts between intersection users.

Appropriate Distribution of Green Time

This objective, under a range of demand conditions from low to high, focuses on ensuring that traffic signals at an individual intersection serve all intersection users (vehicles, pedestrians, bicyclists, transit vehicles, etc.) as fairly as possible according to agency policies and community goals. This objective allows agencies to distribute intersection and arterial capacity fairly across all movements and modes. Agencies may prioritize movements according to need without excessively delaying other movements. This objective also focuses on keeping signal operations appropriate for current traffic conditions and consistent with current operational policies. This objective seeks to balance delays and wait times of all intersection users.

Table 2. Relationship between common program objectives and agency goals.

Program Objectives	Agency Goal: Safety	Agency Goal: Mobility	Agency Goal: Quality Customer Service	Agency Goal: State of Good Repair
Assign ROW Safely	X	–	–	–
Appropriate Distribution of Green Time	–	X	–	–
Provide for Pedestrian and Bicycle Comfort and Convenience	–	X	–	–
Provide Preferential Service to Specific Intersection Users	–	X	–	–
Provide Smooth Flow	–	X	–	–
Maximize Throughput	–	X	–	–
Manage Queues	–	X	–	–
Respond to Stakeholder Needs	–	–	X	–
Comply with Agency Policies and Standards	–	–	X	–
Minimize Life-Cycle Costs	–	–	–	X
Maintain Infrastructure State of Good Repair	–	–	–	X
Sustain Systems and Technology Reliability/State of Good Repair	–	–	–	X

"X" denotes that Program Objective provides primary support to Agency Goal; "–" denotes that Program Objective provides secondary benefit to Agency Goal.

Source: Federal Highway Administration.

Provide for Pedestrian and Bicycle Comfort and Convenience

This objective focuses on accommodating vulnerable road users, such as pedestrians and bicyclists. The *Manual on Uniform Traffic Control Devices* (MUTCD)(6) is a regulatory standard, see 23 CFR 655.603; it provides minimum operating requirements for pedestrian control. Agencies may need to deploy additional signal operating strategies where local community goals promote and encourage pedestrian and bicycle comfort and convenience. Agencies may also wish to deploy special operating strategies around special pedestrian and bicycle generators, such as schools, parks, and shopping locations.

Provide Preferential Service to Specific Intersection Users

Some agencies may need to provide preferential service to specific intersection users, such as transit vehicles, emergency service vehicles, trucks, and bicyclists. This objective allows agencies to define the situations and circumstances under which to provide preferential treatment to specific classes of road users. Satisfying the objective may require agencies to work cooperatively with different road user groups to develop strategies for addressing their needs at intersections.

Provide Smooth Flow

Attaining this objective means vehicles are able to move through the network without stopping. To achieve this objective, agencies may use strategies and tactics to coordinate the operations of multiple intersections progressively to allow groups of vehicles (platoons) to move through the system and only rarely have to slow down or stop. This objective may also require agencies to work cooperatively with neighboring agencies to develop and implement progression across jurisdictional boundaries.

Maximize Throughput

This objective seeks to operate the traffic signal system and technology to maximize the total number of users serviced through the intersection when high to congested demand conditions are present at individual intersections or at the network level. This objective may involve implementing timing strategies and other capacity enhancement techniques to maintain the highest vehicle flows (or degree of saturation) to relieve or prevent congestion.

Manage Queues

This objective seeks to manage the location and size of residual queues when congested demand conditions are present at individual intersections or at the network level to minimize the effect of queuing within the network. This objective may involve ensuring that traffic demands do not spill back to impede other intersections' operations. Agencies may also use timing strategies and tactics to hold traffic demand at locations that have sufficient capacity to store excess demand, even though other movements do not require the additional green time. Agencies may implement strategies that regulate short-term fluctuations in demand as well.

Respond to Stakeholder Needs

From an organizational perspective, this objective seeks to maximize the responsiveness of agencies to satisfy the needs of different stakeholders. Stakeholders might include pedestrian and bicycle communities, transit operations, law enforcement, and emergency service providers. Stakeholders might also include neighborhood advocacy groups or decisions-makers. This objective also focuses on implementing strategies and techniques to balance competing community objectives. Under this objective, agencies can also deploy strategies and tactics to manage surges in traffic (both planned and unplanned). This objective may also require agencies to deploy systems and technologies that identify areas with changing traffic patterns, particularly in growing communities or areas with recurring planned special events (e.g., concerts, sporting events, or community activities).

Comply with Applicable Policies and Standards

This objective focuses on ensuring traffic signals are planned, designed, operated, and maintained in compliance with all applicable Federal, State, and local requirements, including the MUTCD, a regulatory standard, see 23 CFR 655.603.(6) Regardless of the objective chosen, it is important to note that agencies must ensure that the strategies and tactics they employ to achieve all of their objectives continue to comply with applicable requirements.

Minimize Life-Cycle Costs

This objective focuses on the practices and procedures that agencies use to provide good stewardship over their resources and assets. This objective enables decision-makers to find the least total-cost alternatives that satisfy the agency and community goals. Under this objective, decision-makers can make fiscal decisions that produce the best long-term results, or the greatest return related to the systems and technologies used by the program. In addition, agencies can also implement strategies and tactics for managing not only the traffic signal systems and technologies but also program support equipment and facilities.

Maintain Infrastructure in a State of Good Repair

This objective focuses on ensuring that agencies keep the physical components of the traffic signal system (the support poles, mast arms, signal heads, etc.) in good working order according to their performance requirements. Under this objective, agencies can implement strategies and tactics for identifying operational and maintenance issues that impact the overall performance of the signal system. Agencies can also use this objective to develop strategies and tactics for monitoring and improving the efficiency of their maintenance practices.

Sustain System and Technology Reliability

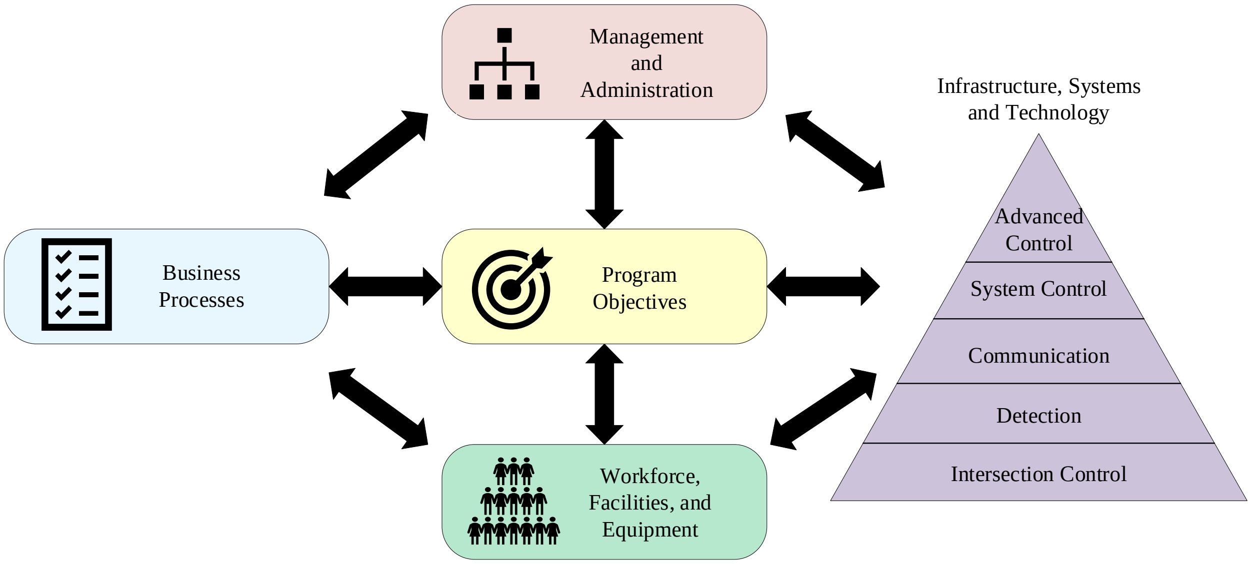
System and technology reliability focuses on ensuring that traffic signal systems and technologies consistently and predictably meet the user requirements used to design and procure the system. This objective focuses on guaranteeing that the traffic signal program is capable of serving a variety of expected field conditions in an effective manner.

TRAFFIC SIGNAL PROGRAM ELEMENTS

As shown in Figure 5, a traffic signal program, regardless of the size or scale of the organization, involves interactions between objectives and the following four program elements:

- Management and administration.
- Workforce, facilities, and equipment.
- Business processes and practices.
- Infrastructure, systems, and technology.

These four elements work in concert with one another to attain the objectives of the program and the goals of the organization.



Source: Federal Highway Administration

Figure 5. Graphic. Elements of a Traffic Signal Program

Management and Administration

One core element of a traffic signal program is management and administration. Management and administration set the overall vision and direction of the program and orchestrate the processes by which agencies identify, pursue, measure, and report progress toward program objectives. This program element provides the organizational structure and assign roles and responsibilities to the units within the program. Critical functions performed in this program element-include the following:

- Setting the overall vision, direction, and priorities for the program.
- Securing funding and budgeting resources to program activities.
- Developing measures that describe the output and outcome of the program's activities.
- Assessing program performance against established performance objectives and targets.
- Communicating and coordinating the activities within and external to the program.
- Assigning roles and responsibilities for individual program areas.
- Forming and supporting partnerships within and external to the program to integrate and coordinate system management and operation based on regional needs.

- Establishing and ensuring compliance with applicable policies and standards.
- Identifying and establishing workforce performance standards and criteria.
- Establishing a workforce development program.

Workforce, Facilities, and Equipment

Workforce, facilities, and equipment comprise the second core element of a traffic signal program. This program element consists of the human and physical assets and resources used in planning, designing, constructing, operating, and maintaining a traffic signal program. This program element interacts with infrastructure, systems, and technologies to attain program objectives. The workforce element includes the human resources who possess the knowledge, skills, and abilities (KSAs) needed to plan, design, construct, operate, and maintain the systems and technologies. The equipment element includes all the necessary tools, software, computers, and devices needed by the workforce to do their jobs. Examples include items such as bucket trucks, work tools (wire strippers, screwdrivers, etc.), and equipment testers. The facilities component contains the work and storage space dedicated to ensuring that the infrastructure is operating and maintained in a state of good repair. Examples of these facilities include maintenance shops and traffic management centers. Table 3 lists examples of the key items included in this program element.

Business Processes

A third core element of a traffic signal program centers around its business processes. Business processes include those recurring activities associated with planning, designing, constructing, operating, and maintaining traffic signals. Most of these processes are directed at infrastructure, systems, and technologies and depend on the KSAs of the workforce, with guidance and resources provided by management and administration. These processes may be performed either in whole or in part by in-house staff or contracted out to external service providers. Business processes may also use technology and tools to automate and support decision-making and execution of tasks. Table 4 lists examples of the common tools and business processes used in traffic signal programs. Agencies may perform business processes on an ad hoc basis based on the expertise of the staff. Business processes become more mature and effective when agencies document and routinely evaluate and revise them based on measures that are defined according to objectives. Measures related to business processes can be output- or outcome-oriented.

Table 3. Examples of workforce, equipment, and facilities needed in a traffic signal program.

Workforce	Equipment	Facilities
• Traffic engineer or manager • Signal operations engineer • Traffic analyst/technician • Traffic signal technicians/electrical technicians • Construction inspectors/technicians	• Malfunction Monitor Unit (MMU) Tester (required for annual National Electronics Manufacturers Association [NEMA] certification) • Controller test units/cabinet displays • Test controller • Traffic simulation/signal timing optimization software • Trouble ticket/recordkeeping system • Bucket trucks • Spare controller • Extra • Temporary traffic control (stop signs, cones, arrow panels, etc.) • Communications testers/cable splicer (time domain reflectometer/optical time domain reflectometer) • Lifts (pole lifts, forklifts, etc.)	• Climate controlled warehouse space • Operations/communications center (direct communications to cabinets in the field) • Traffic management center • Maintenance shop • Dispatch centers/radio room • Secured outdoor storage/parking area • Meeting space/common area/break room • Conference room/office space • Garage space/bays

Source: Federal Highway Administration.

Table 4. Examples of business processes used by traffic signal programs.

Planning	Design/Construction	Operations	Maintenance
• Long-range transportation planning. • Regional traffic light synchronization program. • Capital improvement planning. • Comprehensive development plan review.	• Traffic signal design policies and practices. • Standardized plans, specifications, and estimate (PS&E) documents. • Formalized construction inspection protocols/checklists.	• Automated traffic signal performance monitoring. • Traffic signal timing/re-optimization program. • Citizen request tracking system. • On-call operations contracts with external entities. • Regional traffic signal operational agreements.	• Preventative maintenance policies and practices • Inventory/asset management policies and systems • Detector management/replacement program • Light-emitting diode (LED) conversion program • Recordkeeping policies and practices • Outsourcing

Source: Federal Highway Administration

Infrastructure, Systems, and Technology

Infrastructure, systems, and technology can be grouped into three broad categories based on their relationship to core functions:

- Assignment of ROW.
- System monitoring and management.
- Advanced operations.

The complexity and sophistication of devices, systems, and technologies increase as the need for more advanced control concepts increases. Table 5 provides examples of the relationship between devices, systems, technology, and core functions.

TRAFFIC SIGNAL MANAGEMENT PLAN (TSMP)

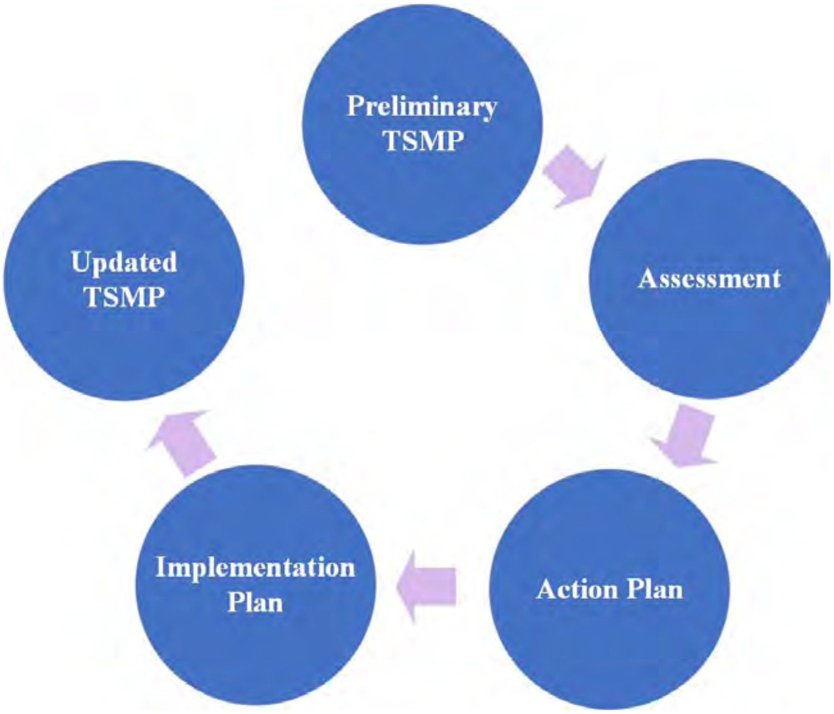
A TSMP is a document that clearly articulates the relationship between the activities and actions performed in a traffic signal program and the overall TSMO goals and objectives defined by the agency. The TSMP allows an agency to connect activities performed in the traffic signal program to the overall safety, mobility, reliability, and resiliency goals defined by decision-makers for the jurisdiction or region. It formally articulates and documents an agency's operational philosophies, goals, objectives, and performance measures related to the operation, design, and maintenance of traffic signals systems in its jurisdiction. Figure 6 illustrates the process of developing a TSMP, which is discussed further in *Traffic Signal Management Plans: An Objectives and Performance-Based Approach for Managing Traffic Signal Programs.*(2)

Table 5. Relationship between devices, systems, technology, and core functions.

Assignment of ROW	System Monitoring and Management	Advanced Operations
• Poles/mast arms. • Foundations. • Signal displays. • Controller. • Cabinet. • Local detection: o Pedestrian. o Bicycle. o Vehicle. • Preemption circuits.	• Communications. • Master controllers. • Central management systems. • System detection. • Time-based coordinators.	• Priority detection systems. • Connected vehicle (CV) technologies (roadside units). • Interactive traveler support system. • Multimodal intelligent systems. • Intelligent, sensor-based infrastructure. • Urban automation. • Decision support systems.

Source: Federal Highway Administration

The traffic signal management plan development process should begin with documenting of the current state of the program, in the form of a preliminary TSMP. The preliminary TSMP creates a snapshot and establishes the baseline state of the program, and documents how things are currently done, who is involved, a clear statement of objectives, and how all activities are currently managed to set the stage for assessment and development of an action plan. A development and maintenance workflow is illustrated in Figure 6, starting with the development of the preliminary TSMP. Once the baseline state of the program is documented in the preliminary TSMP, an assessment is conducted to evaluate risks to sustained attainment of objectives and opportunities to improve existing program components. A matrix of priorities and risks should be developed and evaluated to determine the best approach to address any gaps that are identified. The Action Plan, the third step in the workflow, documents deficiencies and opportunities to improve capabilities within the component areas of the program, with a keen understanding of the interdependencies between the program areas described above. Depending on the complexity and time involved in addressing a gap identified in an Action Plan, it may be useful to break these down into smaller implementation plans that can be assigned, developed, and executed systematically to manage change. These smaller discreet actions should be documented in the fourth step in the workflow, the Implementation Plan. As actions are implemented, they may influence business processes, workforce, management, and administration or infrastructure, systems, and technology such that it may be necessary to update the TSMP.



Source: Federal Highway Administration.

Figure 6. Graphic. Process for developing a TSMP.

Appendix A of the *Traffic Signal Management Plans: An Objectives and Performance-based Approach for Improving the Design Operations and Maintenance of Traffic Signal Systems*(2) contains a template that agencies can follow to develop their own TSMP. The template suggests that a TSMP plan include the following sections:

- *Executive Summary*—This section provides a brief overview of the content of the document. At a minimum, the executive summary should list the TSMP objectives and discuss how they connect strategies and tactics to agency goals.
- *Introduction and Background*—This section introduces the document and summarizes the existing traffic signal system. It provides context for the system and records the baseline of activities currently being performed by the agency.
- *Program Objectives*—This section summarizes the agency's transportation goals and related traffic signal management objectives. This section also describes the context within which the TSMP exists.
- *Maintenance*—This section documents the maintenance strategies and tactics that an agency will use to meet the traffic signal management objectives. It describes proactive, reactive, and administrative procedures that agencies plan to apply to keep the system operating in a good state of repair.
- *Operations*—This section documents the strategies and tactics that an agency will employ to improve and manage the operations of the signal system. It also lists and describes the strategies agencies are using to support defined operational objectives.
- *Design*—This section documents the design strategies (or standards) that the agency will use to meet operational objectives. It links design standards to maintenance and operational resources and also shows how design elements need to be driven by operational strategies.
- *Management and Administration*—This section describes the strategies and tactics that are associated with enabling management, administrative, and customer support activities. It describes the agency's approach to managing staff, facilities, and equipment, as well as the programming and budgeting associated with operating the traffic signal program.
- *Action Plan*—This section identifies the actions and activities that the agency plans to take to improve performance. It documents the existing state of current practices and identifies the desired future state. It also lists the activities and actions the agency plans to take to get it from the present to the desired future state. In addition, it defines the timeline over which the action is to occur.

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CHAPTER 3. ASSESSING AND IMPROVING A TRAFFIC SIGNAL PROGRAM

This chapter identifies and summarizes various tools available to support the assessment of traffic signal programs. It recaps the outcomes of prior National efforts to characterize and benchmark the state of the practice for traffic signal management and operations. This chapter then continues to describe a capability maturity modeling approach agencies can use to assess how reliable the activities and processes within each area of a traffic signal program are in supporting sustained attainment of program objectives.

TRAFFIC SIGNAL BENCHMARKING AND STATE OF THE PRACTICE

Benchmarking traffic signal infrastructure, current practice, and technology implementation is essential for informing the investment decisions of policy makers, department managers, and transportation professionals, both now and into the future. Three *National Traffic Signal Report Cards* were released in 2005, 2007, and 2012 and assigned incrementally increasing National scores of D-, D, and D+, respectively.(1, 2, 3) These previous traffic signal report cards focused primarily on evaluating individual agency practices relative to best practice(s). The National Operations Center of Excellence recently completed the 2019 *Traffic Signal Benchmarking and State of the Practice Report*.(4) The 2019 version of the report card provides information about National trends in traffic signal infrastructure, systems and technology and organizational characteristics, and the state of the practice in organizational management.

CAPABILITY MATURITY FRAMEWORK (CMF)

The AASHTO Capability Maturity Model (CMM) was developed to support the effective implementation of Intelligent Transportation Systems (ITS) strategies through an assessment of current capabilities and subsequent identification of gaps and actions to improve capabilities. The AASHTO CMM was adapted from a Department of Defense model and consists of six dimensions of capability with four levels of maturity within each dimension. The AASHTO CMM was adapted to support the strategy area of traffic signal systems. The Traffic Signal Program CMF further refines the AASHTO's CMM to address the needs of a traffic signal program. The projection of the AASHTO CMM onto the traffic signal program model was initially formulated to evaluate organizational capability within the 2019 *Traffic Signal Benchmarking and State of the Practice Report*.(4) The Traffic Signal Program CMF provided herein updates the CMM provided in the *Traffic Signal Benchmarking and State of the Practice Report* (4) by focusing more on process-driven approaches to support attainment of objectives than on prescribing specific activities.

Focus of Traffic Signal Program Area Capability

The dimensions used in the Traffic Signal Program CMF are as follows:

- *Infrastructure, Systems, and Technology*—The capability of the signalized intersection's physical components, systems, and technology to meet all operations and maintenance objectives.

- *Business Processes*—Formal scoping, planning, programming, and budgeting broken down by processes specific to design, implementation, operations, maintenance, and management.
- *Workforce, Facilities, and Equipment*—Staff development, recruitment, and retention.
- *Management and Administration/Leadership*—This area consists of the following subdimensions:
    - *Culture*—Technical understanding, leadership, outreach, and program legal authority.
    - *Organization and Staffing*—Programmatic status, organizational structure, roles, and responsibilities.
    - *Collaboration*—Relationships with public safety agencies, local governments, metropolitan planning organizations (MPOs), and the private sector.
    - *Performance Measurement*— Define measures of effectiveness, identify the data and processes needed to develop each of the measures.

Traffic Signal Program Levels of Maturity

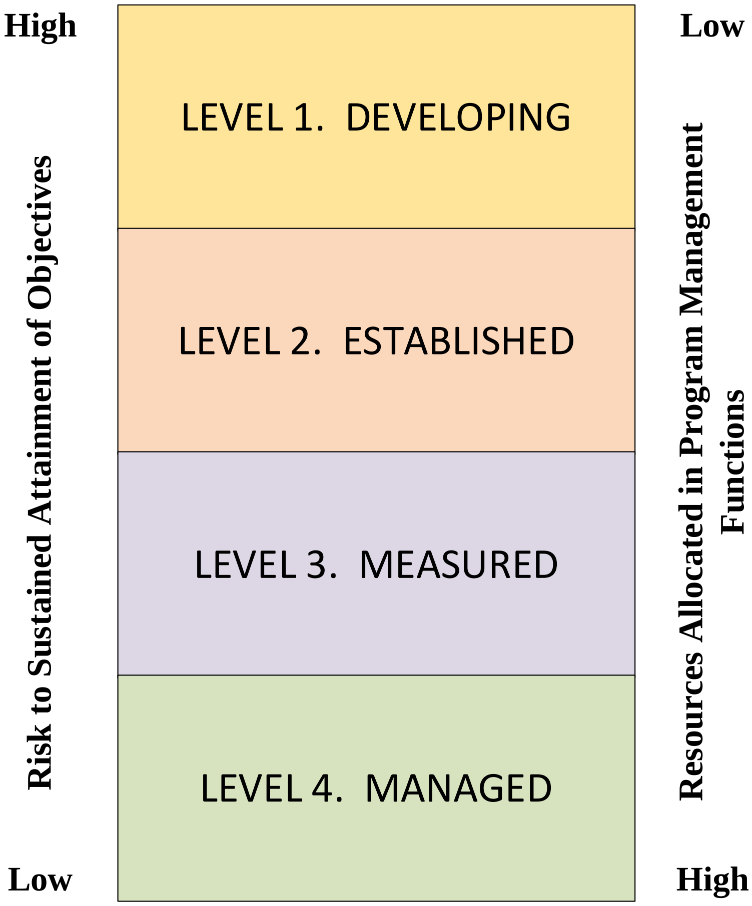
Table 6 summarizes the four incremental levels of capability maturity that the CMF uses to assess the current state of maturity and identify improvement targets for each program area.

Table 6. Traits of agencies at different levels of capability maturity.[(4)]

Levels of Maturity	Description
Level 1: Developing	Activities and processes are largely ad hoc, informal, and champion-driven, substantially outside the mainstream of other DOT activities.
Level 2: Established	Basic strategy applications understood; key processes support requirements identified and key technology and core capacities under development but limited internal accountability and uneven alignment with external partners.
Level 3: Measured	Standardized strategy applications implemented in priority contexts and managed for performance; TSMO technical and business processes developed, documented, and integrated into DOT; partnerships aligned.
Level 4: Managed	Full, sustainable core DOT program priority, established based on continuous improvement with top-level management status and formal partnerships.

Source: Federal Highway Administration.

As illustrated in Figure 7, this framework examines the manner in which agencies attain objectives at each level. Under Level 1, agencies attain their objectives primarily through the ad hoc efforts of champions. Because these agencies at Level 1 tend to have fewer resources allocated to support program management activities, a high risk exists that they may not be able to sustain the attainment of their objectives (or even become nonperforming) if they lose key individuals critical to their success. Level 2 agencies have established processes that are routinely followed, which minimize the risks associated with losing key people but present the risk of the agency focusing on attaining processes and not outcomes. Level 2 agencies tend to devote more of their resources to program management functions. Level 3 agencies measure the effectiveness of their processes in supporting performance outcomes. Under Level 3, agencies have fully embedded continuous improvement processes in their culture, which consistently improve their abilities to sustain attainment of their objectives over time but also require more resources to support and maintain program management tools and processes. Level 4 agencies continuously improve their processes through optimization so that those processes reliably and efficiently support the attainment of objectives. Each level represents less risk than the one below it but greater process measurement and control costs (until, perhaps, Level 4, where optimization may reduce process control costs). Each agency should assess the resource investments that may be required to progress to higher levels of capability; and how attaining a higher level of capability addresses the risks posed to sustained attainment of objectives.



Source: Federal Highway Administration.

Figure 7. Graphic. Trade-off between risk to sustained attainment of objectives and resource allocations to program management functions for levels of program capability maturity.

Agencies around the country have different understanding and knowledge of their own capabilities and organizational maturity. Effective agencies tend to implement strategies on an incremental basis from their own starting points. To do this, an agency will first start by reviewing its current level of maturity in each of the dimensions. If an agency finds that its level of program capability is sufficient to sustain achievement of its operational objectives, then no action is needed. However, if an agency finds that it is unable to consistently achieve its objectives, then the agency can use the CMF to identify strategies to improve its capabilities. Agencies can then develop an action plan to implement actions designed to improve its capabilities. An action plan is a set of specific strategies and tactics that focus on addressing risks that are related to particular dimensions and levels of capabilities.(4)

SYSTEMS AND TECHNOLOGY PROGRAM AREA

The systems and technology program area deals with the physical elements of the program. The systems and technology area includes both the physical devices as well as the software, processes, and functions performed by hardware devices.

Examples of the types of software processes and functions considered to be systems and technologies include the following:

- Traffic signal intersection-level control.
- Detection.
- Communications.
- System control.
- Advanced control.

The attainment of virtually all operations and organizational objectives is contingent on the reliability of systems and technology in the field.(5) As indicated in *Improving Traffic Signal Maintenance and Operations: A Basic Service Model*,(5) some agencies may purposely use systems and technologies that demand more capital initially (often at the expense of using systems and technology that barely meet minimum standards at other intersections) to offset a maintenance or operational limitation. A more reliable and resilient component, while costlier, may result in fewer maintenance or operational issues.

Assessing Program Capabilities

Table 7 shows the attributes and characteristics of agencies at different levels of maturity as they relate to the capabilities of their systems and technologies. Agencies can use this table to self-identify the level of maturity that is most appropriate for their organization and circumstances and that is needed to achieve their operational objectives.

Table 7. Assessing program system and technologies capability maturity.

Level	System and Technologies Capability
1. Developing	• The requirements to support the procurement of systems (e.g., local control, central control, detection, communication) are not well defined. The agency selects systems and technology based on the preferences of key individuals or past procurements. • The appropriate function and performance of systems and technology are not well defined, and the capability to evaluate performance is limited and typically dependent on complaints. The agency uses visual observations and citizen complaints as the primary means of determining the effectiveness of signal operation and maintenance strategies. • System components are typically replaced beyond the life cycle or after an equipment failure.
2. Established	• The agency has established requirements to support the procurement of systems and technologies (e.g., local control, central control, detection, communication) via systematic processes (systems engineering, architecture standards, etc.) that link operations and maintenance objectives and needs to requirements. • The agency bases its selection of system and technology upon the functional and performance requirements of identified operational and maintenance strategies. • The agency replaces its system components at regular, predefined intervals without understanding the life-cycle needs of the systems and technologies.
3. Measured	In addition to Level 2: • The agency has processes to verify that systems provide the required functionality, support the attainment of operations and maintenance strategies, and attain objectives. • The agency compares measured performance against established criteria to trigger the replacement of traffic signal equipment.
4. Managed	In addition to Level 3: • The agency routinely integrates its systems and technologies across multiples systems to provide coordinated, system-level responses (e.g., integrated corridor management). • The agency continuously evaluates systems and technology needs against the attainment of operations and maintenance objectives to identify deficiencies and opportunities for improvement. • The agency uses data-driven processes and tools (such as an asset management system) to identify systems and technology needs, identify gaps in functionality, and inform planning, budget, and resource allocation decisions.

Source: Federal Highway Administration.

Improvement Strategies

Strategies that agencies can use to improve the reliability of the signal program systems and technologies include the following:

- *Practice System Engineering Processes*—Systems engineering provides a process for reducing the risk of procuring an ineffective system by documenting agency needs, including those needs related to the purpose of a system, and deriving requirements from those needs that can then be used to guide procurement. Systems engineering processes minimize the risk that the resulting system will not address the agency's needs or that the system procured will address the wrong needs. The process helps ensure that the scarce resources for procuring systems address the agency's most important needs first. FHWA developed two model system engineering documents—*Model System Engineering Documents for Adaptive Signal Control Technology*(6) and *Model System Engineering Documents for Central Traffic Signal Systems*(7)—to guide agencies through the process of developing systems engineering documents for traffic signal systems. The documents provide a structure within which the agency can examine its current operation (or the operation the agency expects to have in the near future), assess what types of improvements are needed to address the identified issues, and then decide what type of systems and technologies might be right for the situation. The model documents provide templates for developing the appropriate systems engineering documents for the agency's situation as well as instructions on how to select appropriate answers to questions, how to select statements from provided examples, and what additional information agencies can gather and include in the documents. Agencies can use these model documents to prepare a set of requirements and specifications against which vendors may propose a solution.

- *Deploy Maintainable Systems and Technologies*—Another approach that agencies have used to extend resources is to limit the number of more advanced technology solutions, reserving the use of these technologies to locations that truly require more complex operations.(5) Instead, agencies should match the capability requirements of the technologies to the operational objectives. In many cases, agencies have found that simpler systems and technologies are adequate to achieve the operational objectives defined by the agency.

INFRASTRUCTURE PROGRAM AREA

The infrastructure program area represents the physical components associated with a traffic signal and includes items such as the following:

- Traffic control devices.

- Signal displays.

- Support structures and equipment (poles, mast arms, cabinets, ground boxes, etc.).

- Wiring and power supplies.
- Communications media (landline or wireless devices).

One key concept discussed in FHWA's *Improving Traffic Signal Maintenance and Operations: A Basic Service Model*(5) is that agencies should avoid constructing infrastructure that (a) cannot be maintained or supported, and (b) does not progress toward an identified operational objective. More effective agencies place a high priority on providing good basic service first, with less emphasis on attempting advanced service models.(5)

Assessing Program Capabilities

The assessment tool for this program area focuses on the policies, procedures, and practices that agencies have implemented to ensure consistency in the placement and use of hardware components and devices to support the identified program objectives. It assesses items such as the use of standards and processes to evaluate the condition and guide placement, visibility, recognition, necessity, and function of traffic control devices and associated infrastructure such as foundations, poles, mast arms, and signal displays. Table 8 shows the four maturity levels for assessing an agency's infrastructure management capabilities.

Improvement Strategies

Agencies have employed the following strategies as ways of improving their capabilities to manage and improve their infrastructure:

- *Improve Resilience*—One strategy for improving infrastructure reliability is to improve the resiliency (the ability to recover quickly from difficulties) of infrastructure components. For example, Puerto Rico, Florida, and other States have deployed tactics—such as quick-release mounting brackets for their signal heads, conversion to Light Emitting Diode (LED) signal indication, and incorporating battery backup units (BBUs) and generator connections—to reduce the effects of hurricanes and aid with recovery of the infrastructure.(8) Snowbound States are deploying snow-proof LED signal heads to reduce the impact of snow and ice buildup on signal display visibility.(9) Utah DOT is implementing cyberlocks on their traffic signal controller cabinets to increase security for their traffic signal cabinets.(10)

- *Reduce Design Complexity*—Another approach to improving infrastructure reliability is to reduce the complexity of the infrastructure.(5) Sometimes agencies desire the most recent and complex system only to find that they do not have sufficient technical or financial resources to keep the system operational. Further, agencies often attempt to train their best technicians to handle the more advanced technologies (rightly so), only to lose them to outside employment. Another approach is to use infrastructure designs and operational approaches that do not exceed the agency's technical capabilities and resources.

Table 8. Assessing program infrastructure capability maturity.

Level	Program Infrastructure Capability
1. Developing	• Specifications and requirements for infrastructure functionality are not well defined and are unique for each new installation. The selection of components is made based on the preferences of key individuals or past procurements. The agency does not have documented processes for assessing infrastructure needs. • The agency does not have documentation to confirm that the current condition and functionality of deployed infrastructure components (e.g., poles, mast arms, span wire, wiring, signal heads) is consistent with operations and maintenance requirements. Determining the state of repair of infrastructure components depends on one or more skilled individuals. Criteria for assessing the state of repair is not well defined or inconsistently applied. • The agency does not perform regular inspections of the state of repair of infrastructure structure components. The agency typically does not discover issues with infrastructure components maintenance until after they have failed. • The identification of the type and location of infrastructure devices placed at an intersection requires a site visit each time the agency initiates design, operations, and maintenance activities. The agency is required to perform a field inspection because of inadequate or inefficient recordkeeping.
2. Established	• The agency bases its selection of infrastructure components on established operations and maintenance needs. • The agency has established operations and maintenance requirements and criteria to assess the current state of repair and operational performance of signalized infrastructure components (e.g., poles, mast arms, span wire, wiring, signal heads). • The agency has documented specifications and requirements for most intersection infrastructure components. • The agency maintains readily accessible documentation on the location and placement of infrastructure components to support ongoing design, maintenance, and operations activities. • The agency conducts regularly scheduled inspections of infrastructure components to ensure they are in a state of good repair.
3. Measured	In addition to Level 2: • The agency uses defined processes and measures to track the state of repair and operational condition of infrastructure components. • The agency monitors the performance of infrastructure components to ensure they continue to operate within design specifications and criteria. • The agency has adopted test procedures and criteria to ensure that the infrastructure provides and maintains the required functionality (visibility, recognition, and understanding) to meet objectives and compliance with National standards.

Level	Program Infrastructure Capability
4. Managed	In addition to Level 3: • The agency regularly manages the infrastructure components to ensure the attainment of program objectives. The agency bases its investment decisions on filling gaps in functionality and addressing performance shortfalls. • Recordkeeping process (such as an assessment management tool, or geographic information system) exists for managing the information about the infrastructure location, and placements are routinely evaluated to ensure they are consistent with workforce and business process constraints. • The agency performs periodic assessments to ensure that test procedures and criteria are consistent with established State or National standards.

Source: Federal Highway Administration.

- *Utilize Capital Funds to Replace Failing Infrastructure*—There can be a tendency for agencies to scrimp on the design and installation of systems so that they can spread the deployment over a wider area. Following more robust design and construction processes upfront may, in the long-term, produce a more economical deployment because doing so reduces maintenance needs. Although this approach may limit the number of locations covered by capital funds, agencies often find that capital funds are more widely available than maintenance funds and that the more robust designs tend to increase the amount of time the system functions in a good state of repair.

BUSINESS PROCESSES PROGRAM AREA

Business processes include four subareas: planning and design, operations, maintenance, and management activities.

Planning and Design Business Processes

Good basic service begins with the KSAs of those planners and designers who are responsible for operating and maintaining the infrastructure through a process that yields traffic signals that support a wide range of operations. Good traffic signal design is often considered to be an art and requires good forethought into all the potential use cases and users of the intersection. Because operational strategies and objectives may change over time, designers should carefully consider all the traffic signal infrastructure that should be included in the design to accommodate a wide range of potential users and types of operating objectives, recognizing that operational objectives are likely to vary by time of day, day of the week, and season. Designers also need to consider other factors that might impact design, such as the need for monitoring and measuring performance; interoperability and maintenance of equipment; capability of the operations and maintenance workforce; and needs and requirements to support multiple users of the transportation system (including not only motorized vehicles but also pedestrians, bicyclists, emergency vehicles, transit vehicles, and others).

The design processes include activities such as the development of PS&E documents for traffic signals and associated infrastructure; related inspection during construction activities; final inspection; and acceptance testing that conforms to applicable standards. In addition, design processes can also support operations and maintenance activities as well as multimodal transportation.

Assessing Program Capabilities

Table 9 shows the capabilities associated with the different levels of capability maturity of agencies for the planning and design processes employed by traffic signal programs. Agencies can use this table to assess their design process capabilities.

Table 9. Assessing program planning and design business processes capability maturity.

Level	Planning and Design Business Processes Capability
1. Developing	• Design activities rely on the expertise of a few individuals. The agency does not maintain well-documented design practices. New staff typically require on-the-job training to learn and become familiar with accepted practices. The agency bases new designs primarily on tradition instead of a thorough analysis of goals, context, and selection of objectives. • Criteria that guide the selection and placement of traffic signal control devices are not well documented or outdated.
2. Established	• The agency has developed standards, specifications, guidelines, and processes to support the uniform design and application of systems and technologies. • Operations and maintenance objectives are considered and guide the design process to ensure that what gets built can be operated and maintained within existing and projected resource constraints. • Design standards are established and based on Nationally accepted guidelines or State and local standards that are routinely updated and that conform to National guidelines.
3. Measured	In addition to Level 2: • Objectives and strategies are well defined, and performance measures (output and outcome) are defined to support the evaluation of design activities. • The agency routinely updates or revises design standards based on feedback from the periodic assessment of measures.
4. Managed	In addition to Level 3: • The agency evaluates traffic signal design activities to identify deficiencies and proactively identify opportunities to make improvements that add value to design activities and processes. • The agency monitors trends in maintenance and operational performance data to identify any deficiencies correctable through design.

Source: Federal Highway Administration

Improvement Strategies

Strategies that agencies can employ for improving design processes in a traffic signal program include the following:

- *Develop a Traffic Signal Design Manual*—To promote uniformity and consistency of design, many agencies have developed traffic signal design manuals that describe the process and requirements for designing traffic signals for their jurisdiction. These manuals generally include information on the following design-related topics:(12)
    - Signal permitting and design processes.
    - Traffic signal pole design and placement.
    - Span wire and mast arm support infrastructure.
    - Pedestrian signal infrastructure.
    - Cabinet assemblies.
    - Communication and interconnect infrastructure.
    - Wiring standards.
    - Conduits and ground box sizing and placement.
    - Traffic signal-related signs and markings.
    - Traffic signal indications configuration and placement.
    - Detection system design and placement.

  Some agencies also include information on the design of ramp meters, temporary traffic signals, pedestrian signals, hazard beacons, railroad preemption interconnection and operations, emergency traffic signals, and more.

- *Develop Robust Traffic Signal Design Standards and Specifications*—Many agencies have also developed standard detail sheets and specifications that prescribe how different infrastructure elements should be constructed and deployed for their jurisdiction. Examples of the design items contained in standard design sheets include the following*:*
    - Design options for different types of traffic signal pole assemblies.
    - Design plans for different types of traffic signal pole foundations.
    - Requirements for different mast arm and span wire connections.
    - Design and construction requirements for ground boxes and conduit connections.

  - Conductor and connection requirements for the electrical system, including service hook-ups.
  - Design and placement of BBU systems.
  - Details on a typical traffic signal system.
- Develop Design Checklists—Some agencies have also developed checklists that designers can use to verify and certify that their designs conform to the policies and practices of the agency.(12) These checklists are intended to help agency personnel ensure that the correct and appropriate information is collected during the field investigation phase as well as the design phase of a signal installation. Design checklists also help an agency ensure that plans prepared by external sources provide for consistency in level of details for new signal construction.

Operations Business Processes

Business processes associated with operations include activities related to developing, implementing, and monitoring signal timing settings to attain operations objectives. Examples of key activities performed in this business process include the following:

- Measuring and monitoring the performance of the traffic signal system to determine if operation objectives are being satisfied, which might trigger systems and technology processes.
- Identifying, developing, and implementing necessary modifications to signal timing strategies to achieve identified program objectives.
- Performing engineering investigations to identify potential mobility or safety enhancements to the signal system.
- Managing the traffic signal system timing databases.
- Identifying potential equipment malfunctions and maintenance impacting the performance of the signal system.
- Responding to citizen requests for improving traffic signal performance.
- Implementing signal timing strategies for managing network performance during special events or incidents.

Assessing Program Capabilities

Table 10 shows the attributes and characteristics of agencies at different levels of capability maturity in terms of their operational business practices. Agencies can use this table to self-identify the types of business processes that they need to implement to achieve their desired operational objectives.

Table 10. Assessing program operational business processes capability maturity.

Level	Operations Business Processes Capability
1. Developing	• Operations activities are not well defined and based on tradition or expediency—not data-driven. The day-to-day approach to operations might be described best as "firefighting." • Priorities and processes are ad hoc, driven by individuals with adequate or developing skills and expertise to implement operations strategies. • Little or no documentation exists to guide operations and processes. Updates to existing guidelines are rare and not tracked.
2. Established	• The agency uses established operation strategies and tools to develop and implement signal timings based on appropriate objectives (e.g., smooth flow, appropriate distribution of green time, managed queues) and context (e.g., traffic demand, user mix, network configuration). • Guidelines and strategies are well established to support the design and evaluation of signal timing to provide consistency, manage results, and capture experience. • Efforts by the agency to make improvements to operations processes are limited, tend to be reactive, and have limited accountability.
3. Measured	In addition to Level 2: • The agency has implemented formalized processes to collect data and evaluate performance against operational objectives routinely (e.g., automated traffic signal performance measurement system). • The agency uses performance measures (output and/or outcome) to validate the attainment of objectives and effectiveness of strategies. • The agency has integrated the reporting of operational outputs and outcomes into core business practices. • Operational decision-making is data-driven based on measured conditions.
4. Managed	In addition to Level 3: • The agency has fully integrated operations objectives, strategies, and performance measures across the program. The agency acknowledges the relationship between activities, processes, systems, and performance through its efforts to predict, detect, and proactively make improvements that add value to operations activities and processes. • The agency applies trend analysis to identify deteriorating or changing operational conditions. The agency makes proactive efforts to improve operations. • The agency uses operational trends to identify and forecast the needs for capital capacity enhancement projects.

Source: Federal Highway Administration.

Improvement Strategies

Agencies have employed the following strategies to improve their operations-oriented business processes:

- *Establish Clear, Unambiguous Operational Objectives*—Developing specific, measurable, attainable, realistic and time-bound (SMART) objectives that consider relevant operational context is a key business process for traffic signal programs. Operational contexts such as pedestrian, bicycle, vehicle and transit demand, along with network configuration and surrounding land use must be considered adequately to identify what must be attained to make progress towards state, regional and local goals. Examples of vehicle centric operations objectives include balanced distribution of green time, smooth flow, throughput, or queue management. Operations objectives could also be focused on pedestrian, bicycle or transit needs to direct strategies and tactics that prioritize safety, comfort, and convenience of venerable users above vehicle efficiency.

- *Utilize an Objective-Driven, Performance-Based Approach*—Effective traffic signal programs often use an objective-driven, performance-based approach for operating their traffic signals. An objective-driven, performance-based approach to traffic signal operations is based on the concept that "what gets measured gets managed." By using an objective-driven, performance-based approach, agencies can allocate resources (funding and personnel) to ensure that the agency objectives are met, resulting in improved overall transportation system performance.(13) The *Signal Timing Manual, 2nd Edition* describes an outcome-based approach to managing traffic signal operations.(14) Using this approach, agencies base their traffic signal operations decisions on the operating environment, user priorities by movement, and local operational objectives. Further, using this approach, agencies monitor performance measures to assess how well their operational decisions and timing strategies meet identified program objectives. Figure 8 illustrates an outcome-based approach for managing traffic signal operations.

Maintenance Business Processes

Maintenance is a critical factor in sustaining good basic service. Poorly operating traffic signals gain negative attention from the traveling public and could create unsafe conditions depending on the severity of the malfunction. environment for the traveling public. Malfunctioning detectors and inappropriate timing parameters waste time and fuel, increase the release of pollutants from vehicles, and frustrate drivers.

Source: National Academy of Science.

Figure 8. Graphic. Outcome-based approach to managing traffic signal timings.(14)

Agencies typically perform the following types of maintenance activities:(15)

- *Response (Emergency) Maintenance*—This type of maintenance includes those activities and actions that must be taken immediately to repair an operational deficiency and physical malfunction. The goal of this type of maintenance is to return the traffic signal to normal operations as quickly as possible. Response maintenance repairs can be either permanent or temporary.

- *Preventative Maintenance*—This type of maintenance involves periodic scheduled maintenance to minimize future problems. It includes inspection, calibration, cleaning, testing, sealing, painting, and so forth, and typically follows a predefined schedule to minimize the probability of unexpected failure and to maximize the life of the equipment.

Agencies typically perform preventative maintenance activities at every intersection, usually annually or semiannually.

Assessing Program Capabilities

Table 11 shows the attributes and characteristics of agencies at different levels of capability maturity in terms of their maintenance business practices. Agencies can use this table to self-identify the types of maintenance business processes appropriate for their desired program level.

Table 11. Assessing program maintenance business processes capability maturity.

Level	Maintenance Business Processes Capability
1. Developing	• Maintenance activities are not well defined, ad hoc, and are driven by individuals who are equipped with or developing the skills and expertise to implement maintenance strategies. Maintenance activities tend to be reactive. • Little or no documentation exists to guide maintenance processes. The agency rarely updates existing maintenance guidelines. • Processes to evaluate infrastructure conditions are not well defined. The systems, technology, and infrastructure components may be dated (potentially obsolete), exhibit gaps in functionality, and typically need to be replaced upon failure.
2. Established	• The agency has established maintenance strategies, activities, and processes to guide preventative, routine/scheduled, and emergency maintenance. • Guidelines, checklists, or other documentation are available or under development to support traffic signal maintenance to ensure the reliability of infrastructure, systems, and technology. • Efforts to make improvements to maintenance processes are limited, tend to be reactive, and have limited accountability.
3. Measured	In addition to Level 2: • The agency has defined measures (output and/or outcome) for maintenance-related activities. It uses these measures to validate the attainment of maintenance objectives and to assess the effectiveness of maintenance strategies. • Reporting of maintenance output and outcomes is integrated into core business practices. Impacts of deferred maintenance can be estimated based on measured data. • The agency uses a data-driven approach to prioritize maintenance activities. It uses data to estimate the life cycles of crucial systems and technologies.

Level	Maintenance Business Processes Capability
4. Managed	In addition to Level 3: • Maintenance objectives, strategies, and performance measures are fully integrated across the program. • The agency uses the relationship between activities, processes, systems, and performance to predict, detect, and proactively make improvements. • The agency continuously validates the effectiveness of day-to-day maintenance activities. It deploys systems and technologies and develops workforce capabilities to support the attainment of maintenance objectives. • The agency uses maintenance trends to identify and forecast large-scale systems and technology replacement needs.

Source: Federal Highway Administration.

Improvement Strategies

Examples of strategies that agencies have employed to improve their maintenance processes:

- *Implement a Preventative Maintenance Program*—Preventative maintenance is an example of a strategy that agencies can use to improve the reliability of their field infrastructure. This type of maintenance is periodically scheduled to minimize future problems. It includes inspection, calibration, cleaning, testing, sealing, painting, and so forth, in accordance with a predefined schedule to minimize the probability of unexpected failure and to maximize the life of the equipment. Preventative maintenance helps agencies reduce the frequency and severity of malfunctions, reduce agency liability, reduce life-cycle costs, and extend the life of traffic signal installations.

- *Develop and Implement Maintenance Checklists*—To ensure consistency in maintenance efforts, many agencies have developed maintenance checklists. These checklists contain the activities and types of inspections maintenance personnel are required to complete when performing maintenance inspections or preventative maintenance activities at an intersection. Generally, the traffic signal maintenance technician completes the checklists during the visit and places a copy of the checklist in the cabinet. Identified potential issues and safety concerns are reported back to the agency for further investigation, prioritization, and mitigation using a risk management approach. Examples of the types of maintenance activities contained in a typical maintenance checklist include the following:

  - Inspecting seals around the cabinet base.
  - Inspecting wiring for loose wires and connections.
  - Checking operations of circuit breakers, load switches, and relays.
  - Inspecting performance of detection amplifiers and pedestrian pushbuttons.
  - Re-lamping vehicular and pedestrian signal indications.
  - Documenting structural damage to poles, foundations, and cabinet.

  - Lubricating cabinet hinges and locks.
  - Replacing cabinet air filters.
  - Removing and trimming vegetation.
  - Removing graffiti and other paraphernalia on the cabinet.

- *Develop Maintenance-Oriented Performance Measures*—It is important for agencies to monitor the effectiveness of their current maintenance program to ensure that it is working properly and determine if changes are needed. If the performance measures decline, agencies may want to allocate more resources to their maintenance program, change maintenance contractors, and so forth. The following are typical performance measures that agencies use to monitor and assess the effectiveness of their maintenance activities:
  - The annual number of emergency calls per intersection.
  - The number of burnout/nonfunctioning lights replaced per year.
  - The average response time for emergency calls.
  - The average time to complete an emergency repair.
  - The percentage of response calls fixed with new parts from inventory.
  - The percentage of functioning detection sensors.
  - The maintenance records showing all maintenance performed at each signal, including the technician and the date.
  - The number of traffic signal operational improvements to existing traffic signals.
- *Employ Maintenance and Service Agreements and Contracts*—To keep traffic signal systems in a good state of repair; some agencies contract for maintenance and other services with either other agencies or private contractors. Agencies typically use these types of contracts when they are unable to provide adequate personnel to support these activities or when the technologies require expertise beyond their capabilities. Generally, these contracts specify the type of services the contractor is to perform. Contracts generally specify the following:
  - Agreement terms and effective dates.
  - Activities and services to be performed under the agreement, including the maintenance of the physical infrastructure, signal timing adjustments, and replacement for failed or malfunctioning equipment.
  - Responsive times and performance expectations.
  - Compensation requirements and accounting procedures.

  - Reporting frequency and documentation requirements.
  - Spare materials and equipment availability requirements.
  - Equipment and facilities requirements.
  - Key personnel qualification and availability requirements.
  - Indemnification and insurance requirements.
  - Method and place for giving notice, submitting bills, and making payments.

Program Management Business Processes

Business processes for management activities involve the budgeting and programming of general operating and capital improvement program budgets, staffing considerations and supervision within this context, customer service to the public and elected leaders, and engagement with the media and stakeholders.

Assessing Program Capabilities

Table 12 shows the attributes and characteristics of agencies at different levels of capability maturity in terms of their management business practices. Agencies can use this table to self-identify the types of management business processes appropriate for their desired program level.

Improvement Strategies

Some strategies that agencies can use to improve their program-level management business practices include the following:

- *Develop a Traffic Signal Management Business Case*—A business case is a well-formed argument that provides justification for having or developing a traffic signal program. It uses both qualitative and anecdotal information as well as technical analyses to rationalize and justify the need for the program. A compelling business case generally includes the following characteristics:
  - It is tailored to satisfy local priorities.
  - It uses current experiences and events to indicate the full range of current agency programs' effectiveness and benefits.
  - It specifies the strategic changes the agency needs to make, including the specific actions and the desired outcomes.

Table 12. Assessing program management business processes capability maturity.

Level	Program Management Business Processes Capability
1. Developing	• The clear articulation of the of the traffic signal program objectives relies on one or more program champions. • The loss of key staff due to attrition or retirement presents a risk to continuity of administration activities. • Little or no documentation exists to provide direction, vision, and goals to guide traffic signal program processes. The agency has not fully developed documentation to support the day-to-day activities in the areas of design, operations, and maintenance. • The relationship between workforce, systems and technology, asset management, and agency goals is reliant on key individuals. The agency does not generally update existing management processes as the program evolves.
2. Established	• The agency mitigates the potential loss of continuity resulting from the attrition of critical staff by documenting program objectives in a TSMP. • The TSMP references National standards and guidelines to support agency practices. • The TSMP considers and documents the need for collaboration among traffic signal-related activities. • The agency has documented procedures for monitoring and updating workforce competencies, asset inventories, and procurement processes (e.g., systems engineering). • The agency maintains an inventory of infrastructure components.
3. Measured	In addition to Level 2: • The agency has defined performance criteria (outputs and/or outcomes) to measure the effectiveness of management-related activities as well as the overall program. • The capability and processes to validate and routinely report on the attainment of program objectives and strategies are developed or under development. • An asset management system is available to track the life cycle of the equipment.
4. Managed	In addition to Level 3: • The agency continuously monitors and improves program business processes to validate the effectiveness of the day-to day activities, systems and technology, and workforce capabilities. • The agency uses tools such as asset management, core competencies, and life-cycle planning to ensure that decision-makers are informed when making investment decisions in innovation and technology. • The agency identifies the priorities and needed investments in the agency's strategic plan.

Source: Federal Highway Administration.

    - It relates the changes to the appropriate decision-making levels, accounting for individual and unit's span-of-control and responsibilities.
    - It includes both external and internal benefits and payoffs at the program level.
    - It describes the required levels of effort and resources associated with the needed changes.
    - It identifies the relationships between costs, benefits, and risks.
    - It uses a targeted approach to reach specific audiences.

  Many agencies use a Traffic Signal Management Plan (see Chapter 2) to develop and articulate the business case for a Traffic Signal Program. For more information on developing a business case, see FHWA's *Advancing TSMO: Making a Business Case for Institutional, Organizational, and Procedural Changes*.(16)

- *Implement an Asset Management System*—NCHRP Report 632(17) defines transportation asset management as "a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well-defined objectives."(17) Agencies can use transportation asset management to perform the following key decision processes:(18)
    - Daily operations and management.
    - Identification of system deficiencies.
    - Development and evaluation of preservation and improvement options.
    - Resource allocation and budgeting.
- *Utilize Regional Funding Programs to Support Traffic Signal Operations*—Many jurisdictions have regional funding programs that can be used to make operational improvements to traffic signal systems. Traffic signal synchronization programs allow agencies to collaborate on the development of traffic signal timing plans that span multiple jurisdictions. These programs typically fund projects designed to optimize signal timing and modify the infrastructure necessary to improve coordination. Because of their regional nature, MPOs or councils of governments typically administer traffic signal synchronization programs.

WORKFORCE PROGRAM AREA

The workforce program area focuses on how agencies identify, define, and address their workforce needs to meet their defined objectives. This dimension examines the extent to which agencies have identified (a) the staff competency levels; (b) the methods and strategies they use to train and develop the critical skills needed to achieve their objectives; and (c) the skills and experience required to carry out tasks, interact with systems and technology, and provide the information that is critical to the management and administration program area to prepare for and address resource needs. The elements of the workforce capability maturity dimension include the positions and roles within the organization as well as the employee's knowledge, skills, and abilities, which describe an individual's qualifications.

- *Knowledge*—The understanding of concepts, theoretical ideas, and principles. This quality is the underlying understanding of a topic or tool and the ability to directly apply it.
- *Skills*—The capability or proficiencies developed through training or hands-on experience. Skills are the practical application of knowledge and are typically observable behaviors that someone can perfect.
- *Abilities*—The traits or talents that a person brings to a task or situation. This quality is the application of skills to apply the needed understanding to the task at hand competently or perform an observable behavior. Abilities may also relate to personal and social attributes that tend to be innate or acquired without formal instructions.

This dimension concentrates on the development, training, and competency of qualified staff across all levels in the program, including technical, engineering, and management.

As agencies begin to transition to a traffic signal program, they may encounter a shortage of management, professional, and technical staff with the appropriate skills and knowledge. Therefore, staff position descriptions may need to be updated and new roles defined within the organization. This staffing and workforce development should involve close coordination with a human resource professional to identify and develop these new capabilities, such as allocating and hiring the staff needed to perform the tasks required, create systems, and use the appropriate technologies to attain desired operational performance.(19) In addition, the workforce for a traffic signal program can be cultivated internally (funded positions within the agency's structure) rather than by utilizing external resources (hired technical or specialized service providers).

Assessing Program Capabilities

The capability of the workforce to carry out activities (strategies) and methods (tactics) that attain the traffic signal program's objectives is an outcome of the collective KSAs. Education, training, beliefs, attitudes, and behaviors greatly influence KSAs; therefore, traffic signal programs should identify current and needed skills and a strategy for recruiting, training, developing, and retaining qualified personnel.(19) Agencies should systematically conduct an internal review to explore the current industry standards and review staff KSAs.

Table 13 shows the four maturity levels for assessing the workforce dimension of a traffic signal program.

Table 13. Assessing program workforce capability maturity.

Level	Workforce Capability
1. Developing	• The minimum required capability of the workforce is not well defined. The existing skills and expertise of the workforce are relied upon to complete design, operations, or maintenance activities. • Staff may individually identify training preferences, and a limited budget exists to support improvements in workforce capability. • Workforce competencies/position descriptions are not well defined. • Training is periodic and lacks formal structure. Funding to support training, development of core skills, and certification is limited.
2. Established	• Workforce competencies are clearly defined. The agency has aligned job descriptions to support design, operations, and maintenance objectives. • Workforce development is supported fiscally with structured internal and external training and certification as appropriate to maintain the competency of the workforce.
3. Measured	In addition to Level 2: • Workforce competencies are linked to current and planned program needs in each area of the traffic signal program and monitored for consistency. • The agency tracks training and certifications needs to ensure that staff capability is consistent with program needs.
4. Managed	In addition to Level 3: • The agency routinely evaluates workforce competencies to ensure consistency with industry standards and program needs. It actively supports the updating of core competencies to improve the KSAs of its personnel. • The agency routinely evaluates appropriate program performance measures to identify and address potential gaps between staff capability and program needs. The agency prescribes training and certifications to address these gaps.

Source: Federal Highway Administration.

Improvement Strategies

Strategies for improving the maturity level of a program's workforce include the following:

- *Identify Core Competencies*—Competency is a characteristic of an employee that contributes to job performance and achievement of organizational results. It is a measurable pattern of KSAs, behaviors, and other characteristics that individuals need to perform work roles or occupational functions effectively. Each competency should have the following components:

  - *Definition*—A statement or series of statements describing the competency in broad terms. The definition applies across all career levels from entry through senior and/or expert levels.
  - *Key Behaviors*—Examples of how the competency is demonstrated on the job.
  - *Recommended Learning Opportunities*—Examples of recommended learning opportunities for each competency. This information includes formal and informal learning opportunities. Not all competencies are associated with learning opportunities, either due to a lack of available training or because the competency is largely developed through on-the-job training.
  - *Proficiency Level*—A measure of a person's ability to demonstrate competency on the job. Typical behaviors for each competency (universal and technical) illustrate how a specific competency is applied at different levels of the spectrum so that an individual can compare his/her current level to a top performer in the same occupation.
- *Implement Training to Build KSAs*—Another strategy that agencies can use to improve the capabilities of their workforce is to implement training programs to build the KSAs of their personnel.

MANAGEMENT AND ADMINISTRATION PROGRAM AREA

The management and administration dimension encompasses the overall direction, outreach, and resources of an agency program. The management and administration dimension includes the subareas of culture, organization and staffing, collaboration, and program performance measurement. Those organizational aspects govern various technical or administrative functions such as human resource management, contracting and procurement, information technology, partnering commitments, sustainable funding, internal awareness, support, and agreements. This dimension involves ensuring that adequate resource levels are sustained to support program functions; internal and external interactions are sustained to report outcomes; and collaboration is sustained to achieve program goals, the establishment and evolution of organizational culture, and the satisfaction of program customers and stakeholders. Routine assessments of the program's capability and maturity, as well as the development of an action plan that is oriented around identifying and addressing potential risks to attainment of program objectives, is a function of the management and administration area of the program. In many cases, the management and administration/leadership dimension goes beyond the day-to-day operational activities to those tasks requiring broader institutional support and involvement to address.

The management and administration/leadership dimension includes the following subdimensions:

- Organizational culture.
- Organizational structure and staffing.
- Performance measurement and outreach.
- Coordination and collaboration.

Each of these subdimensions is discussed below.

Organizational Culture

Culture refers to the collective beliefs, attitudes, and behavior of the individuals within an organization. Culture is the combination of values, assumptions, knowledge, and expectations of an organization in its institutional and operating context and as expressed in its mission and values.(4) Personal experiences, education, and training all influence an organization's culture.

Many State and local transportation agencies are undergoing a cultural shift from capacity expansion to operation sustainability.

Assessing Program Capabilities

Table 14, adapted from the *Traffic Signal Benchmarking and Self-Assessment*,(4) shows the typical characteristics and capabilities of agencies at different levels of maturity in terms of their organizational culture. Agencies can use this table to assess their current level of maturity associated with their organizational culture to determine whether a change is needed to achieve their program goals. Agencies can also use the table to identify the attributes and capabilities of agencies at higher levels of capability maturity.

Table 14. Assessing organizational culture capability maturity.

Level	Program Culture Capability
1. Developing	• The underlying beliefs, assumptions, values, and ways of interacting internally and externally are not well defined or documented but established by a single or small number of champions responsible for articulating the program's value, activities, and needs. • Program units have difficulty identifying and evaluating customer needs. • Program units tend to function independently. Organizational decision-making is fractured and occurs in silos or is concentrated in a single individual. • Signal operations and performance are a low priority within the overall transportation program. • Budgetary and resource needs are allocated based on the "loudest" voice among program components.
2. Established	• The underlying beliefs, assumptions, values, and ways of interacting are defined and documented in a plan. • The program has a clearly defined mission and vision for accomplishing defined objectives. • The agency has established policies and documented procedures for identifying, recording, and tracking customer needs and requests. • The agency plans and constrains budgetary and resource needs based on objectives, workforce, strategic needs, and limitations.
3. Measured	In addition to Level 2: • The agency samples employee satisfaction and performance to assess the alignment of the program culture with program objectives. • The agency periodically samples and assesses customer satisfaction and needs. The agency may report metrics related to response times and the number of requests serviced. • Budgetary and resource needs are assessed based on overall program goals and priorities.
4. Managed	In addition to Level 3: • The agency continuously monitors employee performance and satisfaction to identify opportunities to improve the program culture. • The agency identifies and monitors opportunities to improve customer satisfaction at regular intervals to assess overall program benefits. • The agency uses a data-driven approach to identify program budget and resource needs. Opportunities to improve fiscal support is continuously evaluated and reflected in investments.

Source: Federal Highway Administration.

- *Identify Traffic Signal Program Champions*—Champions develop support from within their agency, public officials, and other top-level leaders. Typically, champions emerge in response to criticism that an agency receives or to proactively meet a specific new challenge. Champions facilitate the dialogue between stakeholders and chart a course of action for the group to follow. Champions can come from varying backgrounds and disciplines (traffic management, transit, emergency services, regional planning authorities, etc.), and often a single area may have multiple champions. Some of the skills that a traffic signal program champion should possess include the following:
    - Understanding of traffic signal operations.
    - Knowledge of traffic signal operations, systems, and projects.
    - Vision for improvement and opportunities.
    - Ability to build consensus/facilitate.
    - Executive-level access to resources.

Organizational Structure and Staffing

Transportation agencies have historically organized around a core mission to expand and deliver infrastructure capacity; however, more and more agencies are recognizing the importance of focusing on managing and operating infrastructure elements to improve quality of service. Organizational structure considers the interactions and linkages between programmatic components (e.g., planning, design, operations, and maintenance) and operational units (e.g., engineering, technical services, information technology). Organizational structure also addresses the roles and responsibilities of each of these components/units as well as opportunities for intra- and interagency integration. Having a clearly defined leadership and organizational structure that supports operations and management is important for effectively advancing an operations-oriented culture and executing TSMO strategies within an agency. FHWA has shown that developing an organizational structure and staffing plan with a focus on operations and management can help agencies:(20)

- Create an organizational mission centered on delivering good basic service.
- Sustain and institutionalize operations at a core element of a program.
- Support identification and prioritization of the financial and staff resources needed to provide effective delivery of program elements.
- Respond to unique user needs, situations, and issues.

Assessing Program Capabilities

Table 15 characterizes the attributes and capabilities associated with programs of different levels of organizational structure and staffing capability maturity. The CMF focuses on the processes and procedures agencies have implemented to organize their program elements and staffing to support their operational objective. The assessment tool examines not only how agencies organize their activities to support the mission of the program but also the processes and procedures they have implemented to ensure that staffing and resource needs change as their programs evolve.

Table 15. Assessing program organization and staffing capability maturity.

Level	Organization and Staffing Capability
1. Developing	• An organizational structure exists that splits the responsibility for designing, constructing, operating, and maintaining traffic signal performance into silos. • The roles of organizational units may lack a precise definition, resulting in redundancy or voids in needed activities (e.g., asset management, procurement, monitoring, reporting). Job descriptions for key positions are generic and out-of-date. • Staffing levels are not sufficient to attain program objectives. Agencies routinely defer some operational and maintenance tasks due to staffing shortages. • Staff retirements, promotions, and rotation within the organization or attrition occur haphazardly.
2. Established	• An agency's organizational structure supports (does not hinder) attainment of program objectives. • The agency uses performance-based criteria for identifying staffing needs and levels. • The agency has developed a formal document (such as a TSMP) that defines the roles and responsibilities of organizational units within the program. • The roles and responsibilities of critical positions are understood and documented through accurate job descriptions.
3. Measured	In addition to Level 2: • The program routinely measures the effectiveness of coordination among business units to verify that the activities and processes of each business unit support the attainment of objectives. • The output of organizational units is measured and reported. • The agency routinely monitors and revises staff succession and retention policies and rotates personnel to achieve cross-training across program units.
4. Managed	In addition to Level 3: • The agency adapts its organizational structure to facilitate coordination and collaboration between crucial program units. It routinely reviews the roles and activities of business units to identify and take advantage of opportunities for improvements. • The agency routinely evaluates staffing levels and modifies as needed to maximize the output and outcomes of the program. • Program leaders manage staff succession, retention, and rotations within the organization to minimize the impacts of the loss of key personnel. • The agency has documented career paths for critical positions.

Source: Federal Highway Administration.

Improvement Strategies

Strategies that agencies can employ to improve their level of maturity in the organization and staffing subdimension include the following:

- *Clarify Roles and Responsibilities*—Clarifying the roles and responsibilities of key personnel is one strategy to improving organizational structure and staffing. A role is the function assumed or part played by a person or thing in a particular situation, while a responsibility is the state or fact of having a duty to deal with something or of having control over someone. A single individual within a program has multiple roles, and each role may have specific responsibilities. Every individual within a program should have clearly defined roles and responsibilities and understand how those roles and responsibilities are critical to achieving the mission of the program. The following represent a sample of roles and responsibilities commonly clarified in a traffic signal project agreement:
    - Purchasing and deploying any necessary communications and field equipment upgrades.
    - Fine-tuning timing plans once they have been implemented.
    - Evaluating different aspects and features associated with the project.
    - Operating and maintaining the field equipment and/or timing plans once the project is complete.
    - Preparing specific documentation (e.g., expense reports, final reports, and outreach documentation) associated with the project.
    - Performing the data collection necessary to develop timing plans.
    - Developing and implementing the timing plans in the field.
    - Outlining what restrictions, if any, exist on when timing plans can be changed (i.e., the duration before an agency can change the timing plans after deployment).
- *Develop an Organizational Structure that Supports Operations*—The development of a structure for a new traffic signal program will require coordination between traffic signal program managers at both the Statewide and the district/regional level, with support from the agency's top management. Moreover, program leadership at the Statewide and district/regional levels should establish relationships between the program and other support units. A lead manager will recognize the need to include participation from key units involved in the development and delivery of traffic signal program functions, key public safety entities, and private service providers, such as support contractors.
- *Perform Succession Planning*—Succession planning is the process of identifying and developing new leaders who can replace old leaders when they leave an organization. Succession planning increases the number of experienced and capable employees who are prepared to assume these leadership roles as they become available. Succession planning is

an important element that ensures the sustainability of a traffic signal program. Succession planning can take many forms, including:

  - Cross-training across functional boundaries.
  - Leadership development training.
  - Certification and training academies.
  - Informal and formal mentorship programs.

  The extent to which an agency can perform succession planning depends on several factors, including State governance, political environment, and local labor market conditions.(20) Some State DOTs have succession plans and midlevel training academies and programs. For example, California has an extensive succession plan for executive development as well as leadership training for all managers. Other States have special mentorship programs in which highly skilled employees remain in place beyond retirement to mentor their replacements.

- *Outsource Program Activities*—Outsourcing is another tool that some agencies use to expand the capabilities of their programs. Outsourcing is the business practice of hiring a party outside an agency to perform services and create goods that traditionally were performed in-house by the agency's employees and staff.(21) Some of the functions that agencies may outsource are as follows:

  - Designing and constructing a traffic signal system infrastructure.
  - Installing, maintaining, and replacing detection sensors.
  - Performing preventative and emergency maintenance.
  - Designing or maintaining communication systems and technologies.
  - Developing timing and coordination plans for use at intersections and corridors.
  - Developing and monitoring traffic signal performance.

Performance Measurement and Outreach

It is important to have the capability to describe how day-to-day program activities and resource investments in infrastructure, systems, and process improvements support the attainment of objectives and progress toward goals to gain support from decision-makers. Often, practitioners who should provide this clarity magnify the problem by not effectively managing expectations or by over-promising results in support of their projects. The classic example is the defense of traffic signal systems based on performance measures wholly related to improved timings without the recognition that improved timings can be implemented without a system. Using performance measures allows agencies to manage their field infrastructure to attain specific improvements in traffic performance.

Agencies can link their performance measures clearly to objectives. Performance measures should demonstrate the effectiveness of critical program activities. Typically, performance measures are actionable and automated to the greatest extent possible to minimize the level of effort involved in collection and analysis. The type of reports will depend on the audience. Decision-makers generally want a high-level overview of the system performance and impacts on motorist perceptions and program budgets. Engineers typically require highly technical reports that may suggest that they revise or tweak some signal settings, like offsets and splits, and look at troubleshooting calls and maintenance issues. Junior-level technicians, on the other hand, can use an automated system that identifies the problem and suggests some solutions to be implemented to address the problem.

Assessing Program Capabilities

The performance measurement dimension focuses on the use of performance measures to gauge the effectiveness of programs in achieving objectives. This dimension focuses on processes and procedures that agencies use to measure, process, and report performance of their systems. It also considers how agencies use performance measures to assist in critical program-level decision-making, such as resource distribution, staffing and workforce allocations, infrastructure capital management, and more.

Table 16 shows the tool that the *Traffic Signal Benchmarking and Self-Assessment*(4) uses to assess the level of maturity of a program's performance measures and outreach activities. Agencies can use this tool to gain a perspective on how to use performance measures to improve overall operations.

Improvement Strategies

Key strategies that agencies can employ to improve their performance measurement and outreach capabilities include the following:

- *Implement Automated Traffic Signal Performance Measures (ATSPM)*—ATSPM improve the traditional retiming process by providing continuous performance monitoring. ATSPM consist of a high-resolution data-logged capability added to existing traffic signal infrastructure and data analysis techniques. This technology allows signal retiming efforts to be based directly on actual performance without using software modeling or manually collecting data. Further, the data provide agency professionals with the information they need to proactively identify and correct deficiencies with traffic signal maintenance, operations and mobility, and safety. ATSPM were developed through collaboration between FHWA, AASHTO, State DOTs, and academic research efforts. Through collaboration between State DOTs and FHWA, an open-source software option that provides a framework for continued innovation in data analysis techniques was developed via the Traffic Signal Systems Operations and Management Transportation Pooled Fund Study.(22) Collaboration has continued, and ATSPM have been developed to produce several implementation options to fit a wide range of agency capabilities and resources. Multiple State and local transportation agencies have implemented ATSPM systems.

Table 16. Assessing program management performance measures and outreach capability maturity.

Level	Program Management Performance Measures and Outreach Capability
1. Developing	• The evaluation of program areas (e.g., design operation and maintenance) occurs on an as needed basis and is usually informal and qualitative. • Measures of system performance relative to program objectives are not clearly defined. • Workforce capability or systems and technology may not be able to support program evaluation needs. Program and project evaluations are usually contracted out to others.
2. Established	• Outcome and output measures and methods are established to evaluate the effectiveness of the program and the performance of the system. • Limitations in systems and technology, business processes, or workforce capability may result in data collection that is discontinuous, potentially project-oriented, and may hinder the ongoing evaluation of program effectiveness.
3. Measured	In addition to Level 2: • Documented measures and methods direct evaluation of day-to-day activities, projects, and the performance of the system. • Performance measures are collected and reported to demonstrate accountability but may not directly feed into budgeting and resource allocation decisions. The feedback loop may not be well connected to external regional and State transportation programs.
4. Managed	In addition to Level 3: • Performance measures inform decision-making and planning for all workforce, business process, and systems and technology needs. • Performance measures inform budget and resource allocation decisions, as well as asset management and system and technology investments.

Source: Federal Highway Administration.

According to FHWA's *Every Day Counts Program*, the benefits of using ATSPM include the following:(23)

- *Increased Safety*—A shift to proactive operations and maintenance practices can improve safety by reducing traffic congestion that results from poor and outdated signal timing.
- *Targeted Maintenance*—ATSPM provide the actionable information needed to deliver high-quality service to customers, with significant cost savings to agencies.
- *Improved Operations*—Active monitoring of signalized intersection performance lets agencies address problems before they become complaints.

- *Develop Real-Time Performance Dashboards*—Real-time performance dashboards provide live traffic maps with up-to-the-minute information along roadways specifically depicting speed and congestion information. The objective of these dashboards is to keep travelers informed about the current operating conditions of the roadway network and to disseminate information to travelers on where potential congestion and trouble-spots may exist in the network. In addition, agencies can create dashboards to provide live traffic camera information as well as update widgets/graphics containing information about daily speeds, average time-of-day speeds, average travel time, or congestion. The primary purposes of real-time dashboards include (but are not limited to) the following:
    - Visualizing ITS data into various plots, charts, graphs, widgets, and maps that people can easily understand.
    - Providing real-time traffic information to the public in a timely and accessible way through maps, images, and text/email alerts.
    - Monitoring, tracking, and reporting congestion levels and travel reliability trends by corridor, direction, month, hour, and day.
    - Enhancing the number and quality of traveler information services.
    - Converting unprocessed freeway data into meaningful information for various audiences.
    - Evaluating the effectiveness of operational strategies.
    - Helping to allocate resources and prioritize implementation.
- *Develop Project Benefit Summaries*—Benefit summaries of projects provide a list of benefits/performance metrics and the corresponding projects that were completed, along with their extents, project limits, and other various descriptions. Typically, these benefits target goals that demonstrate the benefits of capital improvements and improvement in the overall system capabilities. The purpose of the summaries is to show the effect each project had on the overall traffic system and to provide an annual synopsis of improvement. Benefit summaries allow program managers to compare annual work output to a set of performance goals. This information is key in systemically measuring the program for efficiency, improvements, program effectiveness, and overall sustainability.

Coordination and Collaboration

Effective traffic signal performance often requires collaboration with both internal and external stakeholders. For traffic signal operators, internal stakeholders might include the following, depending on the structure of their organization:(24)

- Roadway geometric designers.
- Groups responsible for long-range and advance project planning.

- Infrastructure/pavement management groups.
- Information technology groups.
- Procurement and budgeting groups.

Because of the need to provide interoperability of technologies and regional connectivity across multiple jurisdictions, collaboration with regional external stakeholders is important. Examples of external stakeholders for traffic signal system operators and managers might include the following:

- Transit system operators/managers.
- Traffic signal system operators/managers from other jurisdictions.
- Pedestrian and bicycle advocacy groups.
- Private land developers and commercial establishments.
- Commercial fleet operators.
- Paratransit and ride-sharing groups.
- Emergency service providers (fire, police, ambulance, snowplow operators, etc.).
- Special event coordinators/promoters.
- Roadway construction managers and supervisors.

Assessing Program Capabilities

Table 17 and Table 18 show capability maturity levels derived from the *Traffic Signal Benchmarking and Self-Assessment*(4) that define the attributes common to agencies of each maturity level with respect to their internal and external collaborations. Using this tool, agencies can determine what types of internal and external collaborations might be needed to support their desired program objectives.

Table 17. Assessing program internal program coordination and collaboration capability maturity.

Level	Internal Collaboration Capability
1. Developing	• Coordination between the traffic signal program and other organizational units (e.g., planning, safety, construction, and engineering) is not well-defined and does not occur routinely. • Program units rarely collaborate with other internal groups to coordinate responses to requests or pursue funding opportunities. Key personnel coordinate with other internal organizational units only on a project-by-project or as-needed basis.
2. Established	• The agency has identified and documented organizational relationships with other internal agency units. The agency maintains an accurate listing of key organizational contacts with other internal organizational units. • The agency has documented processes and workflows (such as design checklists, review checklists, and sign-offs) that support the attainment of organization objectives. • Informal relationships exist between key personnel in other organizational units.
3. Measured	In addition to Level 2: • Key decision-makers internal to organization routinely meet to discuss opportunities for collaboration to pursue resources to attain program objectives. • Organizational units work together to identify changes and adapt internal workflow processes to assist in attaining program objectives (e.g., incorporate maintenance requirements into signal design processes). • Key program units work together to identify budgetary needs for the program.
4. Managed	In addition to Level 3: • Program units routinely review and monitor project opportunities and program activities that may mutually benefit from coordination. • Collaboration between internal program units is organic, occurring naturally without direction from program-level decision-makers.

Source: Federal Highway Administration.

Table 18. Assessing program external program coordination and collaboration capability maturity.

Level	External Collaboration Capability
1. Developing	• The program does not routinely coordinate with other public or private organizations (e.g., MPOs, police, emergency services, schools, colleges, special event facilities) to plan, coordinate, or respond to activities or share information to support day-to-day operations. • Top-level managers or administrators form collaborations with external organizations and jurisdictions. These collaborations are usually formal and occur more at the organizational level (as opposed to the program level). • The traffic signal program does not have any direct interaction with regional and State transportation activities.
2. Established	• Relationships with external public and private partners are identified and documented in a TSMP. • The agency uses memorandums of understanding or formal agreements as needed to facilitate collaboration. Special events, incidents, and emergencies are appropriately planned for and coordinated. • The program participates in regional and State transportation planning activities. • The agency performs coordination and collaboration on a project-by-project basis. Collaboration primarily occurs between champions or key personnel. • Unit managers are familiar with counterparts in other external organizations or jurisdictions.
3. Measured	In addition to Level 2: • Collaboration and coordination with external partners result in coordinated responses across jurisdictional boundaries (e.g., coordination of traffic signal timing responses between organizations for special events or incidents). • The program monitors the outcome of regional planning activities to ensure appropriate consideration of needs. • Coordination and collaborations with external partners exist at organizational unit levels.
4. Managed	In addition to Level 3: • The traffic signal program routinely coordinates with partners to attain shared objectives. • Agencies leverage appropriate local, State, and Federal resources to integrate activities, processes, and systems in support of regionally shared objectives. • Formal mutual aid and support agreements exist between regional partners.

Source: Federal Highway Administration.

Improvement Strategies

Some strategies that agencies can use to improve their level of coordination and collaborations associated with traffic signal programs include the following:

- *Utilize Appropriate Informal and Formal Institutional Agreements*—Agencies also use project-level agreements as part of the normal course of business for their traffic signal programs. Agencies can use project-level agreements (sometimes referred to as interlocal, interagency, or interjurisdictional agreements) to initiate a specific improvement project within a program. Generally, these types of agreements are legally binding, and agencies use them when they need to exchange funds between the agency responsible for distributing funds (i.e., the regional entity) and the agency responsible for performing the work (i.e., the local entity). Project agreements usually only exist between two governmental entities and not between a public entity and a private consultant firm. Agreements with private entities generally require a different type of contracting mechanism. While the exact content can vary from location to location, the project agreement generally describes the roles, responsibilities, and relationships between the regional and local entities. Agencies should use project-level agreements to clarify the roles and responsibilities between agencies. Project agreements also may specify the amount of money that each agency is responsible for contributing to the project. These responsibilities include the amount and type of matching requirements (i.e., hard match, soft match, or in-kind match) that the local entity must provide, if any. Often, project agreements also contain a payment reimbursement schedule and a project delivery timeframe. Table 19 lists the different types of agreements commonly used to facilitate and foster collaborations and coordination between agencies in a traffic signal program.(26)

- *Create Regional Traffic Signal Forums*—One method to improve collaboration in a region is to create regional traffic signal forums. In a regional traffic signal forum, representatives from State, regional, and local signal operators routinely gather to discuss and develop strategies to address operational problems common to all agencies.(27) Through regional traffic signal forums, agencies can set regional performance objectives, establish project selection criteria, and identify regional priority corridors for operations. Regional traffic signal forums can promote interagency cooperation and can facilitate strategies for implementing common operational strategies across jurisdictional boundaries. Some regional forums provide training for operational staff to raise the level of operational capabilities across the entire region.

Table 19. Types and attributes of common institutional agreements used with traffic signal programs.[(4)]

Type of Agreement	Attributes of Agreement
Informal Partnerships	• Agencies agree to work cooperatively, often without any written agreement. • Agencies build upon existing working relationships between key personnel. • Agencies band together through spoken or handshake agreements to formalize the agreed-upon signal timing strategy or solution.
Memorandum of Understanding (MOU)	• Is a written agreement between two or more entities that describes an agreed-upon course of action to be pursued by each entity to address a common situation or approach as a common goal. • Is often used to outline the basic tenets and purpose of the arrangement. • Describes the purpose and intent of the collaboration, the relationship between the partner agencies, and the planned governance of the collaboration. • Is generally a nonbinding agreement.
Cooperative Agreement	• Is similar in concept to an MOU but is considered a legally binding document. • Contains many of the same basic elements as an MOU (e.g., a description of the program’s organizational structure, the program’s functions, and the roles and responsibilities of each partner agency). • Is used when one agency will be responsible for performing specific services or functions for another agency, usually for a fee. • Obligates one or more of the agencies to make a financial commitment to the program.
Cost-Sharing Agreement	• Is used to share the responsibility of funding the costs for the functions and services that the regional entity performs (e.g., developing timing plans, monitoring arterial performance, improving infrastructure, or maintenance). • Is generally based on the percentage (or ratio) of traffic signals within a single jurisdiction compared to the total number of traffic signals under the control of the regional entity.

Source: National Academy of Sciences

- *Develop Regional Concept of Transportation Operations*—A regional concept of transportation operations (RCTO) is a management tool that agencies can use to define how agencies within a region will respond or react to regional situations and circumstances. RCTOs lay out a collective strategic approach that agencies in a region can collectively and collaborative employ to improve transportation management and operations in a sustained manner.(26,27) Agencies can use the RCTO to develop consensus on what has to be accomplished in the next three to five years to address immediate safety, mobility, environmental, and reliability challenges that exist on a regional perspective. Traffic signal systems are often a key element of most RCTOs, and traffic signal operators should work collaboratively with other key regional stakeholders to develop consensus on how to achieve regional goals. Agencies can find more information on RCTOs in *Regional Concept of Transportation Operations: A Tool for Strengthening and Guiding Regional Transportation Operations Collaboration and Coordination.*(28)

- *Implement a Regional ITS Architecture*—A regional ITS architecture is a specific regional framework for ensuring institutional agreement and technical integration for the implementation of ITS projects in a particular region(29) It is a plan for deploying ITS systems and technologies—which include traffic signal systems—in the region, often in an incremental fashion as funding and technology become available and agencies resolve institutional issues. A regional ITS architecture defines the structure and interconnectivity between regional projects so that they build upon one another efficiently. A regional ITS architecture can identify opportunities for making ITS investments more cost effective by utilizing interagency cooperation during the planning, implementation, and operation of these ITS projects.

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CHAPTER 4. SYSTEMS ENGINEERING FOR TRAFFIC SIGNAL SYSTEMS

Systems engineering provides a process for documenting agency needs and deriving requirements from those needs to guide the procurement of systems and technology. The processes minimize the risk that the resulting system will not address the agency's needs by ensuring that the most important needs are documented first and that the requirements to fulfill those needs are clearly articulated. Chapter 4 presents a needs-focused, requirements-driven engineering and procurement process to support objectives related to the systems and technology area of the traffic signal program. The FHWA *Model Systems Engineering Documents for Central Traffic Signal Systems*(1) provides a foundation for developing a Concept of Operations and Requirements documents to guide the procurement of small-scale, central traffic signal systems (CTCC); adaptive signal control (ASC); and automated traffic signal performance measures systems. FHWA developed the model documents to include the traceability and verification processes that are important to realizing desired outcomes when procuring systems and technology.

INCORPORATING SYSTEMS ENGINEERING TO SUPPORT IMPLEMENTATION OF SYSTEMS AND TECHNOLOGY

As discussed in Chapter 2, infrastructure, systems, and technology provide a foundation for the attainment of multiple program and organizational objectives. The systems engineering process supports the clear identification of needs and requirements to support procurement and adequate testing to ensure that requirements are fulfilled and that the system deployed meets the agency's needs. It helps to ensure that infrastructure investments provide the needed capabilities to support attainment of desired outcomes.

When the capabilities of existing systems do not meet current or future needs, thus limiting the attainment of program objectives, it may become necessary to upgrade or replace some or all components of a system. As systems age beyond their expected life cycle or new capabilities emerge, a systems engineering analysis can be instrumental in developing requirements to support the procurement of systems and devices. One or more of the following use cases may be relevant:

- Using adaptive control in the area to address high variability in demand. An adaptive traffic signal system can modify key signal timing parameters to accommodate and address changes in the traffic conditions that can benefit from redistribution of capacity.

- Using automated traffic signal performance measurement and monitoring to validate and optimize how well single and multiple intersections function in attaining the agency's operational objectives.

- Monitoring the performance of new or existing coordinated traffic signal systems.

- Replacing systems that are beyond their life cycle.

- Replacing or extending the field device infrastructure with equipment that is effective, manageable, and sustainable. Traffic signal controllers have a functional lifespan that may be shorter than their operational lifespan, which means that even though they continue to work, they no longer support the functions needed to attain the agency's operational objectives in a manageable and sustainable way.

- Integrating regional signal systems to provide seamless operation or management across system boundaries.

MODEL SYSTEMS ENGINEERING DOCUMENTS FOR CENTRAL TRAFFIC SIGNAL SYSTEMS

The *Model Systems Engineering Documents for Central Traffic Signal Systems*(1) extracts needs and requirements from these use cases to support the development of a Concept of Operations and Requirements, which lays out user needs. The model systems engineering documents provide a framework for agencies to clearly articulate their needs and specify succinct and comprehensive system requirements to guide the procurement and implementation of ITS. Target procurements include those projects that:

- Cannot reasonably afford development of systems engineering documents from scratch.

- Make selections from existing device and software products in the market rather than from new product or software development.

These model documents make it possible for agencies to develop meaningful systems engineering documents that will effectively support procurements and reduce risk for smaller, more routine ITS implementation projects. The model documents support signal system procurements including basic signal system operation, traffic-responsive pattern selection, adaptive control, and performance monitoring. They are limited to projects that will select an existing systems product, which is usually the case with conventional systems. The model documents implement a sequential systems engineering process.

Sequential Systems Engineering

Most traffic signal system operation is well established, and needs and requirements can be documented with confidence using sequential systems engineering processes, as depicted by the following steps:

- Document project purpose, generally taken from planning documents.
    - Document user needs (in a Concept of Operations).
    - Document system requirements (in a requirements document).
        - Validate requirements against the needs.

- Develop a design (plans and specifications) that fulfills the validated requirements.
  - Verify the design against requirements.
  - Validate the design against the needs.
- Implement the verified and validated design, one portion at a time.
  - Test the portion to ensure compliance with the design.
  - Verify the portion against requirements.
  - Validate the portion against needs.
- Integrate tested, verified, and validated system components into a complete system.
  - Test the system to ensure compliance with the design.
  - Verify the system against requirements (usually this is when a contractor's work is completed and accepted).
  - Validate the system against needs.
- Operate the system consistently with the purpose and needs.
- Ultimately, document system deficiencies over time to support ongoing revision (as part of a support activity) and eventual retirement and replacement.

When to Use Iterative Processes

Iterative systems engineering processes are more appropriate for emerging technologies and innovations when needs and requirements may not yet be fully understood or documented (e.g., integration of traffic signal systems with automated or connected vehicles, transit control systems, traveler information systems, smart pedestrian management systems, and other emerging technologies). The use cases, needs, and requirements for these emerging innovations may not yet be fully understood or documented. Thus, agencies making use of these approaches may need to apply iterative systems engineering. With iterative processes, the requirements are usually not fully documented at first, but the system is prototyped based on initial requirements, and the prototype is evaluated to determine how to refine the requirements, which leads to new or revised requirements and prototypes that fulfill them. The iterative process may be more demanding from a process perspective but can provide quicker exploration of alternative approaches and ideas and often leads to a better product, especially when innovative approaches and new software are being developed.

Systems that include innovative elements typically also include conventional elements that can utilize sequential processes. The iterative approaches can be limited to those parts of an implementation that cannot be adequately addressed using the model documents.

DOCUMENT PLANNING AND PURPOSE

The presence of robust operational planning documents can be leveraged during the systems engineering process to establish the purpose of planned system improvements. Operational planning documents typically describe the operational problems the agency needs to solve and the traffic operations strategies the agency will employ to mitigate them. Operational problems may include the following:

- Management of the signal timing database. Changes to the signal timing that are not adequately tracked may cause unintended operation that is not consistent with attaining operational objectives.

- Field device failures, including communication failures, controller failures, and detector failures. These failures cause operation that no longer attains operational objectives.

- Inability to maintain field infrastructure reliability. Maintenance monitoring may be inadequate because the resources necessary to identify and correct operational deficiencies is limited as a result of the distance and travel time required to monitor operations and maintenance status from the maintenance shop to the field devices.

- Unresponsiveness of the operation to unpredictable and changing operational context. As the context changes, so do the operational objectives. In some cases, traffic signal systems play a role in noting changes in demand and responding to those changes with a change in operation that is needed to attain operational objectives (including an understanding of when those objectives need to shift).

Thus, the purposes for implementing a traffic signal system that addresses these operational problems may include the following:

- Adaptive control in the area to overcome operational defects related to unpredictable changes in operation. An adaptive traffic signal system is one in which some or all the signal timing parameters are modified in response to changes in the traffic conditions in real time.

- Automated traffic signal performance measurement and monitoring to validate and optimize how well single and multiple intersections are attaining the agency's operational objectives.

- Replacement of outdated or unsustainable (or unmaintainable) existing systems. The agency should identify and document the reasons why the current system is unsustainable to ensure that the new system is sustainable. For example, a system based on computer technology that the agency lacks the expertise to maintain may be unsustainable, and the new system should make use of technology the agency can maintain.

- Addition of performance monitoring capabilities to a new or existing coordinated traffic signal system.

- Replacement or extension of the field device infrastructure with equipment that is effective, manageable, and sustainable. Traffic signal controllers have a functional lifespan that may be shorter than their operational lifespan, which means that even though they continue to work, they no longer support the functions needed to attain the agency's operational objectives in a manageable and sustainable way.

- Integration of regional signal systems to provide seamless operation or management across system boundaries.

DOCUMENT USE CASES

Once the agency understands and documents the purpose of the system, the agency should then document the operational needs. The first step is to document *use cases*. Use cases describe who will do what using the system. The *Model Systems Engineering Documents for Central Traffic Signal Systems*(1) extracts a library of needs and requirements from these use cases. Agency professionals may use these needs and requirements to develop the basic documents of the systems engineering process, including a Concept of Operations, and a requirements document. The model documents support signal system procurements that include basic signal system operation, traffic-responsive pattern selection, adaptive control, and performance monitoring. They are limited to projects that are selected from existing systems products, which is usually the case with conventional systems. The model documents implement a sequential systems engineering process.

Example use cases from the *Model Systems Engineering Documents for Central Traffic Signal Systems* are discussed in the following sections.(1)

Configuration of the CTSS Management System

This use case covers the overall configuration of a CTSS Management System, including configuring the traffic signal controller's network connection and managing access to the signal system. The configuration of operator access to the signal system as well as access to the databases is set up by the appropriate system manager. The system manager also generally configures the overall CTSS Management System's architecture, fallback operation, and intersection display map. Fallback configuration for a controller is set up by the signal system user in the event of communications failure.

Managing the Local Signal Controller Database

This use case covers operations performed by the signal system operator when managing the database residing in local signal controllers. It covers user operations for the following:

- Data entry.

- System validity checks to ensure that the central system database matches the controller database.

- Database transfers.
- Viewing and printing timing sheets.
- Developing multiple versions of the timing database.
- Uploading and downloading the timing database.
- Database comparison and validation.
- Database change tracking and searching for intersection databases.

Monitoring the Traffic Signal Network

This use case covers the user monitoring the traffic signal network using the signal system. The user configures the signal system to monitor specific groups of traffic signal intersections and overall signal system status.

Managing the Traffic Signal Network

This use case covers the management of the traffic signal network by the user. These operations include the following:

- Enabling diversion plans.
- Synchronizing the time clocks for a group of controllers.
- Selecting plans based on time of day, either local time of day or central system time of day.
- Selecting plans based on traffic-responsive patterns.
- Selecting plans manually.
- Synchronization of time-of-day clock with external systems.
- Overriding time-of-day operation.
- Remotely placing vehicle and pedestrian calls.
- Managing external devices.
- Managing emergency vehicle preemption (EVP).
- Managing bus and light-rail signal priority.
- Managing rail preemption.

Performance Monitoring

This family of use cases covers the performance monitoring functions of the traffic signal network by the user and includes the following:

- Configuring the mapping of the enumerated data to the intersection.
- Retrieving and storing enumerated data for the system.
- Retrieving and storing high-resolution traffic detection data.
- Initiating the processing of the enumerated and high-resolution traffic detection data into performance measurements.
- Configuring and retrieving reports of system performance measures.
- Configuring and retrieving reports of performance data.

Adaptive Operation

The family of use cases for adaptive traffic signal operations include the following:

- Implementing adaptive strategies based on the agency's operational objectives.
- Determining how the adaptive system controls the signal network using adaptive capabilities.
- Preparing the adaptive system to coordinate with an adjacent jurisdiction to facilitate coordination of adaptive progression.
- Modifying adaptive operation based on queuing conditions.
- Accommodating pedestrians within an adaptive operation.
- Operating the system non-adaptively under certain situations and conditions.
- Managing the sensitivity of adaptive operations to changing conditions.
- Supporting the use of special signal controller features that require operational settings (as part of the controller database management using a traffic signal system) and features that a traffic signal system or adaptive system must allow to operate as the user intended.
- Securing adaptive control features.
- Monitoring adaptive operation to ensure it is performing correctly within a range of operating conditions.
- Measuring and monitoring system performance and effectiveness during adaptive operations.

- Retrieving performance metrics from the adaptive system.
- Providing failure notifications under adaptive operations.
- Sustaining adaptive operations during preemption and priority events.
- Responding to adaptive-related system failures.

Traffic Signal System Maintenance

This use case involves the user maintaining the signal system by performing and testing all system capabilities both locally and remotely and by performing remote updates of the signal controllers, controller firmware, and signal system software.

Interfacing with External Systems

This use case includes the user interfacing with external systems to perform the following:

- Monitoring and operating signal controllers and detectors from different manufacturers within the signal system.
- Replacing signal controllers and detectors from different manufacturers within the signal system.
- Specifying different signal controller and detector interface standards within the signal system.
- Specifying (by the system designer) the existing signal controller and detector interfaces to integrate new signal controllers and detectors into an existing system.
- Specifying the existing signal controller and detector interfaces to integrate a new system with existing signal controllers and detectors.
- Accessing external signal systems to access information regarding signal controllers, intersections, and groups of intersections.
- Directing external signal systems to receive information regarding signal controllers, intersections, and groups of intersections.

OPERATIONAL NEEDS

If following the model documents, operational needs describe what the user will do using the system, as outlined in the use cases. In the model document, operational needs are expressed using the following sentence structure:

The User needs to do something, somehow.

The following is an example of an operational needs statement from the model documents:(1)

> *4.1.4.4 The TSS Operator needs to view the status of an intersection or group of intersections even when another TSS Operator is editing the intersection database.*

The model documents organize user needs around use case in the following sections:(1)

- 4.1 System Configuration.
- 4.2 Managing Signal System and Field Device Database.
- 4.3 Control.
- 4.4 Adaptive System Operation.
- 4.5 Traffic and Operational Performance Measurement, Monitoring, and Reporting.
- 4.6 Data Storage.
- 4.7 Constraints.
- 4.8 Training.
- 4.9 External Interfaces.
- 4.10 Maintenance, Support, and Warranty.

User needs are linked to requirements such that all needs are addressed by requirements, and all requirements are driven by needs.

REQUIREMENTS

Requirements state what the system needs to do to meet the user's needs. The sentence structure of a requirements statement is as follows:(1)

The System shall do something, somehow.

Requirements should be singular, feasible, measurable, testable, and verifiable. They should avoid specifying technology, which is the role of specifications as a part of design. Good requirements avoid technological specifications that will untimely date them.

For example, the following is a requirement from the model documents:(1)

> *3.1.1.4 The system shall allow XX number of users to log on to the system simultaneously.*

Requirements may describe the function of a system or a range of other attributes, but those requirements that use verbs like *do* are usually functional requirements. Functional requirements generally supplement specifications, which usually cover environmental and specific technological requirements and other attributes. Functional requirements are particularly important for software-based products like traffic signal systems.

The model documents organize functional requirements around systems functions using the following sections:

- 3.1.1 Access Control.
- 3.1.2 Security.
- 3.1.3 System Configuration.
- 3.1.4 Database Development.
- 3.1.5 Database Management.
- 3.1.6 Failure Events and Fallback.
- 3.1.7 Monitoring.
- 3.1.8 Control (includes traffic-responsive pattern selection).
- 3.1.9 Adaptive Operations.
- 3.1.10 Adaptive Advanced Controller Operation.
- 3.1.11 Adaptive Pedestrians.

- 3.1.12 Adaptive Special Functions.
- 3.1.13 Adaptive Detection.
- 3.1.14 Adaptive Railroad and EVP.
- 3.1.15 Adaptive Transit Priority.
- 3.1.16 Traffic and Operational Performance Measurement, Monitoring, and Reporting.
- 3.1.17 External Interfaces.
- 3.1.18 Software.
- 3.1.19 Training.
- 3.1.20 Maintenance, Support, and Warranty.

TASKS AND DELIVERABLES

Because systems engineering depends on documented user needs, it also depends on meetings with users. Users of signal systems include more than just traffic engineers who calculate signal timings. Users also include maintenance technicians, office technicians, and managers, and may also include peers in other agencies. The first step is identifying who will be the person in each user role.

Although there are certifications for systems engineers, the best way an agency can ensure getting comprehensive systems engineering is to include all the necessary steps in the scope of work. The Appendix describes one formulation of these steps. Even an agency doing their systems engineering in-house (which is the intention of the model documents) should take these steps. Larger and more complicated projects likely need more depth and time spent on each step, but smaller and simpler projects should still address all these tasks up to an appropriate level.

The Appendix is not intended to be prescriptive but rather describe the sorts of activities involved in performing systems engineering. Other formulations may be just as valid. Note that the burden of demonstration should be on the systems engineer so that when an agency hires a consultant to perform these tasks, the consultant demonstrates the validity of the documents in meetings. This approach reduces the amount of effort required by agency professionals reviewing documents.

Systems engineering succeeds when the requirements document is *complete* and *correct.* It is complete when it describes everything expected of the system (as evidenced by addressing all the needs), and it is correct when the agency has confidence that a system exactly fulfilling the requirements (no more and no less) will meet their needs. If the agency professionals do not have that confidence in the requirements document, then more work may be needed. However, further effort might not bring additional results unless it is to align deficient requirements with the user needs. When those deficiencies are noted, systems engineers should start with the user needs to determine what gap in those needs statements led to the gap in the requirements. That approach most efficiently fills those gaps correctly.

Moreover, for smaller and simpler projects, the roles described in these tasks may be performed by one individual.

FEDERAL REQUIREMENTS FOR SYSTEMS ENGINEERING ANALYSIS

Title 23 of the Code of Federal Regulation (CFR) defines ITS projects when using federal aid funds and specifies that a systems engineering analysis accompany projects meeting that definition. The definition of ITS and an ITS project is in 23 CFR 940.3:(2)

- ITS: "[E]lectronics, communications, or information processing, used singly or in combination to improve the efficiency or safety of a surface transportation system."
- ITS Project: "Any project that in whole or in part funds the acquisition of technologies or systems of technologies that provide or significantly contribute to the provision of one or more ITS user services as defined in the National ITS Architecture."

23 CFR 940.11 establishes the requirements for a systems engineering analysis:

§ 940.11 Project implementation.

> *(a) All ITS projects funded with highway trust funds shall be based on a systems engineering analysis.*
> *(b) The analysis should be on a scale commensurate with the project scope.*
> *(c) The systems engineering analysis shall include, at a minimum:*
> *(1) Identification of portions of the regional ITS architecture being implemented (or if a regional ITS architecture does not exist, the applicable portions of the National ITS Architecture);*
> *(2) Identification of participating agencies' roles and responsibilities;*
> *(3) Requirements definitions;*
> *(4) Analysis of alternative system configurations and technology options to meet requirements;*
> *(5) Procurement options;*
> *(6) Identification of applicable ITS standards and testing procedures; and*
> *(7) Procedures and resources necessary for operations and management of the system.*

The tasks presented in the Appendix provide all the elements for a systems engineering analysis required by 23 CFR 940.11.

The model documents help address this need for smaller projects, but agencies may further streamline the process by developing a single systems engineering analysis that can apply to a whole class of projects. For example, a State DOT may implement many small closed-loop signal systems in fringe suburban areas or on State highways in towns. All these implementations may respond to the same users, the same needs, and the same requirements. They may share the same architecture and interface definitions. One set of documents could serve all those projects and can be applied categorically. As projects develop meaningful systems engineering documentation, the need for fresh systems engineering effort may diminish substantially, but such improved efficiency over time depends on the quality of the documents being used for later projects. They should avoid a dependence on specific technologies, which are likely to change more rapidly than needs and requirements.

For projects that must develop new software or implement technologies never subjected to requirements verification, detailed systems engineering from scratch may be necessary to fully define the project and mitigate the risk of outcomes that do not meet expectations. Such efforts can be focused on those portions of a project that are not already served by existing documents or application of the model documents.

CHAPTER REFERENCES

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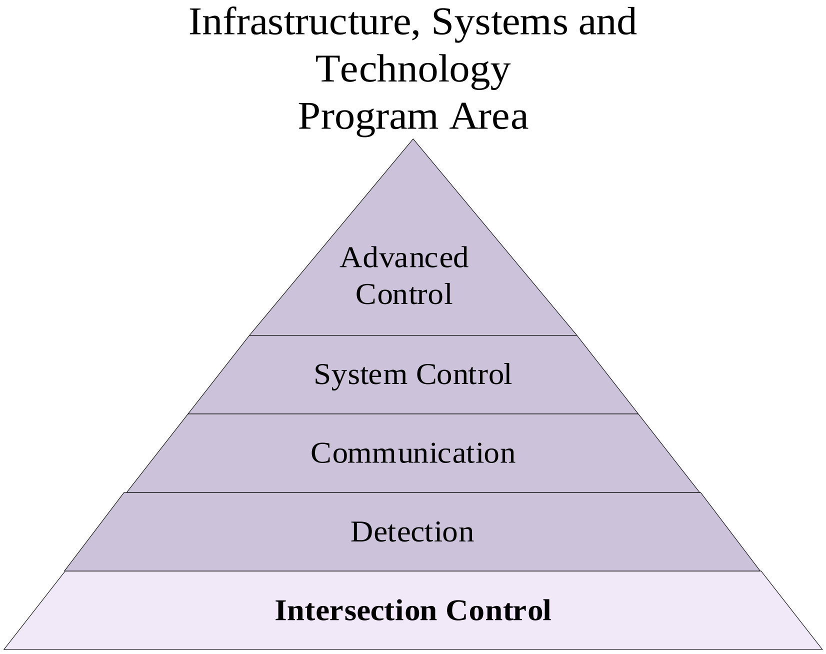
CHAPTER 5. INTERSECTION CONTROL

As illustrated in Figure 9, intersection control is the foundational component of the hierarchy of investment; it provides the base capabilities to manage intersection displays, monitors requests for ROW, and assigns ROW to all the users of signalized intersections. The discussion of intersection control in this chapter extends from the decision point of establishing a signalized intersection and presumes that a robust planning process, operations plan, and predesign activities, such as a warrant analysis, have been effectively analyzed and completed. This chapter focuses on the intersection control capabilities as they pertain to the attainment of program objectives. This chapter updates intersection control information provided in prior editions of the TCSH and identifies key references that cover related topics, supplementing them here rather than duplicating or incorporating that content.



Source: Federal Highway Administration.

Figure 9. Graphic. Intersection control as the foundational component of the traffic signal systems and technology infrastructure.

The discussion of intersection control presumes that an engineering study that may include an *intersection control evaluation* (ICE) and warrant analysis demonstrates that a traffic signal is the most appropriate form of intersection control. The infrastructure and systems implemented at the intersection control level establish the capabilities needed to manage the ROW at a signalized intersection and form the basis for pursuing virtually all traffic signal program objectives. Subsequently the selection and configuration of infrastructure, systems, and technology at all levels of the hierarchy of investment should be driven by objectives. Performance measures should be identified and routinely evaluated to validate that infrastructure, systems, and technology reliably support the attainment of objectives. If gaps in the reliable attainment of objectives are identified, an opportunity may exist to improve infrastructure, systems, and technology to reduce risks associated with the sustained attainment of objectives.

Table 20 identifies relationships that exist between intersection control and program objectives. By linking the capabilities of infrastructure, systems, and technology to objectives and goals and evaluating them with performance measures, a framework is created to guide investments that sustain the delivery of good basic service. Investments in infrastructure, systems, and technology program areas may prompt the need for investment in other program areas. Ensuring that each program area mutually supports others and validating them with measures helps to sustain the ongoing attainment of all objectives by identifying and mitigating risks.

The systems engineering principles discussed in Chapter 4 can be applied to the implementation of infrastructure, systems, and technology. In its simplest form, this application means identifying needs and developing requirements and specifications to guide procurement. The ability to integrate and coordinate systems within and across jurisdictional boundaries begins by considering those needs at the intersection control level. This chapter discusses the intersection control level elements listed below in terms of their basic functionality and relationship to objectives. Specific products and proprietary systems are not discussed.

Key references and resources that an agency may wish to consult when designing and selecting technology to implement at the intersection control level include the following:

- *Part 4: Highway Traffic Signals. Manual on Uniform Traffic Control Devices for Streets and Highways.*(2)
- *Signal Timing Manual, 2nd Edition.*(3)
- *Equipment and Material Standards of the Institute of Transportation Engineers.*(4)
- *Signalized Intersections: Informational Guide.*(5)
- *Manual of Traffic Signal Design.*(6)
- *ITS Standards Program.*(7)
- *Transportation Management Systems and Associated Control Devices*.(8)
- *Resources: ITS Standards*.(9)
- *Traffic Signal Program Management.*(10)
- *Automated Traffic Signal Performance Measures*.(11)
- *Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach*.(12)

Table 20. Relationship between intersection control and program and operational objectives.

Intersection Control	Responsiveness to Stakeholder Needs	Comply with Agency Policies and Standards	Sustain Infrastructure in State of Good Repair	Minimize Life-Cycle Costs	Safe Assignment of ROW	Appropriate Distribution of Green	Provide Smooth Flow	Maximize Throughput	Manage Queues	Minimize Delay for Prioritized Modes
Signal Indications and Displays	X	X	X	X	X	X	X	X	X	X
Poles and Supports	X	X	X	X	–	–	–	–	–	–
Conduit and Ground Boxes	X	X	X	X	X	X	X	X	X	X
Traffic Signal Controllers	X	X	X	X	X	X	X	X	X	X
Traffic Signal Cabinets	X	X	X	X	X	X	X	X	X	X
Ancillary Equipment	X	X	X	X	–	–	–	–	–	–
Preferential Treatment	X	X	X	X	–	–	–	–	–	X
Performance Measurement	X	X	X	X	X	X	X	X	X	X

“X”= Objective Supported Directly; “–” = Objective Not Supported Directly

Source: Federal Highway Administration.

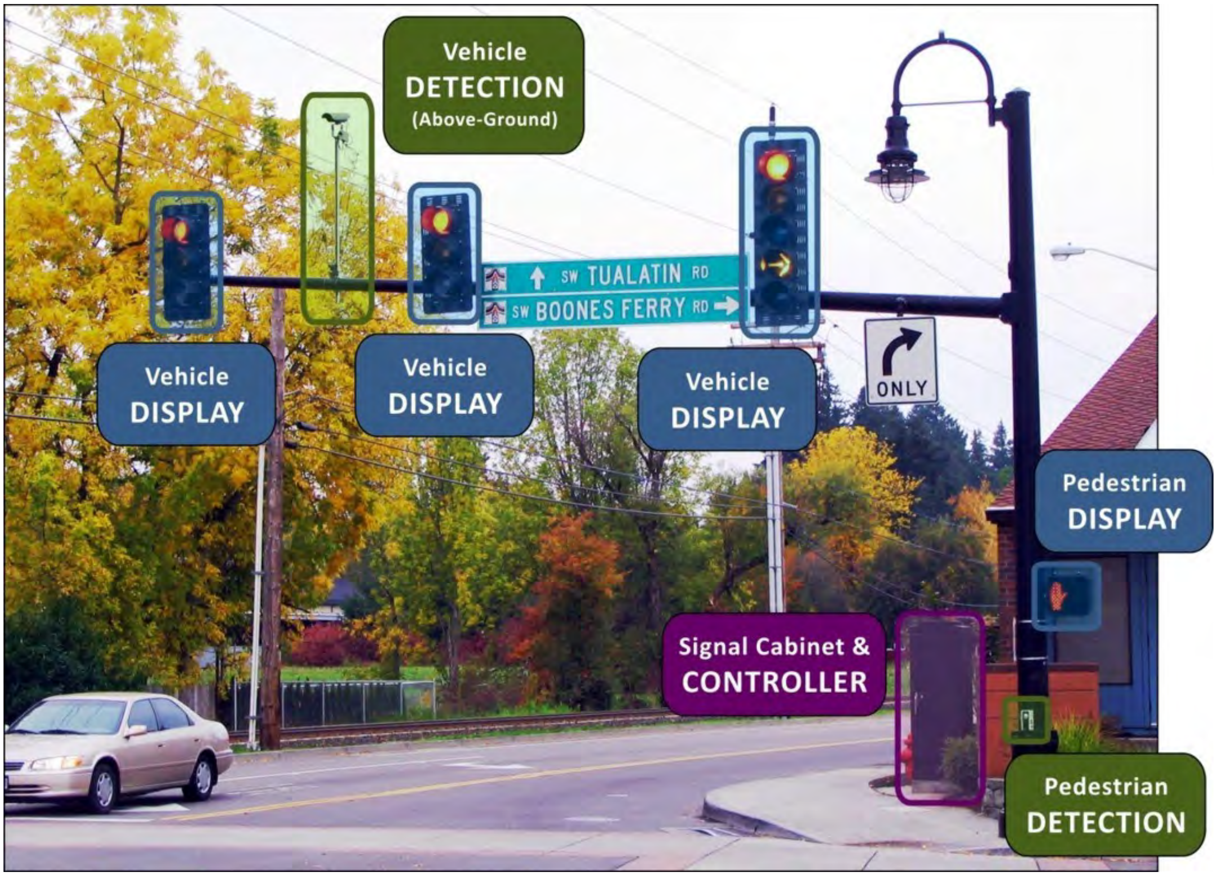
SYSTEMS AND TECHNOLOGIES TO SUPPORT INTERSECTION CONTROL FUNCTIONS

As illustrated in Figure 10, a fully functional traffic signal generally features the below infrastructure components:

- A group of signal indications and displays that control the movements of vehicles and pedestrians at the intersection (labeled as Vehicle Displays and Pedestrian Displays in Figure 10).
- Poles and connectors that hold and support the signal indications in the proper position for them to be visible to the users of the intersection.
- A series of electrical circuits that energize the signal indications that illuminate the appropriate signal displays.
- A detection system capable of detecting the presence of approaching users or stopped users waiting at the intersection.
- An enclosure/traffic signal cabinet for providing a weather-tight environment for the traffic signal controller and the ancillary electrical components (labeled as Vehicle Displays and Pedestrian Displays in Figure 10). This enclosure generally contains the following:
    - A traffic signal controller that manages and energizes the sequencing and duration of each signal indication.
    - An electronic monitoring device that ensures that the controller does not display signal indications to conflicting movements.
    - Power supply, load switches, and equipment that manage.

Agencies will often supplement these infrastructure components with other systems and technologies to enhance the control functions at signalized intersections. Examples of the other types of technologies agencies may install at signalized intersections include the following:

- Communication equipment to enable communication with the operators.
- Video surveillance equipment to facilitate visual monitoring of user movements through the intersection.
- Systems and technologies for measuring and monitoring performance and efficiencies at the intersection.



Source: National Academy of Sciences

Figure 10. Graphic. Components of a signalized intersection(3)

SIGNAL INDICATIONS AND DISPLAYS

Signal indications and displays are the primary interface devices with the end-user and are the most visible component of a traffic signal installation. The indication in a signal head is primarily a function of the type of user, detection, and the traffic signal controller. The users range from vehicles, to pedestrians, to bicyclists. *Part 4: Highway Traffic Signals* of the MUTCD is a regulatory standard, see 23 CFR 655.603, that regulates displays of signal indication for all traffic control devices installed on any street, highway, or bicycle trail open to public travel. (2)

Vehicle Signal Indications

Section 4D.06 of the MUTCD states that the requirements of *Vehicle Traffic Control Signal Heads* that pertain to the aspects of the signal head design that affect the display of signal indications must be met. *Vehicle Traffic Control Signal Heads* is Chapter 2 of the publication "Equipment and Materials Standards of the Institute of Transportation Engineers,"(4) and provides specifications for vehicle signal indications. Section 4D.06 of the MUTCD also states that the intensity and distribution of light from each illuminated signal lens should comply with *Vehicle Traffic Control Signal Heads* and *Traffic Signal Lamps*, which is Chapter 1 of "Equipment and Materials Standards of the Institute of Transportation Engineers."

The vehicle signal indication assembly consists of the following components: an optical unit, a housing, visors, and a mounting bracket. The optical unit consists of a lens, a reflector, a light source, and other components, such as wiring terminals. These requirements are discussed in further detail in *Vehicle Traffic Control Signal Heads*. (4)

Lenses

The MUTCD is the national standard for all traffic control devices installed on any street, highway, or bicycle trail open to public travel. See 23 CFR 655.603. Under paragraph 9 of Section 4D.06 of the MUTCD: "Except as provided in Paragraph 10, the requirements of the publication entitled 'Vehicle Traffic Control Signal Heads' (see Section 1A.11) that pertain to the aspects of the signal head design that affect the display of the signal indications shall be met." Paragraph 10 states: "The intensity and distribution of light from each illuminated signal lens should comply with the publications entitled 'Vehicle Traffic Control Signal Heads' and 'Traffic Signal Lamps' (see Section 1A.11)."

Section 1A.11 reads: "To the extent that they are incorporated by specific reference, the latest editions of the following publications, or those editions specifically noted, shall be a part of this Manual." That section includes "'Vehicle Traffic Control Signal Heads,' Part 1 – 1985 Edition; Part 2 (LED Circular Signal Supplement) – 2005 Edition; Part 3 (LED Vehicular Arrow Traffic Signal Supplement) – 2004 Edition (ITE)"

Section 8 of *Vehicle Traffic Control Signal Heads*(4) provides specifications regarding traffic signal head lenses, such as the basic chromaticity requirements of the red, yellow, and green signal indications used in traffic control signals. Chromaticity is generally expressed in terms of trichromatic coefficients x, y, and z (which represent the red, green, and blue content of a color). Per Section 8.04 of *Vehicle Traffic Control Signal Heads*, the chromatic coordinates of color lenses must fall within a range of chromatic coordinates to display the correct color specifications.(4)

Section 8.03 of *Vehicle Traffic Control Signal Heads* requires that lenses be made of either glass or ultraviolet stabilized plastic durable enough to last through prolonged exposure to weather, and must be uniformly colored throughout the body of material and free from streaks, wrinkles, chips, or bubbles that in any way prohibit the optical assembly from meeting required specifications.(4)

Arrow lenses convey the ROW to traffic moving for a certain duration during a specific interval. Section 9.03 of *Vehicle Traffic Control Signal Heads* states that directional arrow lenses must follow the same chromaticity as their counterpart round indications; however, pursuant to Section 9.04, except for the arrow itself, the lens must be covered with an opaque material of sufficient thickness to prevent light from emanating behind. Section 9.04 states that the opaque material must be hard and durable and bonded in such a way that it does not peal or flake when subjected to the heat of a lamp operating at the proper wattage. The arrow is the only portion of the signal lens that can be illuminated. (4)

Light Source

To illuminate a signal indication, each traffic signal display needs a light source. Chapter 1 Section 3 of ITE's *Equipment and Materials Standards* provides the minimum recommended illumination intensity and design for incandescent light sources for use with traffic signal control.(4) Chapter 1, Section 4 of ITE's *Equipment and Materials Standards* provides procedures and criteria for testing the conformance of lamps to design specifications.(4)

Section 135 of the Energy Policy Act of 2005 (P.L. 109-58) required that any traffic signal module or pedestrian module manufactured on or after January 1, 2006, meet the performance requirements of the Environmental Protection Agency (EPA) Energy Star program for traffic signals. As a result of this requirement, most new traffic signal installations now use LED technology as the light source for traffic signal indications. The advantages of LED signal indications include the following:

- Because they do not require a reflector in the traffic signal head assembly, an LED traffic light does not produce a phantom effect.
- LED traffic signal indications do not require as much power to produce a light output as incandescent light sources. Because LEDs use less power, BBU systems may be installed to continue powering traffic signal indications in the event of an interruption of electrical service.
- LED traffic signals require less maintenance. With incandescent light sources, the bulb must be replaced immediately when it fails. Because LED traffic signals are comprised of an array of light source, the meaning of the signal indication is not lost when one or more light source fails.

The ITE has developed the following standards to support the procurement and use of LED technologies in traffic signal indications:

- *Vehicle Traffic Control Signal Heads: Part 2: LED Circular Signal Supplement.*(13)
- *Vehicle Traffic Control Signal Heads—Part 3: LED Vehicular Traffic Signal Supplement.*(14)
- *Pedestrian Traffic Control Signal Indications—Part 2: LED Pedestrian Traffic Signal Modules.*(15)

Section 4D.06 of the MUTCD states that the requirements of the publications "Vehicle Traffic Control Signal Heads: Light Emitting Diode (LED) Circular Signal Supplement" and "Vehicular Traffic Control Signal Heads: Light Emitting Diode (LED) Vehicle Arrow Traffic Signal Supplement" must be met for the aspects of the signal head design that affect the display of the signal indications for LED traffic signal modules. Further, Section 4E.04 of the MUTCD requires that signal indications for pedestrian signal heads in LED signal modules conform to the specifications in the publication "Pedestrian Traffic Control Signal Indications – Part 2: LED Pedestrian Traffic Signal Modules."

Housing

The housing contains the optical unit. Section 3.02 of *Vehicle Traffic Control Signal Heads*(4) indicates that each signal indication shall have its own housing, with multiple housings combined to provide the desired configuration of the signal indications (3, 4, or 5 sections). Housing units can be made of cast aluminum alloy or plastic that has been stabilized against heat and ultraviolet damage, and generally have doors hinged to allow access to the optical unit for relamping. Signal indications are displayed through lens openings in the door consistent with the size of the signal indication.

Visors

Per Section 4D.12 of the MUTCD, signal visors should be used on signal faces to aid in directing the signal indication specifically to approaching traffic, as well as to reduce a *sun phantom* effect, which occurs when an external light source (such as the sun at a low angle) causes the signal indications to appear to be illuminated.(4).

Backplates

Backplates are thin plates of material that extend outward from and parallel to a signal face on all sides of the housing, thereby surrounding the signal indications.(4) Their purpose is to improve the visual contrast between the signal indications and the surrounding environment by providing a consistent and controlled contrast background. They are typically made of aluminum or acrylonitrile butadiene styrene (ABS) plastic. Aluminum backplates can be painted to match the color of the signal housing, while ABS backplates have a fixed set of colors. Figure 11 shows an example of a typical signal indication with a backplate.

Research by FHWA(16) found that adding a 1- to 3-inch retroreflective border to the perimeter of a backplate significantly improves visibility of the signal in both daytime and nighttime conditions and enhances the visibility of traffic signals for aging and color-vision-impaired drivers. Figure 12 shows examples of traffic signals with retroreflective backplates.

Source: Texas A&M Transportation Institute.

Figure 11. Photograph. Traffic signal indication with a solid backplate.

Source: Oregon Department of Transportation

Figure 12. Example of traffic signal indications with retroreflective backplates.

Pedestrian Signal Indications

Agencies use pedestrian signal indications to assign ROW to pedestrian movements at signalized intersections. Per Section 4E.02 of the MUTCD, a pedestrian signal consists of signal head indications with the following meanings:(2)

- A steady WALKING PERSON (symbolizing WALK) signal indication means that a pedestrian facing the signal indication is permitted to start to cross the roadway in the direction of the signal indication, possibly in conflict with turning vehicles. The pedestrian must first yield the ROW to any vehicles lawfully within the intersection at the time that the WALKING PERSON signal indication activates.

- A flashing UPRAISED HAND (symbolizing DON'T WALK) signal indication means that a pedestrian shall not start to cross the roadway in the direction of the signal indication, but any pedestrian who has already started to cross on a steady WALKING PERSON signal indication shall proceed to the far side of the traveled way of the street or highway, unless otherwise directed by a traffic control device to proceed only to the median of a divided highway or only to some other island or pedestrian refuge area.

- A steady UPRAISED HAND (symbolizing DON'T WALK) signal indication means that a pedestrian shall not enter the roadway in the direction of the signal indication.

- A flashing WALKING PERSON signal indication has no meaning and should not be used.

Per Section 4E.07 of the MUTCD, pedestrian signal heads at crosswalks where the pedestrian change interval is more than 7 seconds must include a countdown timer, while pedestrian signal heads at crosswalks where the pedestrian change interval is 7 seconds or less may or may not have a countdown timer. The countdown indication is active only during the pedestrian change interval (i.e., the flashing DON'T WALK) and displays the number of seconds remaining until the end of the pedestrian change interval. The MUTCD prohibits the use of a countdown timer during the WALK interval and the red clearance interval of a concurrent vehicle phase.(2) Countdown timers only vary in the display of pedestrian signal indication and not the operation of the timings.

Bicycle Signal Indications

Bicycle signals are typically used to improve identified safety or operational problems involving bicycle facilities. Bicycle signal heads may be installed at signalized intersections to indicate bicycle signal phases and other bicycle-specific timing strategies. In the United States, bicycle signal heads typically use standard three-lens signal heads in green, yellow, and red lenses. Bicycle signals are typically used to provide guidance for bicyclists at intersections where they may have different needs from other road users (e.g., bicycle-only movements, leading bicycle intervals).(17)

Bicycle signal indications help agencies achieve the following:(17)

- Separate bicycle movements from conflicting motor vehicle, streetcar, light-rail, or pedestrian movements.
- Provide priority to bicycle movements at intersections (e.g., a leading bicycle interval).
- Accommodate bicycle-only movements within signalized intersections (e.g., providing a phase for a contra-flow bike lane that otherwise would not have a phase). Through bicycle travel may also occur simultaneously with parallel auto movement if conflicting automobile turns are restricted.
- Protect bicyclists in the intersection, which may improve real and perceived safety in high-conflict areas.
- Improve operation and provide appropriate information for bicyclists (as compared to pedestrian signals).
- Help to simplify bicycle movements through complex intersections and potentially improve operations or reduce conflicts for all modes.

Typical applications of bicycle signal indications include the following:(17)

- At intersections where a stand-alone bike path or multiuse path crosses a street, especially where the needed bicycle clearance time differs substantially from the needed pedestrian clearance time.
- To split signal phases at intersections where a predominant bicycle movement conflicts with a main motor vehicle movement during the same green phase.
- At intersections where, if turning movements are significant, a bicycle facility transitions from a cycle track to a bicycle lane.
- At intersections with contra-flow bicycle movements that otherwise would have no signal indication and where a normal traffic signal head may encourage wrong-way driving by motorists.
- To give bicyclists an advanced green (like a leading pedestrian interval) or to indicate an "all-bike" phase where bicyclist turning movements are high.
- To make it legal for bicyclists to enter an intersection during an all-pedestrian phase (may not be appropriate in some cities).
- At complex intersections that may otherwise be difficult for bicyclists to navigate.
- At intersections with high numbers of bicycle and motor vehicle crashes.
- At intersections near schools (primary, secondary, and university).

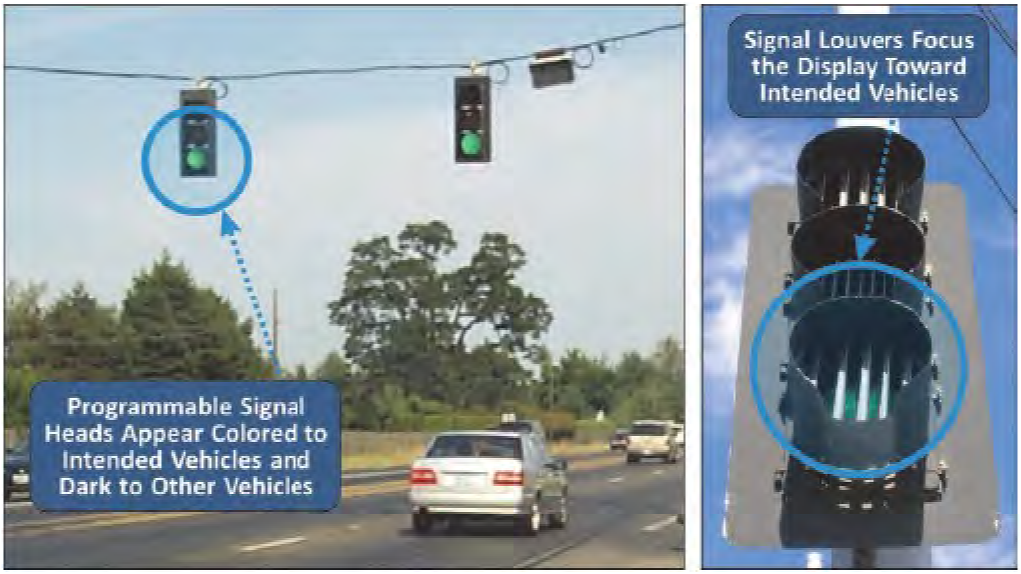
Figure 13 shows an example of a bicycle traffic signal display. Bicycle traffic signals allow specialized traffic signal timing to be provided for bicycle movements at signalized intersections. When bicycle traffic signals are provided at an intersection with bicycle detection or bicycle push buttons, it is possible to provide an operation that minimizes delays for all users when bicycles are present. Alternatively, the National Association of City Transportation Officials (NACTO) suggests that traffic signals recall bicycle-only indications if implemented without detection.(17) Without detection, bicycle phases would be serviced each cycle regardless of the presence of bicycles, with the potential to increase awareness of the interval for motorists and bicyclists.(17) As shown in the figure below, bicycle signals may separate bicycle movements through the intersection from right-turning vehicles. When this occurs, prohibiting right turns when the signal is active will minimize the potential for conflicts between vehicles and bicycles when the bicycle signal is active. This feature can be accomplished by the provision of a traffic signal with red, yellow, and green arrow displays. An active display (NO TURN ON RED) is recommended to help emphasize this restriction.(17)

Source: Oregon Department of Transportation

Figure 13. Graphic. Example of bicycle traffic signals at urban intersection.

Programmable Signal Heads

Optically programmed (or visibility-limited) signals are designed to limit the field of view of the signal indications.(18) Agencies may want to consider using programmable signal heads to control the motorist's lateral or longitudinal field of view of the traffic signal indications in situations where they can become confused or misdirected by seeing a signal indication intended for another approach before seeing the signal indications for their own approach. Programmable signal heads can be used to provide lateral separation between signal indications (e.g., separating left- or right-turn lanes or locations with adjacent parallel lanes). Programmable signal heads can also be used to provide longitudinal separation between closely spaced intersections. (3) Figure 14 shows the use of programmable traffic signal indications to limit cross-lane visibility at an intersection.



Source: Traffic Signal Manual Second Edition

Figure 14. Photograph. Example of programmable vehicle signal heads and signal louvers.

Disadvantages of programmable signal heads include the following:(18)

- They require rigid mounting instead of suspension on overhead wires.
- Glare on the signal face can limit or obscure the visibility of the signal indications.
- In some situations, drivers may initially perceive that the signal is malfunctioning because they cannot see the signal indication until they get closer to the intersection and notice the signal indication.
- Signal-visibility alignment requires attention both in design and in field maintenance.

POLES AND SUPPORTS

Three primary types of signal configurations display vehicle signal indications:

- Mast arms.
- Span wire configurations.
- Pedestal or post-mounted signal displays.

Mast arm installation requires the use of signal poles and mast arms, which facilitate the placement of signal heads and other necessary infrastructure over the travel lanes (Figure 15).

Source: Texas A&M Transportation Institute.

Figure 15. Photograph. Typical mast arm traffic signal installation.

Such an installation enables accurate placement of signal heads and signs to improve visibility. Mast arms can also facilitate the placement of detection equipment and preemption emitters in an optimum location for maximum effectiveness. Mast arm installations are more expensive than a span wire installation due to the cost of the poles, mast arms, foundations for the poles, and trenching and boring of the conduits. Limits to the lengths that mast arms can extend over the roadway may also exist.

Span wire installations usually consist of wooden poles installed in the ground with a span wire hung between the poles. Ties connect all the cables required for operating the signal heads and detection to the span wire. The signal heads and signs are hung from the span wire at optimum locations, as shown in Figure 16. Span wire installations are typically inexpensive. Usually, span wire installation can be completed in a short period. Agencies often use span wire installations for temporary signals (like for construction work zones). One disadvantage of span wire installation is that the agencies have to install the detection equipment on poles at the corners of the intersection, which may reduce the effectiveness of the detection technology. Mast arms also are more stable in the wind, and thus the signal heads are more stable during windy conditions.

Source: Texas A&M Transportation Institute

Figure 16. Photograph. Example of a span wire installation.

Pedestal supports are commonly found in downtown areas or where supplemental signal indications are needed. They are typically constructed of either steel or aluminum and are bolted to an unground concrete foundation. The pedestal is typically hollow and the cable from the signal head passes through the inside of the pole to a conduit located in the foundation of the pole and then through a conduit back to the traffic signal cabinet. Pedestal poles are generally 8 to 10 ft in length, and the signal head is generally mounted toward the top of the pole. Figure 17 shows an example of a traffic signal mounted on a pedestal support.

Table 21 lists some of the advantages and disadvantages of the different types of traffic signal supports.

Source: Texas A&M Transportation Institute

Figure 17 Photograph. Example of pedestal-mounted traffic signal.

Table 21. Advantages and disadvantage of different traffic signal support systems.[(19)]

Support Type	Advantages	Disadvantages
Mast Arm	• Flexibility in placing head placement. • Lower maintenance costs. • Many pole aesthetic options.	• Costlier than span wire. • Mast arm lengths can limit use for some large intersections.
Span Wire	• Easier to accommodate large intersections. • Flexibility in signal head placement. • Lower cost than mast arms.	• Higher maintenance costs. • Wind and ice can cause problems. • Aesthetically unpleasing. • Visibility not as good as mast arm.
Pedestal (Post-mounted)	• Lowest cost. • Less impact on view corridors. • Lower maintenance cost. • Aesthetics. • Good for supplement signals.	• May be difficult to meet MUTCD visibility requirements, particularly at large signalized intersections.

Source: Federal Highway Administration.

CONDUITS AND GROUND BOXES

Conduits and ground boxes are the unseen connectors and junctions that transfer the detection actuations from the sensors to the signal controller cabinet and transfer the signal indications from the signal controller cabinet to the signal heads. Conduits can either be trenched or bored based on surface preparation. Trenching is far cheaper than boring; however, boring is the only option when agencies install the conduit under a finished surface. The conduit should be large enough to accommodate existing cables and any additional cables to be pulled through in the future.

The number of bends in the conduit should be kept to a minimum, with generally no more than three 90-degree bends for every 100 feet of cable length. Agencies minimize bends in the conduit by using ground boxes. Ground boxes (also known as hand-holds, junction boxes, or splice boxes) are underground compartments made of various materials like steel, concrete, or plastic. Figure 18 shows an example of a ground box. Typically, agencies will locate ground boxes adjacent to the signal controller cabinet, signal pole, and every location where detectors and other devices that connect to the signal controller cabinet are located on the ROW. Agencies typically install ground boxes at a spacing of 175 feet except where cable lengths are long where agencies will typically double the spacing between ground boxes to 350 feet.(6)

Source: Federal Highway Administration.

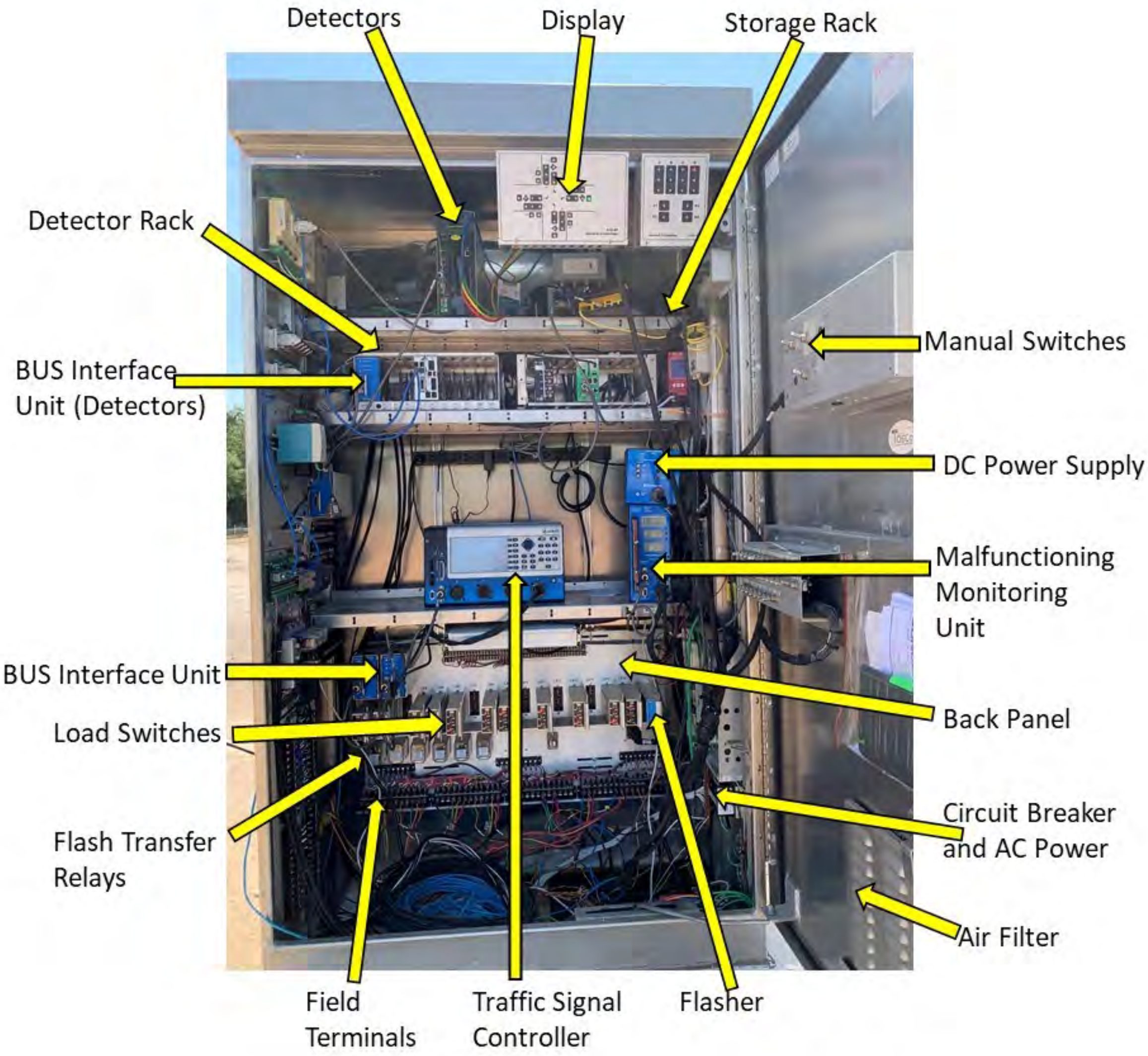
Figure 18. Photograph. Example of a ground box at a signalized intersection.

TRAFFIC SIGNAL CONTROL ASSEMBLY

The traffic signal control assembly is a collection of electrical components and devices installed at the intersection that controls the operations of the signal indications. Each traffic signal control assembly includes the following components:

- A cabinet which contains and protects the electrical devices and components from the environment.
- A traffic signal controller which controls the sequencing and durations of the traffic signal indications displayed at the intersection.
- A power supply for converting the 120 volt (V) alternating current (AC) electrical service line in the 24V, 12V, and 5V direct current (DC) used by the electronics inside the cabinet.
- A malfunction monitoring unit (MMU), also commonly referred to as the conflict monitor, which monitors the operations of the traffic signal controller and the cabinet to ensure safe operations of the signal displays to intersection users.
- Vehicle and pedestrian detectors devices which provide user demand inputs into the traffic signal controller.
- Output circuit drivers (loads switches, flashers, and flasher relays) which drive the signal displays at the intersection.
- Internal interface devices which allow the various cabinet components to pass information internally within traffic cabinet.

Figure 19 shows the components inside a typical traffic signal cabinet. The following provides a more detailed discussion of the traffic signal controller assembly components.



Source: Texas A&M Transportation Institute

Figure 19. Graphic. Typical components inside a traffic signal controller cabinet.

Standard Specifications

The standardization of traffic signal control devices and equipment is the outcome of the documentation of specifications and electrical equipment standards that date back to the early 1970s. This section will list the dominant specifications and standards that have been developed to support interoperability among these devices and equipment to ensure the safe and reliable operation of signalized intersections. Agencies in the United States use three primary traffic signal standard specifications: one promulgated by the National Electrical Manufacturers Association (NEMA), another by the California Department of Transportation called the Traffic Electrical Equipment Specifications (TEES), and another promulgated jointly by AASHTO, NEMA, and the ITE, known as the Advanced Transportation Controller (ATC). The use of the standard specifications is voluntary by agencies.

Before 1975, manufacturers of early electronic controllers used vendor-specific methods for operating a signalized intersection. The mechanical controllers of the day also used proprietary parts but typically used the same external coordination interface that provided discrete signals over a hardwire interconnect. The NEMA TS1 specification standardized the basic operations of a traffic signal controller, the controller inputs and outputs, and the hardware connections between the cabinet and the controller. Although these controller assemblies are known for their discrete wiring technique, making them easy to troubleshoot using a test light, limitations exist on the number of input and output channels they can support.

NEMA TS2 specifications were developed in 1992.(21) The TS2 specifications go further than the TS1 specifications in defining controller functions and standardizing controller functions—like coordination, preemption, plan-base control automatic flash operations, detection operations, output monitoring, and event logging in the controller. TS2 traffic controller assemblies also introduced serial communication to communicate with detection and other equipment in the cabinet.

The California Department of Transportation (Caltrans) developed a Transportation Electrical Equipment Specification (TEES) to support the development, deployment, and operation of traffic control equipment in the State of California. The specifications cover the Model 170 and Model 2070 Traffic Signal Controller Unit as well as provide specifications for detector sensor units, traffic control cabinets, changeable message signs, and communications modules to support other ITS applications and devices. Many jurisdictions outside the State of California use these specifications to support their own traffic control deployments.

The ATC is a suite of standard specifications for an open architecture hardware software platform to support a variety of Intelligent Transportation Systems (ITS) applications. The ATC suite of standards includes the following:

- *The Advanced Traffic Controller (ATC) ATC 5201 Standard* which define the field computer that manages the cabinet functions.
- The *ITS Standard Specification for Roadside Cabinets ATC 5301* which include various constructs (e.g., input files) and subassemblies/subsystems to support the control and monitoring of field devices at intersections/highway locations.

- The *ATC Application Programming Interface (API) ATC 5401 Standard*, which defines a software suite for allowing the sharing of input-output and other controller resources for multiple applications at a street/field location.

- The *ATC Application Programming Interface Reference Implementation* (APIR) which is a software representative of the ATC 5401 standard.

Traffic Signal Cabinet

The traffic signal cabinet is an environmentally-hardened enclosure that contains the hardware used to control all operational aspects of the signal. Although the cabinet and hardware may vary slightly from cabinet to cabinet, the general function of each cabinet is the same.

No matter the type of cabinet, each traffic signal cabinet contains the following:

- Traffic signal controller containing all the programming information necessary for proper functioning of the signals.

- Conflict monitor to ensure safe operations of the controller.

- Detection card rack to place calls to the controller from the detections system.

- Load switches for turning on and off the traffic signal indications at the intersection.

- Flasher relays for flashing the signal indication either according to plan or during a fault situation.

- A power supply for distributing power to the electronic components in the cabinet.

The type of signal controller dictates the type of traffic signal controller cabinet that an agency can use at an intersection. Most operators currently use one of the following types of signal controller cabinets.

NEMA Cabinets

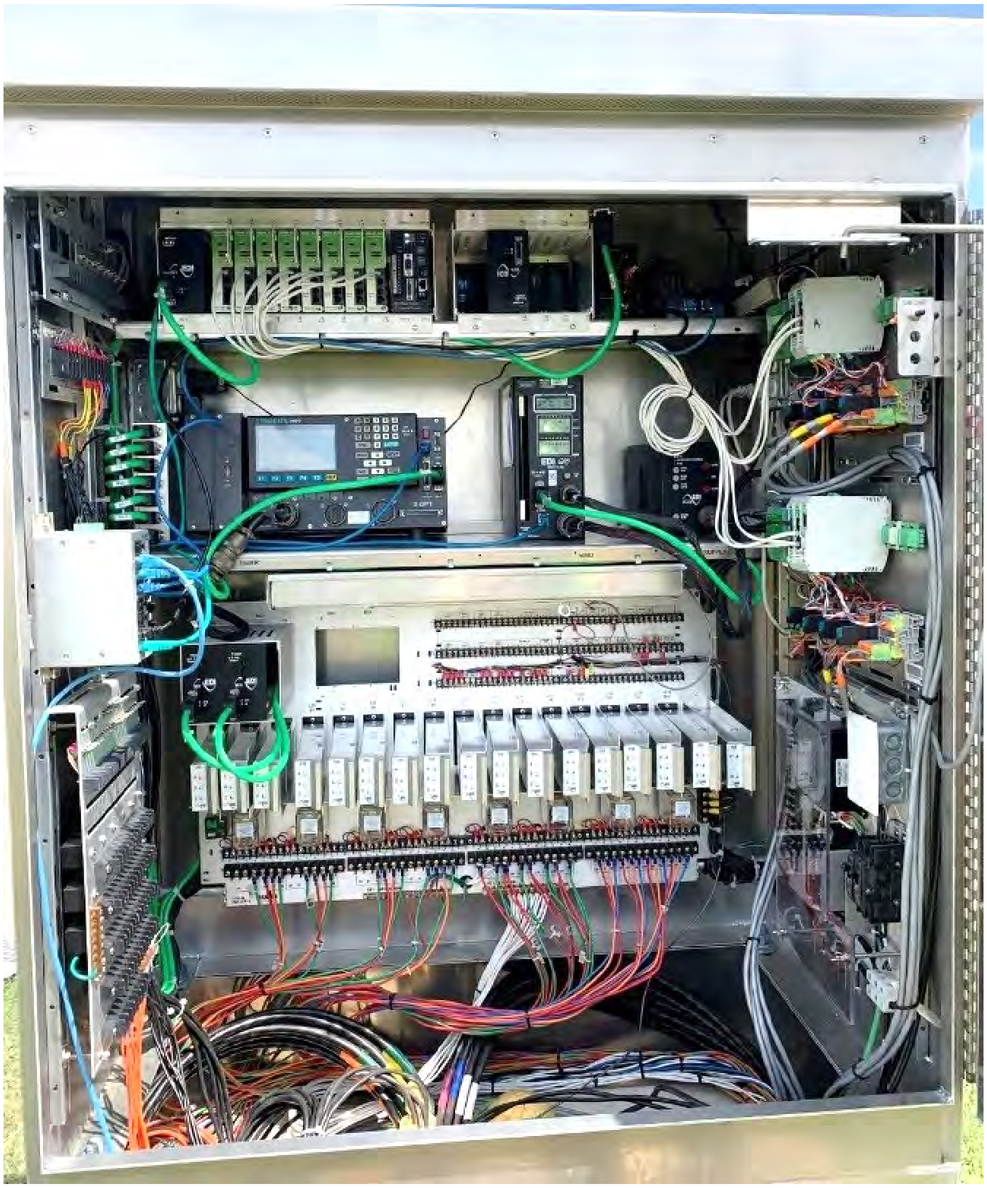
The NEMA TS1 cabinet is the original cabinet used with traffic signal systems. TS1 cabinets use discrete wiring, in which a hardwire connection exists between every component in the cabinet. The traffic signal controller communicates to the various subsystems through a series of large wire harnesses. These harnesses culminate in a connector in the signal controller called A, B, and C and in a non-standard D connector. The logic in the controller monitors the state of that wire connection to determine the presence of a vehicle in the detection zone. Although having hardwire connections makes the troubleshooting of any problems simpler, it causes a TS1 cabinet to have a limit on the number of inputs and outputs.

Figure 20 shows an example of a NEMA TS1 controller in a NEMA TS1 cabinet. The photograph shows the large bundle of wires that connects the traffic signal controller to the cabinet. Each wire represents a discrete connection between the controller and the cabinet, with each wire representing a single input or output to and from the controller to the cabinet.

Source: Federal Highway Administration.

Figure 20. Photograph. Example of a NEMA TS1 cabinet.

NEMA TS2 cabinets use the standardized SDLC serial communications to communicate between various components within a cabinet. TS2 controllers communicate with other components—like the detector rack, malfunction monitoring unit (MMU), and other components in the traffic signal cabinet—using serial communications. Serial communications enable agencies to swap out one type of controller and replace it with a different type of controller but still maintain all functionality. Figure 21 shows an example of an NEMA TS2 controller in a NEMA TS2 cabinet.



Source: Federal Highway Administration.

Figure 21. Photograph. Example of a NEMA TS2 cabinet.

Caltrans TEES Cabinet

The California Department of Transportation (Caltrans) developed a specific traffic signal controller cabinet, sometimes referred to as the Model 33X cabinet, to support the use of the Model 170/Model 2070 traffic signal controllers. Like a NEMA TS-1 cabinet, Model 33X cabinets use traditional parallel wiring (i.e., one-to-one wiring) between the controller and the cabinet inputs and outputs. The Model 33X cabinets are pre-wired to provide a typical 8-phase, 4-pedestrian phase intersection operations. Depending on the specific cabinet types, Model 33X cabinets are also hardwired to support a prespecified number of detector inputs – between 16 and 36 detector inputs depending on the model selected.

Advance Transportation Controller Cabinet/ITS Cabinet

ITE, NEMA and AASHTO jointly developed the Advanced Transportation Controller Cabinet (ATCC) standard. ([25]) It uses an open-architecture, and standards-based components for all cabinet elements, except for the controller, detectors cards, and load switches. It uses serial communications to connect the controller to the cabinet assemblies. It also uses a Cabinet Monitor Unit (CMU) to monitor the operations with the cabinet and transfer control from the control to a flashing mode when issues are detected within the cabinet. The standard specifications also support two types of cabinets —a high-voltage cabinet to support traditional 120V AC service voltage to control 120V AC low power (non-incandescent) signal heads, and a low-voltage version to support operations from a 48V DC power source (like under battery- or solar) to control low voltage signal heads. Key advantages of an ATCC include the following:(25)

- Significant power savings enabling the use of alternate power sources, such as solar and battery backup systems.
- Standard alternative to mercury relays.
- Standard interchangeable plug-in devices among manufacturers.
- Standard electrical signals and protocols among cabinet types to simplify service personnel training.
- Mechanical size, shape, and internal layout that adapts to local owner/operator specifications.
- Low voltage option to conform with any applicable State legislation, providing safety to service personnel, pedestrians, and drivers.

Figure 22 shows an example of an ATCC/ITS Cabinet.

More information on the ATCC/ITS Cabinet can be found through the ITE Standards website at https://www.ite.org/technical-resources/standards/.

Source: Texas A&M Transportation Institute

Figure 22. Graphic. Example of an advanced traffic signal controller cabinet.

Traffic Signal Controller

A traffic signal controller is the electronical component in the cabinet that controls the selection and duration of the traffic signal displays at the intersection. Modern traffic signal controllers have the following basic hardware components:

- A user inface (keypad and display) for accessing and entering traffic signal timing parameters.

- A central processing unit (microprocessor, memory, etc.) that contain the processes and logic for controlling the selection and duration of the signal indications.

- External communication connectors (serial, Ethernet, USB, wiring harnesses, etc.) for communicating with the other components in the cabinet.

- A power supply for converting 120 AC to 24V, 12V, and 5V DC current used internal to the controller.

- Optional additional serial communications processes (e.g., Frequency Shift Key (FSK) modem, and RS-232 communications).

NEMA Controllers

NEMA controllers are designed to operate in a NEMA traffic signal cabinet. The NEMA TS1(20) specification standardized the basic operations of a traffic signal controller, the controller inputs and outputs, and the hardware connections between the cabinet and the controller. The NEMA TS1 specification provided minimum functional specifications for the controller to provide effective actuated intersection control as well as requirements for testing and environmental operating conditions. Because the TS1 cabinet uses a one-to-one, direct wire connection to all the components inside the cabinet, a TS1 controller can only operate in a TS1 cabinet. In order for a TS1 controller to receive a call from the detection system, a wire that connects the controller to the detection panel transmits the detection call. While this makes them easy to troubleshoot, a TS1 traffic signal controller can only operate in a TS1 cabinet. Figure 23 shows an example of a NEMA TS1 controller.

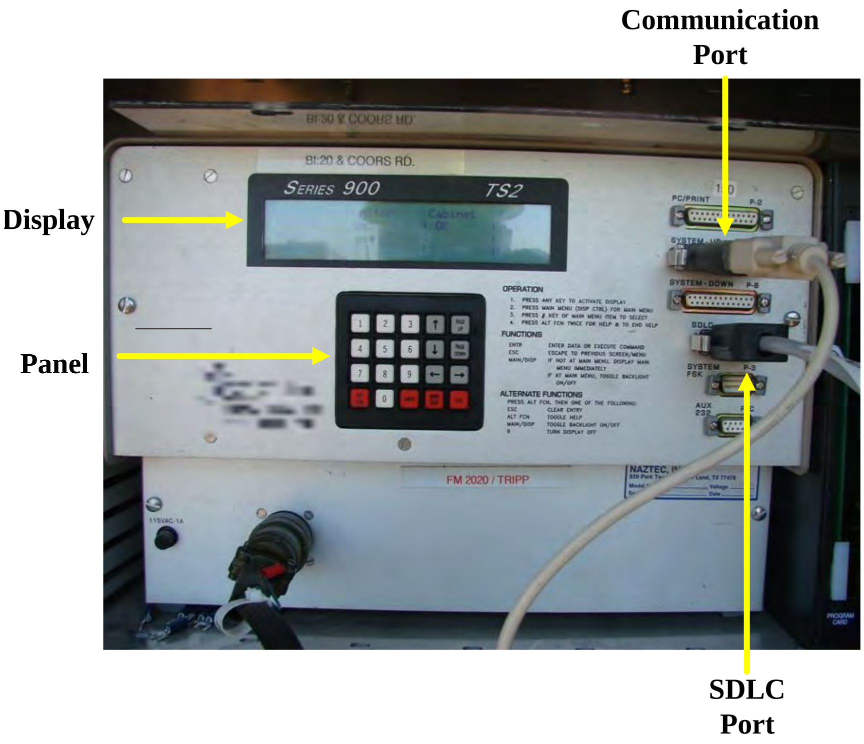
NEMA considers TS1 controllers to be legacy equipment and does *not* *recommend using TS1 controllers for new installations.* (20)

Source: Texas A&M Transportation Institute.

Figure 23. Photograph. Example of a TS1 controller.

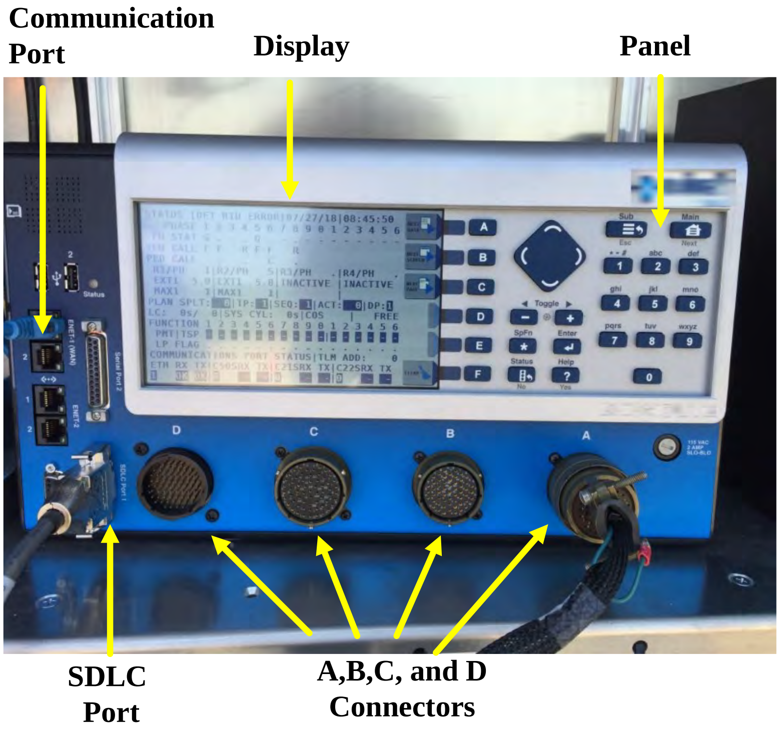
The NEMA TS2[(21)] specifications go further than the TS1 specifications in defining controller functions and standardizing additional functions, such as coordination, preemption, plan-base control automatic flash operations, detection operations, output monitoring, and event logging in the controller. TS2 controllers also use serial communication to communicate with detection and other equipment in the cabinet.

Two types of NEMA TS2 traffic signals controller exist. The TS2 Type 1 traffic controller uses a single connector and a single harness to provide power to the controller. The controller communications with the other components in the cabinets via a synchronous data link control (SDLC) port. A TS2 Type 2 controller use the same wiring harness as in a TS1 traffic controller assembly but also include a SDLC port. A TS2 Type 1 traffic controller can operate only in a TS2 cabinet while a TS2 Type 2 traffic controller assembly can be used in both a TS1 cabinet or in a TS2 cabinet. Figure 24 and Figure 25 illustrate the differences between the two types of TS2 controller configurations.



Source: Texas A&M Transportation Institute.

Figure 24. Photograph. Example of a NEMA TS2-Type I traffic signal controller.



Source: Texas A&M Transportation Institute.

Figure 25. Photograph. Example of a NEMA TS2-Type II traffic signal controller.

Model 170 Controller

The Model 170 controller was developed by Caltrans in 1977 and was the first application of a general-purpose computer to control multiple field applications, the most common of which included traffic signal control. The Model 170 is a rack-mounted controller (rather than the shelf-mounted components used in the NEMA cabinets). Because the Model 170 specifications do not specify software functionality, agencies can procure (or develop) their own software for controlling the signal indication. It contains the same basic components of controller, detection system, conflict monitor, terminals and facilities module, and interfaces. The hardware interface between a Model 170 controller and the cabinet is a 100-pin rectangular connector on the back of the controller. Model 170 controllers were used by the California DOT, the New York State DOT, and a number of cities in the United States.(22)

Model 2070 Controller

Caltrans developed the Model 2070 controller as a replacement for the Model 170 controller. The Model 2070 controller was designed to operate in a Caltrans Model 33X cabinet. Like the Model 170 controller, the Model 2070 controller is an open architecture hardware and software platform that can support a wide variety of traffic management applications, including intersection control, ramp metering, variable message signs, and lane control signals. The controller is a field-hardened computer consisting of a central processing unit (CPU), operating system (OS), memory, and external and internal interfaces. Software applications are designed to run on the hardware to support traffic signal operations and other traffic management applications. These software applications can be procured separately from the Model 2070 controller hardware.

For more information on the Model 2070, please consult Caltrans' *Transportation Electronical Equipment Specifications.*

Advanced Transportation Controller

Like the Model 270 Controller, the Advanced Transportation Controller (ATC) is an open-architecture hardware and software platform. The standard specification for the controller was developed jointly by the ITE, AASHTO, and NEMA to support a wide range of ITS applications requiring a field-implementable controller. The platform can support not only traffic signal control, but also any type of application that requires a field-implementable controller, such as ramp control, traffic monitoring, lane use signals, field masters, general ITS beacons, lane control, and access control. The ATC allows agencies to develop a modular control system intended to promote interoperability between hardware and software components regardless of the manufacturer. (22) The ATCs can be configured to operate in all types of traffic signal cabinets – NEMA TS1, NEMA TS2, Caltrans Model 33X, or the ITS Cabinet.

For more information on the ATC, please consult the ITE *Standards* website.(9)

Detector Inputs

Signal engineers design, install, and operate vehicle detectors to improve signal operations. They use detection systems to make the signals more responsive to demands at the intersection.

Engineers also use detection systems to improve safety on high-speed approaches. Many agencies use system detectors to support performance monitoring at their intersections. Based on operational needs, budgetary constraints, and other factors, engineers use the following types of detection systems:

- Inductive loops.
- Video.
- Radar.
- Magnetometer (pucks/pods).
- Infrared/thermal/microwave.

Figure 26 shows an example of a detector (the device shown in the middle of the photograph) mounted in a detector rack in a TS2 cabinet. The device to the far left in the photograph is the interface unit (discussed below) that permits detection inputs to be communicated to the traffic signal controller through the internal communications system.

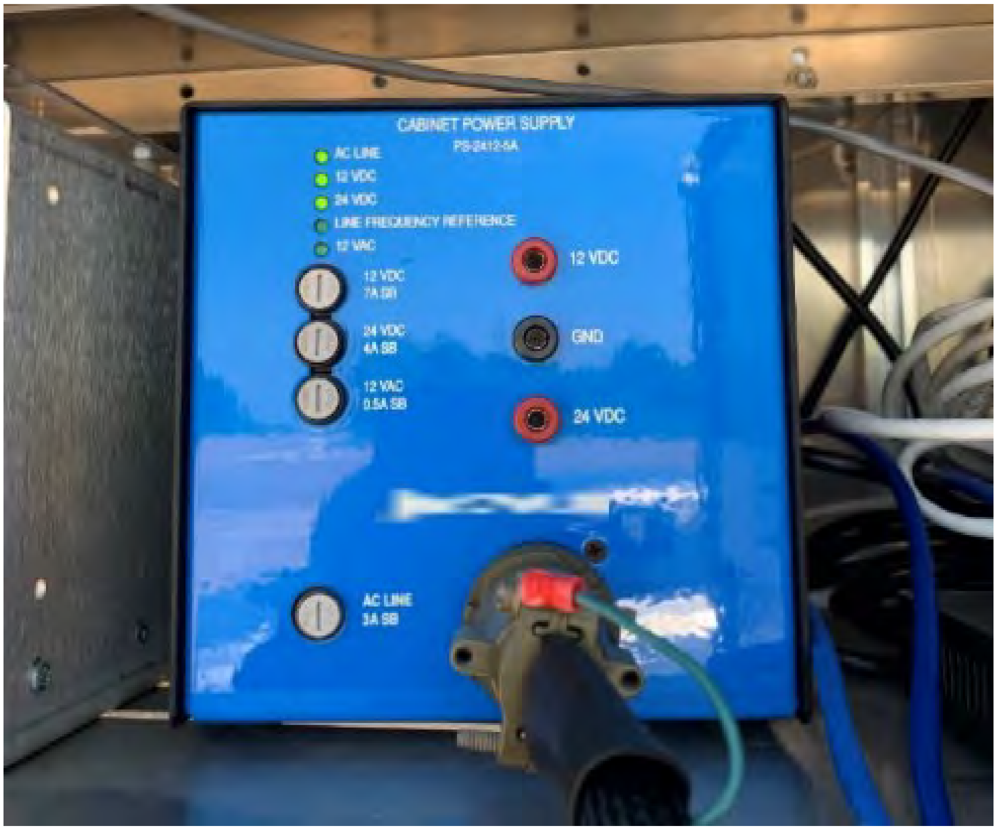
Source: Texas A&M Transportation Institute.

Figure 26. Photograph. Example of a rack-mounted detector input in a NEMA TS2 cabinet.

Chapter 6 of this handbook provides a more detailed discussion of detection systems and technologies.

Power Supply

The power supply unit in a traffic signal cabinet is an electrical device that converts AC to direct current DC voltage for the various devices. The power supply generally has wires terminated to the bus bars, terminals on the front of the back panel, detector panels, or connector as appropriate. Figure 27 shows an example of a power supply unit for a NEMA TS2 cabinet.



Source: Texas A&M Transportation Institute.

Figure 27. Photograph. Example of a power supply unit in a NEMA TS2 cabinet.

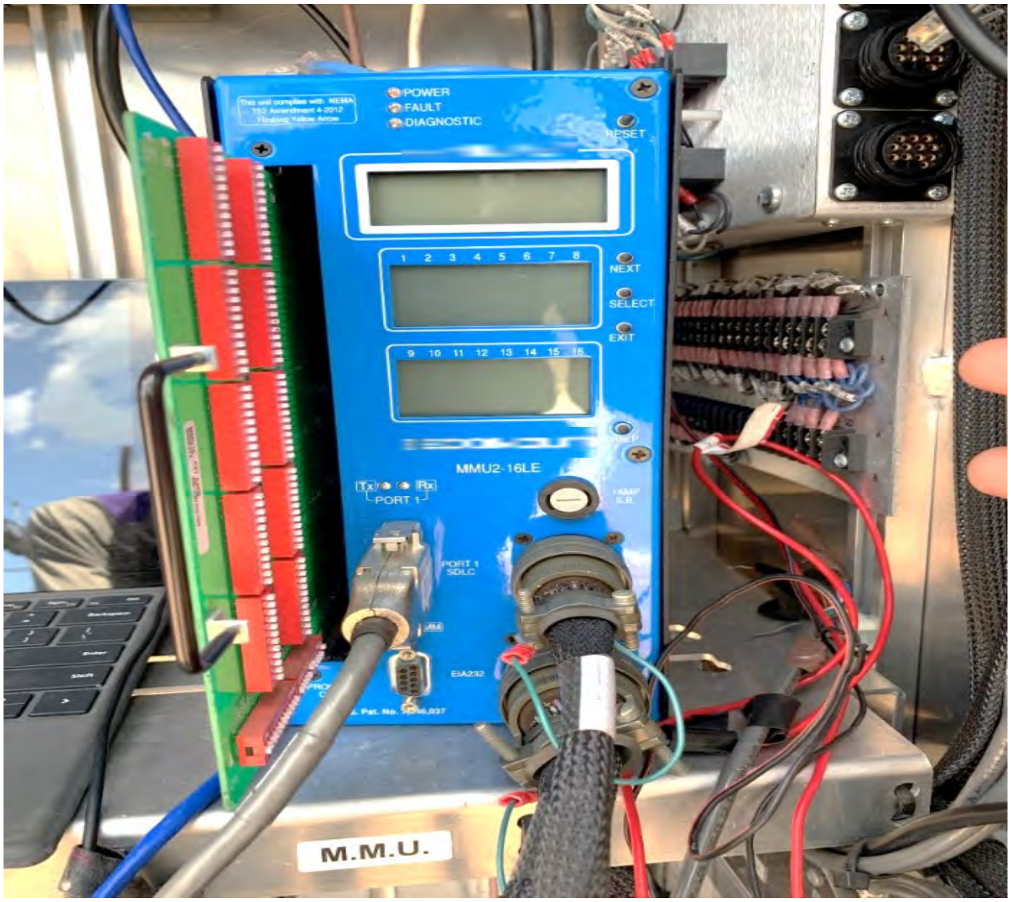
Malfunction Monitoring Unit

The malfunction monitoring unit (MMU) is responsible for guaranteeing fail-safe operations. The purpose of the MMU is to detect and respond to improper activations of signal indications for conflicting movements and improper operating voltages in the controller assembly. It serves as a “watchdog” in the cabinet, looking for the following conditions to occur:

- The presence of voltage on the vehicle and pedestrian indications for conflicting movements.
- The absence of proper voltages on all the field connection terminals of a channel.

- The presence of satisfactory operating voltages within the controller unit.

Upon sensing one of these fault conditions, the MMU causes the controller to operate in a fail-safe mode, usually with flashing reds for all movements. Figure 28 provides an example of an MMU in a TS2 traffic signal cabinet.



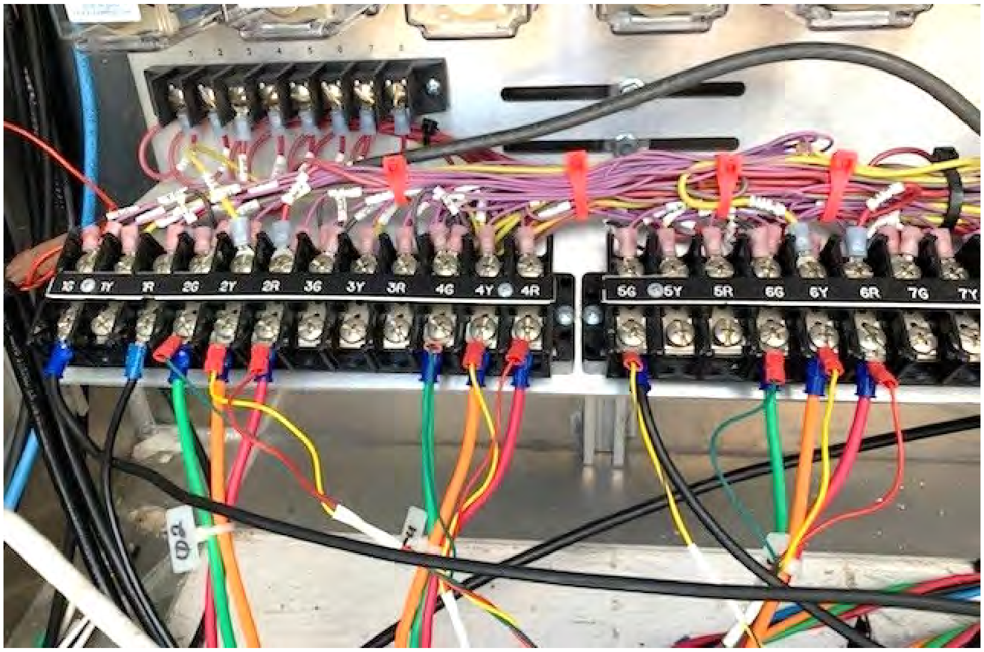
Source: Texas A&M Transportation Institute.

Figure 28. Photograph. Example of a malfunction monitoring unit.

In an ATCC, the malfunction monitoring splits the fault detection between two subcomponents: the cabinet monitor unit (CMU) and the auxiliary monitor unit (AMU). The CMU is located in the power distribution assembly (PDA) and is the main fault detector for the entire cabinet. It monitors the main cabinet functions, such as the condition of the cabinet power, door status, and status of the flashers. It communicates with the AMU located in the output assemblies and compares the requested actions (from the controller) to the actual cabinet operations (load switches) to detect errors, conflicts, and other anomalies. The AMU is housed in each output assembly and monitors the output voltages and current of each circuit and load switch. If a fault occurs in either the CMU or the AMU, the system then directs the cabinet to a flashing or fail-safe operating condition. This design allows agencies much greater flexibility in cabinet configuration than previous cabinet designs.

Field Terminal Strips

Every traffic signal controller cabinet, regardless of its type, uses terminal strips to terminate the electrical cables from the signal indications (both vehicular and pedestrian) inside the cabinet. Different cabinet manufacturers configure terminal strips slightly differently; however, their functionality is similar in that all signal and wiring into and out of the control cables are attached to the terminals on the backside of the back panel. A technician can refer to the cabinet's electrical plans to troubleshoot any problems in the cabinet. Figure 29 shows a close-up example of the field terminal strips connecting the signal indications and the cabinet. The wires shown in the bottom of the photograph are the connections to specific signal indications installed at the intersection.



Source: Texas A&M Transportation Institute.

Figure 29. Photograph. Example of the terminal strip for connecting the signal indications to the traffic signal cabinet.

Load Switches

Load switches are electrical gating devices that direct voltage to the various signal heads. A load switch installed in a load switch socket receives the signal from the controller via the main terminal switch, and its output connects to the field wiring terminal. The number of load switches depends on the number of phases/overlaps/pedestrian phases. Although most cabinets will have at least 12 load switches, many of the modern cabinets usually come with 16 load switches. Figure 30 shows examples of load switches in a NEMA TS2 traffic signal cabinet.

Source: Texas A&M Transportation Institute.

Figure 30. Photograph. Example of load switches in a NEMA TS2 cabinet.

Interface Units

In a NEMA TS2 cabinet, the traffic signal controller communicates with the traffic signal cabinet through bus interface units (BIUs). The BIUs control the communication between the controller as well as detectors. A TS2 cabinet can support up to four BIUs. Most controller operations require a single BIU (BIU #1); however, some advanced operations like diamond operations will need a second BIU (BIU #2), and some other advanced systems may require additional BIUs (BIU #3 and BIU #4).

Figure 31 shows a picture of two BIUs in a NEMA TS2 cabinet. These two BIUs are responsible for communicating the channel outputs of the signal indications from the traffic signal controller to the load switches in the cabinet (shown in the bottom of the photograph).

Figure 32 shows a picture of the BIU hub. The BIU hub is the location where all inputs from the various BIUs in the cabinet are passed to the traffic signal controller.

Source: Texas A&M Transportation Institute.

Figure 31. Photograph. Example of BIUs in NEMA TS2 traffic signal cabinet.

Source Texas A&M Transportation Institute.

Figure 32. Photograph. Example of a BIU hub in a TS2 traffic signal cabinet.

In an ATCC, the interface between the traffic signal cabinet and the controller occurs through the Serial Interface Unit (SIU). The SIU connects the outputs of the serial bus of the ATC to the input/out assemblies in the traffic signal cabinet.

Flasher Units

The flasher unit controls the circuits that causes the signal displays to flash. Most flashers are solid-state, two-circuit flashers.(21) The flasher inserts into the flasher socket, which is on the back panel. The output of the flasher connects to the flash transfer relays. Figure 33 shows an example of the flasher unit in a NEMA TS2 cabinet.

Source: Texas A&M Transportation Institute.

Figure 33. Photograph. Example of a solid-state flasher unit in a NEMA TS2 cabinet.

Flash Transfer Relay

The flash transfer relay is used to transfer red or yellow field indications from normal signal operation to flashing operation. Normally, there are six flash transfer relays on the back panel. Each relay can handle the signal for two phases. The relays are energized by the MMU, which determines the operational mode of the intersection. Figure 34 shows an example of the flash transfer relays in a NEMA TS2 cabinet.

ANCILLARY EQUIPMENT

Agencies will often supplement these infrastructure components with other systems and technologies to enhance the control functions at signalized intersections. Examples of the other types of technologies agencies install at signalized intersections include the following:

- Communications Communication equipment to enable communication with the operators.
- Video surveillance equipment to facilitate visual monitoring of user movements through the intersection.
- Systems and technologies to measure and monitor the performance and efficiencies at the intersection.

Source: Texas A&M Transportation Institute.

Figure 34. Photograph. Examples of flash transfer relays in a NEMA TS2 cabinet

Remote communications to the components in the traffic signal cabinet can be a valuable asset. The primary function of the communication infrastructure is to enable the signal operator to monitor, troubleshoot, and update the signal timings at the intersection remotely. In the absence of communication, the signal technicians would need to make a field visit to carry out these functions. The secondary function of communications is to enable coordinated operations. Coordinated operations allow the signal controllers to maintain clocks as well as communicate the onset of a coordination plan. Finally, communication also can enable the use of video cameras at intersections. Communication to the intersection facilitates remote monitoring of the intersection that can allow for changes to be made to the intersection operations as well as assessments of-the health of the intersection,

Historically, agencies have used wired media such as twisted-pair, coaxial cable, and fiber-optic cables to achieve communications; however, advancements in technologies have made wireless technologies more affordable and practical for many agencies.

Chapter 7 provides more information regarding communication systems for traffic signal implementations.

Video Monitoring Units

Video (or closed-circuit television [CCTV]) cameras can be an important component at a signalized intersection. Video surveillance allows operators to obtain visual feedback about the operations at the intersection. Agencies use these cameras to observe current operations from a remote setting (such as a traffic management center) to ensure that the intersection is operating as intended. Agencies also use these cameras to investigate service complaints they receive or identify through the performance monitoring system and to confirm they have resolved these issues satisfactorily.

Blank-Out and Variable Message Signs

Some intersection operations also require the use of blank-out signs or dynamic lane assignment signs in the vicinity of the intersection. Many of the modern signal controllers have modules that can operate these signs. Signal engineers may also be able to use a combination of special functions in the controllers and available load switches in the cabinets to operate the signs. Figure 35 shows an example of the use of blank-out signs at signalized intersections.

Source: Texas A&M Transportation Institute.

Figure 35. Photograph. Example of blank-out sign operated by a traffic signal.

Supplemental Power Supply Systems

Recently there has been increased awareness about operating traffic signals safely even during a power failure. Agencies have traditionally used two forms of supplemental power at intersections: uninterruptible power supply (UPS) and generators. A UPS/BBU system provides emergency power to connected equipment by supplying power from a separate source (batteries) when utility power is not available. BBU systems can provide hours of uninterrupted power during a power outage. Although BBU systems may increase the cost of the intersections, they can improve intersection safety, particularly at intersections that are near railroad grade crossings (for preemption) and intersections with complex geometric layouts. Some BBU systems can gradually shift to varying levels of intersection control when the power is out for extended periods.

Some State standards for all traffic signal controller cabinets include requirements for a generator panel.(26) The panel allows for the easy connection of a portable generator to the traffic signal cabinet. At a minimum, the generator panel consists of a manual transfer switch, or an automatic transfer switch where required, and a twist-lock connector for generator hookup. The connection allows authorized personnel to access, connect, and secure an external power source to the cabinet for power restoration within minutes of arrival at the location.

Accessible Pedestrian Signals

Accessible pedestrian signals (APS) and detectors provide information in nonvisual formats (such as audible tones, speech messages, or vibrating surfaces). These devices are generally used in combination with traditional pedestrian signal timings and displays. Typically, vendors will integrate the accessible pedestrian signal features into a pedestrian detector (pushbutton) and produce audible tones and messages from the pushbutton housing. APSs can have ~~a~~ pushbutton locator tones and tactile arrows and can include audible beaconing and other special features. The information provided by the accessible pedestrian signal indicates which pedestrian crossing the traffic signal is currently serving. Figure 36 shows an example of an accessible pedestrian signal installation.

Accessible pedestrian signals may have both audible and vibrotactile walk indications. A tactile arrow on the pushbutton that vibrates during the walk interval provides the vibrotactile walk indications. Accessible pedestrian signals also may have an audible walk indication that is active during the walk interval only. The audible walk indication activates at the beginning of the associated crosswalk interval and lasts for the same duration as the pedestrian walk signal (except when the pedestrian signal rests in walk).

The MUTCD a regulatory standard, see 23 CFR 655.603; provides standards for the application of accessible pedestrian signals at signalized intersections (Sections 4E.09-4E.13).(2) Local organizations that provide support services to pedestrians who have visual or hearing disabilities often act as important advisors to the traffic engineer when consideration is being given to the installation of devices to assist such pedestrians. Additionally, orientation and mobility specialists or similar staff also might be able to provide a wide range of advice. The U.S. Access Board provides technical assistance for making pedestrian signal information available to persons with visual disabilities.(27)

Source: Federal Highway Administration.

Figure 36. Photograph. Example of an accessible pedestrian signal installation.

Enforcement Lights

Enforcement lights (or *tattletales*) are small indications agencies sometime use to assist law enforcement personnel with red-light running violations. The signal is connected through the back panel and is illuminated when the corresponding red indication is active. Law enforcement personnel can use the indication to tell if the vehicle enters the intersection during a red indication. Figure 37 shows an example of an enforcement light mounted on the pole at a mast arm installation.

Source: Texas A&M Transportation Institute.

Figure 37. Photograph. Example of an enforcement light mounted to a pole at a mast arm installation.

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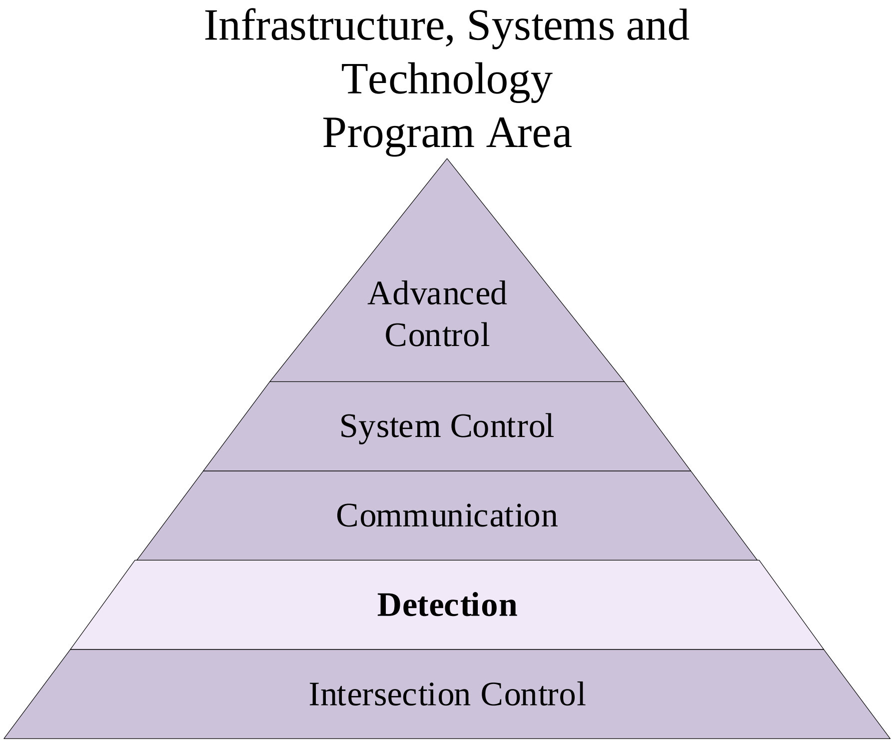
CHAPTER 6. DETECTION

As shown in Figure 38, after intersection control, detection represents the next fundamental building block of a reliable and robust traffic signal system. Detectors sense the presence of roadway users and produce information that the controller uses to determine the duration and sequencing of the signal displays provided to each movement at the intersection. The output of the detection system allows the control equipment to identify the presence (and potentially other characteristics) of intersection users. The controller is programmed by a user to receive input from detection devices in order to initiate phases or special functions that will be served in compliance with traffic signal control logic rules. Data from the detection system can be stored by the controller or transmitted to a central control system in a format that supports other functions, such as traffic-responsive control or performance evaluation. The quality and reliability of the detection system in conjunction with traffic signal timing design dramatically influences the capability of traffic signal operations strategies and tactics to attain operational objectives.



Source: Federal Highway Administration.

Figure 38. Graphic. Detection as the next foundational block of a traffic signal program.

Agencies should consult the following key references when designing and deploying intersection detection systems:

- *Traffic Detector Handbook*:(1)
    - Volume I (FHWA-HRT-06-108), Chapters 1 through 4.
    - Volume II (FHWA-HRT-06-139), Chapters 5 and 6 and all Appendixes.
- *Signal Timing Manual, 2nd Edition*.(2)
- *Traffic Signal Operations Handbook.*(3)
- *Part 4: Highway Traffic Signals. Manual on Uniform Traffic Control Devices for Streets and Highways.*(4)
- *Part 9: Traffic Control for Bicycle Facilities. Manual on Uniform Traffic Control Devices for Streets and Highways*.(5)
- *Urban Bikeway Design Guide*.(6)
- *Performance Measures for Traffic Signal Systems, An Outcome-Oriented Approach*.(7)

The reader should also consult the specific standards and guidance documents that many agencies have developed concerning the use, installation, and maintenance of detector technologies for their traffic signal programs.

PROGRAM OBJECTIVES SUPPORTED BY DETECTION

A well-designed and well-maintained detection system supports multiple program and operational objectives and should reliably function under various demand and environmental conditions. At the individual intersection level, the primary function of the detection system is as follows:

- Provide input to the control layer to identify calls for service.
- Extend active phases to accommodate current demand.
- Detect gaps in traffic flow to safely terminate active phases and transfer ROW.
- Detect the presence of queues.
- Trigger special functions to provide preferential treatment for different intersection users.

The detection system may also need to support system-level control functions and operations (such as traffic-responsive or traffic-adaptive signal operations). At the system level, the primary purpose of the detection system is as follows:

- Count vehicles to support the identification of changing traffic patterns for matching traffic signal timing plans and control strategies.
- Monitor the formation and growth of congestion in the network.
- Measure the quality of progression and throughput within the system.

Another critical and sometimes overlooked function of the detection system is performance monitoring. The quality of performance of the detection systems can be measured by merging data about the status of the signal indications from the controller with high-resolution data collected by the detection system (as detector status can be gathered every 1/10th of a second). By monitoring detector inputs into the controller, performance measures such as arrival during the green interval, phase failures, and others that directly relate the quality of performance of the signal timing can be produced. Some detection systems can also monitor their own operational status and report issues that impact their effectiveness.

Table 22 shows how these functions support the attainment of programs and operational objectives.

Table 22. Relationship between detection system functions and program and operational objectives.

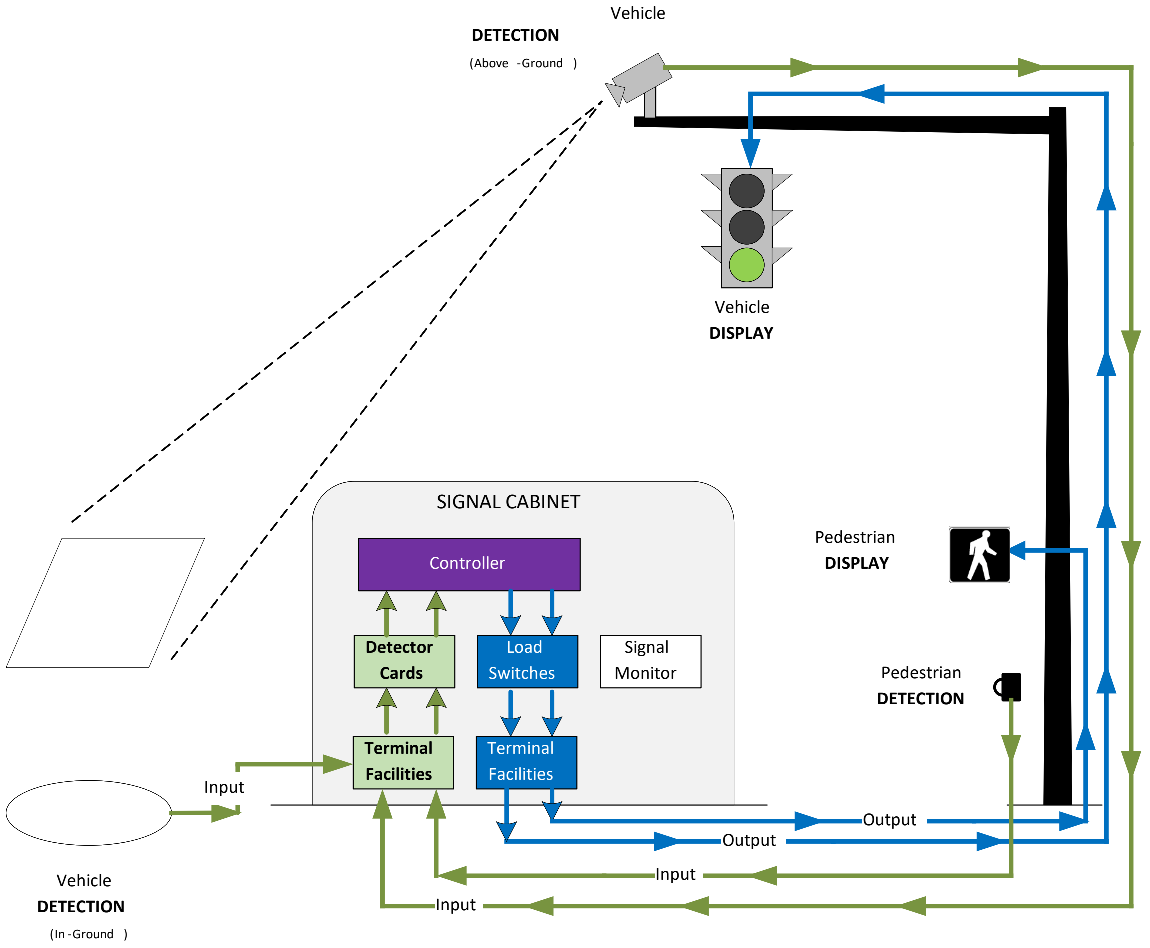
Detection System Functions	Responsiveness to Stakeholder Needs	Comply with Agency Policies and Standards	Sustain Infrastructure in State of Good Repair	Minimize Life-Cycle Costs	Safe Assignment of ROW	Appropriate Distribution of Green	Provide Smooth Flow	Maximize Throughput	Manage Queues	Minimize Delay for Prioritized Modes
Sense the presence of a road user (vehicles, pedestrians, bicyclist, transit vehicles, etc.) and issue calls for services.	X	–	–	–	X	X	–	–	–	–
Extend active phases to accommodate existing demand.	X	–	–	–	X	–	–	X	–	–
Enable the safe transfer of ROW.	X	X	–	–	X	–	–	–	–	–
Detect the presence of queues.	X								X	
Trigger special functions to provide preferential treatment for different intersection users.	X	X	–	–	–	–	–	–	–	X
Detect sudden surges in demand on portions of the network.	X	–	–	–	–	–	–	X	X	–
Identify changing traffic patterns.	X	–	–	–	–		X	X	X	–
Monitor the formation and growth of congestion in the network.	X	–	–	–	–	–	X	X	X	–
Measure the quality of progression and throughput of the system.	X	–	–	–	–	–	X	X	X	–
Measure and monitor performance.	X	–	X	X	–	–	–	–	–	–

“X”= Objective Supported Directly; “–” = Objective Not Supported Directly

Source: Federal Highway Administration.

INTERSECTION-LEVEL DETECTION

Each detection activation represents a notification (or call for service) by a user. Users may be motorized (such as passenger cars, commercial fleet vehicles, transit vehicles, light- or heavy-rail trains, emergency vehicles) or nonmotorized (such as pedestrians and bicyclists). The traffic control equipment responds to the input demand by activating signal indications that govern how various users move through the intersection. Figure 39 illustrates how detection data flow at an individual intersection. Detectors sense the presence of users and provide input to the traffic signal control technology with requests (or calls) for service for different signal displays. The traffic signal control equipment interprets and translates these inputs to manage the sequencing and duration of the signal displays that allow the users to move through the intersection.



Source: *Signal Timing Manual, 2nd Edition.*(2)

Figure 39. Graphic. Detection information flows for individual intersection control.

Sensing Presence of Road Users and Issuing Calls for Service

The primary function of the detection system is to sense the presence of road users (whether motorized or nonmotorized) and issue calls for service from the traffic signal. This function is essential for ensuring the safe transfer of ROW at the intersection. Sensing the presence of road users at the intersection also allows the controller to distribute green time appropriately based on demand. In selecting and implementing a detection technology, the following factors should be considered:

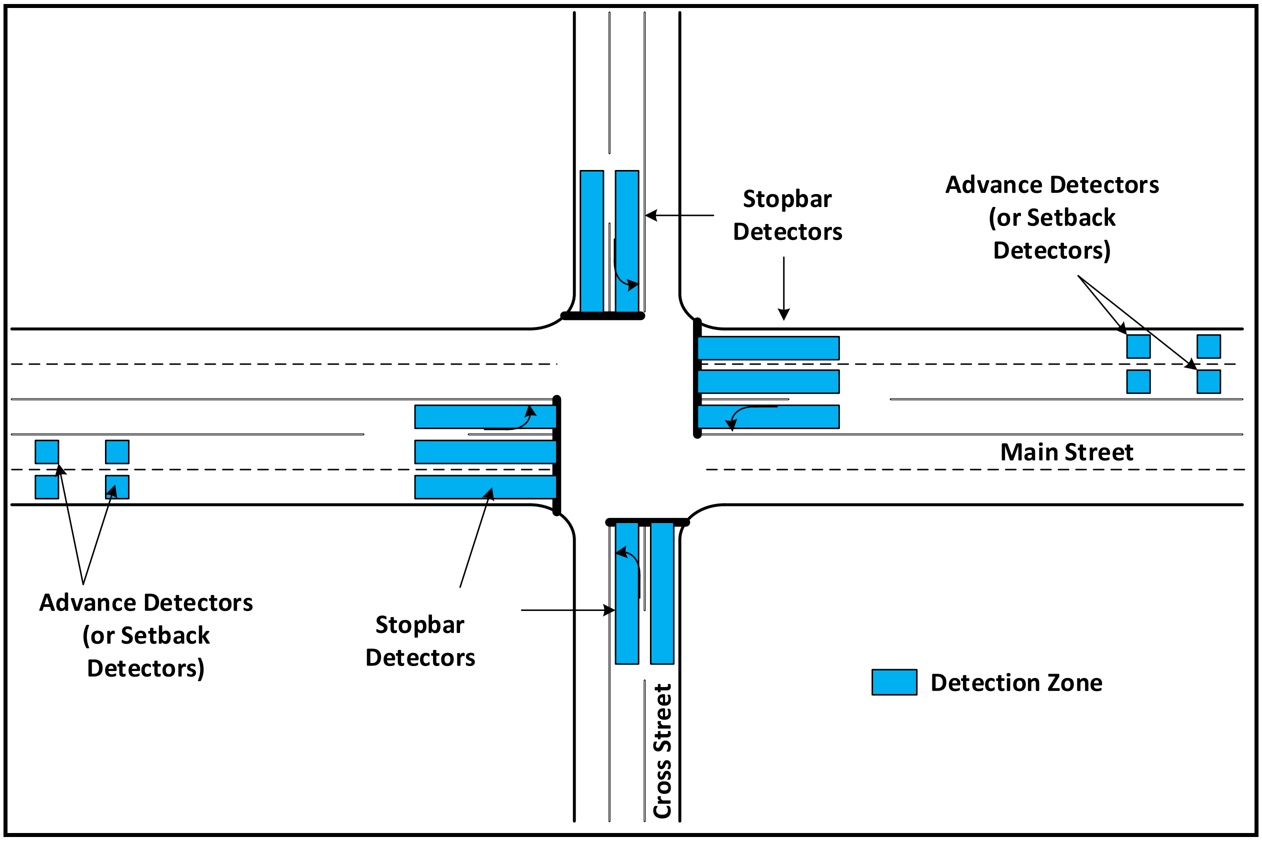
- The geometric design and configuration of the approaches to the intersection.
- The prevailing speeds of traffic approaching the intersection.
- The types and amount of different intersection users.
- The capabilities of the maintenance personnel and resources.
- The operational objectives the agency wishes to attain.

The following provides guidelines on the use and placement of detection zones for different types of road users.

Detecting Motorized Vehicular Demands

Vehicular demands, at a basic level, include demands from motorcycles, passenger cars, buses, and trucks. Although buses and trucks sometimes receive preferential treatment, each vehicle uses the same call for service at an intersection to request a phase. The detection system then notifies the controller that a user is within a defined detection zone.

Figure 40 shows the typical detector configuration for operating a traffic signal in a fully actuated mode. All the legs of the intersection, including through and left-turning movements, have stop-bar detection to communicate a request for service by vehicles waiting at the stop bar. Stop-bar detection is typically the only detection available for left-turn movements and cross-street approaches. The main street typically has upstream detection to enable the controller to transfer ROW, if needed, to the main street earlier and provide better flow for those approaches.



Source: Federal Highway Administration.

Figure 40. Graphic. Typical detector configuration for fully actuated control intersection.(3)

Detecting Through Movement Demands. Generally, agencies use stop-bar detection for low-speed movements (i.e., when the 85th percentile speed is 40 mi/h or less). The objectives of stop-bar detection are to (a) ensure that the presence of waiting traffic is made known to the controller, and (b) ensure that the traffic signal services the queued traffic for each phase. Generally, agencies operate these stopbar detectors in the presence mode, which means that they are active only when vehicles are in the detection zone. The length of the detection zone and desired flow rate are used to determine the appropriate extension settings in the controller.(2) Typically, for through movements, the length of the detection zone is between 20 and 80 feet. The optimal size represents a trade-off in the desire to avoid both premature termination and excessive extension of green. Although agencies commonly use 40 feet for stop-line detection zones,(3) research indicates that the ideal length of the stop-line detection zone is about 80 feet.(7) This length allows the passage time setting to be small, resulting in efficient detection of queues while minimizing the likelihood of terminating the green prematurely.

Agencies typically use advance detectors (also referred to as setback detectors as shown in Figure 40) on high-speed approaches to extend the green indication to vehicles on the intersection approach. Research indicates that using advance detection to terminate a phase on high-speed approaches can reduce rear-end crashes.(3) Generally, the detection zone is between 2 to 4 seconds in travel time upstream of the stop line. The controller extends the green interval for a short duration (1 to 3 seconds) to allow the detected vehicle to reach the stop bar before activating the yellow interval. Generally, an agency will operate the advance detection in a locking memory mode so that the controller will recognize that a vehicle is between the detection zone and the stop bar. If an intersection only has advance detectors for an approach, the minimum green time for the movement must be long enough to clear the vehicles queued between the stop line and the advance detector.

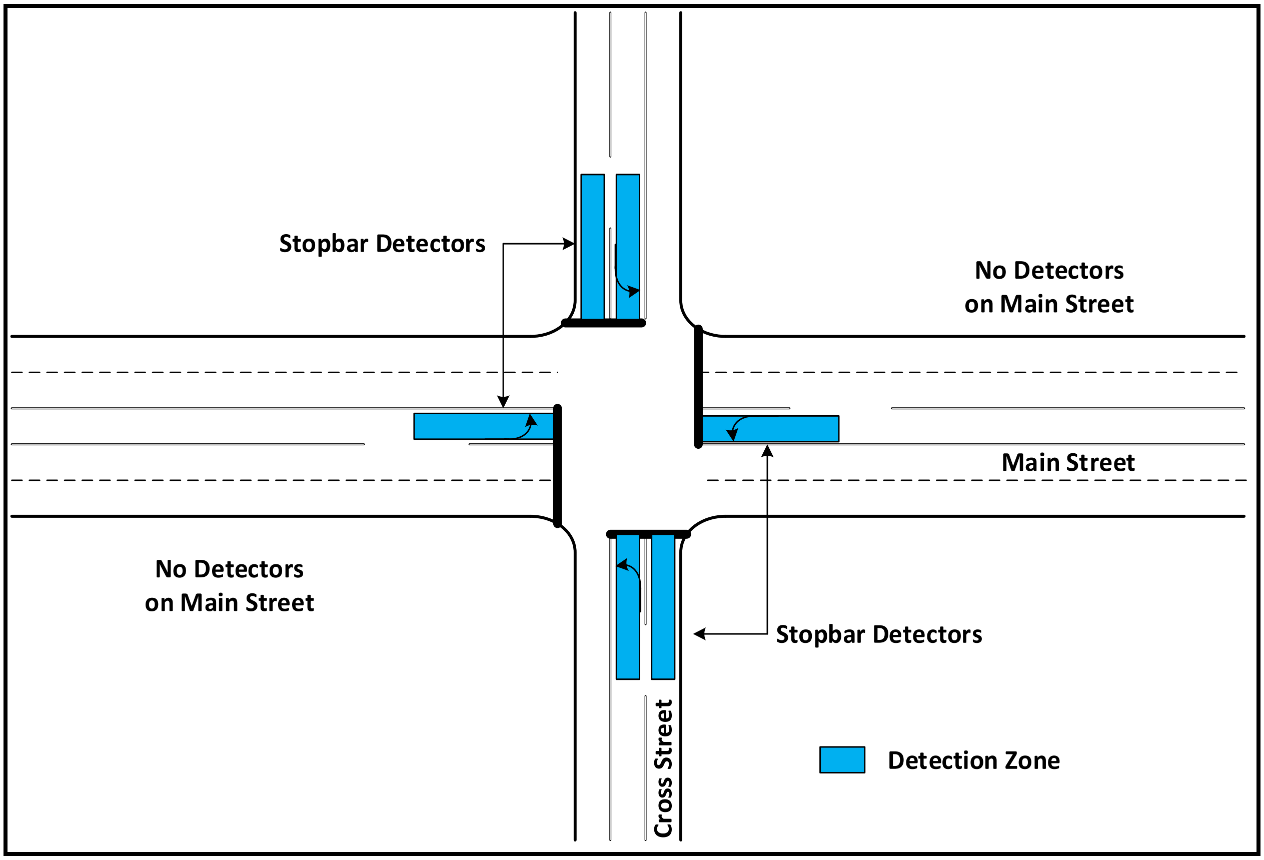
Sometimes agencies will use both advanced detection and stop-bar detection in combination to detect through movement demands. The controller then switches between the two detection zones. For example, when the signal indication is red, an agency may use the stop-bar detection zones to identify demand for the movement. When the signal indication turns green, detection then switches to the advance detection zones for determining when to terminate the through movement phase.

Figure 41 shows a typical detector configuration when the intersection operates in semi-actuated control. In semi-actuated control, detection is provided only on the minor movement at the intersection. To ensure that the controller services the main-street movements, operators use a recall feature in the controller. Several types of recalls exist:

- The *Minimum Recall* feature ensures that the major-road movements receive a green indication at the earliest possible time in the cycle. Using minimum recall for the main-street phases causes the signal to remain green for the through movements when the demand for the conflicting phases is low.

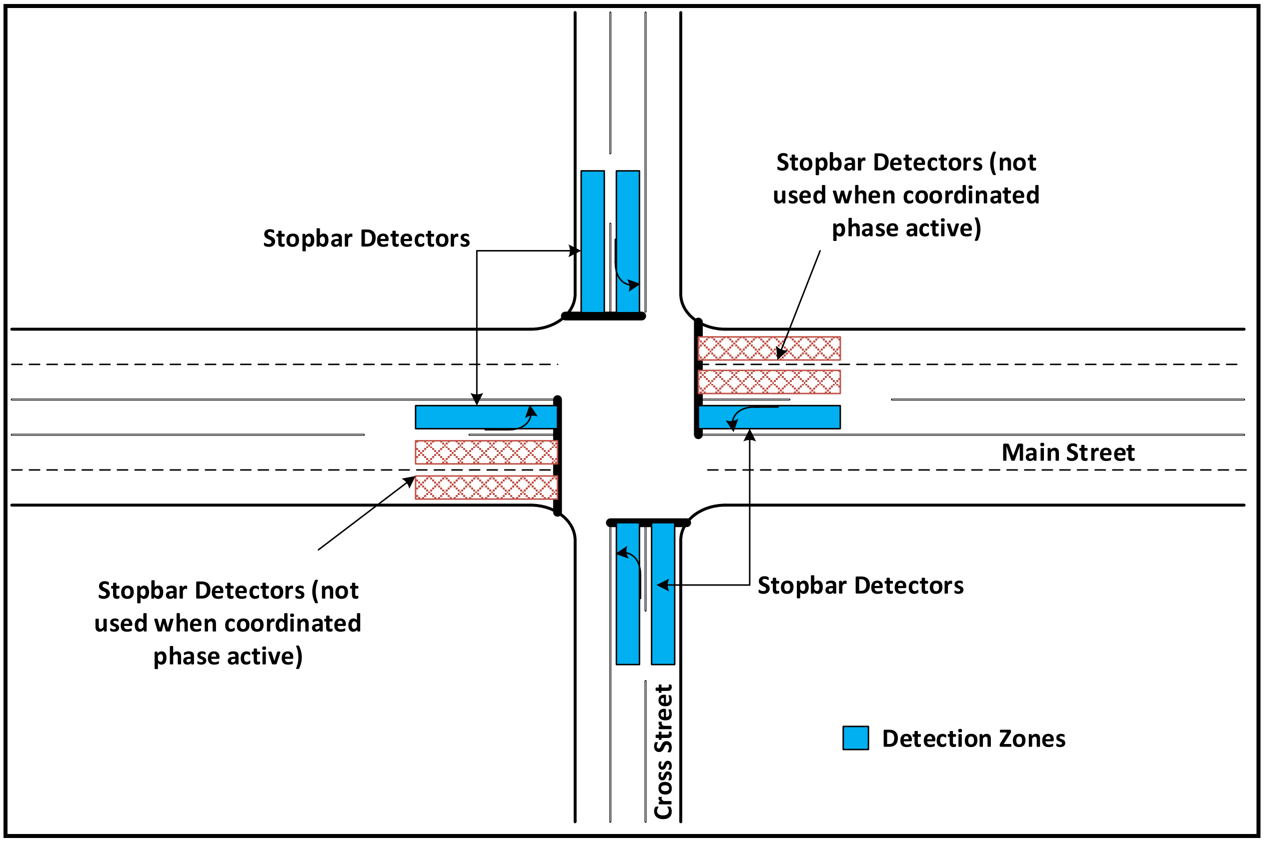
- *Maximum Recall* occurs when vehicle detection is out-of-service or not present. Using maximum recall ensures that, in the absence of detection, the controller serves the phase to its maximum duration. Agencies also use the maximum recall feature to force the intersection to operate like a fixed-timed operation. This application requires the agency to set all phases to maximum recall. The maximum green settings used for this application should equal the green interval durations for the optimal fixed-timed timing plan. Regardless of the application, maximum recall can result in inefficient operation during low-volume conditions (e.g., during nights and weekends), and should be used only when necessary.

- *Soft Recall* is applied at non-coordinated intersections to allow the controller to dwell in the main-street phases when cross-street traffic is light but operate in an actuated mode when traffic demands are heavier. Typically, this setting is used when detection exists for the major road through phases. Figure 42 illustrates a detector configuration where a soft recall would be appropriate for the main-street movements.



Source: Federal Highway Administration.

Figure 41. Graphic. Common detector configuration for semi-actuated control.(3)



Source: Federal Highway Administration.

Figure 42. Graphic. Illustration of another detector configuration used with semi-actuated control.(3)

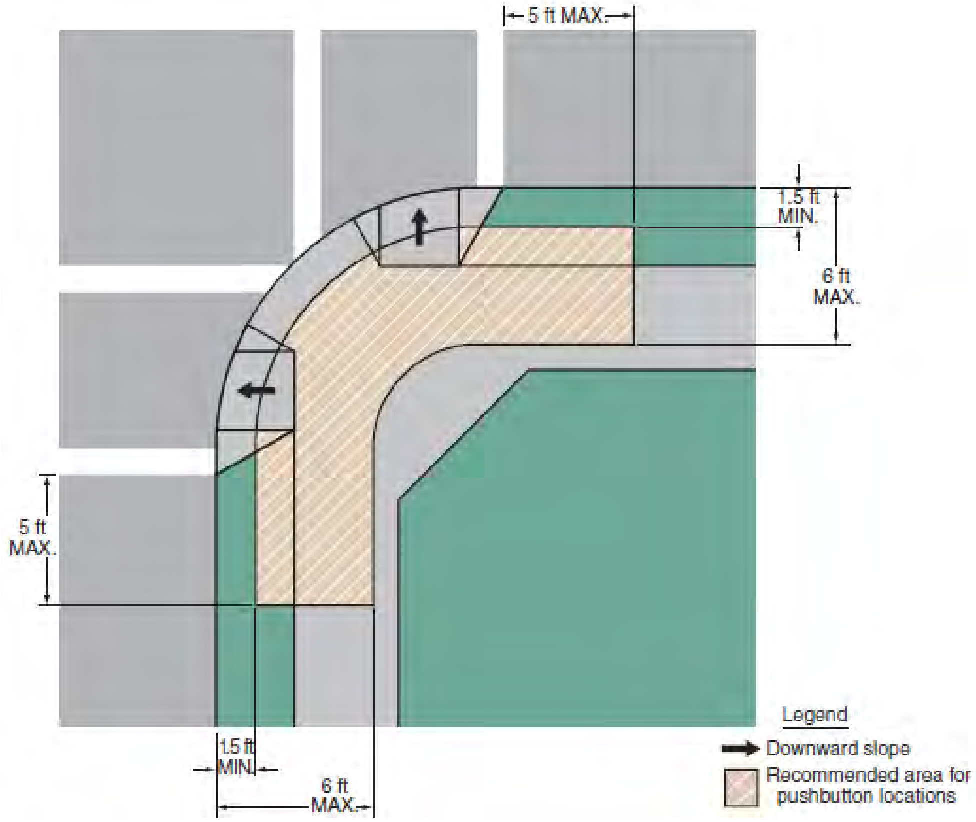
Generally, detection is provided when the left-turn movement occurs from an exclusive (or dedicated) lane or lanes. The type of phase patterns an agency uses for servicing the left-turn demand impacts the design and operations of the left-turn detection zones. A similar design and operations setting as the through movements can be used when the left turns operate in a protected-only or permissive-only mode. Typically, the detections zones for left turns are between 20 and 80 feet in length and operate in the presence mode (which means that they will place a call for service only when vehicles occupy the detection zone). Generally, the trailing end of the detection zones is set 5 to 10 feet behind the stop bar to allow the controller to begin clearing the left-turn phase as the last vehicle in the queue is turning. At intersections where the left-turn movements operate in a permissive-only mode (and where the controller does not service the through movements automatically), some agencies extend the detection zone 5 to 10 feet beyond the stop bar. Extending the detection zones past the stop bar helps minimize the potential for stranding turning vehicles in the intersection at the end of the vehicle phase.

For intersections where protected/permissive phasing is used to service left-turn demands, a delay in placing a request for service for the protected portion of the phase occurs for several seconds to allow waiting vehicles to turn during the permissive part. Delaying the call for service minimizes unnecessary activations of the protected phase and can improve the overall operational efficiency of the intersection. Delay values typically range between 5 and 12 seconds, with agencies using larger values when a higher speed or volume exists on the opposing approach.

Detection may be provided for right-turn movements when an exclusive right-turn lane (or lanes) exists. In general, the detection design for a protected or protected/permissive right-turn movement is like that for left turns. The detection zone should be between 20- to 60-feet and detectors should be programmed to operate in the presence mode. Many agencies will use a delay setting in the controller to postpone placing a call for service immediately to account for right-turn-on-red.

Detecting Pedestrian Demands

Any pedestrian phases that are not on recall require detection to notify the controller that a pedestrian needs service. Typically, pedestrians call the pedestrian phase through a pedestrian pushbutton, which should be easily accessible from a wheelchair and have a tone locator so that it can easily be found by pedestrians with reduced visual abilities. The MUTCD provides standards for accessible pedestrian pushbutton design in section 4E.09 through 4E.13.(4) Figure 43, a copy of figure 4E-3 from the MUTCD, illustrates the appropriate locations for placing pedestrian pushbuttons at a signalized intersection.



Source: Federal Highway Administration.

Figure 43. Graphic. Typical pedestrian pushbutton location area.(4)

Passive detection is another methodology used for placing calls for a pedestrian phase. Passive pedestrian detection places a call for a pedestrian phase if a pedestrian is detected standing in a location indicative of a desire to cross. This detection method, however, comes with the risk of placing calls for service when the pedestrian does not intend to cross the intersection.

Detecting Bicycle Demands

Bicycle detection is used at actuated signals to adjust the signal timing in response to bicycle demand on a particular approach. The NATCO suggests the use of bicycle detection at signalized intersections when the following conditions exist:(6)

- In the travel lane on intersection approaches without bike lanes where actuation is required.
- At intersections where an agency uses exclusive bicycle signal heads and bicycle-specific phasing to service bicycles.
- In bike lanes on intersection approaches that are actuated.
- In left-turn lanes with actuated left-turn signals where bicyclists may also turn left.
- To increase the green signal phase on intersection approaches whose minimum green plus yellow plus all red is insufficient for bicyclists to clear the intersection when starting on a green indication. Advanced bicyclist detection can be applied to extend the green phase or to call the signal.
- At clearly marked locations to designate where a bicyclist should wait.

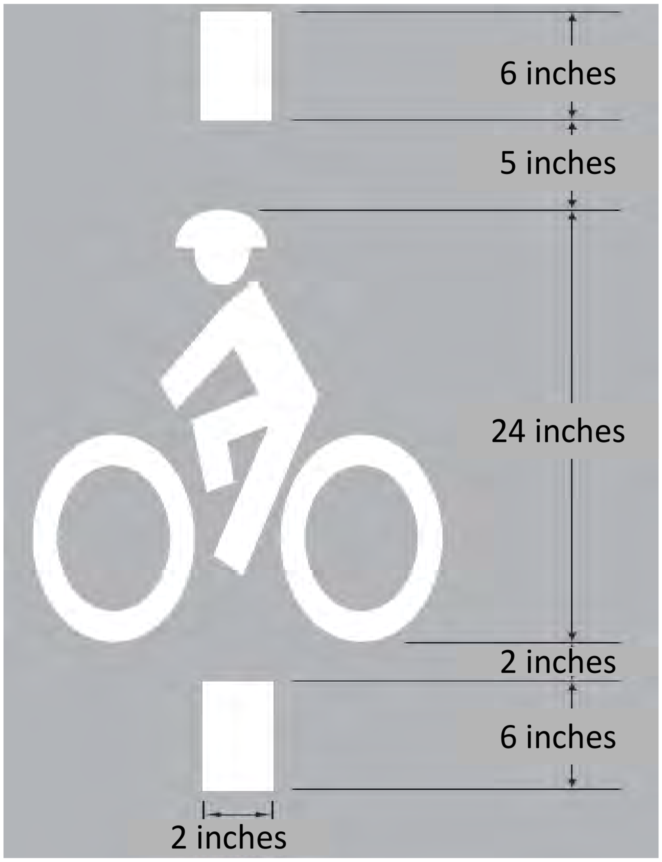
If a pushbutton is the means for a cyclist to request service, current best practice is to place the pushbutton so the cyclist can activate the request for service without dismounting. An additional pushbutton can be installed along the roadside if desired. The installation of a supplemental sign facing the bicyclists to increase the visibility of the pushbutton is encouraged.

Several technologies exist for detecting bicycle demands at an intersection. For example, the motor vehicle detection areas can be located in a manner that is also conducive to bicyclists. Agencies may also want to consider placing side-street detection areas at the stop bar. The various detection technologies agencies use to detect bicycles include the following:

- Inductive loops embedded in the pavement.
- Video detection aimed at bicyclist approaches and calibrated to detect bicyclists.
- User-activated push buttons mounted on a pole facing the street.
- Narrow-beam microwave radars that pick up non-background traffic.

Each technology requires that a technician adjust the sensitivity from the standard settings to ensure that they detect bicyclists.

The MUTCD provides a standard marking to communicate the optimum position for a bicyclist to request service in Section 9C.05.(5) This symbol can apply to any detection technology. The NACTO *Urban Bikeway Design Guide* provides some recommendations on how to install loop detectors with the symbol.(6) Figure 44 shows figure 9C-7 of the MUTCD, the optional symbol provided by the MUTCD to indicate the optimal position for where a bicyclist can actuate a signal, which can improve the detection of bicyclist demands at a signalized intersection. These markings are especially helpful if the detection zone is not within a bike lane, shoulder, or cycle track. When bike lanes or shoulders are provided, the detection should be positioned to cover where bicyclists typically travel and wait. Upstream detection is possible for facilities with bike lanes or shoulders.



Source: Manual on Uniform Traffic Control Devices

Figure 44. Graphic. Standard pavement marking for communicating the optimum position for a bicyclist to request service.(5)

A detection zone for video and microwave detectors can be placed directly on the bike detection symbol, but loop detectors require a configuration of the loop detectors around the symbol. Figure 45 shows some sample loop detector configurations around the bicycle detection symbol.

Source: National Association of City Transportation Officials.

Figure 45. Graphic. Example of different strategies for enhancing bicycle detection.[(6)]

Bicycle boxes are a treatment that places bicyclists in front of motor vehicles at a red signal instead of within the vehicle queue. The bicycle box is placed in front of the stop bar, removing the bicyclist from the vehicle queue, and is especially helpful for left-turn movements. Bicycle boxes are markings on the pavement to indicate to a cyclist where they should wait to place a call. Bicycle boxes should be used only where bicycle lanes are present. Figure 46 shows an example of a bicycle box.

Source: National Association of City Transportation Officials.

Figure 46. Graphic. Illustration of a bicycle box used at an intersection.[(6)]

Enabling the Safe Transfer of ROW

One function of the detection system is to assist the controller in determining when to terminate a green indication. This strategy helps the program in the safe assignment of ROW objectives since it helps reduce the probability of rear-end crashes and red-light running caused by unexpected behavior between vehicles.(9) The detection systems and the controller work together to identify gaps that indicate traffic flow has declined below a specific level. Signal efficiency performance begins to decline when the headways between vehicles become longer than 2 to 3 seconds in each lane.(2)

Approaches under Actuated Control

In actuated control, a controller uses the passage timer (also called unit extension or gap timer) to determine when to terminate an active green indication safely. The passage timer starts to time down the instant the traffic clears the detection zone. If the passage time expires before the detection system on the approach detects another vehicle, the traffic signal controller will "gap out" (meaning that it has found a gap in the traffic stream that is sufficient to allow it to terminate the green) and proceed to the yellow interval. However, if the controller detects another vehicle entering the detection zone before the passage timer expires, it will reset the passage timer to its initial value and begin the countdown process again. Longer detection zones require shorter passage times. Short detection zones increase the probability that a phase will terminate when traffic flow is reduced below the desired level.

The passage time set in the controller depends on the length design of the detection zone (i.e., the type, the number of lanes covered by the detection zone, the size of the detection zone), the operating mode of the detection system (pulse or presence), and the speed of approaching traffic. Table 23 provides typical passage time values to sustain a flow rate of 1,200 vehicles per hour (3-second headways) for a range of speeds and detection zone lengths. It is important to understand that passage times are for a single detector in a single lane. The following items describe when the passage values may need to be reduced:(2)

- A detection zone covers multiple lanes (i.e., a wide-area detection scheme).
- A single lane uses both advance and stop-bar detection.

Table 23. Recommended passage time (seconds) for different posted approach speeds.(2)

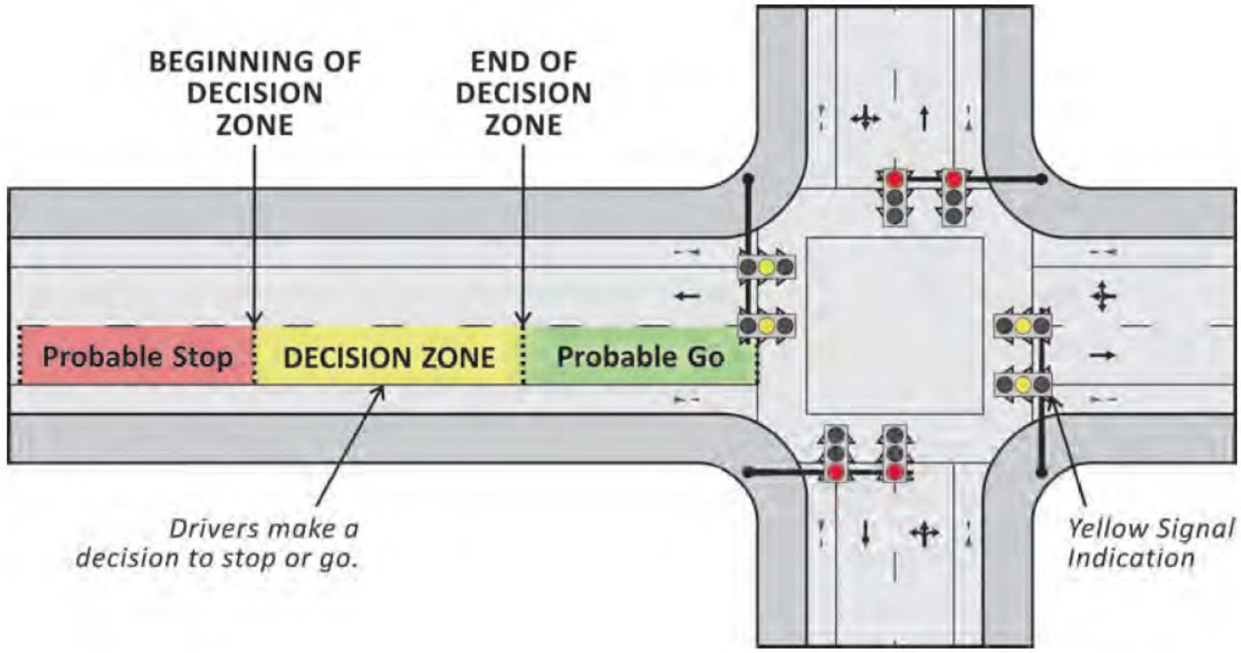
Detection Zone Length (Feet)	25 mi/h	30 mi/h	35 mi/h	40 mi/h	45 mi/h	50 mi/h	55 mi/h
6	2.3	2.4	2.5	2.6	2.6	2.6	2.7
20	1.9	2.1	2.2	2.3	2.4	2.5	2.5
40	1.4	1.6	1.8	2.0	2.1	2.2	2.3
60	0.8	1.2	1.4	1.6	1.8	1.9	2.0
80	0.3	0.7	1.1	1.3	1.5	1.6	1.8

Source: National Academy of Sciences

High-Speed Approaches and the Decision Zone

> High-speed approaches (approaches with speed limits greater than or equal to 35 mi/h) represent unique challenges to detection designs, connected with the idea of the decision zone. The decision zone is the length of the roadway in which each driver may make a different decision—whether to proceed or stop—upon seeing a yellow signal indication. Source: *Signal Timing Manual, 2nd Edition.*(2)

Figure 47 illustrates the concept of the decision zone. Unlike the dilemma zone (when the vehicle change interval is too short for the vehicle to enter the intersection safely, but the vehicle is too close to stop at the stop bar safely), the decision zone is a function of driver perception, reaction, and judgment. The decision zone tends to be between 5.5 and 2.5 seconds of travel time upstream of the stop bar.(2) When drivers are more than 5.5 seconds upstream of the intersection, a high probability exists that a driver will stop if presented with a yellow interval. The 5.5-second threshold defines the beginning of the decision zone. When drivers are 2.5 seconds from the intersection, a high probability exists that a driver will keep going if presented with a yellow indication. The 2.5-second threshold defines the end of the decision zone. Table 24 provides the limits of the decision zone for various approach speeds.



Source: *Signal Timing Manual, 2nd Edition.*(2)

Figure 47. Graphic. Representation of the decision zone approaching a signalized intersection.(2)

Table 24. Limits of decision zone.(2)

Approaching Vehicle Speed	Beginning of Decision Zone (5.5 seconds from Stop Bar)	End of Decision Zone (2.5 seconds from Stop Bar)
35 mi/h	285 feet	125 feet
40 mi/h	325 feet	145 feet
45 mi/h	365 feet	165 feet
50 mi/h	405 feet	180 feet
55 mi/h	445 feet	200 feet

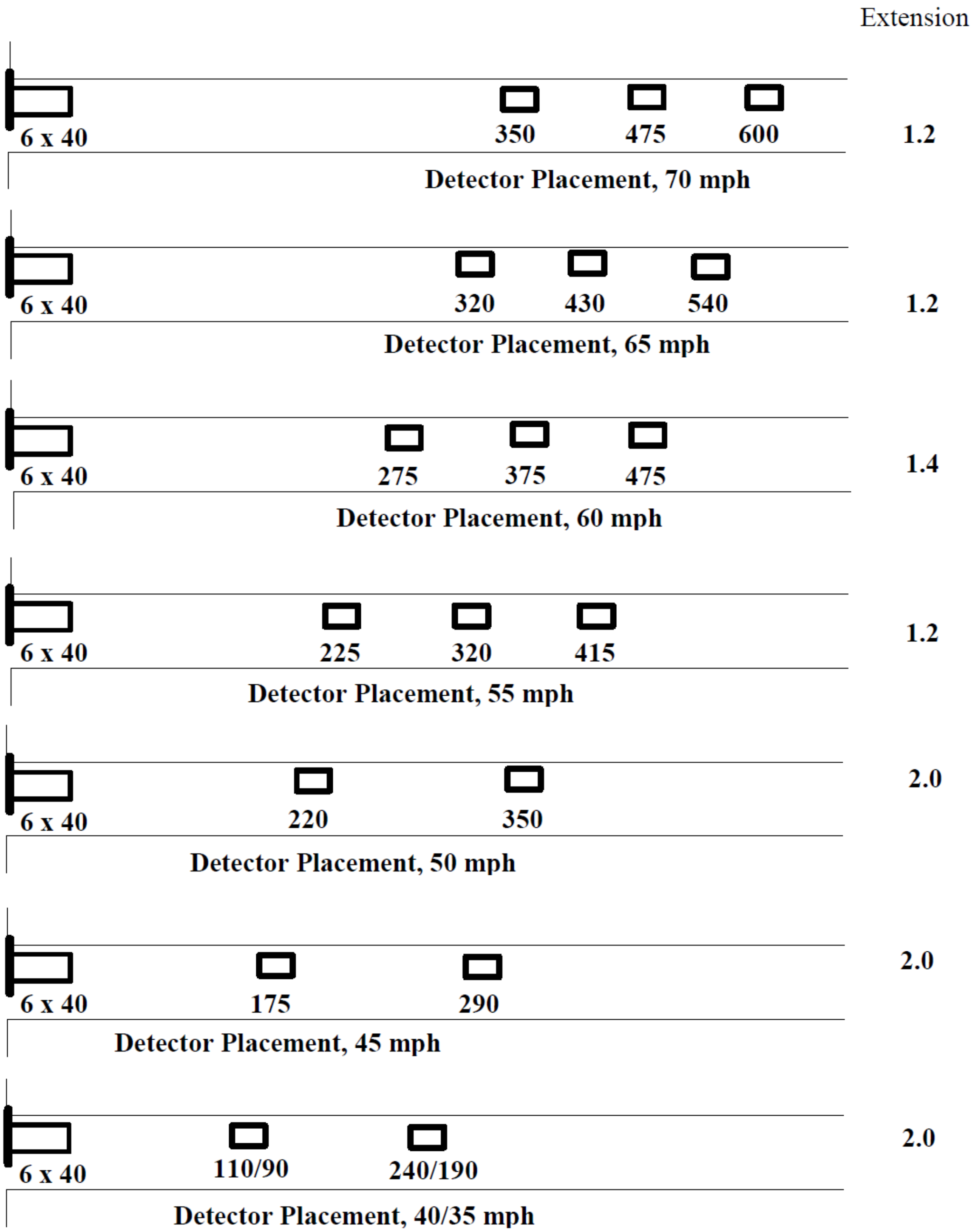
Source: National Academy of Sciences

Typically, agencies will place a detector at the beginning of the decision zone and use the passage timer to prevent the phase from terminating before a vehicle clears the decision zone. Some agencies will use a combination of both advance and stop-bar detection on major street approaches. Most modern controllers have a stop-bar detector disconnect feature that can transfer the passage timer to the setback detector when the green indication is active. In this case, advance detectors typically have passage times between 2 and 3 seconds, assuming a single detection zone in each lane.(3) The *Signal Timing Manual, 2nd Edition*(2) provides additional guidance and insight into the relationship between detection design and passage timing.

On approaches with very high speeds (speeds ≧ 45 mi/h), a multipoint detection scheme can be used to assist the safe termination of a phase. The location of the uppermost detection zone upstream of the intersection is at the safe stopping distance from the intersection for the highest approach speed. The next detection zone is placed at the safe stopping distance for a vehicle traveling 10 mi/h less than the assumed speed of the first detection zone. The location procedure repeats for each successive detection zone until the last zone is within 2.0 seconds of the intersection. Figure 48 summarizes one agency's approach to using a multipoint detection scheme for high-speed approaches.

Activating Special Operations

Many programs use their detection system to enter different modes of special operations or to provide automated traveler information. These processes relate to the reliability of the network for specific types of vehicular road users, like emergency vehicles, buses, and, to various degrees, trucks. Strategies like preemption and priority treatment impact the operational effectiveness of these particular intersection- users by reducing their delay. The detection role of the detection system is to detect the presence of these specific intersection users.



Source: Texas Department of Transportation.

Figure 48. Graphic. Example of multiple detection zones to provide decision zone detection.(3)

Preemptions

There are two common types of preemption: rail and emergency vehicle. Rail preemption is typically considered a higher priority and the proximity to the intersection of a grade crossing on an intersection approach controlled by a STOP or YIELD sign may even can qualify an intersection for signalization under Signal Warrant 9 in the MUTCD (section 4C.10).(4) Although the MUTCD does not require agencies to provide preemption for emergency vehicles, a program might pursue it depending on key objectives and funding. In either case, preemption is a method to increase safety by immediately providing green time to these high-level intersection users.

The MUTCD provides standards for the use of traffic control signals installed near or within a grade crossing or if a grade crossing with active traffic control devices is within or near a signalized highway intersection.(4) Agencies may use rail preemption at intersections that have queues that extend across nearby rail crossings. Intersections may also benefit from rail preemption when the downstream traffic storage can overflow and interfere with signalized operations. The operations can involve preemption and a change in operations at an intersection to omit phases that cannot operate due to blockage from the train. In either case, a program should consult with the railroad operator to identify train detection and the related warning time. Section 8C.08 of the MUTCD requires flashing lights to operate for at least 20 seconds before the arrival of any rail traffic.(10) If the minimum warning time is not sufficient, the train detection system may need a different design or advanced preemption, which should be coordinated with the rail operator. The American Railway Engineering and Maintenance-of-Way Association (AREMA) *Communications and Signal Manual* (AREMA 2004, Part 3.3.10) (11) should also be consulted for more information on the design and use of train detection systems.

Agencies use emergency vehicle preemption (EVP) to improve response time and safety for first responders. The detection system for EVP can use several technologies, including light-based, infrared-based, and global positioning (GPS) systems. Table 25 shows the attributes associated with common EVP technologies.

Table 25. Summary of attributes of EVP detection technology.(1)

Attributes of EVP Technology	Strobe Activated	Siren Activated	GPS Activated
Dedicated Vehicle Emitter Required	Yes	No	No
Susceptible to Electronic Noise Interference	No	No	No
Clear Line of Sight Required	Yes	No	No
Affected by Weather GPS Activated	Yes	No	No
Possible Preemption of Other Approaches	No	Yes	No

Source: Federal Highway Administration.

Although GPS-activated EVP does not require an emitter, it does require a GPS unit in the vehicle that can communicate through a system to intersections along the route of the emergency vehicle to place the preemption requests.

Priority

Under priority control, requests for service can occur two ways: from a traffic management center or from the vehicle itself. In this control mode, the controller will attempt to provide early or extended green time to a phase but will not compromise any existing coordination plan at the intersection. The methodology for providing priority treatment is like preemption.

Table 26 lists some of the more common types of detection that are typically used to request priority at intersections. Infrared detection systems are the most widely used technology for generating priority service requests; however, GPSs are increasingly becoming commonplace. Typically, where light-rail transit systems and transit vehicles operate in exclusive lanes, sensors are embedded in the pavement in the travel pathway of the vehicles.

Traffic management center can also generate priority service requests.(11) Under this approach, a transit management center or emergency dispatch center communicates with a traffic management center. The transit management center or emergency dispatch center determines the need for priority service and transmits the request to the traffic management center via a center-to-center communications link. The traffic management center then prioritizes all requests for service and sends the appropriate command to the intersection controller through the traffic signal center-to-field (C2F) communication network. For this approach to function, agencies should have strong interagency cooperation and reliable communications links between centers.

Table 26. Common detection technologies used in preferential treatment (priority) systems.

Detection Type	Equipment Required	Strengths	Limitations
Vehicle-based GPS	• An in-vehicle computer that uses GPS to update vehicle location continuously. • Field unit in the cabinet.	• No unobstructed line-of-sight requirement. • Notification is received when a vehicle has cleared the intersection. • Potentially larger detection ranges (i.e., requests received sooner).	• Some systems may not adequately sample vehicle locations at closely spaced intersections. • Acquiring satellites in urban environments can be challenging.
Pavement Embedded Sensors	• A transponder is attached to the underside of the vehicle (coded with unique identification numbers for automatic vehicle identification). • Sensors embedded in the pavement. • Common technologies include hard-wired loops and magnetometers	• Similar to commonly used loop detectors. • No unobstructed line-of-site requirement. • Relatively easy to implement downstream check-out detection.	• Requires in-pavement detectors, which need appropriate placement and maintenance. • These systems are distance based (rather than time based), requiring an estimate of speed (which may change with traffic conditions).
Infrared (Light-Based)	• Infrared strobe emitter on the vehicle (which can contain a unique identification number for tracking purposes). • Agencies must place an infrared detector at each intersection. • Deployments require the placement of a detection interface device in the cabinet.	• Widely used, allowing regions to utilize uniform systems for emergency and transit vehicles. • Agencies have many years of experience using this technology.	• Deployments require a line of sight between the vehicle and detector. • Roadway geometry, weather problems, and obstructions such as tree foliage can hinder effective operations.

Source: *Signal Timing Manual, 2nd Edition.*(2)

DETECTOR PERFORMANCE RELIABILITY

Two dimensions define detector performance reliability: precision and accuracy.(7) Precision directly relates to the latency (or time difference) between when a detection zone enters a new state and when the detection system reports that the new state has occurred. Accuracy relates to the number of false calls and missed calls produced by the detection system. A detection system that is both imprecise and inaccurate results in the most undesirable operating condition for a detection system, leading not only to missed and false detections (inaccurate) but also inconsistent activations of signal displays. A detection system has accuracy but lacks precision may produce relatively few missed and false detections but may result in sluggish responses and delays in activating signal timing changes. A case in which the detection system is precise but lacks accuracy results in unnecessary phase activations and wasted green time serving phases with no demand. A system that is both highly accurate and precise simultaneously result in optimal signal performance.

Using this concept of precision and accuracy, the Indiana Department of Transportation (INDOT) developed performance criteria for detector acceptance based on tolerances for applications specific to traffic signal actuation and green time extension.(14) INDOT used two types of latency to define precision tolerance: activation latency and termination latency. *Activation latency* is the time difference between when a vehicle enters the detection zone and when it is detected. *Termination latency* is the time between when the vehicle leaves the detection zones and the detector returns to the unoccupied state. INDOT also uses the number of missed and false calls to assess the accuracy of the detection technology. A *missed call* is defined as any time the detector fails to detect a vehicle, and a *false call* is defined as when the sensor reports a vehicle as present even though it is not.

More information on development and use of these tolerance can be found in *Performance Evaluation of Traffic Sensing and Control Devices.* (7)

DETECTION TECHNOLOGIES

Detection systems come in a variety of technologies, and not all technologies have equal capabilities. Some detection methods only enable point detection, while others provide detection over a wide area. Proper selection of detection technology is crucial to ensure both adequate operations and efficient use of capital.

The locations and sizes of detection zones are key features in designing a detection system at an intersection. Longer detection zones with shorter extension times help the intersection remain responsive to demands and are more efficient, while shorter detection zones need more extension time to avoid premature phase terminations (or gap outs). The technology used within a system impacts the detection zone length. Some technologies cost more for different size detection zones. For example, longer inductive loop designs require additional wire and more labor to install. Other technologies have negligible differences in cost for different detection zone lengths (i.e., video detectors). Additionally, detection zone configuration may include advanced detection for performance measurement, such as collected speed data or arrival on green data.

Inductive Loops

Agencies have used inductive loops to operate their traffic signal systems for decades. Inductive loops detect the presence of road users using the metal in the vehicle. Loops are typically wound wire installed in a pavement cut. When energized, this coil of wire creates a magnetic field that is disrupted by the passage of a vehicle. The amplifier in the controller cabinet detects this disruption. Alternately, loops can be pre-formed and installed in the substrate. Table 27 lists the strengths and weaknesses associated with inductive loop detection technologies.

Table 27. Strengths and weaknesses of inductive loop detection technologies.(1)

Strengths	Weaknesses
• Flexible design to satisfy a large variety of applications. • Loop detection is a mature, well-understood technology. • Agencies have a large experience base. • Loop detection provides basic traffic parameters (e.g., volume, presence, occupancy, speed, headway, and gap). • Loop detection is insensitive to inclement weather such as rain, fog, and snow. • The technology may provide the best accuracy for count data in comparison to other commonly used techniques. • Common standard exists for obtaining accurate occupancy measurements. • High-frequency excitation models provide classification data.	• Installation requires pavement cut and may not be appropriate for all structures. • Improper installation decreases pavement life. • Installation and maintenance require lane closure. • Wire loops are subject to stresses of traffic and temperature. • May not function on steel support structures. • Multiple loops usually required to monitor a location. • Detection accuracy may decrease when the design requires the detection of a large variety of vehicle classes.

Source: Federal Highway Administration.

Magnetometers

Magnetometers are a passive sensing technology that detects the presence of vehicles in each lane. They operate by detecting changes in the horizontal and vertical components of the Earth's magnetic field caused by the passage or presence of a vehicle. The sensors are generally installed flush with the pavement surface. The installation requires drilling a hole into the roadway surface. This sensor technology can support both presence and passage traffic signal applications.

The sensors communicate wirelessly to an access point installed aboveground (usually on a traffic signal pole or light standard) adjacent to the roadway. Agencies will sometimes use repeaters to extend the range of an access point. The repeater relays the information between other repeaters, sensors, and access points. Repeaters are needed when the distance between the sensors and the access point are greater than the practical limits of the wireless technology, or when the angle between devices results in poor signal reception.

Typically, a traffic signal installation will use an interface card to connect the sensors to the traffic signal controller. The interface card installs directly in the detector rack in the cabinet. The card emulates the calls generated by a traditional loop detector. The detection area of a single sensor is approximately a 6-foot diameter zone where detection is most effective, 4 feet in front of and 2 feet behind the sensor. Multiple sensors can be used to achieve traditional long detection zones. The sensors themselves are battery-powered; however, power and communications are required to connect the access point to the traffic signal controller.

Table 28 shows the strengths and weaknesses of this technology. Magnetometers are useful on bridge decks and viaducts, where the steel support structure interferes with loop detectors and where loops can weaken the existing structure. Magnetometers are also useful for temporary installations in construction zones.

Table 28. Strengths and weaknesses of magnetometer detection technologies.(1)

Strengths	Weaknesses
• Installation can occur in a relatively short period (less than 15 minutes). • Less susceptible than loops to stresses of traffic. • Insensitive to inclement weather, such as snow, rain, and fog. • Some models transmit data over a wireless radio frequency link. • The technology can be used where traditional detection technologies are not feasible (e.g., bridge decks). • Some models can be installed by boring under the roadway.	• Most sensors are installed by drilling into the pavement. • Improper installation decreases pavement life. • Installation and maintenance require lane closure. • Models with small detection zones require multiple units for full lane detection.

Source: Federal Highway Administration.

Video Image Processing

Video detection is a nonintrusive detection technology. The video image detection system consists of a detector and an image processor. The camera is fixed-mounted, usually on a far-side mast arm assembly or a steel pole (see Figure 49). The camera feeds an image of the approach to the processor. The device is configured by superimposing detection zones on the image. The processor senses contrast changes within the zones and then outputs a call to the controller unit. The processor may be programmed to provide outputs that emulate a loop detection system (pulse, presence, delay, and extension). If desired, the processor will accumulate data such as volume, occupancy, speed, and vehicle classification.

Source: Federal Highway Administration.

Figure 49. Photograph. Example of video detection cameras installed on traffic signal mast arm.

Three types of video detection systems are commonly available:(14)

- *Standard Video Detection*—This video technology uses an optical camera to create a video image for processing. Optical cameras can be monochrome or color. Optical cameras may have difficulties in dimly lit areas, under certain weather conditions, and when sun glare is present. Headlight bloom at night may also cause errant actuations.

- *360-degree Video Detection*—This video technology uses a high-resolution color optical camera equipped with a fish-eye lens, which allows a single camera to see all approaches of an intersection. A single 360-degree camera can provide detection for an entire intersection under certain circumstances, though typically advance cameras are still required for arterial detection. 360-degree cameras have the same drawbacks as optical cameras. A special video detection processor is also required, but this processor will work with up to four advance cameras or thermal sensors and one 360-degree camera.

- *Thermal Video Detection*—This video technology uses a thermal imaging sensor to create a monochromatic heat-based image for processing. Thermal sensors do not require illumination to detect accurately and still work properly during adverse weather and in direct sunlight.

Thermal sensors, however, typically generate a lower resolution image than optical cameras.(3)

The *Traffic Signal Operations Handbook* suggests the following when designing a video detector placement:(3)

- The ideal detector mounting location is in front of the approaching vehicle and as high as possible with an unobstructed line of sight to the area of detection. The view of a detector mounted low or at an angle may be obstructed by an adjacent lane vehicle, which is known as cross-lane occlusion. The camera position should minimize occlusion of left-turning vehicles when the approach view is at an angle.
- The recommended mounting height is 20 to 35 feet. The suggested rule is a 1 to 10 ratio of the mounting height to the distance to the detection zone. A low mounting height may cause occlusion of approaching vehicles.
- Detectors should be in the range of 300–400 feet from the furthest detection zone.
- Optical cameras should have a clear view of the headlights of approaching vehicles. Agencies may need to install addition external overhead illumination to reduce false calls due to headlight glare.
- Thermal detectors can be used on east-west approaches to negate the glare from a rising or setting sun. Intersection with poor illumination may benefit from thermal detection.
- 360-degree cameras can detect all approaches to an intersection from a single unit. One camera is generally sufficient for most intersections; however, for large intersections, agencies may need to use two 360-degree cameras:
- For single-camera installation, the camera should be mounted as follows:
    - On the interior side of the intersection.
    - At least 30 feet above the roadway.
    - No more than 75 feet from the center of the intersections.
    - No more than 150 feet from the front of the furthest stop bar.
- For two camera installations, consideration should be given to installing the cameras on opposite corners of the intersection.
- Each camera should be able to radially track and detect vehicles up to 200 feet away.
- If mounted on the mast arm, the camera should be no more than 50 feet from the center of the intersection. Mounting the camera at the height of less than 30 feet reduces the maximum detection distance.

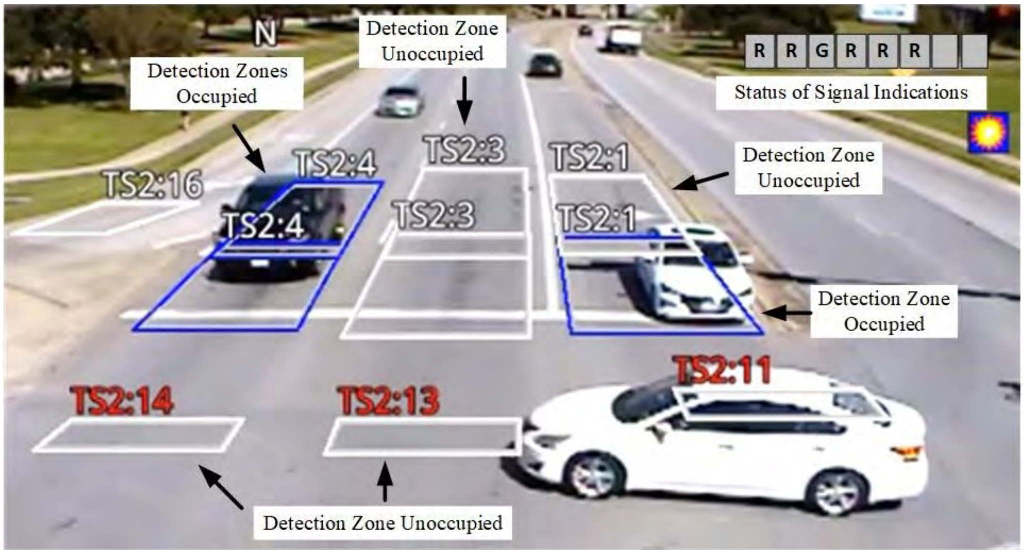
- 360-degree cameras may be co-mounted on the same mounting bracket with either an optical or a thermal advance detector.

- The grade of the approach may affect the detection zone and detector placement.

- The final detector mounting location should be as recommended by the specific manufacturer's representative. Before construction, a site survey should be performed and documented by the contractor and the representative to identify and resolve any potential issues with the video image detection design.

One strength of video detection is the limitless ways in which video detectors can be combined and configured to control the intersection. Operators can place detection zones within a lane or across multiple lanes. Video detection supports both pulse mode and presence-mode detectors, and the latter can have any desired length. Video detection can also support a large number of detection zones. The placement of the detection zones can range from the stop line to several hundred feet in advance of it. Video detection systems can also detect only those vehicles traveling in one direction (i.e., directional detectors). Multiple detection zones can also be linked to each other using Boolean functions (i.e., AND, OR) to increase the accuracy and flexibility of detection at an intersection.

Figure 50 illustrates the location of detection zones on an intersection approach. In this image, the agency has mounted the camera on the mast arm. Each zone consists of a series of rectangular detectors. Detectors are located beyond the stop line to enhance vehicle detection during nighttime hours. The agency has positioned the detection zones to detect the headlights of vehicles stopped behind the stop line.



Source: Texas A&M Transportation Institute.

Figure 50. Photograph. Illustration of stop-line detection zone layout using video detection.

Table 29 shows the strengths and weaknesses associated with using video detection technology in traffic signal applications.

Table 29. Strengths and weaknesses of video detection technologies.(1)

Strengths	Weaknesses
• Monitors multiple lanes and multiple detection zones/lane. • Easy to add and modify detection zones. • Sensors can provide a rich array of data available. • Sensors can provide a wide-area detection when information gathered at one camera location can be linked to another. • Generally, the sensors are cost effective when many detection zones within the camera field of view or specialized data are required.	• Installation and maintenance, including periodic lens cleaning, require lane closure when the camera is mounted over roadway (lane closure may not be required when the camera is mounted at the side of roadway). • Performance is affected by inclement weather, such as fog, rain, and snow; vehicle shadows; vehicle projection into adjacent lanes; occlusion; day-to-night transition (unless using thermal); vehicle/road contrast; and water, salt grime, icicles, and cobwebs on the camera lens. • Some models are susceptible to camera motion caused by strong winds or vibration of the camera mounting structure. • Movement from other structures (i.e., span wires or overhead conductor) within the field of view can cause problems.

Source: Federal Highway Administration.

Radar

Radar or microwave detection is a nonintrusive method of detecting objects that uses the reflection of radio waves to determine the location, direction and speed of objects. It can be used to detect motorized and non-motorized vehicles and is typically applied on an approach where other detection types are not feasible. The cone of detection for most microwave detectors is 30 degrees. The sensor can be set to monitor either approaching or departing vehicles. If the sensors are set to detect approaching vehicles, it will exclude departing vehicles. The microwave detector is directional and requires vehicles to be moving in its observation field for vehicle presence in the detection zone to be registered. The microwave sensors can hold calls as long as the vehicles are moving at least 5 mi/h within the detection zone. When vehicles are stationary in a microwave detection zone, the controller must be configured to use locking memory to retain a call for service. Figure 51 shows an example of this type of detector installed on a traffic signal pole.

Source: Federal Highway Administration.

Figure 51. Photograph. Example of a microwave/radar sensor installed on a traffic signal mast arm.

Table 30 shows the strengths and weaknesses associated with using microwave/radar sensors in traffic signal applications.

Table 30. Strengths and weaknesses of microwave/radar sensor technologies.(1)

Strengths	Weaknesses
• Typically insensitive to inclement weather at the relatively short ranges encountered in traffic management applications. • Direct measurement of speed. • Multiple lane operation is available. • Transmits multiple beams for accurate measurement of vehicle position, speed, and class.	• Sensors may not detect stopped vehicles. • Some models have a problem when used in large steel structures. (i.e., steel bridges). • Overhead conductors within beam cone can cause problems. • Complex setup and maintenance. • Occlusion.

Source: Federal Highway Administration.

Microwave sensors are typically affixed to a support structure (e.g., the span pole or mast arm assembly) or a tall pedestal. To maximize effectiveness, an unobstructed line of sight to the area of detection should be provided. The most desirable location is in front of and above the approaching vehicle. Mounting heights typically range between 15 and 24 feet to minimize opportunities for occlusion and to maximize the line of sight for the detector. Generally, agencies do not use these detectors for left-turn lanes with concurrent through movement.

Combination Sensors

Combination, or hybrid, detectors combine technologies from multiple detection types. This detection technology concept combines other detection technologies into one unit to provide advantages of both components. For example, one sensor could combine video and radar technology to enable the use of video detection at the stop bar and radar detection at the advance detection zones meant for dilemma zone detection or speed measurement.

Other Sensor Technology

Other sensor technologies exist, such as ultrasonic detectors and acoustic detectors; however, agencies generally do not use them for traffic signal applications. The reader may want to consult the *Traffic Detection Handbook*(1) for more information on these types of sensors.

DETECTION OPERATING SETTINGS

How detectors are configured is vital to the overall performance of the intersection operations. This section explains the following detector configuration parameters and operating modes and how they might impact intersection performance:

- Pulse versus Presence Detection Mode.
- Locking versus Non-Locking Memory.
- Delay.
- Extend.
- Detector Switching.

Pulse versus Presence Detection

Detectors can operate in one of two modes—pulse or presence. Detectors that operate in the pulse mode provide a single momentary activation (an “ON”). Detectors that operate in the presence mode provide a continuous activation to the controller for the duration the vehicle is inside the detection zone. Agencies typically do not set intersection detectors to operate in the pulse mode (except when they use a system detector) at signalized intersections.

Locking versus Non-locking Memory

Controller memory is a term that refers to a controller's ability to "remember" (i.e., retain) a detector activation. There are two modes of controller memory—locking and non-locking. In the locking mode, the controller retains the activation even after the vehicle leaves the detection zone. A controller operating in the non-locking memory mode will drop the call as soon as the vehicle leaves the detection zone. An agency might use the locking memory mode at intersections with advance setback detectors (but no stop-bar detectors) to ensure that vehicles stored between the stop bar and the detector receive service from the controller. Generally, agencies will operate stop detectors in the non-locking memory mode, in combination with large detection zones, to prevent the controller from servicing calls by vehicles that vacate the detection zone (e.g., right-turn-on-red vehicles).

Delay

The delay feature is a setting that temporarily disables the output of a detector for a user-defined interval, essentially preventing the controller from recognizing a vehicle activation immediately. The controller will recognize the activation only if the detection zone occupied after the delay timer has expired. This feature can be set either in the controller or the detection system. Agencies will typically apply the delay feature under the following conditions:

- Stop bar detection zones are located in exclusive right-turn lanes.
- Left-turn lanes where crossing or turning vehicles may accidentally traverse through the detection zone, causing an erroneous call for service.

The *Signal Timing Manual, 2nd Edition*(2) provides guidance on the typical time values for different uses of the delay feature.

Extend

The extend feature (not to be confused with a vehicle extension) holds the activation for the user-defined duration after the vehicles have vacated the detection zone.(2) Agencies use the extend feature to combine multiple setback detectors on high-speed approaches to allow vehicles traveling at (or above) a particular speed to extend the green interval long enough to allow an approaching vehicle to reach the next downstream detection zone. Vehicles that reach the next detection zone before the extend timer expires prevent the controller from terminating the phase; otherwise, the signal will terminate and move to the next phase. This feature can also be used to provide lane-by-lane passage time.(2)

The *Signal Timing Manual, 2nd Edition*(2) provides guidance on the typical time associated with using the extend feature for high-speed approaches with multiple detectors.

Detector Switching

Detector switching is another common detector function in modern traffic signal controllers.(2) Detector switching allows detectors to extend a phase during one portion of the cycle and then call another phase during another portion of the cycle. Agencies commonly use detector switching on left-turn lane detectors operating under protective-permissive operations. The detectors in the left-turn lanes can extend the through phase during the permitted portion to provide more time for vehicles making a left-turn maneuver but operate as a call detector for the protected phase during other parts of the cycle.(2)

The *Signal Timing Manual, 2nd Edition*(2) provides guidance on the uses of detector switching.

SYSTEM-LEVEL DETECTION

Detection is a critical component of system control. Under system control, the objective of detection systems changes from identifying gaps in the traffic stream for terminating signal indications to identifying significant shifts in demand and traffic patterns at the arterial or network level. Therefore, the use, design, and placement of the detection sensors differ significantly under system control. Generally, system-level detectors use a combination of volume and occupancy to quantity traffic demands and evaluate changes in these parameters over time to detect shifts in travel conditions in the network. This section describes the needs and requirements of system-level detection for three common types of system-level control operations.

Traffic-Responsive Systems Detection

A traffic-responsive traffic control system is an operating mode that matches coordination plans to field-measured traffic conditions.(2) In this mode, the selection of signal timing plans is from a library of preconfigured signal timing plans that the agency has designed for specific operating conditions. Traffic-responsive timing plans generally cover a wide range of field scenarios. If detection data indicate that the scheduled plan responds inefficiently to the observed traffic patterns, the system switches the scheduled plan to a more suitable alternative.

Traffic-responsive algorithms rely on detector data from system detectors to determine which timing plan or pattern to implement.(2) Volume and occupancy are most commonly used to select timing plans in traffic-responsive operations.(2) Volume is often the most easily obtained and accurate variable. Occupancy generally is less accurate, since it can depend on vehicle profile and other factors. Measuring and detecting occupancy is extremely important since it will continue to increase as intersections become saturated. Volume measures level off to a constant that is proportional to green time divided by average vehicle headway.

As a general practice, system detectors should be located where they can best detect the following changes in traffic conditions:(15)

- Changes in demand levels requiring the selection of a new cycle length.
- Shifts in directional demand that might require different offset plans.
- Changes in cross-street directional demand that might require different split plans.

All system detectors should be outside the area of influence of adjacent intersections.(16) System detectors should be located upstream of the area where standing queues usually form (usually 295 to 345 feet). System detectors should be located beyond the acceleration zone of traffic departing the upstream intersection (usually 230 feet). Short roadway segments that cannot satisfy these criteria should not have system detection. Additional suggestions related to the placement of system detectors for traffic-responsive control include the following:

- Detectors should be located in the center of the traffic flow—not necessarily the center of the marked lane. The center of the flow can be identified by examining the wheel paths in the travel lanes.

- System detectors should be in areas of stable flow and avoid roadway segments that have excessive weaving or high-volume driveways.

- Where a major driveway exists, system detectors should be at least 50 feet downstream of the driveway, provided the detector is at least 200 feet upstream of the stop bar.

- Detectors should not be within 10 feet of any utility access hole, water value, or other appurtenance located within the roadway. This distance is required to permit sufficient clearance to allow work on the utility access hole without damaging the detector.

Detection for ASC

Adaptive Signal Control (ASC) adjusts signal timing plans in real time based on the current traffic conditions, demand, and system capacity. An ASC usually includes algorithms that adjust a signal's split, offset, phase length, and phase sequences to minimize delays and reduce the number of stops. The system requires extensive surveillance, historically in the form of pavement loop detectors, and a communications infrastructure that allows for communication with the central and local controllers.

Various ASCs use a combination of detection layouts to estimate the current state of traffic and adjust the traffic control in a network. Most ASCs locate their detectors in four general areas:(18)

- At the stop bar (e.g., as seen in common actuated operations in the United States and the Sydney Coordinated Adaptive Traffic System [SCATS] ™).

- Advance detectors located 30 to 50 feet (10 to 15 meters) upstream of the stop bar (e.g., as used in Germany by BALANCE and MOTION).

- Upstream (midblock) detectors, which can estimate reasonably long queue lengths (e.g., as seen at some Californian intersections and used by ACS Lite).

- Upstream (far-side) detectors located at the exit point of the upstream intersection (as used by SCOOT®, UTOPIA®, and optionally by RHODES).

The layout of the ASC detection zones correlates with the adaptive control logic that is used to adjust signal timings for the prevailing traffic conditions. Some ASCs use specialized detection layout to measures traffic demands for the adaptive control logic (e.g., in SCOOT, upstream detectors are selected to accommodate for Traffic Network Study Tool [TRANSYT] logic). Other adaptive traffic control systems use the existing detection layouts as inputs into the timing plan selection process (e.g., SCATS logic for stop-bar detectors).

Queue Flushing Detection

In some cases, a traffic control strategy may aim to clear an excessive queue of determined length via an extended phase length for certain operations, referred to as queue flushing. A program may consider using a queue flush if a queue backs onto an uninterrupted flow facility, increasing the probability of rear-end conflicts. Another application for queue flushing is for low-volume approaches that experience predictable spikes in demand (such as a school driveway that requires longer green time to clear queues). During a queue flush, the controller provides a green indication until either the detection system indicates that the queue has cleared or a set length of time has passed such that the program expects the queue to clear.

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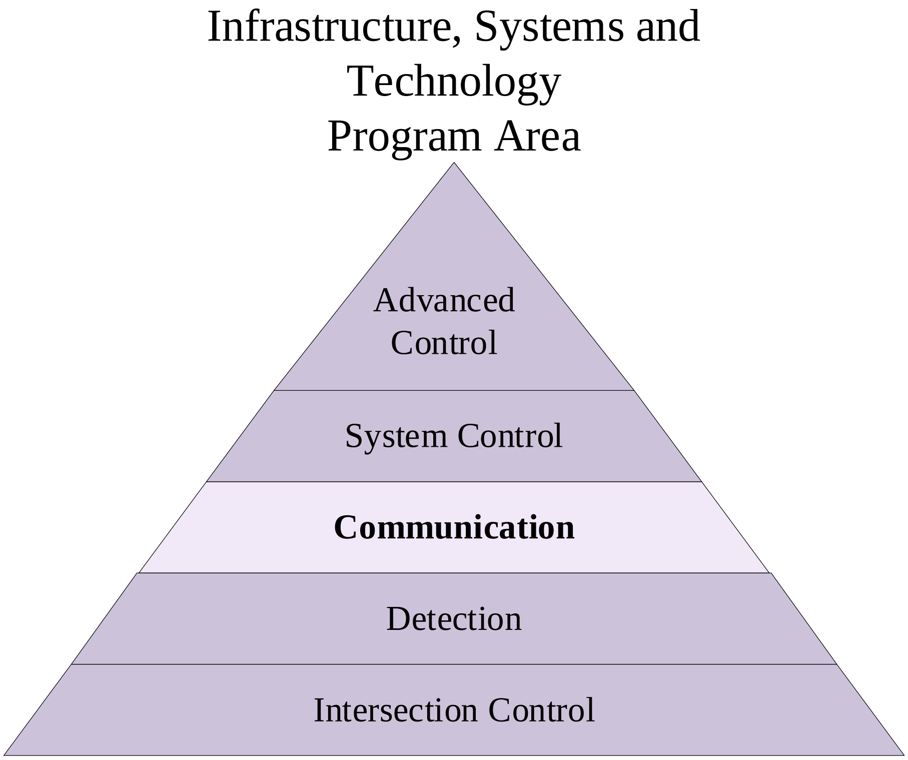
CHAPTER 7. COMMUNICATIONS

As shown in figure 52, the communications network is the next fundamental technological building block of a traffic signal program. The communications network is the mechanism by which data and information are exchanged. It provides a medium that can increase the speed at which functions of other systems are performed when those functions involve data exchange. Planning, implementing, and maintaining communication between traffic control systems and devices is integral to maintaining a state of good repair and effectively managing and operating infrastructure to promote safety, mobility, reliability, and efficiency goals. The inherent value of communications is its ability to provide access to infrastructure and systems that would otherwise require the workforce to physically travel to visit intersections to make observations, collect data, conduct analysis, and modify system settings to improve performance or to ensure the reliability of field infrastructure.

A communication network is a system and technology strategy that supports the following objectives:

- Maintaining infrastructure in a state of good repair.
- Sustaining system technology reliability.



Source: Federal Highway Administration

Figure 52. Diagram. Foundational traffic signal systems and technologies: communications.

A robust and reliable communications system provides agencies with the capability to:

- Remotely monitor the operational activity and maintenance conditions of intersection device components.
- Upload and download signal timing parameters remotely.
- Collect operational metrics remotely from intersections to support performance assessments.
- Obtain visual confirmations of reported field conditions and operational issues.
- Configure and update software and firmware of infrastructure field devices remotely.
- Synchronize the devices at multiple intersections to a common time reference.
- Implement corridor- or system-level changes in traffic signal operations in response to events or unusual field conditions.
- Provide center-based traffic signal priority operations.
- Provide for the direct transfer of signal plans and timing information to vehicles.

Table 31 shows how these traffic signal program capabilities support the attainment of agency objectives.

This chapter describes common systems and technologies that agencies use when deploying communication systems. The chapter also outlines some of the advantages and disadvantages of a variety of communications architectures and technologies agencies frequently use when designing and implementing communication systems for traffic signals.

The following are key resources that can be consulted when designing and selecting communications systems and technologies for traffic signal systems:

- *Traffic Control Systems Handbook*—Chapter 9: Communications.(1)
- *Communications Handbook for Traffic Control Systems*.(2)
- *Telecommunications Handbook for Transportation Professionals: The Basics of Telecommunications*.(3)
- *Model Systems Engineering Documents for Central Traffic Signal Systems.*(4)

Table 31. Relationship between program and operational objectives and the communications system.

Communications System Functions	Responsiveness to Stakeholder Needs	Comply with Agency Policies and Standards	Sustain Infrastructure in State of Good Repair	Minimize Life-Cycle Costs	Safe Assignment of ROW	Appropriate Distribution of Green	Provide Smooth Flow	Maximize Throughput	Manage Queues	Minimize Delay for Prioritized Modes
Monitor the status traffic signal control devices remotely.	X	–	X	X	–	–	–	–	–	–
Upload and download signal timing parameters remotely.	–	–	X		–	–	–	–	–	–
Collect intersection performance metrics.	–	–	X	–	–	–	–	–	–	–
Configure and update field device operating system remotely.	–	–	X	–	–	–	–	–	–	–
Synchronize the devices at multiple intersections to a common time reference.	–	–	X	–	–	–	X	–	–	–
Implement corridor- or system-level changes in traffic signal operations in response to events or unusual field conditions.	X	–	–	–	–	–	–	–	–	X
Provide center-based traffic signal priority operations.	X	–	–	–	–	–	–	–	–	X
Provide for the direct transfer of signal plans and timing information to vehicles.	X				X	–	–			X

“X”= Objective Supported Directly; “–” = Objective Not Supported Directly

Source: Federal Highway Administration.

KEY CONSIDERATIONS IMPACTING COMMUNICATIONS TECHNOLOGY SELECTION

The following sections describe several factors to be considered when designing and selecting communications systems and technologies for traffic signal operations.

Throughput and Data Transfer Needs

The selected communication technology should provide the bandwidth to facilitate the data transfers needed to support the systems identified by the agency. In digital communication, bandwidth is defined as the throughput (or average rate of completed data transfers) through a communications path.(2)

One key factor in determining the required bandwidth is the desire of the agency to stream video from field devices. Video streaming allows the operator to view real-time traffic conditions from a remote facility. Video allows agencies to respond quickly and efficiently to emergencies and undesirable traffic conditions. However, the ability to stream video requires high bandwidth, which increases the cost of the system and limits the types of communication mediums.

The speed at which devices need to transfer data to accomplish identified operational strategies should also be considered. Some functions, such as syncing clocks once a day or downloading and uploading traffic signal timing plans, are not dependent on real-time data transfer. Some strategies, such as the broadcast of signal phasing and timing data (SPaT data) from the infrastructure to vehicles, require real-time transmission. Just like bandwidth, the required speed of data transfer will dictate the communication technologies used.

Latency

Latency is defined as the time difference between when a source transmits a data value and when a source receives the same data value. It is a measure of how long it takes to complete the transfer of data between two devices.

Latency is impacted by the types of protocols used to establish connections and to transfer data. In communications, a protocol is a set of rules that allow two or more devices in a communication system to transmit information over any media. Protocols cover authentication, error detection and correction, and signaling. Protocols also control the formatting (structure, syntax, semantics, and synchronization) and data elements of the messaging. In protocols that require a lot of back-and-forth (“handshaking,” error checking, etc.), high latency can slow the data rate down to far below the nominal bandwidth. In protocols that do not require much back and forth (such as video streaming), high latency is less damaging.

Reliability

A communication system is reliable when messages are guaranteed to reach their destination complete, uncorrupted, and in the order they were sent. It is a measure of the accuracy and repeatability of the data and is a function of the amount of data transferred and the physical separation of the sender and the receiver.

Different management and control processes employed by systems impose different requirements on communications in terms of reliability, latency, and bandwidth. It is possible to achieve high operational reliability by avoiding the use of low-reliability communications for those functions that require high reliability. For example, an agency may elect to use a low-reliability communication technology for transmitting video images to a control center, depending on the context in which it is used (such as if it is not directly impactful to the operational need of the traffic signal system). Low-reliability communications technology may also be used to support functions that do not require real-time interaction (e.g., management of traffic signal controller databases). However, high-reliability communications may be needed to support certain traffic signal control and management functions (such as a central-based adaptive control system or a real-time status display of indications at each traffic signal). Agencies should perform an analysis of the critical functions where a loss of communication would threaten public safety or negatively impact a primary function of the transportation system. Just like with bandwidth and latency, a high level of reliability typically increases the cost of the system and equipment requirements.

Fixed Path versus Broadcast

Fixed-path communications are links serving stationary entities in which a fixed path of data is transmitted and received. Broadcast communication involves a flow of information using a protocol that enables others who know how to listen to that channel to receive the information. Fixed-path communications require the operator to be at the device (field device or computer) to monitor or control the physical objects. If the communications system broadcasts data, the operator has access from anywhere for greater flexibility.

Leased-Line Communications

Historically, most agencies have preferred to own their own wired communications infrastructure; however, leasing a landline service is an alternative to jurisdiction-owned cable. This type of communication is good for areas with limited ROW and rolling terrain. It offers flexibility to agencies because of the low cost for setting up a communications network; however, leased landline communications can result in high operational costs, especially if an agency requires continuous communication. Leased-line communications also provide agencies with opportunities to have external parties handle maintenance. A leased-line communications system is good for transporting video images back to a traffic management center.

Table 32 lists some of the advantages and disadvantages associated with leased-line communications.

Table 32. Advantages, disadvantages, and Limitations of leased-line communications.(3)

Advantages	Disadvantages/Limitations
• Network infrastructure already in place. • Lower cost for installation and design. • A franchise agreement may provide for government use of cable and bandwidth at a reduced rate. • A good level of service for subscribers is provided.	• Some leased-line operations may have equipment or channel limitations. • Can result in higher (and recurring) operations costs. • Video channels take up most of the available bandwidth. • Only the least desirable frequencies are available for channels, which are susceptible to noise and inferences. • Area coverage and network layout may not coincide with traffic signal location.

Source: Federal Highway Administration.

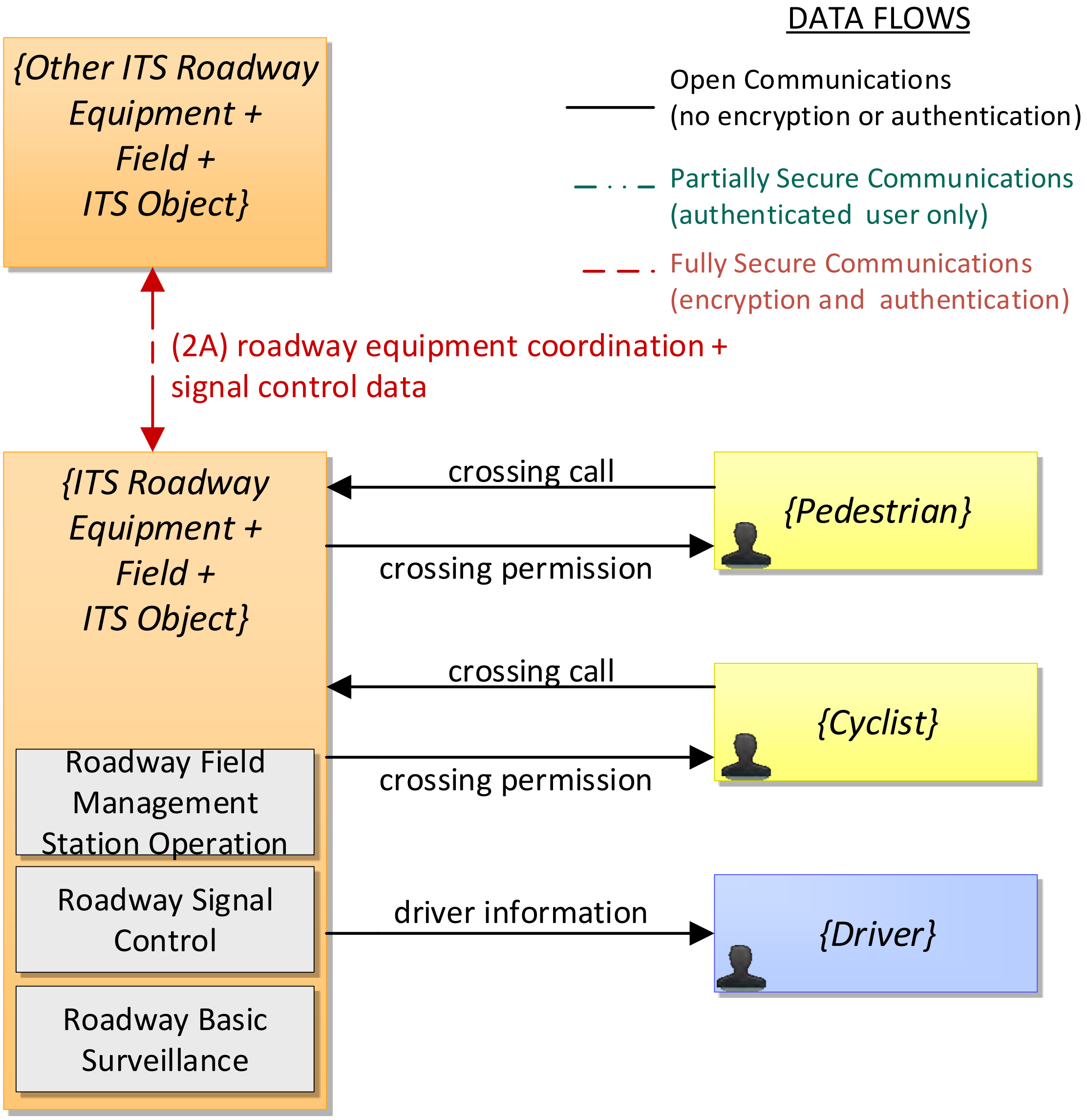
COMMUNICATIONS ARCHITECTURES

A traffic signal system uses several different types of communications architectures. To attain program objectives, information needs to flow between devices in the field, between a traffic management center and devices in the field, and, in some cases, between centers. This section describes the different types of communications architectures using *National ITS Reference Architecture*, (also known as the Architecture Reference for Cooperative and Intelligent Transportation, or simply ARC-IT) terminology.(5)

Peer-to-Peer Communications

Peer-to-peer (P2P) communications describe the direct flow of information between field devices. P2P communications transfer information between sensors and driver information systems (e.g., dynamic message signs, highway advisory radio, variable speed limit signs, dynamic lane control signals, etc.) and control devices (e.g., traffic signals, ramp meters, etc.). In traffic signal control, P2P communications pass information directly from one traffic signal controller to one another without the need for a central server. They can also transmit information between devices within the cabinets via a local computer in a network.

Figure 53 shows an example of the types of information flows that exist in the P2P communications architecture. Table 33 provides a description of the types of information that are communicated in these information flows.



Source: USDOT ITS Joint Program Office

Figure 53. Graphic. P2P information flows to support traffic signal management and operations.(6)

Table 33. Description of the types of P2P information flows supporting traffic signal management and operations.[(6)]

Information Flow	Description
Crossing call	Nonmotorized user request to cross the roadway. This call may be an overt (e.g., pushbutton) request from a pedestrian or the physical presence of a pedestrian or cyclist that can be detected by sensors or surveillance systems.
Crossing Permission	Information provided to guide and warn pedestrians at crossings, including crossing permission, crossing time remaining, and real-time warnings of safety threats.
Driver information	Regulatory, warning, and guidance information provided to the driver while enroute to support safe and efficient vehicle operation.
ROW request notification	Notice that a request has occurred for signal prioritization, signal preemption, pedestrian call, multimodal crossing activation, or other source for ROW.
Roadway equipment coordination	The direct flow of information between field equipment. This flow includes transfer of information between sensors and driver information systems (e.g., dynamic message signs, highway advisory radio, variable speed limit signs, dynamic lane signs) or control devices (e.g., traffic signals, ramp meters), direct coordination between adjacent control devices, interfaces between detection and warning or alarm systems, and any other direct communications between field equipment.

Source: USDOT ITS Joint Program Office

Center-to-Field Communications

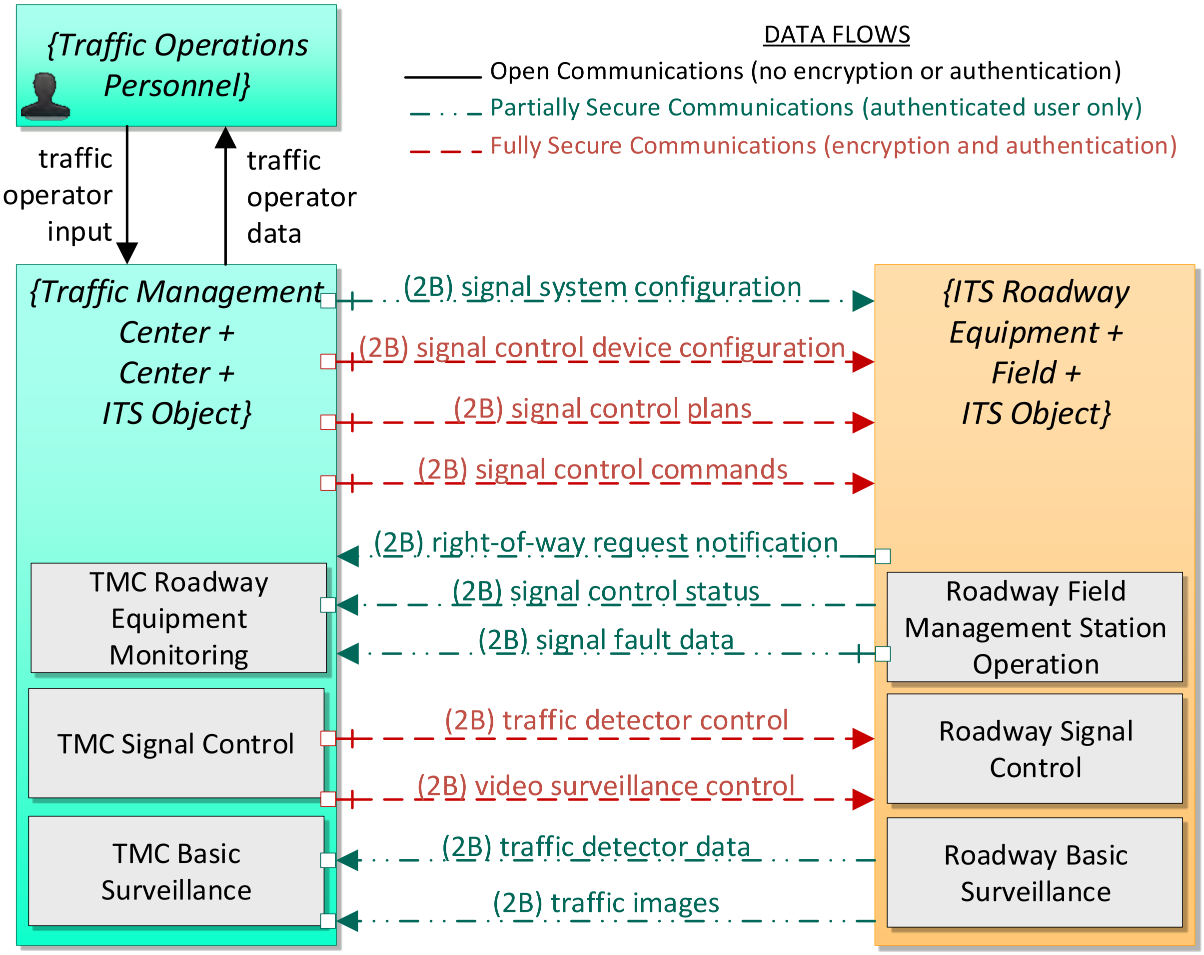
Center-to-field (C2F) communications refer to the type of communications that occur between a central system and multiple control or monitoring devices managed by that center. Most applications of these types of communications involve a center system communicating with various devices at the roadside or on agency vehicles An example of a central system is a traffic signal management system that monitors, manages, and controls the operation of multiple traffic signal controllers in a region. The center system may send instructions to the traffic signal controllers to change signal timings as traffic conditions change, and the controllers send status and traffic flow information to the central system's computer. Other examples of this type of communications include the following:

- A system onboard a transit vehicle that is communicating with a traffic signal device to facilitate transit priority.

- A freeway management system that is communicating with detectors and ramp meters on freeways.

- A traffic management system that is controlling roadway lighting, CCTV cameras, dynamic message signs, advisory radio transmitters, environmental sensors, and traffic count stations on roadways.

Agencies use this communication system design in environments where a traffic center system routinely polls each field device individually. Figure 54 shows the information flows typically supported by a C2F communications architecture for traffic signal management and operations. The figure shows the physical architecture view of the Traffic Signal Control Service Package described in the *National ITS Reference Architecture*. Table 34 lists the types of information flows that are typically supported by a C2F architecture.



Source: USDOT ITS Joint Program Office.

Figure 54. Graphic. C2F information flow to support traffic signal management operations.(6)

Table 34. Types of C2F information flows supporting traffic signal management and operations.(6)

Information Flow	Description
Signal control commands	Control of traffic signal controllers or field masters, including clock synchronization.
Signal control data	Information used to configure local traffic signal controllers.
Signal control device configuration	Data used to configure traffic signal control equipment, including local controllers and system masters.
Signal control plans	Traffic signal timing parameters, including minimum green time and interval durations for basic operation and cycle length, splits, offset, phase sequence, etc., for coordinated systems.
Signal control status	Operational and status data of traffic signal control equipment, including operating condition and current indications.
Signal fault data	Faults reported by traffic signal control equipment.
Signal system configuration	Data used to configure traffic signal systems, including configuring control sections and mode of operation (time-based or traffic-responsive).
Traffic detector control	Information used to configure and control traffic detector systems, such as inductive loop detectors and machine vision sensors.
Traffic detector data	Raw and/or processed traffic detector data that allow derivation of traffic flow variables (e.g., speed, volume, and density measures) and associated information (e.g., congestion, potential incidents). This flow includes the traffic data and the operational status of the traffic sensor system.
Traffic images	High-fidelity, real-time traffic images suitable for surveillance monitoring by the operator or for use in machine vision applications. This flow includes the images and meta data that describe the images.
Traffic operator data	Presentation of traffic operations data to the operator, including traffic conditions, current operating status of field equipment, maintenance activity status, incident status, video images, security alerts, emergency response plan updates, and other information. These data keep the operator appraised of current road network status, provide feedback to the operator as traffic control actions are implemented, provide transportation security inputs, and support review of historical data and preparation for future traffic operations activities.
Traffic operator input	User input from traffic operations personnel, including requests for information, configuration changes, commands to adjust current traffic control strategies (e.g., adjust signal timing plans, change DMS messages), and other traffic operations data.
Video surveillance control	Information used to configure and control video surveillance systems.

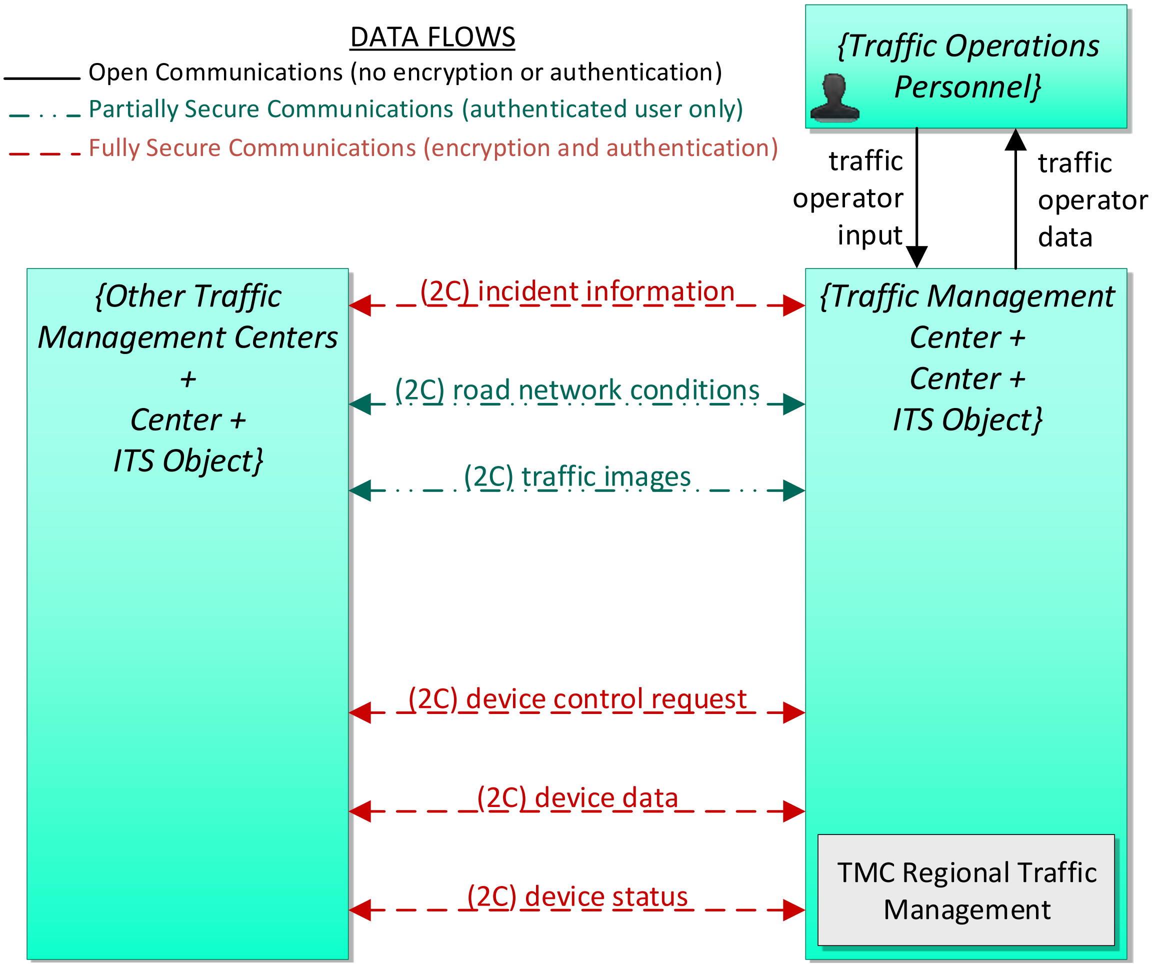
Source: USDOT ITS Joint Program Office.

Center-to-Center Communications

Center-to-center (C2C) communications involve messages sent between two or more traffic management center systems. C2C communications support regional traffic management strategies that involve interjurisdictional, real-time, coordinated traffic signal control systems and coordination between freeway operations and traffic signal control systems within a corridor. Other examples of this type of communication include the following:

- Two or more traffic signal systems exchanging information (including second-by-second status changes) to achieve coordinated operation of traffic signals managed by the different systems and to enable personnel at one center to monitor the status of signals operated from another center.
- A transit system reporting schedule adherence exceptions to a transit customer information system and to a regional traveler information system, while also asking a traffic signal management system to instruct its signals to give priority to a behind-schedule transit vehicle.
- An emergency management system reporting an incident to a traveler information system, or a freeway, traffic signal or transit management system.
- A freeway management system informing an emergency management system of a warning message just posted on a dynamic message sign on the freeway in response to its notification of an incident.
- A weather monitoring system informing a freeway management system of ice forming on the roadway so that the freeway management system can post warning messages on dynamic message signs as appropriate.

Figure 55 shows how information might flow between two traffic management centers to support regional traffic signal management and operations. Table 35 describes the types of information flows that agencies support using C2C communications.



Source: USDOT ITS Joint Program Office.

Figure 55. Graphic. C2C information flows to support regional traffic signal management and operation.(6)

Table 35. Description of the types of C2C information flows supporting regional traffic signal management and operations.(6)

Information Flow	Description
Device control request	Request for device control action.
Device data	Data from detectors, environmental sensors stations, roadside equipment, and traffic control devices, including device inventory information.
Device status	Status information from devices.
Incident information	Notification of existence of incident and expected severity, location, time, and nature of incident. As additional information is gathered and the incident evolves, updated incident information is provided. Incidents include any event that impacts transportation system operations, ranging from routine incidents (e.g., disabled vehicle at the side of the road) to large-scale natural or human-caused disasters that involve loss of life, injuries, extensive property damage, and multijurisdictional response. This information flow also includes special events, closures, and other planned events that may impact the transportation system.
Road network condition	Current and forecasted traffic information, road and weather conditions, and other road network status. Either raw data, processed data, or some combination of both may be provided by this flow. Information on diversions and alternate routes, closures, and special traffic restrictions (lane/shoulder use, weight restrictions, width restrictions, HOV requirements) in effect is included.
Traffic images	High-fidelity, real-time traffic images suitable for surveillance monitoring by the operator or for use in machine vision applications. This flow includes images and metadata that describe the images.
Traffic operator data	Presentation of traffic operations data to the operator, including traffic conditions, current operating status of field equipment, maintenance activity status, incident status, video images, security alerts, emergency response plan updates, and other information. These data keep the operator apprised of current road network status, provide feedback to the operator as traffic control actions are implemented, provide transportation security inputs, and support review of historical data and preparation for future traffic operations activities.

Information Flow	Description
Traffic operator input	User input from traffic operations personnel, including requests for information, configuration changes, commands to adjust current traffic control strategies (i.e., adjust signal timing plans, change DMS messages), and other traffic operations data entry.

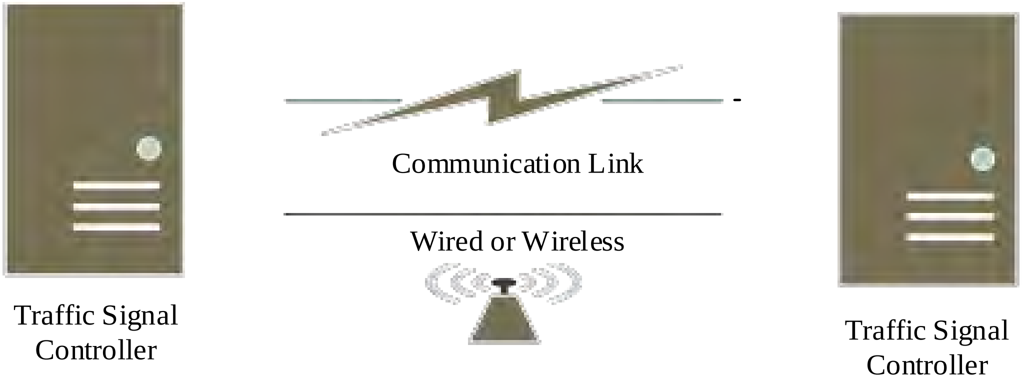
Source: USDOT ITS Joint Program Office.

NETWORK TOPOLOGIES

Topology describes the manner of the physical connection between two or more devices in a communications network. Network topology is independent of transmission media (transmission media is discussed below).

Point-to-Point

In a point-to-point system, a dedicated communication link connects two devices or a device and a controller. Point-to-point communications may be performed by a wired or wireless connection between devices. Leased lines, microwave radio, and two-way radio communications are examples of point-to-point communications. Point-to-point communications dedicate bandwidth to only two devices and therefore have the potential for the most reliable communications, constrained only by the inherent reliability of the communications technology used. Point-to-point communication provides the simplest connectivity of network topologies. Typically, agencies use this method of communication when the devices are near each other. Figure 56 is an illustration of a point-to-point communications architecture.



Source: Federal Highway Administration

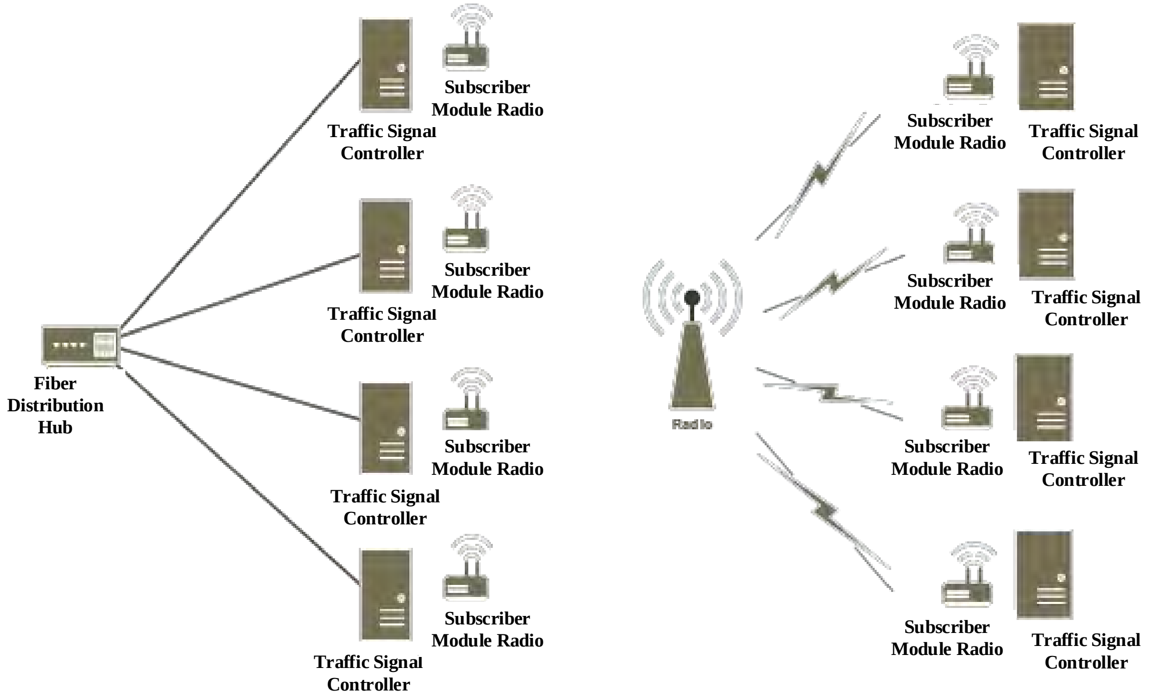
Figure 56. Graphic. Illustration of point-to-point network topology.

Two types of network topologies exist that provide point-to-point communications: linear and ring networks.(2) In a linear network, the devices connect linearly (i.e., start at the first node and connect to the next node, which connects to a third node, and so on.). If the connection to any node or link is lost, then the entire exchange of information is disrupted. Ring networks are designed to overcome this weakness of a point-to-point system. Placing the nodes so that they can always communicate with an adjacent node helps to ensure an available communication path. Ring networks can be unidirectional (the communication signal always travels in one direction around the ring) or bidirectional (the communication signal can travel in either direction).

Point-to-Multipoint

A point-to-multipoint communications architecture connects one device to multiple devices. In this layout, one device is designated as the primary device, while one or more other devices are considered secondary. As shown in figure 57, point-to-multipoint networks can be either wired or wireless.

Agencies can use either a star or mesh configuration for providing point-to-multipoint communications. A star network is simply a multipoint communication system that allows one node to communicate with many nodes (or many to one). Mesh networks are a combination of the star and ring topologies.



Point-to-Multipoint Communications Using a Wired Medium

Point-to-Multipoint Communications Using a Wireless Medium

Source: Federal Highway Administration.

Figure 57. Graphic. Examples of point-to-multipoint network topology.

TRANSMISSION MEDIA

Over the years, agencies have used many different types of media types for providing communications in traffic signal systems. Each medium has advantages and disadvantages, and no medium fits all situations. Transmission media can be either wired or wireless. A high-level overview of the different communications medium commonly used with traffic signals follows.

Wired

Wired communication refers to the transmission of data over a wire-based communication medium. Wire-based technologies include twisted-pair copper wire, coaxial cable, and fiber-optic cable. Most of the traffic signal systems today rely on the use of fiber-optic communication technology. Fiber optics are capable of accommodating far more signals than the older copper wiring used in generations past yet still maintain the integrity of the signal over longer distances.

Compared to wireless communication systems, wired communication systems are generally considered to be more robust in terms of bandwidth, latency, and security but can be costly to operate and maintain. Wired communications systems also require ROW to install.

Twisted-Pair and Coaxial Cable

Many transportation agencies have communication systems that use twisted copper wires or coaxial cable to connect devices. Many consider these technologies to be legacy systems. Although coaxial cable is still commonly used to connect video detection to the controller cabinet, agencies rarely use it as communication media for longer distances.

Fiber Optics

This landline technology has become the most common choice of media for traffic control systems since the 1980s. This technology is most common in point-to-point data communication applications and serves as the backbone of medium and large freeway surveillance systems and centralized traffic signal systems. Fiber optics support the bandwidth and reliability needs for a wide array of traffic control and monitoring systems, such as video surveillance and monitoring, system control, performance monitoring, and traveler information devices.(3) Fiber optics provide high-capacity networks for high-volume communications.

Table 36 lists some of the advantages and disadvantages associated with fiber-optic communications.

Table 36. Advantages, disadvantages, and limitations of fiber-optic communications.(3)

Advantages	Disadvantages/ Limitations
• The technology is capable of carrying high volumes for video and data. • The technology is a cost-effective option for voice and data. • Supports wider bandwidth and has lower attenuation latency (allows longer cable runs).	• Most systems require time division multiplexing (TDM), which is implemented on a bit-by-bit basis to serve a large area. • May require specially trained personnel to manage and maintain the media.

Source: Federal Highway Administration.

Wireless

Technically, all wireless communication is radio-based—what changes in the technology is the frequency over which a system or device transmits the data. Typically, devices that transmit in the lower frequency ranges are limited in the amount of data that can be transmitted, while devices that operate in the higher frequency ranges can transmit more data. For example, if an agency needs to transfer only digital data, then devices that operate in the lower frequency ranges might be suitable; however, if the desire is to stream video or transmit images, devices that transmit in the higher frequency ranges might be more appropriate. The distance the signal must travel also impacts the technology selected. Devices that operate in the lower frequency ranges are generally more appropriate for longer transmission lengths and less subject to line-of-sight restrictions. Devices that operate in the higher frequency ranges are more suitable for shorter distances and require a more direct line of sight between two devices. However, devices that broadcast in the lower frequency ranges are more susceptible to interference from more powerful devices than devices that operate at higher frequencies. Depending on the operation frequency, some wireless communications systems may require a license from the Federal Communications Commission (FCC). Sometimes agencies will use wireless technologies to extend wired networks that already uses a particular type of communications protocol (i.e., ethernet over a fiber-optic cable). In general, the type of wireless communications an agency selects is primarily a function of the following:

- The amount (and type) of data to be transmitted.
- The distance over which the data is to be transmitted.
- The amount of interference that exists in the environment.
- The type of communications infrastructure that already exists in their region.

Some agencies use a combination of wired and wireless communications technologies to accomplish their communications strategies.

Spread Spectrum Radio

These devices can be licensed or unlicensed by the FCC and broadcast in the 900 MHz and 2.4 GHz frequency ranges. These systems often employ spread spectrum techniques that spread the transmission over a group of radio frequencies using either frequency hopping techniques (which means using one frequency at a time before jumping to another frequency at predefined intervals) or spreading the transmission over several frequencies at the same time. Spread spectrum techniques help secure the transmission. Spread spectrum modulation techniques have a principal advantage over other radio techniques in that they distribute a transmitted signal over a wide range of frequency spectrums, which minimizes the amount of power present on any given frequency. The net result is a signal that is below the noise floor of conventional narrowband receivers but is still within the minimum receiver threshold for a spread spectrum receiver. Although a spread spectrum receiver can detect very low signal powers, the receivers are also designed to reject unwanted carriers, including signals that are considerably higher in power than the desired spread spectrum signal. Each spread spectrum transmitter and receiver use unique spreading sequences that effectively cancel the noise. Generally, these devices connect to the traffic signal controller via a coaxial cable, such as an RS-232 or an RS-485 cable.

Many deployers consider spread spectrum radio to be a legacy technology. Although these devices better penetrate objects and have fewer stringent line-of-sight requirements than devices that use higher frequencies, they typically do not provide the bandwidth that modern radio communication systems do.

summarizes the advantages, disadvantages, and limitations of using spread spectrum technologies in a traffic signal application.

Wireless Ethernet Broadband

These radios can support the transmission of an IP-based protocol, which supports the networking of devices. These devices use the IEEE 802.11 family of protocols that supports Wi-Fi communications. Agencies typically use these devices when they wish to operate their signals as part of a wireless local area network (WLAN). This technology is the technology used to provide wireless computer networks. Traditionally, agencies will procure radios in the 2.4 GHz or the 5.8 GHz band. These radios have high transfer rates of data transfer (20 to 60 megabytes per second) that can support the transfer of not only digital data but also streams of video data. Because of the proliferation of devices operating in the 2.4 GHz band, many agencies procure devices that operate in the 5.8 GHz range. These devices tend to have fewer interference problems and support high data transfer rates. The 5.8 GHz devices can also support higher levels of security. Table 38 summarizes the advantages, disadvantages, and limitations of using wireless ethernet broadband technologies in a traffic signal application.

Table 37. Advantages, disadvantages, and limitations of spread spectrum communications.(3)

Advantages	Disadvantages/Limitations
• Can resist the effects of multipath interference. • Flexible installation. • Does not require cable installation and maintenance. • Does not require FCC channel use approval if in the 902–928 MHz bandwidth.(7) • Extremely efficient in high-noise environments. • Use low transmitter power. • Can be used in a mixed system of wired or radio interconnect controllers. • No landline interconnect requirement. • Low equipment cost. • Potential for a broad range of traffic control system applications.	• Require line-of-sight path; however, the signal can be bent around obstacles in some cases. • Topography can affect transmission range (typical transmission range is from 0.3 to 6 miles) • Require an external antenna and cable. • Require more sophisticated equipment and specialized technicians. • Unprotected channel space.

Source: Federal Highway Administration.

Table 38. Advantages, disadvantages, and limitations of wireless ethernet broadband communication.(3)

Advantages	Disadvantages/Limitations
• No need for physical medium (propagates through the atmosphere). • No major installation or maintenance costs. • Limited ROW requirements. • Flexible implementation. • Commercial equipment available off the shelf. • Used in numerous traffic signals. • Low latency.	• The designer must account for fading (variation of received signal power) within the system power budget. • Complex system design and installation. • Line-of-sight path constraints. • Turnaround time considerations. • Systems require external antennas and cable. • Terrain and inclement weather may limit the range and operating frequency. • Need to chain repeaters to extend a line of sight, which requires a small cabinet with power.

Source: Federal Highway Administration.

Cellular

Wireless cellular technologies use commercial cellular services to provide point-to-point communications over a large geographic area. Through a fixed-location transceiver, mobile networks follow a hexagonal cell that provides a slight overlap to ensure a network signal. This network can maximize frequency utilization while minimizing interference among users of the same frequency. However, these technologies tend to be unreliable when paired with traffic detection devices. Cellular technologies can support high-speed data rates with fast broadband networks and can provide connections in areas where other types of networking cannot reach. Cellular technologies also support on-demand types of services when a continuous data stream is not necessary. Table 39 summarizes the advantages, disadvantages, and limitations of using cellular technologies in a traffic signal application.

Table 39. Advantages, disadvantages, and limitations of cellular communication.(3)

Advantages	Disadvantages/ Limitations
• Cost effective for infrequent communications. • Eliminates the need to connect to telecommunications service point or provide owned landline. • Effective for controlling portable changeable message signs. • Effective for temporary installations. • Cellular modems available off the shelf. • Cellular networks cover most of the United States. • Can be an analog or digital system.	• Data plan subscription needed (monthly cost). • Vast variability in data plan prices from providers. • Typically, limited providers in any one area. • Data quality can be limited based on the connection and location of wireless network. • Gaps in coverage, particularly in rural areas. • Malfunctions rely on the service provider to fix the issue. • Online security is needed.

Source: Federal Highway Administration.

EMERGING COMMUNICATIONS TECHNOLOGIES

Communication technologies continue to advance and evolve. Below are some emerging technologies that agencies could potentially use to support future operations.

Wireless Mesh Networks

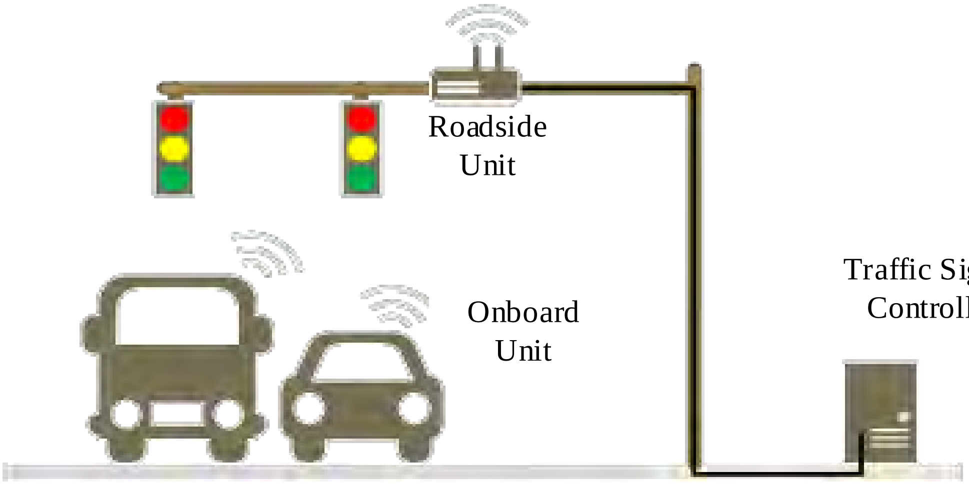
A wireless mesh network is a network of fixed networking stations interconnected together in a mesh fashion.(8) In a mesh network, each base station acts as a node that continuously exchanges information about network conditions with all adjacent nodes across the entire set. Mesh networks do not retransmit all the data passing through among a set of base stations. Most mesh networking systems dynamically adjust radio attributes and channels to create the least possible interference and the greatest possible coverage area to achieve the highest possible throughput. Because of the dynamic routing capabilities of mesh technologies, a base station might send a packet of data to just one other node or it may route the packet through a series of nodes to reach the destination base station.

The primary advantage of a wireless mesh network is that it can dynamically adjust the routing of data. If a node is powered down or crashes, the network can sense the outage and dynamically adjust the transmission pathway. As long as every node can continue to communicate with at least one other node, the network remains operational.

The primary disadvantage of mesh technology is that it tends to use proprietary protocols. Early attempts at establishing this technology did not achieve standardization, and as a result, mesh system technologies are generally not interchangeable.

Vehicle-to-Infrastructure Communication

Vehicle-to-infrastructure (V2I) communication is the next generation of ITS communications technology. V2I technologies capture vehicle-generated traffic data, wirelessly providing information, such as advisories, from the infrastructure to the vehicle that inform the driver of safety, mobility, or environment-related conditions. State and local agencies are likely to install V2I infrastructure alongside, or integrated with, existing ITS equipment. V2I provides short-range communication links that allow vehicles on the roadway to communicate with the adjacent traffic signal controller. Figure 58 provides an illustration of a V2I communications architecture.



Source: Federal Highway Administration.

Figure 58. Graphic. Illustration of vehicle-to-infrastructure communications.

Early deployments of V2I communication used dedicated short-range communications (DSRC); however, the Federal Communications Commission reallocated the bandwidth frequency previously allocated to DSRC. Now, connected vehicle applications are using a cellular vehicle to everything (CV2X) technologies to broadcast messages. The key functional requirements of this technology include the follows:

- *Low latency*—The delays involved in opening and closing a connection are very short—on the order of 0.02 seconds.
- *Limited interference*—The short communications range (~1000 meters) limits the chance of interference from distant sources.

CV2X allows for active safety applications, such as crash avoidance, through the use of driver alerts based on sophisticated sensing and vehicle communications. Developers have also envisioned several other CV2X applications focused on improving mobility. Examples of these applications include the following:

- Transit signal priority.
- Transit vehicle refueling management.
- Personalized taxi dispatch services.
- Integrated transportation financial transactions (e.g., toll collection, parking payment, and rental car payments and processing).
- Enhanced truck roadside inspection.
- Real-time freight logistics.
- Pedestrian safety at intersections.
- Routing and scene management for emergency services.
- Advanced highway-rail and highway-transit grade crossings.

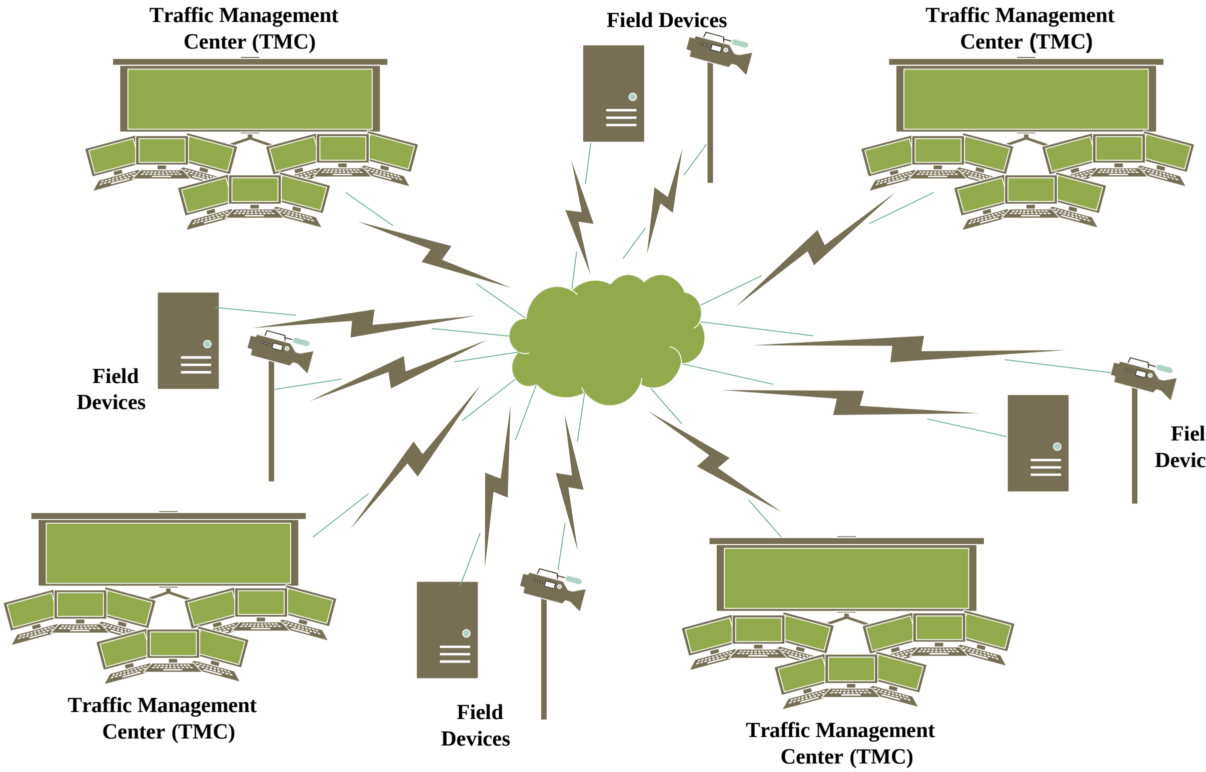
5th Generation Cellular

The evolution of 5th Generation (5G) wireless cellular technologies has expanded upon previous generations of long-term evolution (LTE) data to provide support on smaller wavelength spectrums. 5G technologies allow cellular data to operate on higher bandwidths to potentially produce data rates that provide a high reliability and lower latency to better address scalability issues. Some researchers suggest that both of these targets can be improved simultaneously, while others suggest that achieving reliability at an extremely large scale requires the user to sacrifice latency.(9)

Efforts by both public and private organizations are underway to work together to develop 5G standards to serve a wide range of applications. Standards for 5G appear poised to be developed and adopted in the near future (although this date continues to move with the technology). The new 5G cellular system looks to address many challenges, including improved data communication on high-speed trains, improved three-dimensional connectivity among aircraft, and automated traffic control and driving. In addition, this technology looks to improve network heterogeneity, which consists of the melding of radio access technologies such as Wi-Fi, DSRC, LTE, and varying current and evolving technologies.

Cloud-Based Communications

Cloud communications are internet-based voice and data communications in which telecommunications applications, switching, and storage are hosted by a third party outside of the organization using them, and they are accessed over the public internet.(11) Under a cloud architecture, the signal system deployer is only responsible for the technology of the connection between the device and the cloud provider. Usually, a third party hosts and manages storage, applications, and switching through the cloud, usually for a fee. The customers, in turn, access these services through the cloud and only pay for services that they use. The service provider essentially designs, builds, operates, and maintains the communications infrastructure. All the agency needs to do is provide the technologies to connect devices to the cloud. This type of architectures provides a communication environment that is flexible, immediate, scalable, secure, and readily available. Figure 59 illustrates a typical cloud network.



Source: Federal Highway Administration.

Figure 59. Graphic. Illustration of a cloud communications environment.

COMMUNICATION PROTOCOLS

Communication protocols describe the rules (e.g., format, content, syntax, and semantics) that permit the exchange of information between two devices. Protocols govern items such as packet size, transmission speed, error correction types, handshaking and synchronization techniques, address mapping, acknowledgement processes, flow control, routing, address formatting, and others.

Proprietary versus Open Protocols

Proprietary protocols are owned and protected by an individual or single company, and devices supporting this protocol can only communicate with other equipment supporting the same protocol. In these types of systems, the vendor or supplier maintains control of how these technologies communicate and interact with other systems. Advantages of using proprietary protocols for traffic signal systems include the following:

- Proprietary protocols typically offer some specific features and capabilities that are unique to these systems.

- A proprietary protocol system uses components that have been designed to work together, which means that all elements of its devices are perfectly compatible with each other since they are designed to use the same language of communication.

Disadvantages associated with using a proprietary communications protocol for traffic signals include the following:

- A proprietary protocol means that equipment is running on a unique protocol used only by a specific vendor. It makes it difficult to add devices from other vendors to the system later, and the user will likely be restricted to this one supplier for support and purchase of future products.

- A proprietary protocol may require licensing fees.

- Dependence on a single company for maintenance, support, updates, and upgrades occurs, and the potential for poor service, slow response times, and ongoing maintenance costs exists.

Open protocols use standards-based technologies and devices that can be procured through multiple suppliers or vendors. An open communications architecture provides both interoperability and interchangeability of devices. With an open architecture, an agency can procure and install devices from multiple vendors and expect them to function in a similar fashion and perform similar functions. An open communications system tends to lower total life-cycle costs because an agency is not restricted to procuring equipment or technology from a single vendor or supplier.

National Transportation Communications for ITS Protocols

In the past, traffic signal communications systems relied on proprietary protocols for transporting traffic signal information; however, most modern transportation communications systems and devices now use computer networking communications protocols (such as file transfer protocols [ftp], transmission control protocol/internet protocol [tcp/ip], user datagram protocol [udp], hypertext transfer protocol [http], simple mail transfer protocol [smtp], and others) to transport information from one device to another. Standard development organizations (SDOs) such as the Institute of Transportation Engineers (ITE), the Institute of Electrical and Electronics Engineers (IEEE), the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), the Internet Engineering Task Force (IETF), and others produce communications protocol standards.

The National Transportation Communications for ITS Protocol (NTCIP) family of standards provide protocols that transportation infrastructure devices use to communicate and exchange information. NTCIP standards are open, consensus-based data communications standards.(12) When used for remote control of roadside and other transportation management devices, NTCIP-based devices and software can help achieve interoperability and interchangeability. When used between transportation and emergency management centers, NTCIP standards facilitate agency coordination and information sharing.

Interoperability and interchangeability are two key goals of the NTCIP open standards effort. The terms interoperability and interchangeability generally reflect the ability to use multiple brands of a device on the same communications channel, along with the ability to swap them out. For example, the ability to put any brand of NTCIP-conformant traffic signal controller in the same system at the same time reflects interchangeability for that device type. It is for this reason that the NTCIP family of protocols is embraced widely in traffic signal system design and specified in many new system deployments.

One feature of the NTCIP protocols is that it has standardized the types and definitions of the data elements (called objects) that conforming devices exchange. Equipment manufacturers, system integrators, and agencies use these common definitions and data element structures to provide interoperability of devices. The standards also describe the management information base (MIB) for communicating data between devices. The MIB describes the organization of the database that stores the information in the memory area of the device, which the device in turn uses to control the traffic signals and other devices. The MIB is a text document that can be read by a human and converted by a computer into the special instruction language used by the computer. For NTCIP transportation management systems to work, the applications will need to reference many MIB databases. Applicable NTCIP standards that support traffic signal management and operations include the following:

- NTCIP 1103 v03, *Transportation Management Protocols.*
- NTCIP 1104 v01, *Center-to-Center Naming Convention Specification.*
- NTCIP 1201 v03, *Global Object (GO) Definitions.*

- NTCIP 1202 v03A, *Object Definitions for Actuated Signal Controllers (ASC) Interface.*
- NTCIP 1202 v03A-SE01, *Object Definitions for Actuated Signal Controllers (ASC) Interface (TPG-Enabled).*
- NTCIP 1202 v02, *Object Definitions for Actuated Traffic Signal Controller (ASC) Units*.
- NTCIP 1205 v01Amd1, *Object Definitions for Closed Circuit Television (CCTV) Camera Control.*
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- NTCIP 9001 v04, *The NTCIP Guide.*
- NTCIP 9012 v01, *Testing Guide for NTCIP Center-to-Field Communications.*

COMMUNICATIONS NETWORK SECURITY

Traffic signal systems and other ITS devices are subject to security threats, just like any other information technology system.(13) The need for security applies to all physical objects, personnel, and communication links. Agencies can identify potential vulnerabilities in the system and work with security professionals to protect these vulnerabilities from outside intrusions. Once security measures are in place, agencies may want to deploy systems and technologies to monitor constantly against threats and respond quickly to threats. A good way to monitor the security of the system is to set up alerts from the system monitoring software.

The NEMA *TS 8: Cyber and Physical Security for Intelligent Transportation Systems* (14) defines functional cybersecurity attributes along with minimum performance baselines that owners and operators of critical infrastructure transportation systems can use for procurement purposes. NEMA *TS 8* addresses the following products:

- Signal display and signal elements—for example, signal heads, pedestrian displays, and DMSs.
- Fixed, configurable, and programmable traffic controllers and associated cabinet devices, including traffic controllers, conflict monitors (e.g., MMU, CMU), ramp meters, and auxiliary devices.
- Communications interface devices and systems—for example, NTCIP interface units and others.
- Software and firmware modules (e.g., application system software) and traffic management center (TMC) software.
- Mounting, protection, power supply, and fastening equipment (e.g., cabinets and enclosures).

- Computing assemblies for transportation management systems (e.g., incident monitoring, reporting stations, and toll collection and management stations).
- Associated devices for transportation system management control devices (e.g., automatic vehicle location devices, weigh-in-motion systems, and detection devices such as loop detectors, traffic cameras, and ultrasonic sensors).

Physical Security

All IP-addressable devices should be protected from physical access by unauthorized personnel. If an unauthorized person gains access to the traffic control cabinet, they can access the IP network and therefore have access to the entire network. To prevent this intrusion, each traffic control cabinet in the field should have a locking mechanism. As a second layer of protection, central software systems can send alarms when a traffic signal cabinet door is open, allowing the operator to confirm the access was approved or to respond appropriately. Other field devices, such as dynamic message boards, RSUs, weather information systems, and all other IP-addressable devices, should be vandal resistant.

Personnel Security

A threat can also come from inside the agency by someone with authority to access the system. It is important to develop basic guidelines and restrictions for the agency to follow regarding access to the system. Tactics for addressing personnel may include setting the levels of security regarding controls (permissions) and management of the system. Access to TMCs should be limited to those responsible for daily tasks and maintenance, including management and emergency services.

Network Security

Network security refers to the steps an agency takes to protect its communications links. Compromised network security means an unauthorized user can gain access to critical or sensitive data. Appropriate security for a network can be achieved by making users go through several layers of security before being able to access the desired network. The more layers the system has, the more secure it is. The problem that can arise with a robust security protocol is the restriction of access for operators.

Disaster Preparedness

Security applies to more than just unauthorized access to sensitive information. ITS systems must be secure and robust enough to operate reliably in a disaster, either natural or human made. One important component is access to data if the traffic management center is compromised or cannot be accessed physically.

Security Resources

The NCHRP published Project 03-127—*Cybersecurity of Traffic Management Systems*.(15) This report provides recommendations for State and local transportation agencies on mitigating the risks from cyberattacks on the field side of traffic management systems. It summarizes a variety of cybersecurity efforts applicable to the development of web-based assistance tools and provides State and local transportation agencies an overview of cybersecurity efforts.

COMMUNICATIONS SYSTEM PERFORMANCE

This section discusses measures that agencies use to assess the performance of their communication systems. A reported communication failure may result from equipment failure or uncorrected errors during several consecutive polls. Under conditions of communication failure, the controller typically reverts to another operational mode, such as isolated local operation or backup coordination. The following common performance measures can be used to provide real-time quality assessments of communication operations.

Communications Uptime

The major challenge with new systems is providing a sufficient line of sight within the traffic network while maintaining traffic network uptime. (16,17) Uptime is a metric that represents the percentage of time in which hardware, information technology systems, or devices are operational. This metric is used to determine when a system is working versus when it is offline (known as downtime). To combat communication downtime, a bypass is placed in front of the inline device to redirect information when the appliance goes down or becomes inactive. Maintaining active monitoring of high-volume data networks is the only way to keep communication systems running properly and can ensure maximum uptime by:(16)

- Increasing traffic visibility using filtering techniques that send only relevant data to the monitoring tools in use.
- Ensuring zero network downtime in case an inline device stops functioning or requires replacement.
- Combining multiple network points into a single monitoring zone, reducing the costs involved in monitoring many network links.
- Providing efficient monitoring of every critical network data packet.
- Adding new appliances to the network quickly and seamlessly without compromising the quality of the existing network architecture.

Communications Throughput

Conventional polling techniques may result in larger portions of the messages carrying old, unnecessary information. An alternative approach is to apply contention techniques to provide efficient use of channel capacity. As the total demand begins to approach the channel capacity, delays in accessing the network increase greatly, and depending on the applied technique, the channel throughput may decrease with demand. The total demand should be held well below the system’s maximum throughput capacity to ensure acceptable communication service for the traffic system. Typically, restriction of demand to no more than 50 percent of throughput capacity assures acceptable levels of service within the system.(3)

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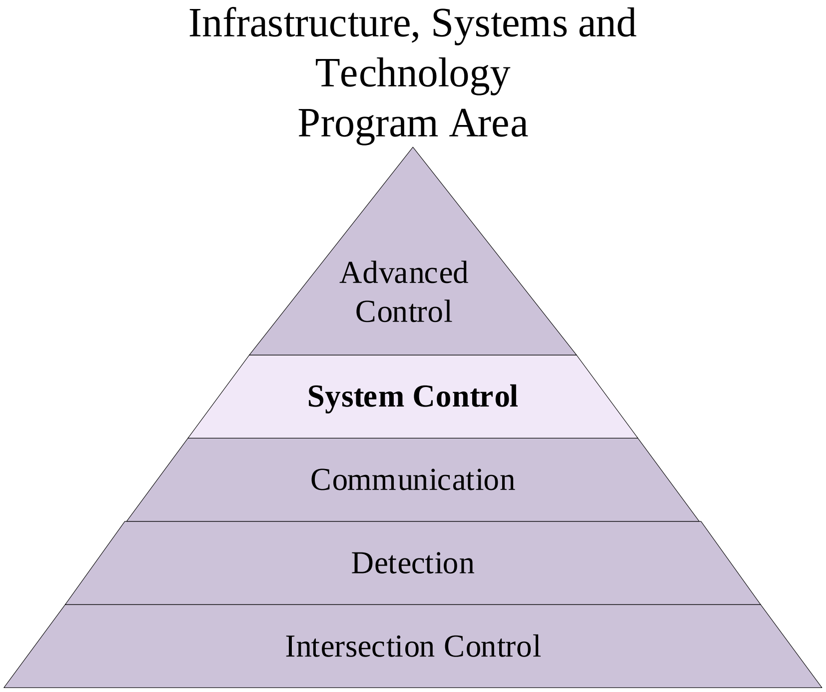
CHAPTER 8. SYSTEM CONTROL

After intersection control, detection, and communication, system control represents the next level of hierarchy associated with traffic signal operations, as illustrated in figure 60. System control provides the capability to coordinate the operation of two or more traffic signals. Coordinated operations is a strategy that directly supports the smooth flow objective to improve traffic flow on the roadway network by eliminating or reducing the duration of unnecessary stops. In congested conditions, system control supports vehicle throughput and queue management strategies. Effective system control requires solid foundations in intersection control, detection, and communications.



Source: Federal Highway Administration.

Figure 60. Graphic. Hierarchy of traffic signal systems and technology: System control.

The National ITS Reference Architecture lists the following as the primary functions of a central traffic signal management system:(1)

- Remotely manage traffic signal operations while providing for control at the local intersection level.
- Collect traffic signal controller operational status and compare it against the control information sent to the center.
- Collect traffic signal fault data from the field.
- Manage (define, store, and modify) control plans to coordinate signalized intersection.

- Implement control plans to coordinate signalized intersections based on data from sensors.
- Manage boundaries of control systems used within the signal system.
- Maintain traffic signal coordination by synchronizing clocks through the system.
- Implement control plans to coordinate signalized intersections based on data from sensors and connected vehicles.
- Adjust signal timing plans in response to signal prioritization, signal preemption, pedestrian calls, multimodal crossing activations, or other requests for ROW.
- Adjust signal timing in response to traffic and environmental parameters at each intersection in real time and adapt so that the traffic network is optimized using the available green time to serve actual traffic demands while minimizing environmental impact.
- Process collected traffic and environmental data from sensors and connected vehicles.
- Support requests from emergency management centers to provide priority to emergency vehicles with signal preemption.
- Monitor, analyze, and store traffic sensor data (such as speed, volume, and occupancy) collected from field elements under remote control for the center.
- Maintain a database of traffic sensors and associated data (including their locations, the type of data they collect, and their owner).
- Remotely control devices to detect traffic in the vicinity of traffic signals.

Table 40 shows how the system capabilities support agency program and operational objectives.

The following is a list of key references that agencies should consult when implementing system control:

- *Traffic Control Systems Handbook.*(2)
- *Signal Timing Manual. 2nd Edition.*(3)
- *Model Systems Engineering Documents for Central Traffic Signal Systems.*(4)
- *Traffic Detector Handbook: 3rd Edition—Volume II.*(5)
- *National Transportation Communications for Intelligent Transportation System Protocol. Field Management Station (FMS)—Part I: Object Definitions for Signal System Masters. (SSM) (NTCIP) 1210v01.*(6)

Table 40. Relationship between program and operational objectives and system control.

System Control Functions	Responsiveness to Stakeholder Needs	Comply with Agency Policies and	Sustain Infrastructure in State of Good	Minimize Life-Cycle Costs	Safe Assignment of ROW	Appropriate Distribution of Green	Provide Smooth Flow	Maximize Throughput	Manage Queues	Minimize Delay for Prioritized Modes
Manage the databases of signal timings for local controller	–	–	X	–	–	X	–	–	–	–
Coordinate/synchronize the time clocks of local controllers	–	–	X	–	–	–	X	–	–	
Select timing plans and coordination strategies	–	–	–	–	–	–	–	–	–	
Provide signal control commands	–	–	–	–	–		X	–	–	–
Monitor the rate of growth and placement of residual queues	–	–	–	–	–	–	–	–	X	–
Communicate requests for service from priority users (through a C2C request)	X	–	–	–	–	–	–	–	–	X
Manage traffic diverting away from freeway that is congested (due to incident)	X	–	–	–	–	–	–	X	X	–
Monitor the effectiveness of local control performance	–	–	X	X	–	–	–	X	X	–
Monitor the operational effectiveness of signal timing plans	–	–	X	X	–	–	–	–	–	–
Monitor the operational status of devices and communication systems	–	–	X	X	X	–	–	–	–	–
Configure control sections and mode of operations (time-based or traffic-responsive) remotely	–	–	X	X	–	–	–	–	–	–
Provide remote management capability to configure traffic signal control equipment, including local controllers and system masters	–	–	X	X	–	–	–	–	–	–

"X"= Objective Supported Directly; "–" = Objective Not Supported Directly

Source: Federal Highway Administration

TYPES OF SYSTEM CONTROL AND COORDINATION

Several levels of system control exist, ranging from simple time-based coordination to complex adaptive system control. Each level of system control provides increasing operational capabilities designed to meet different levels of user needs. However, with increased flexibility comes more complexity and more stringent requirements for system technologies, detection, and communications. Table 41 highlights the difference in the different system-level control types and provides a high-level description of the implementation requirements necessary to support higher system control levels.

Time-Based Coordination

Time-based coordination generally uses fixed timing parameters (e.g., cycle lengths, offsets from adjacent intersections, or phases) and a common time clock to form a predetermined operation plan. Multiple timing plans are developed based on average or typical travel patterns that occur during the day and are activated based on the time of day and day of week or presence of a known or scheduled event. Clock synchronization is essential in time-based system control. Coordination between intersections is maintained by using an accurate time clock (such as a GPS clock). When the period has passed for one time-of-day plan, the controller or center system will transition to the next timing plan. Transitioning requires the system to temporarily drop out of coordination until the new timing plan is fully synchronized.

Time-based coordination should be reassessed periodically to determine if timing plans effectively meet changing travel patterns and characteristics while maintaining intersection safety. Some benefits from up-to-date signal timings include shorter commute times, improved air quality, a reduction in certain types and severity of crashes, and potentially reduced driver frustrations.(7)

Many agencies are now using GPSs to maintain synchronization of their time clocks. This method involves installing a GPS receiver and antenna onto the traffic signal cabinet. GPS units can be either a stand-alone unit or a rack-mounted card. The GPS antenna mounts to the exterior of the traffic signal cabinet and connects to the traffic signal controller through the cabinet's communications network (either the serial BUS or IP network). In a system of intersections, each traffic signal controller has its own GPS unit. Because each traffic signal controller is referencing the same time clock, each controller remains synchronized to a common time source. This time synchronization method does not require the traffic signals to be interconnected.

Table 41. System-level control features and implementation characteristics.[2]

System Category	Feature	Implementation Characteristics
Uncoordinated (Free) Control	• No coordinated operations between local intersections. • Each local intersection responds based on local control parameters and detection inputs.	• No communications required. • Detection system focused on intersection demands.
Time-Based Coordinated Control	• Provides basic coordinated operations between intersections. • Easy to implement in modern controllers. • Control strategies/plan implemented by a time-of-day/day-of-week scheduler. • Time-space diagrams identify bands of flow between adjacent intersections. • Detection used to make minimal adjustments in response to minor demand fluctuations. • Time-of-day estimates of demand based on historical data to develop cycle lengths, splits, and offset. Uses a database of timing plans developed for typical or normal conditions.	• No communications required between intersections. • GPS clock deployed at each intersection can maintain synchronization of internal controller clocks. • Communications with central system needed to support remote management and timing plan configuration.
Interconnected Control • P2P • Master to Field • C2F	• Control strategies/plan implemented by a time-of-day/day-of-week scheduler or plan calls from masters or central. • The center monitors device status, manages timing parameters, and remotely activates predefined timing plans. • The operator/field master can remotely activate new operations by calling the timing plan stored in databases. • Few or no system detectors are required. Historical time-of-day demands drive the development of timing plans.	• Hardwire or wireless connection to maintain synchronization between intersections. • Laptop or desktop computer to perform database management functions. • Signal timing plans require regular maintenance. • Communications technology to support the uploading/downloading of timing plan parameters and monitoring of intersections and device status.

System Category	Feature	Implementation Characteristics
Traffic-Responsive Control	• A field master or central control system selects a timing plan from a library of predefined plans. • System detectors identify shifts in traffic demands and flow patterns. • The field master or central software uses pattern matching to select timing plans based on measured demand conditions from system detectors. • New timing plans are implemented infrequently to limit transition disruptions caused by changing timing plans.	• Interconnection between local intersections and field master/central required. • A minimum of one or two system detectors per intersection approach. • May require increased timing plan maintenance. • A high level of central processing may be required to support the timely processing of detector data.
Traffic-Adaptive Control	• Uses demand data to continuously refine baseline signal timing plans. • May not explicitly use defined signal cycles, splits, or offsets. • Signal indications advanced through commands from an external optimization algorithm. • Systems provided by suppliers usually retain the capabilities of the interconnected control category.	• Higher speed communications than for other categories of control. • Each signalized approach requires enhanced detection. • The increased reliance on detection results in higher detection maintenance needs. • Local controllers may require additional computational capabilities in the form of extra processing power or a separate unit.

Source: Federal Highway Administration.

Interconnected Control

Under interconnected control, the operations of multiple intersections are coordinated using wireline or wireless communications systems. Often, these systems are connected to a traffic signal management software system that allows operators to perform the following management functions:(2)

- Remotely monitor the status of intersection control and detection equipment.
- Upload signal timing plan parameters.
- Deploy or update time-of-day schedules to activate timing plans.
- Configure and monitor detectors for operating traffic intersections.
- Download alarms and alerts that can be used in the performance assessment process.
- Monitor signal operations and performance in real time.
- Implement new signal timing plans to respond to unusual changes in demands caused by incidents or special events.

Interconnected systems use a communications system to maintain coordination between adjacent intersections. A master controller, which is often monitored by a central system, connects to a series of local traffic signal controllers by a communication link. The master controller sends out a time mark to each of the local controllers at predetermined intervals to ensure all controllers in the system have a frame of reference. Upon receipt of the time mark from the master time clock, each controller determines how it needs to adjust its clock to remain synchronized with the master clock. This method requires each intersection to be on the same communications network (i.e., interconnected) as the master device.(2)

Traffic-Responsive Control

Traffic-responsive methods use predetermined timing plans based on a known variety of traffic conditions. Unlike interconnected and time-based coordination control (where the timing plans are deployed based on the time of day and day of the week), traffic-responsive system control selects timing plans based on inputs from the system detectors. The field master controller or a central system typically selects the timing plan from a library of predefined timing plans. The central system (or field master) compares measured traffic volume and occupancy data supplied from the detection system to threshold parameters identified from historical data associated with each predefined timing plan. Although several timing plans may be available to react to different re-occurring or unusual traffic situations, a traffic-responsive system does not create signal timing plans on its own based on current traffic conditions.(2)

Adaptive Signal Control

Adaptive signal control (ASC) uses traffic sensors upstream and downstream of the signalized intersection to compute optimal signal timing based on real-time traffic data information. ASC is ideal for networks that experience day-to-day fluctuations in demand, high levels of incidents, rapid changes in land use or development, or other frequent disruptive events, such as preemption. Traffic-adaptive systems do not rely on pre-set cycle lengths and timing plans. Instead, they depend on advanced algorithms to optimize timing parameters in response to rapid changes in traffic demands. The ability to adjust timing parameters in real time makes adaptive system control desirable at locations with varying high and low congestion periods.

The main benefits of ASC over conventional signal systems are that it can:(8)

- Automatically adapt to unexpected changes in traffic conditions.
- Improve travel time reliability.
- Reduce congestion and fuel consumption.
- Prolong the effectiveness of traffic signal timing.
- Reduce the complaints that agencies receive in response to outdated signal timing.
- Make traffic signal operations proactive by monitoring and responding to gaps in performance.

Each adaptive system utilizes a unique approach to optimize signal timing. Some systems provide an entire system solution evaluated on a second-by-second basis; other systems evaluate and optimize each individual signal on a cyclic basis. Each approach produces similar benefits and requires differing levels of detection, communications, and processing capability that should be selected to be consistent with an agency’s needs, operations, and maintenance capabilities.(8) Table 42 lists some of the software and hardware specifications associated with some of the more frequently used ASC systems.

Table 42. Software and hardware specifications for ASC.(9)

System	Controller	Software	Communications
ACS Lite	• Siemens NEMA (M50 series) or 2070(2002 TEES or later) with SEPAC NTCIP 4.01F firmware. • Econolite ASC/2 with NTCIP firmware w/ACS Lite support. • Peek 3000E with external NTCIP translator. • McCain 170E with BI-TRAN 233 firmware with ACS Lite support.	• ACS Lite software running on field-hardened PC or central server.	• Serial or Ethernet. Serial is a single channel, in which 9600 bits per second supports up to 8 signals. Faster serial can support more signals.
BALANCE	• European controllers.	• GEVAS. • VTnet/View.	• ISDN dial-up line, 2400 bits per second-modem wireless.
InSync	• Existing controllers. Cabinets require InSync processor to communicate with controller using detector cards.	• Internet access to InSync system through a local computer.	• Ethernet communication.
LA ATCS	• Model 170 Controller/172.3 Firmware. • Type 2070 Controllers/City of LA Software.	• PC. • ATCS/Traf Graph Editor.	• Dedicated C2F connection. • 1200 bps using time division multiplexing. • 4 intersections per communication channel. • No P2P communication needed. • Supports multiple communication media.
MOTION	• SITRAFFIC C8xx, C9XX controllers. • Singalbau Huber Actros controllers. • Older Siemans controllers.	• PC. • SITRAFFIC.	• V34 modem. • Ethernet. • Fiber-optic cables.

System	Controller	Software	Communications
			• Central control via wireless links using public communication channels such as Internet/GPRS.
OPAC	• Model 2070/multiple firmwares. • Model 170 with 68360 processor/multiple firmwares. • NEMA controllers. • VME Bus or equivalent.	• PC. • MIST.	• Dedicated central to field connection at 9600 baud or higher. • P2P possible through central. • Supports all communications media.
RHODES	• 2070 ATC with NextPhase-Adpt controller software. • Econolite ASC/2 with Adapt X interface software.	• RHODES software on OS9/Windows/Linux field-hardened, single-board computers.	• P2P over ethernet; bandwidth $\geq$ 9600 bps. Supports all communications media; preference is fiber-optic.
SCATS^{TM}	• Model 170 controllers with SCATS conversion kit, which includes a new processor board with embedded software with 2070 or 2070 N controllers with SCATS proprietary controllers. • NEMA AWA Delta 3N controllers. • There are several RTA-type approved SCATS controllers in current use sourced from Australia (e.g., Tyco Eclipse, QTC, Aldridge ATSC/4, Tyco PSC) and a myriad of legacy controllers still supported (e.g., Phillips PTF).	• PC. • SCATS.	• Requires 300 bps link to each controller using two-wire or equivalent. • Multidrop system is supported that requires a two-wire line or equivalent to the first intersection in a cluster and then to each intersection in the cluster in a daisy-chain configuration. • SCATS supports various configurations that can utilize TCP/IP, leased line, and conventional telephone services (i.e., dial-up).
SCOOT®	• Eagle NEMA Eagle 2070/SEPAC support for 170 can be provided.	• PBS with MS Windows Server 2003.	• Both SCOOT and ACTRA® require a separate channel to controller from the

System	Controller	Software	Communications
		• SCOOT algorithm and ACTRA®.	center—at 9600 baud, 8 controllers can be supported. • Support all communications media; wireless typically not used.
UTOPIA	• Peek's EuroController with MDSL unit.	• PC-based software. Logic is distributed over control units.	

Source: National Academy of Sciences

The detection system's ability to produce reliable and accurate system demands affects an ASC system's ability to compute appropriate timing plans. Therefore, well-maintained, highly-reliable detection and communications systems are essential requirements of ASCs. Various ASCs use a combination of detection layouts to estimate the current state of traffic, which is later used to adjust traffic control in a network. There are generally four major detector locations used by most ASCs:(9)

- Detectors extending up to 10 meters from the stop line (e.g., as commonly deployed with most actuated operations in the United States and SCATS™).
- Detectors located 10–15 meters upstream of the stop bar, (e.g., as used in Germany by BALANCE and MOTION).
- Upstream (midblock) detectors, can be used to estimate reasonably long queue lengths (e.g., as seen at some Californian intersections and used by ACS Lite).
- Upstream (far-side) detectors located at the exit point of the upstream intersection (as used by SCOOT, UTOPIA, and optionally by RHODES).

Communication among the detectors, controllers, and ASC system is vital. Some ASC systems interact with the detectors directly, either (1) through direct hardwire integration with the devices, or (2) through wireless polling of stand-alone detectors. Others rely on communication with the local controller to retrieve detection status. Many systems can accommodate a combination of directly connecting to the detectors and receiving detection status from the local controller. A detailed understanding of existing communications capabilities and ASC needs is important when evaluating alternative systems and their overall cost.(9)

The number of parameters that ASC algorithms use to compute new timing parameters can range from a few to thousands. To ensure the detection system collects the information needed and the algorithms calculate timing plans that work effectively in the real world, extensive calibration and field adjustments are necessary. ASC systems require highly trained staff to monitor and sustain operations at peak performance.

TRAFFIC SIGNAL SYSTEM PLANNING

FHWA's *Model Systems Engineering Documents for Central Traffic Signal Systems*(4) provides a framework for agencies to articulate their needs and specify succinct and comprehensive system requirements to guide CTSSs' procurement and implementation. The guidance targets procurements when agencies:

- Cannot reasonably afford the development of systems engineering documents from scratch.
- Make selections from existing devices and software products in the market rather than support new products or software development.

Using these documents will help to manage the risks inherent to the procurement of traffic control technology and improve the likelihood that the system will meet operational needs over the entire life cycle of the system and within the maintenance capabilities of the organization. This guidance leads the user through the development of the following systems engineering documents:

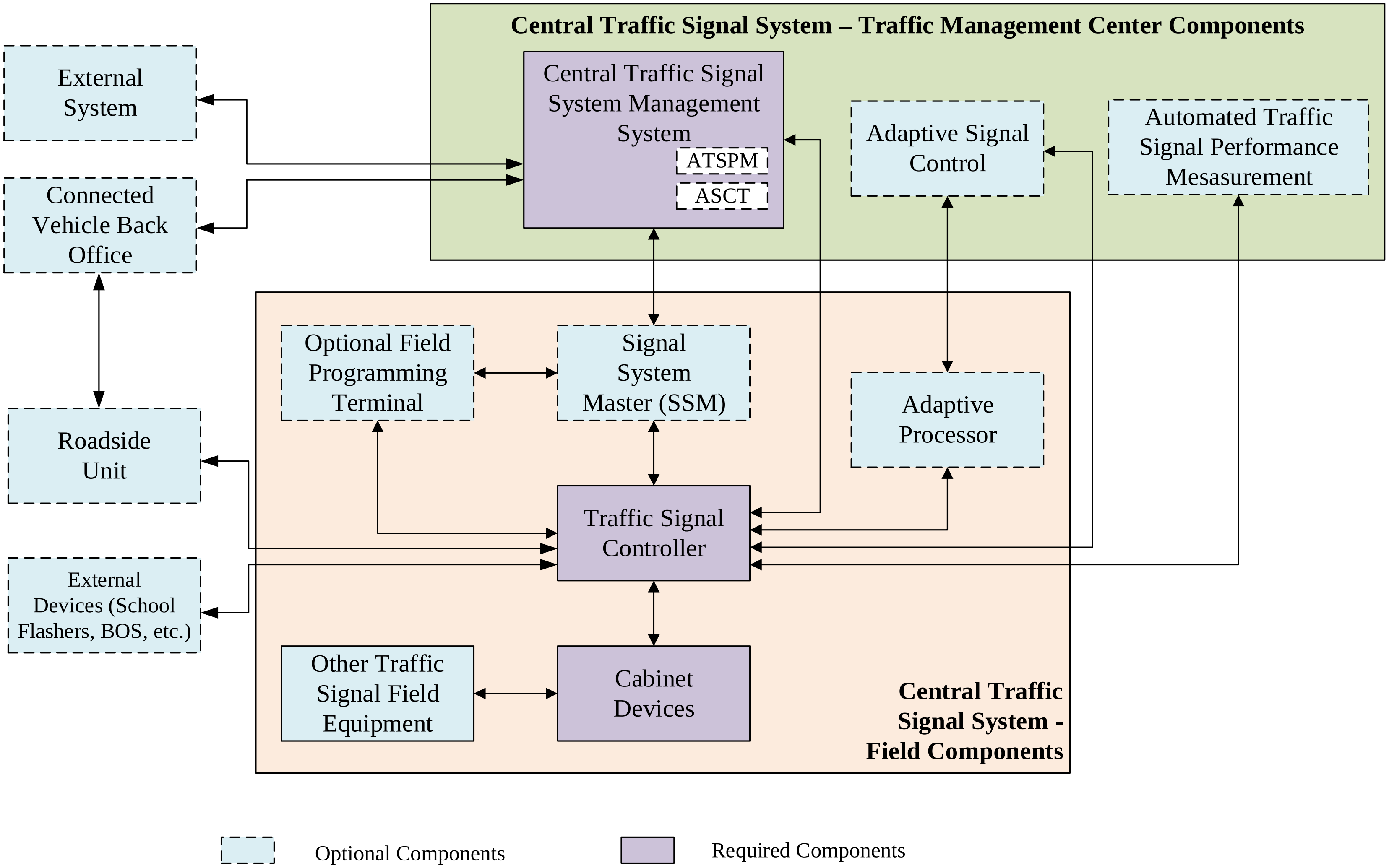
- Concept of Operation.
- System Requirements.
- Verification Plan.
- Validation Plan.

The *Model Systems Engineering Documents for Central Traffic Signal Systems*(4) does not cover requirements related to selecting traffic signal controller technologies but includes the expected functionalities that each location needs to support. When faced with a local controller selection task, the reader is encouraged to use the requirements to supplement whatever process the agency uses to make that selection. While agencies may have preferences as to which technologies to use to implement specific features, the standard feature sets available through most controllers on the market support the wide variety of user needs and requirements. For cases that require special features, the reader is encouraged to develop requirements related to those exceptional cases not supported by off-the-shelf controller technology. The *Model Systems Engineering Documents for Central Traffic Signal System*(4) guides agencies on how to do this.

SYSTEM ARCHITECTURES

Figure 61 shows the reference architecture for a CTSS as defined in FHWA's *Model Systems Engineering Documents for Central Traffic Signal Systems.*(4)

Some system functions require reliable, full-time communications with the intersection controllers, while other system functions require ad hoc communications. In cases where it is inconvenient or infeasible to provide reliable, full-time communications from individual intersections all the way to the system owner's control location, for those functions that require reliability, a field device (called a Field Master or Signal System Master [SSM]) installed in convenient proximity to the group of intersection controllers can distribute the communications back to a traffic management center. The SSM is a field device that communicates with multiple nearby intersections to coordinate and monitor the local intersection controllers' operations. This system architecture can lessen the communication load back to the central computer.



Source: Federal Highway Administration.

Figure 61. Graphic. Reference architecture for a CTSS.(4)

COMMUNICATIONS PROTOCOLS FOR SYSTEM CONTROL

The signal system functions are organized in different ways, depending on the needs of the system. Some control functions require reliable, full-time communications directly with local intersection controllers, while other control and surveillance functions require only ad hoc (or periodic) communications. Chapter 7 of this handbook provides more information on the different aspects of the communications system needed to support system control.

Although initially developed to support the exchange of messages between a traffic signal field master and connected devices (such as a traffic management center or a local intersection controller), *National Transportation Communications for Intelligent Transportation System Protocol* 1210v1(6) provides a standard protocol for communicating data objects associated with traffic signal system control. Agencies can tailor these object definitions and dialog messages to allow the configuration of signal system functionality within any system architecture. NTCIP 1210 describes data objects unique to configuring, operating, and monitoring traffic signal systems. The standard employs standardized dialogs and message sets required to address operational and informational exchanges in a baseline system configuration, such as the following:

- Configuring and uploading timing plans implemented by local controllers.
- Implementing manual, command-based, and time-based traffic signal timing plans.
- Configuring system detectors, plan selection parameters, and signal timing plans for traffic-responsive operations.
- Configuring and synchronizing clocks in local intersection controllers.
- Uploading timing parameters for traffic signal timing plans.
- Monitoring system alerts and traffic conditions.

DETECTION FOR SYSTEM CONTROL

As the level of system control increases, so do the detection needs. Appendix L of the *Traffic Detector Handbook: 3rd Edition—Volume II*(5) describes a series of successively higher sensor density levels for each level of system control. Sensor density is described in terms of a web of sensors needed for different arterial and network traffic control and surveillance systems by link and by lane. Table 43 summarizes the sensor density needed for the different levels of system control and provides an example detector configuration needed to support each operation level.

For more information on the detection needs of various system control strategies, the reader should consult the *Traffic Detector Handbook: 3rd Edition—Volume II.*(5)

Table 43. Summary of traffic detection attributes for traffic signal control systems.(5)

Sensor Web Density Level	System Control Supported	Attributes
0.0	Time-Based Coordination Interconnected (Fixed Time)	• No vehicle detections or sensors. • No sensor maintenance required. • Supports fixed-time, time-based coordination only.
0.5	Time-Based Coordination Interconnected (Semi-actuated/Low-Speed Approaches)	• Stop-bar detection added to minor and cross-street movements. • Measures demands for service for minor movements. • Supports semi-actuated control of minor movements. • Allows time of day/day of week control to be more responsive to cross-street demands.
1.0	Time-Based Coordination. Interconnected. (Semi-Actuated Coordinated with Dilemma Zone Protection).	• Installation of upstream detectors to measure volume and occupancy to measure input demands. • Supports traffic-adjusted TOD/DOW control. • Determination of peak period direction of flow. • Allows for the selection of the timing plan from a fixed library of previously calculated plans.
1.5	Time-Based Coordination. Interconnected. (Full-Actuated Coordinated).	• Adds stop-bar detection to main-street approaches. • Supports traffic fully actuated control functions at critical locations. • Actuated settings may vary by TOD/DOW. • Place sensors at critical locations to facilitate actuated control of minor movements.
2.0	Traffic-Responsive.	• Adds midblock detection to measure directional changes in demand. • Supports traffic-responsive timing plan selection. • Limited prediction capabilities of traffic demands. • Upstream detector to high-speed approaches provides dilemma zone protection.

Sensor Web Density Level	System Control Supported	Attributes
3.0	Traffic-Adaptive.	• Applicable for traffic-adaptive systems. • Adds downstream detection to measure release rates and flow profiles to predict arrival demands at downstream intersections. • Stop-bar sensors used to provide demand inputs. • Per lane basis detection provided.

Source: Federal Highway Administration.

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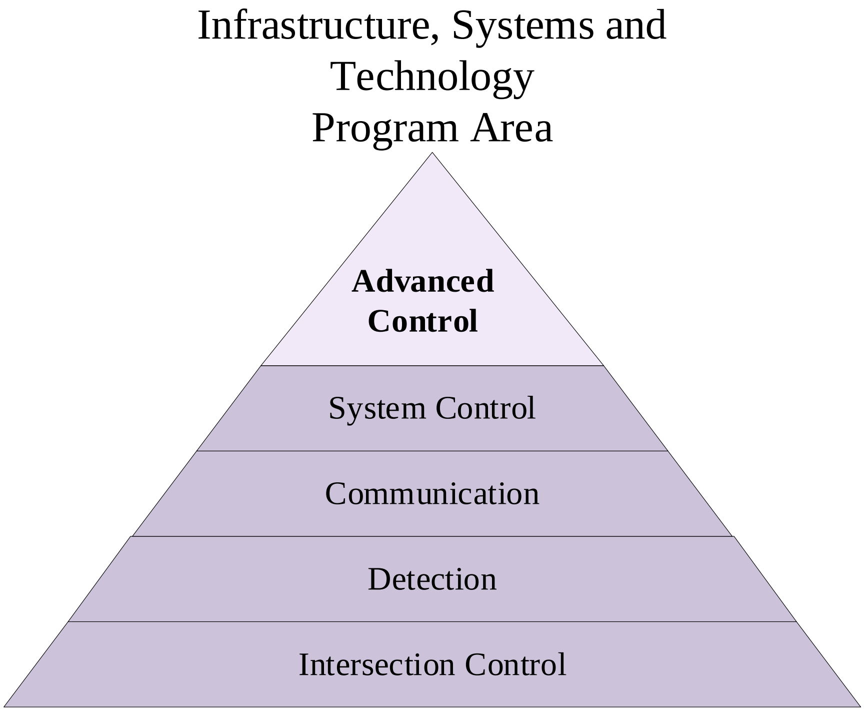
CHAPTER 9. ADVANCED CONTROL

In a full evaluation of context, it is likely that the attainment of appropriate objectives might require the application of strategies that are at the level of advanced control. Advanced control applies in special conditions or situations when options beyond traditional system control are needed to provide advanced capabilities. Advanced control builds upon the other components' foundation and technology program area (see Figure 62). While situations needing advance control represent only a small percentage of a system's signals, they often require the use of special controller features, highly skilled personnel, and, in some cases, considerable resources to implement correctly. Examples of how agencies might apply advance control concepts include the following:

- Automated traffic signal performance measures.
- Preferential treatment, such as preemption and priority control, for different intersection user types.
- Specialized treatments for accommodating left-turn demands.
- Special signal timing strategies at freeway to arterial interchanges.
- Deployment of emerging technologies.



Source: Federal Highway Administration.

Figure 62. Graphic. Hierarchy of traffic signal systems and technology: Advanced control.

Table 44 shows how advanced control can support the program and operational objectives of an agency.

PREFERENTIAL TREATMENT

Preferential treatment is an application that can be used at signalized intersections to adjust operations in favor of a particular user. Various types of preferential treatment exist for different users based on the criticality or urgency with the corresponding levels of impacts on signal operations. Broadly, there are two types of preferential treatments: preemption and priority. From a traffic engineering standpoint, preemption and priority elicit fundamentally different responses from the traffic signal controller. NTCIP 1202 defines *preemption* as "the transfer of normal control (operations) of the traffic signals to a special signal control mode for the purpose of serving railroad crossings, emergency vehicle passage, and other special tasks which require terminating normal control to provide the service needs of the special task."(1) Under preemption, the normal operation of the traffic signal is transferred to a special control mode of operation to serve the preferred vehicle.(2) Because preemption can significantly disrupt normal functions of the traffic signal controller (like coordination, pedestrian service, and phasing patterns), the use of preemption is generally reserved for situations when safety dictates exclusive ROW to a particular vehicle class (such as a train, emergency service vehicle, or a fixed mass transit vehicle). Generally, the use of preemption is limited to loss-of-life type situations.

Priority, on the other hand, is another way of providing preferential treatment to preferred vehicle classes while limiting the amount of disruption to normal traffic signal operations. NTCIP 1211 defines *priority* as "the treatment of one vehicle class (such as transit vehicles, emergency service vehicles, or commercial fleet vehicles) over another vehicle class at signalized intersections without causing the traffic signal controller to drop from coordinated operation."(3) Under priority control, the traffic signal maintains its normal operations in the background to minimize the impacts of providing preferential treatment to vehicles, usually within one or two cycles. Under priority control, the traffic signal makes only slight adjustments to the way the traffic signal operates, usually either through extending a phase (if the priority phase is already green), returning early to the priority phase, or inserting a special phase (if the priority phase is not already active). Depending on where the signal is in its normal phase sequencing, the preferential vehicle may not necessarily receive an immediate green indication but will be serviced appropriately in windows in the timing plan. For a better understanding of the differences between preemption and priority from a traffic engineering standpoint, the reader is encouraged to consult the *Signal Timing Manual, 2nd Edition.*(2)

Table 44. Relationship between program and operational objectives and advanced control functions.

Advanced Control Functions	Responsiveness to Stakeholder Needs	Comply with Agency Policies and Standards	Sustain Infrastructure in State of Good	Minimize Life-Cycle Costs	Safe Assignment of ROW	Appropriate Distribution of Green	Provide Smooth Flow	Maximize Throughput	Manage Queues	Minimize Delay for Prioritized Modes
Automatically monitoring and assessing traffic signal performance.	–	–	X	X	X	X	X	X	X	X
Providing preferential treatment to different intersection user types.	X	X	–	–	X	–	–	–	–	X
Providing specialized treatment of managing left-turn demands.	X	–		–	–	–	X	X	X	–
Managing traffic movements at interchanges.	X	–	–	–	–	X	–	X	X	–
Facilitating regional transportation signal operations.	X	X	–	–	–	–	–	X	–	X
Accommodating emerging technologies.	X	X	–	X	–	–	–	–	–	–

“X”= Objective Supported Directly; “–” = Objective Not Supported Directly

Source: Federal Highway Administration

User Groups Requiring Preferential Treatment

Signalized intersections accommodate numerous unique users, each requiring a unique service. Some of these unique users and their service requests are described in the following list:

- *Rail*—Rail operations along an at-grade crossing located near traffic signals have a significant impact on the design and operation of those traffic signals. Signal controllers use preemption to clear all vehicles that are queued over the railroad tracks before the arrival of the train. Design of rail preemption also considers the impact of pedestrians, transit vehicles, and heavy vehicles carrying hazardous materials.

- *Emergency Responders*—Minimizing delay for emergency responders (like fire trucks, ambulances, and police cars) at traffic signals will reduce response time during emergencies and can save lives. This task is typically accomplished by using preemption in traffic signal controllers. However, preemption will adversely affect normal intersection operations and should only be used when essential. Thus, some agencies implement preemption only for some of their units, like fire trucks, and not for other units, like police cars, which can maneuver more easily in a traffic stream.

- *Transit Vehicles*—The success of transit is dependent on moving people from one place to another in an efficient manner. To make transit more attractive, traffic engineers have employed numerous traffic signal priority (TSP) techniques like green extension, red truncation, or an exclusive bus phase to reduce travel time for transit passengers. However, transit usage is more prevalent in urban and suburban areas where traffic signals usually are coordinated. Thus, TSP techniques that will minimize disruption to coordination modes and not adversely affect the rest of the automobile traffic are usually implemented.

- *Pedestrians*—Pedestrians are one of the most vulnerable users at an intersection. Their crossing needs and requirements are incorporated into the normal operations of the signal; however, pedestrian timing can be disrupted during preemption. Consequently, the traffic engineer should consider pedestrian requirements as a more critical element in the design of priority and preemption operations. This process may include the use of advanced detection technologies to detect priority or preemption users and the use of modern traffic signal controllers that have advanced logic features to schedule these service requests in a more efficient manner. In addition, some agencies have found unique ways to use priority to service pedestrians. For example, wide intersections require a large pedestrian clearance interval. When the pedestrian requirements are much longer than vehicle requirements, intersections can operate in an inefficient manner when operating in a coordinated mode. Some agencies then time their traffic signals without including pedestrian requirements and use priority routines in the controllers to service the pedestrians without disrupting the coordinated operations.

- *Trucks*—Trucks are often overlooked but are important users at signalized intersections. Trucks require a higher stopping distance and therefore require a longer time to stop upon the onset of yellow. Because signal timings are typically designed for automobiles, trucks can find themselves in the indecision zone. This may result in trucks either running the red light

> or braking using a much higher than desirable deceleration rate. Trucks also require a longer startup time to accelerate and speed up after the onset of green, thus delaying the remaining traffic stream. Therefore, minimizing truck stops can have a significant impact on intersection safety and efficiency. Minimizing truck stops can also reduce pavement wear and tear since heavy trucks can damage the pavement when they stop and start up.

Rail Preemption

Section 8C.09 of the MUCTD provides the following guidance related to operations of traffic control signals at or near highway-rail grade crossing:(4)

> *If a highway-rail grade crossing is equipped with a flashing-light signal system and is located within 200 feet of an intersection or midblock location controlled by a traffic control signal, the traffic control signal should be provided with preemption in accordance with Section 4D.27.*
>
> *Coordination with the flashing-light signal system, queue detection, or other alternatives should be considered for traffic control systems located farther than 200 feet from the highway.*

During rail preemption, the signal controller goes through the following phases of operations:

- ROW Transfer Phase—In this phase, the signal controller safely transfers from the current operating state to the track clearance phase. This phase ensures that the appropriate minimum green interval of the current phase has been satisfied, followed by its corresponding yellow change interval.
- Track Clearance Phase—This phase is the most critical, and its function is to move any stopped vehicles off the tracks before the arrival of the train at the grade crossing.
- Dwell Phase—Once the queue clears off the tracks and the track green times out, the controller goes to the next stage of the preemption sequence, called the dwell phase. During the dwell phase, the train most likely occupies the crossing, and the controller can operate in numerous ways while not serving any phases that send traffic toward the track. When in this phase, the traffic signal can operate in a flash mode, steady red, or dwelling green for certain movements only, or provide limited service in which traffic movements that can operate are allowed.
- Exit Phase—Once the train has left the crossing and the preemption call drops, the signal controller enters the exit phase. The operator designates the movements to service during the exit phase. Usually, these movements are the ones that were blocked by the train. After the controller services the exit phases, the signal controller resumes normal operations. However, if the intersection is operating in a coordinated mode, it is recommended that appropriate transition modes are selected to enable a rapid transition from the end of preemption mode to a coordinated plan.

There are two types of rail preemption: simultaneous preemption and advance preemption. Simultaneous preemption occurs when the traffic signal and the rail equipment (namely the flashing lights and gates) begin the preemption sequence at the same time. With simultaneous preemption, the railroad lights start flashing at the same time that the traffic signal controller starts the preemption process. Simultaneous preemption is the most common type of rail preemption implemented.

In cases where an agency may need more time to clear pedestrians or other users and prepare the grade crossing for the arrival of the train, traffic signal operators may request railroad authorities provide additional warning time. The additional warning time, called advance preemption time (APT), allows traffic signal operators to clear vehicles off the track while also serving other critical users at the intersection. Providing additional warning time requires railroad operators to install additional track circuity to detect the presence of trains. In most cases, traffic agencies generally pay an additional cost for this circuit. While additional advanced warning time can help improve safety at signalized intersections near highway-rail grade crossings, the operator has to have a thorough understanding of preemption operations using APT to operate the intersection safely.

Emergency Vehicle Preemption (EVP)

Signal preemption allows emergency vehicles to disrupt a normal signal cycle in order to proceed through the intersection more quickly and under safer conditions. The preemption systems can extend the green on an emergency vehicle’s approach or replace the phases and timing for the whole cycle. EVP can decrease emergency vehicle response times, and it is especially useful where emergency vehicles are likely to have to travel some distance along a corridor. Also, preemption can provide both a safety and operational benefit on high-speed roadways where emergency vehicles need to enter the intersection from a minor road.(5)

Transit Priority (TSP)

TSP is a popular tool for improving transit performance and reliability.(6) Table 45 describes the common strategies that agencies use to provide preferential treatment to priority vehicles at intersections.

Truck Priority

Agencies apply truck priority on high-speed approaches to improve safety and minimize stops. Trucks have different deceleration characteristics and require a longer time to stop. The detector placement to detect a truck and provide priority is different than for other vehicles. However, once a truck is detected, strategies to provide priority are very similar to the strategies for transit priority.

Table 45. Common signal timing strategies for providing preferential treatment.(2)

Strategy Name	Description of Strategy
Green/Phase Extension	Green (or phase) extension is a common strategy used to serve preferential treatment requests. The green extension involves the extension (or holding) of the preferred phase green interval past its normal termination point. Depending on the type of system and detection scheme, the extension period can be for a fixed duration or until the preferred vehicle clears the intersection (subject to a maximum extension period). This strategy prevents long delays for preferred vehicles that are anticipated to arrive near the end of the green interval.
Red Truncation	Red truncation (or early green) is a preferential treatment strategy that shortens the duration of non-preferred phases to return earlier than normal to the green interval of the preferred phase.
Phase Insertion	Phase insertion involves the activation of a special, dedicated phase that is not served during normal (non-preferred) operations but activates only after the detection of a preferred vehicle at the intersection. This strategy is commonly used to provide service to lanes that are exclusive to preferred vehicles only (e.g., an exclusive left-turn lane into a transit transfer point). This strategy is also used to support queue jumps that allow preferred vehicles to enter a downstream link ahead of the normal traffic stream.
Sequence Change	With sequence change, the order of the signal phases is altered to provide more immediate service to the preferred vehicle. For example, changing a left-turn phase from leading to lagging reduces the wait time of the preferred vehicle.
Phase Skipping	Phase skipping delays service to (or skips) non-preferred phases that would normally be displayed to serve the preferred phase more quickly. For example, phase skipping may skip the protected interval at a protected permitted left-turn movement when needed.

Source: National Academy of Sciences

Pedestrians

Based on the type of pedestrian (young children, elderly pedestrians, etc.) and the number of pedestrians (such as in downtown areas or near special events), agencies will sometimes give preferential treatment to pedestrians. Some of the preferential treatments include the following:

- *Advance WALK*—When an agency displays the pedestrian WALK phase before the associated vehicle green phase green. Displaying the pedestrian WALK phase in advance of the vehicle green phase allows pedestrians to enter the crosswalk area before turning vehicles. This strategy makes the pedestrians more visible to turning vehicles.

- *Trailing WALK*—When an agency displays the associated vehicle green phase before activating the pedestrian WALK display. Allowing the pedestrian WALK interval to trail the start of the vehicle green phase allows stored turning vehicles to clear the intersection before pedestrians are allowed to enter the crosswalk.

- *Exclusive pedestrian phase*—When an agency displays a WALK indication independent of the vehicle movement phases. This strategy completely separates vehicle and pedestrian movements at the intersection.

Based on other factors such as the width of the arterial and the availability of adequate storage in the median area, a two-stage pedestrian crossing—when pedestrians cross only halfway through the intersection each cycle—can be implemented. Implementing features like REST IN WALK can also reduce pedestrian wait times at intersections. REST IN WALK allows the WALK indication to be serviced again at the end of the pedestrian clearance in the absence of a conflicting vehicular call. Because they can impact the vehicle movement performance at the intersection as well, pedestrian treatments should be considered carefully.

Bicyclists

When exclusive bicycle lanes are present at a signalized intersection, bicycle signals should operate independent of vehicular indications; however, when bicycles run concurrently with vehicle traffic, the timing of vehicular signals should address the needs of the bicyclists. Bicycles have different operating characteristics, which may alter the computations of the minimum green and all-red clearance intervals. Because they have slower acceleration rates (around 1.5 feet/s^2) and generally only reach speeds of 10 mi/h or less through the intersection when starting from a stop, bicycles require longer minimum green time than automobiles. Agencies may also need to adjust the all-red clearance interval to account for the difference in time that a rolling bicycle needs to cross the intersection. To support bicycle operations, agencies may need to install suitable bicycle detection. More details about these detectors are available in the AASHTO *Guide for Development of Bicycle Facilities.*(7)

AUTOMATED TRAFFIC SIGNAL PERFORMANCE MEASURES (ATSPM)

ATSPMs are a suite of performance measures, data collection, and data analysis tools used to support objectives and performance-based approaches to traffic signal operations, maintenance, management, and design to improve the safety, mobility, and efficiency of signalized intersections for all users. ATSPMs consist of a high-resolution data-logging capability added to existing traffic signal infrastructure and data analysis techniques that provide agency professionals with the information needed to identify and correct deficiencies proactively. They can then manage traffic signal maintenance and operations in support of an agency's safety, livability, and mobility goals.(8)

Equipment Health Monitoring

A traffic signal operator needs to identify if the system is not functioning correctly to maintain infrastructure in a state of good repair. Some behaviors from the detection system can aid the program in determining if the system needs maintenance or repair.

The detection system, like all systems in the field, may fail occasionally. The clearest signs of failed detectors are when a phase has a constant call for service or when a phase fails to receive any actuation over a certain period. Provided communication exists to a TMC, operators can catch these errors without needing a user to call in with a complaint.

The detection system may encounter other less severe errors, such as a detector used to count vehicles for performance monitoring failing to get accurate counts because of dirt or dislocation. These errors will present themselves as inconsistent, irregular, or spurious data in the performance monitoring feed. For example, if a two-lane approach suddenly receives half of the volume counts on a movement within the performance monitoring software, the detection system may be failing to record one of the lanes of travel.

Table 46 lists applicable performance measures that assess the performance of the detection systems.

Intersection Performance Measurement and Monitoring

Effective traffic signal programs use an objective-driven performance-based approach for operating traffic signals. These performance measures relate directly to the objectives that agencies wish to achieve at the intersection. Using performance measures to assess intersection operations allows agency professionals to identify and correct deficiencies proactively. Traffic signal operators also can use performance measures to better manage traffic signal maintenance and operations in support of an agency’s safety, livability, and mobility goals.

Table 47 shows some of the performance measures that can be used to assess individual intersection performance, along with the data required to produce those performance measures. NCHRP 03-122: *Performance-based Management of Traffic Signals* provides suggestions on the development and use of performance measures for signalized intersections.(9)

Although some of these performance measures can be generated through detector data, using high-resolution data provides agencies with richer and more meaningful measures of performance. As a result, agencies are beginning to use ATSPM to assess the quality of service that they provide at the individual intersection level.(10) ATSPM adds high-resolution data-logging capabilities and data analysis techniques to existing traffic signal infrastructure. To collect high-resolution data for ATSPM, the traffic signal controller and the detection system must be capable of producing the necessary phase status and timing and detection status information. ATSPM also require the technology to collect data on an event-driven basis (such as logging the signal status and detector status 10 times a second). The ability to generate meaningful ATSPM depend on the quality of detector data.

Table 46. Measures for monitoring the health status of traffic signal systems and technologies.[9]

Objective	Aggregated Status Report	Individual Signal Performance Measures
Communication Equipment Health	• Percent uptime of communications status. • Number of intersections where communications is offline.	• Communications Status.
Detection Equipment Health	• Percent of detectors fully functional by mode (e.g., vehicle, pedestrian, bicycle, rail, emergency vehicle, transit, or truck).	• Detection System Status. • Vehicle Volumes (high volumes during low-traffic times). • Phase Termination (high number of max-outs, force-offs, and/or pedestrian calls during low-traffic times). • Pedestrian Volumes (high volumes during low-traffic times). • Pedestrian Phase Actuation and Service (high number of pedestrian calls during low-pedestrian times). • Preemption Details (high number of requests). • Priority Details (high number of requests).
Traffic Signal Equipment Health	• Percentage of traffic signals offline. • Average duration traffic signal offline. • Percentage of time traffic signal operating in specialized mode.	• Flash Status. • Power Failures. • Number of False Preemption/Priority Events

Source: National Academy of Sciences

Table 47. Measures for assessing performance of signal operations at individual intersections.[(9)]

Operational Objective	Aggregated Status Report	Individual Signal Performance Measures
Provide Preferential Service to Specific Intersection Users	• Average number of preemptions per intersection per day. • Average duration of preemptions. • Average number of priority service requests. • Average number of priority service requests granted. • Frequency of method to service requests (early return, green extension).	• Details associated with each preemption request (time, duration, etc.). • Details associated with each priority request (time, duration, etc.).
Appropriate Distribution of Green Time	• Average vehicle delay. • Percent of cycles with unserved vehicles. • Percent of movements at or near capacity.	• Vehicle volumes. • Number of phase terminations by type (Gap outs, and max outs) • Average phase duration. • Number of split failures. • Estimated vehicle delay.
Provide for Pedestrian Comfort and Convenience	• Minimum, maximum, and average pedestrian delay. • Percent of movements with high pedestrian activity.	• Pedestrian volumes. • Pedestrian phase actuation and service. • Estimated pedestrian delay.
Provide for Bicycle Comfort and Convenience	• Minimum, maximum, and average bicycle delay. • Percent of movements with high bicycle activity.	• Bicycle and vehicle volumes (applied to capacity analysis). • Estimated vehicle delay (if bicycle detection is separate).
Assign ROW Safely	• Percent of movements with queues that exceed storage. • Percent of vehicles entering on red. • Number of conflicting movements.	• Estimated queue length. • Estimated pedestrian conflicts. • Yellow/red actuations. • Red-light running (RLR) occurrences.

Source: National Academy of Sciences

System Performance Measurement and Monitoring

Several automated performance measures exist to assess the quality of different coordination strategies under system control. Agencies can also use these measures to fine-tune system performance and identify issues that can cause coordination breakdowns. Coordination breakdown can occur for several reasons, including out-of-date timing plans, inappropriate offsets, detection malfunctions, stuck pedestrian activation, and more. These performance measures help an agency ensure the coordination strategy is functioning as anticipated and troubleshoot user complaints.

Table 48 shows some of the performance measures that can be used to assess system-level performance, along with the data required to produce those performance measures. NCHRP 03-122: *Performance-based Management of Traffic Signals* provides suggestions on the development and use of performance measures for signalized intersections.(9)

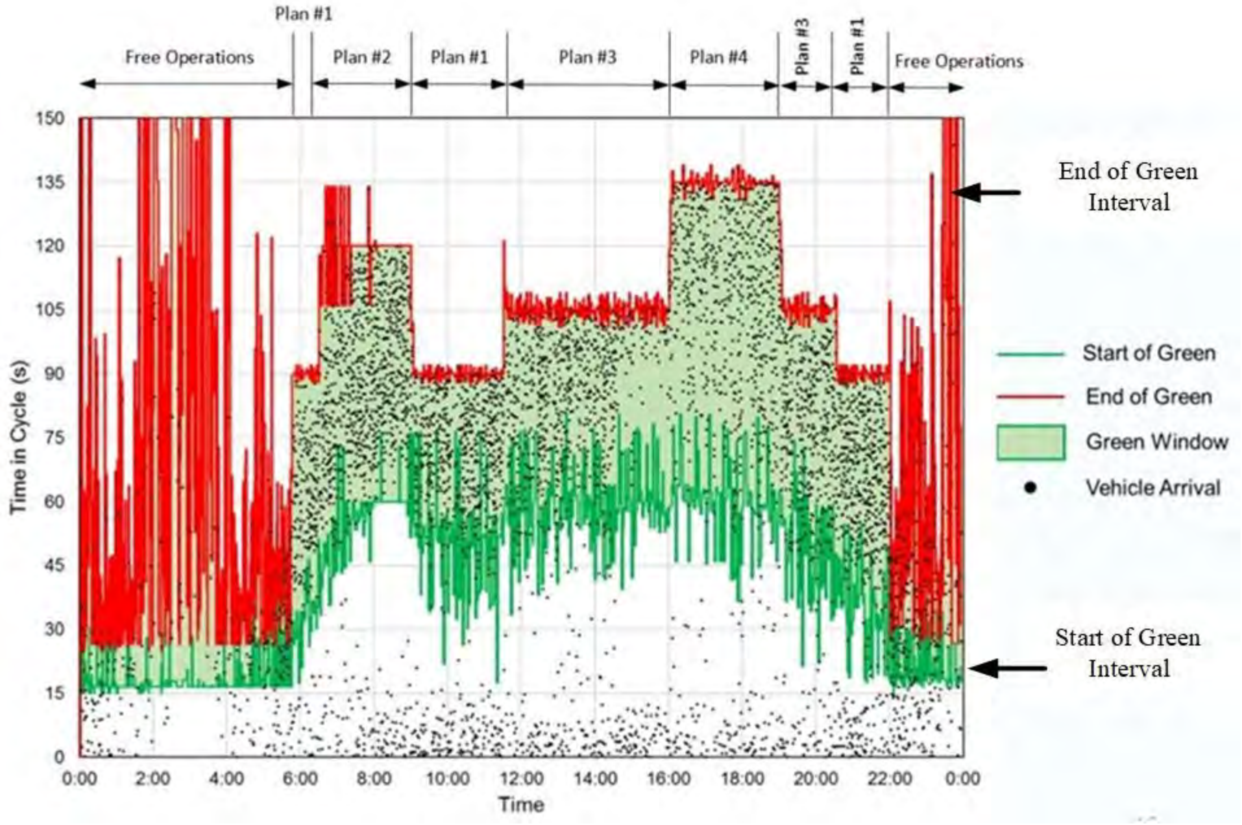
Purdue Coordination Diagram (PCD)

This graphical method illustrates the stage of a cycle at which vehicles arrive at an intersection. For any specific approach, the arrivals can be plotted against time to see the vehicle arrival pattern (the dots in figure 63). The green (lower) and red (upper) lines represent the start of the green and red intervals, respectively, during each cycle. The duration of the green interval is shown as the shaded areas between the two lines. The uppermost red line represents the cycle length occurring at the intersection. This diagram enables practitioners to compare the operating effectiveness of coordination on a particular approach before and after making any signal timing improvements. Dots above the green (lower) line represent vehicles that arrive during the green indication of the cycle. In contrast, the dots below the green (lower) line represent vehicles that arrive during a red portion of the cycle. The quality of progression can be determined based on the clustering of vehicle arrivals that occur throughout the day. The denser the arrivals of vehicles in the green interval, the better the quality of progression. Clusters of vehicles arriving during the red interval would imply poor quality of progression.

Table 48. Measures for assessing system-level performance of signal operations.(9)

Operational Objective	Aggregated Status Report	System-Level Performance Measures and Data
Provide Smooth Flow	Quality of progression. Total number of stops. Average stop duration.	Percentage arrivals on green. Platoon ratio. Arrival type. Purdue coordination diagram.
Maximize Throughput	Total vehicles serviced. Total vehicle miles traveled. Maximum bandwidth. Bandwidth attainability.	Cyclic flow profile. Time-space diagram. Offset adjustment diagram.
Manage Queues	Average queue length. Maximum queue length. Travel time reliability. Percentage of time operating in congested conditions. Percentage of intersection operating in congested conditions.	Estimated queue length. Oversaturation severity index. Travel times/average speed/stopped delay.

Source: Source: National Academy of Sciences



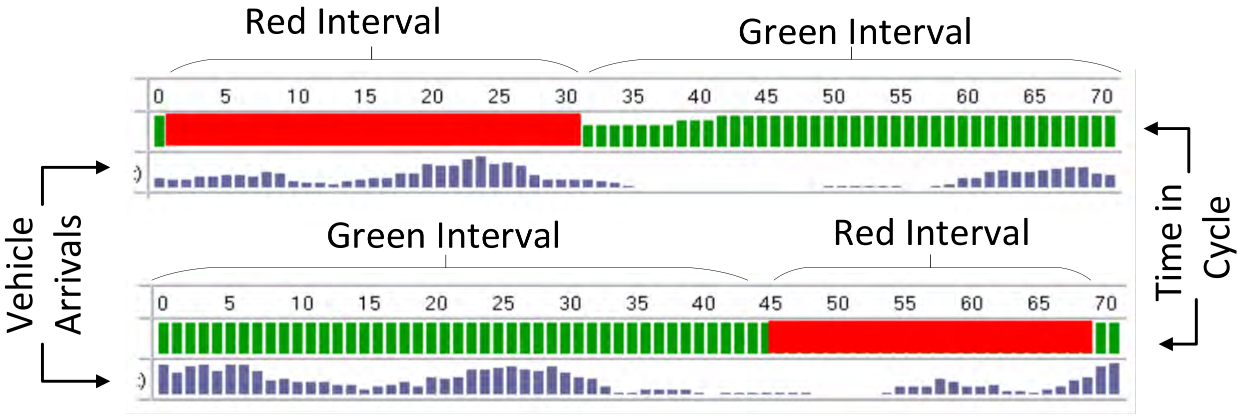
Source: Federal Highway Administration.

Figure 63. Graphic. Sample Purdue Coordination Diagram.

To collect the data needed for the PCD, an agency can place a detection zone approximately 400 feet behind the stop bar. Detection zones located too far upstream can overrepresent the number of vehicles arriving on the green signal indication. The detector's location should begin where the vehicle would need to stop (at free-flow speed) just as the signal turned red.

Percent Arrival on Green

This performance measure determines the quality of progression between different corridors. It typically quantifies progression quality as a percentage or a ratio. This metric compares the relative proportion of vehicles arriving during green to the intersection's total arrivals. Even the most coordinated/optimized corridors will have vehicles that arrive on a red indication at some intersections. Higher percent arrivals on green indicate better quality of progression at the intersection. Figure 64 illustrates the data used to calculate percent arrivals on green.



Source: Federal Highway Administration.

Figure 64. Graphic. Data used to calculate percent arrival on green.(14)

Platoon Ratio and Arrival Type

Arrival Type is also used to describe the quality of progression from one signalized intersection to the next along a coordinated corridor. (X) Arrival type is based on the percentage of vehicle arriving during the green indication, when they arrive during the green interval and density of the arriving platoon. Figure 65 illustrates how the arrival type can be used to graphically compare two signal timing conditions.

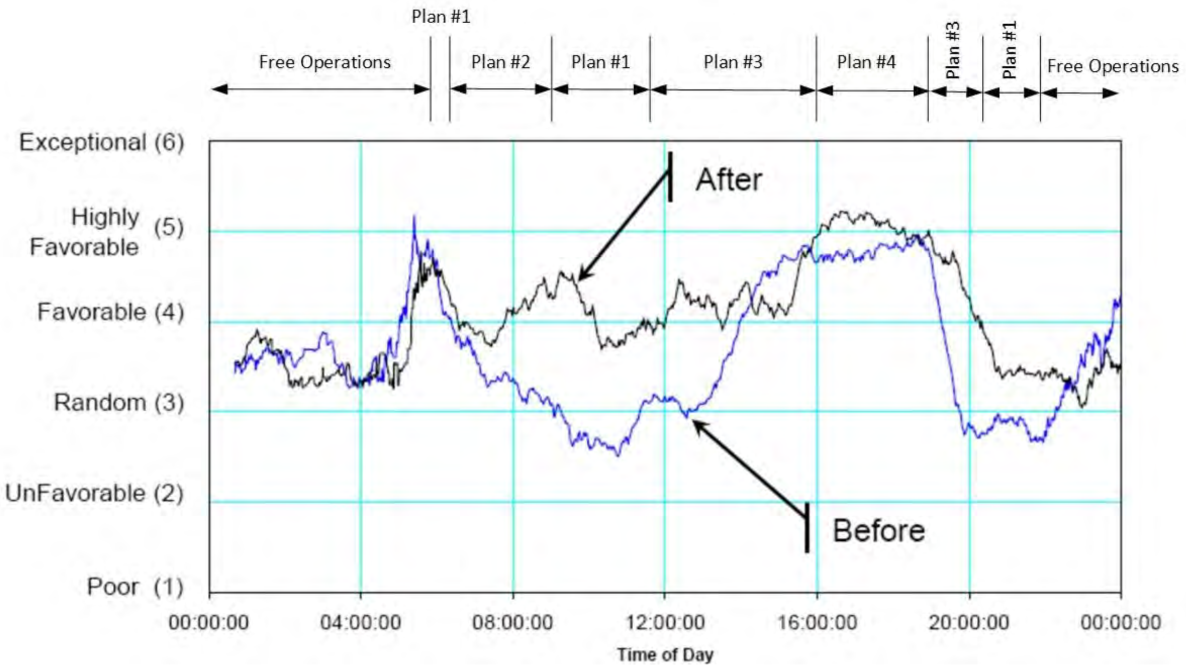
Platoon ration is a measure that quantifies the quality of progression from one signal to another along a coordinated corridor. It is the percentage of vehicles arriving during the green indication (AoG) divided by the green interval (g) to cycle time (C) ratio.(15) It applies for an individual link and not a whole corridor, similar to percent arrivals on red/green.

Table 49 shows the relationship between arrival type and platoon ratio.(14)

Table 49. Relationship Between Arrival Type and Platoon Ratio (14)

Arrival Type	Range of Platoon Ratio	Midpoint Value	Progression Quality
1	≤ 0.50	0.33	Very poor
2	>0.50 – 0.85	0.667	Unfavorable
3	>0.85 – 1.15	1.00	Random arrivals
4	>0.85 – 1.15	1.333	Favorable
5	>1.50 – 2.00	1.667	Highly favorable
6	>2.00	2.000	Exceptional

Source: Federal Highway Administration



Source: Federal Highway Administration.

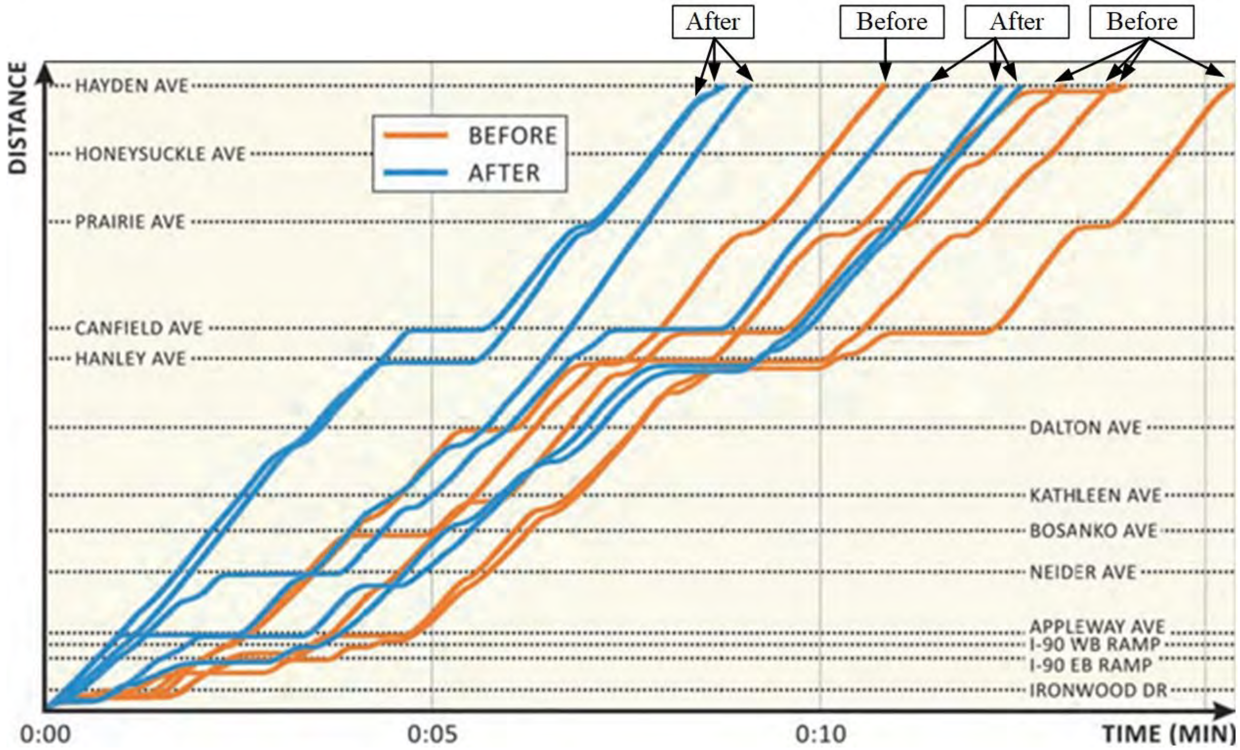
Figure 65. Graphic. Illustration of arrival-type performance measures.(14)

Flow Profiles

A flow profile measures vehicles' average flow past a given point averaged over a specified interval. The arrival flow is useful information to understand the relationship of vehicle streams between the upstream and downstream intersections. Macroscopic models, such as TRANSYT-7F, SCOOT, and ACS Lite, predict flow profiles. Agencies also create flow profiles by aggregating PCDs in 4-second bins. In an efficiently coordinated corridor, the green indication should start when the flow profile is highest.

Travel Time

Travel time measurements are useful in determining the performance of an arterial in an easy-to-understand manner. Several technologies exist for collecting travel time measurement, including Bluetooth technologies, magnetometers, loops, or connected vehicles. Figure 66 illustrates an example of a before and after comparison of a time-space diagram to characterize travel time along an arterial. Overall, the example shows that progression improved along the corridor and travel time decreased significantly.



Source: *Signal Timing Manual 2nd Edition*

Figure 66. Graphic. Comparison of before and after travel times using vehicle trajectories.(2)

Many public agencies are installing equipment to have a more automated means to assess arterial performance. This technology, known as an anonymous re-identification device, is a low-cost, low-maintenance, nonintrusive device (such a device using Bluetooth technology or electronic toll tag sensors) to measure travel times between two locations.(12) This technology is simple to integrate into the current traffic signal infrastructure and uses sensors to identify vehicles as they travel through the roadway network. Measuring the travel time of an individual vehicle along a road segment is as simple as comparing the time difference between the detection time of the vehicle at the beginning of the segment and the detection time of the vehicle at the end of the segment. Dividing the length of the segment by the vehicle's travel time yields an average speed for the segment. Installing multiple Bluetooth sensors along a corridor allows the operator to compare the unique media access control address of a device at two locations and estimate the travel time.

Readers should consult *Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach(11)* for more information on how to compute and use travel time measures to assess the signal system performance.

Travel Time Reliability

Although rarely used to measure the effectiveness of traffic signal performance, travel time reliability can be an important measure of the robustness of traffic signal operations. Travel time reliability is a measure of the consistency or dependability in travel times, as measured from day-to-day and across different times of day.(13) Examples of travel time reliability measures include the following:(14)

- 95th percentile travel time.
- Buffer time.
- Planning time.
- Buffer index.
- Planning index.

For more information on the use of travel time reliability measures as they relate to traffic signal operations, the reader should consult *Effectiveness and Validation Guidance for Adaptive Signal Control Technologies*.(14)

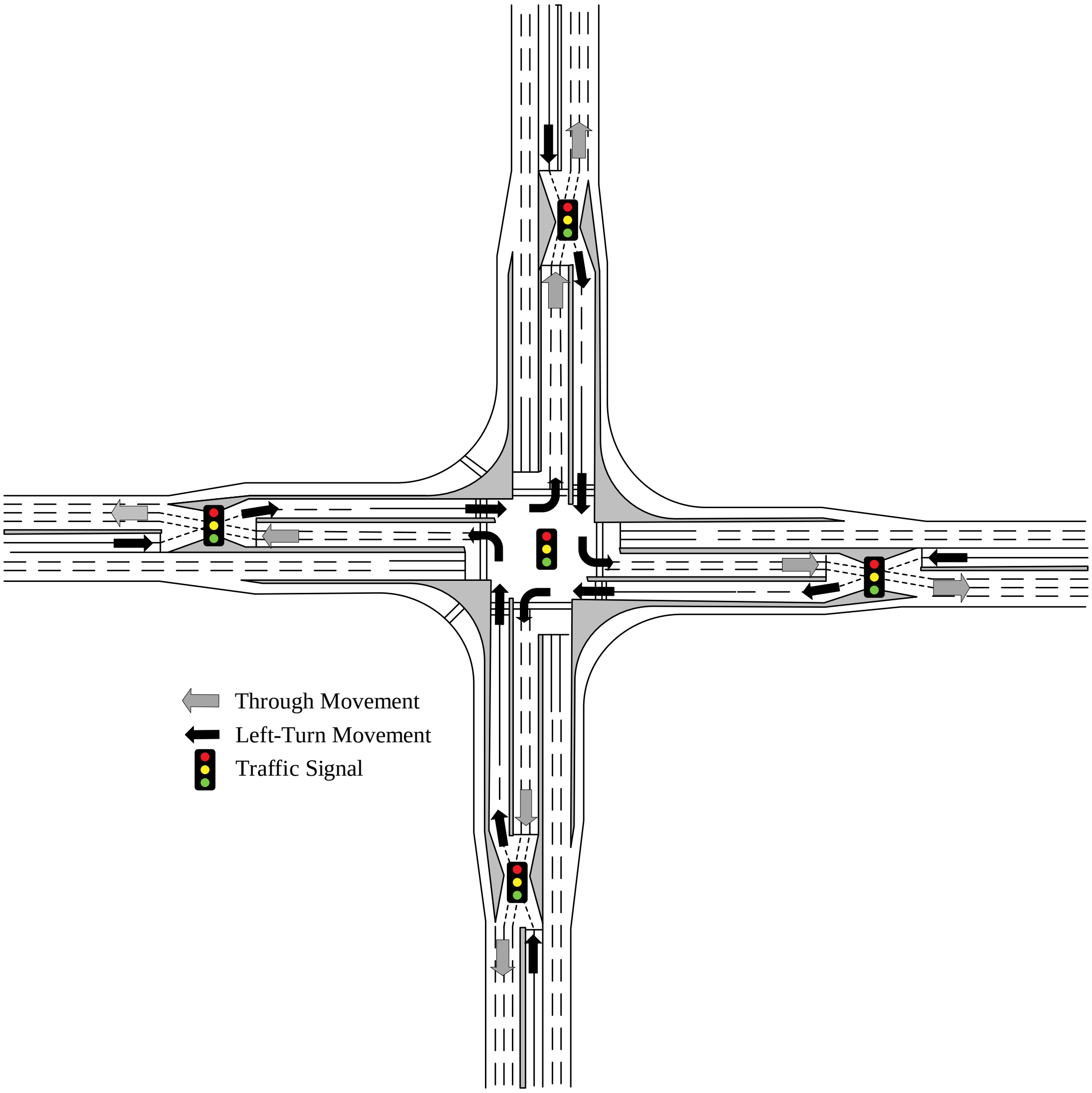
ALTERNATIVE LEFT-TURN DESIGNS

At most urban signalized intersections, accommodating left-turn demand occurs through traditional signal phasing. Traditional signal timing tactics for managing left-turn demand include a combination of protective and permission phasing strategies and the application of turn restrictions. However, some agencies provide unique signal timing treatment for specialized left-turn designs and situations. The following sections describe signal timing strategies to accommodate these unique left-turn design strategies.

Displaced Left Turn

At conventional intersections, the left-turn movements are generally made from separate left-turn lanes and must cross the oncoming path through traffic. At Displaced Left Turn (DLT) intersections, left-turning traffic crosses over the opposing through movement at a location that is several hundred feet upstream of the major intersection. The left-turning traffic then travels on a separate roadbed outside the opposing through lanes as those vehicles proceed toward the major intersection. When these left-turning motorists reach the major intersection, they can proceed without conflicting with the concurrent opposing through traffic. Because the traffic signal does not control the left-turn movements, some agencies refer to DLT intersections as continuous flow intersections.

Figure 67 provides an example of an intersection with displaced left turns. Traffic signals control the crossovers and the main intersection. The shaded arrows indicate left-turn crossover movements, and the black arrows indicate opposing through movement at a signal-controlled crossover. There are five junctions with traffic signal control at a full DLT intersection. Usually, a DLT will operate more efficiently if a single traffic signal controller operates all five junctions. However, conducting the signal design of such an intersection can be complicated.



Source: Federal Highway Administration.

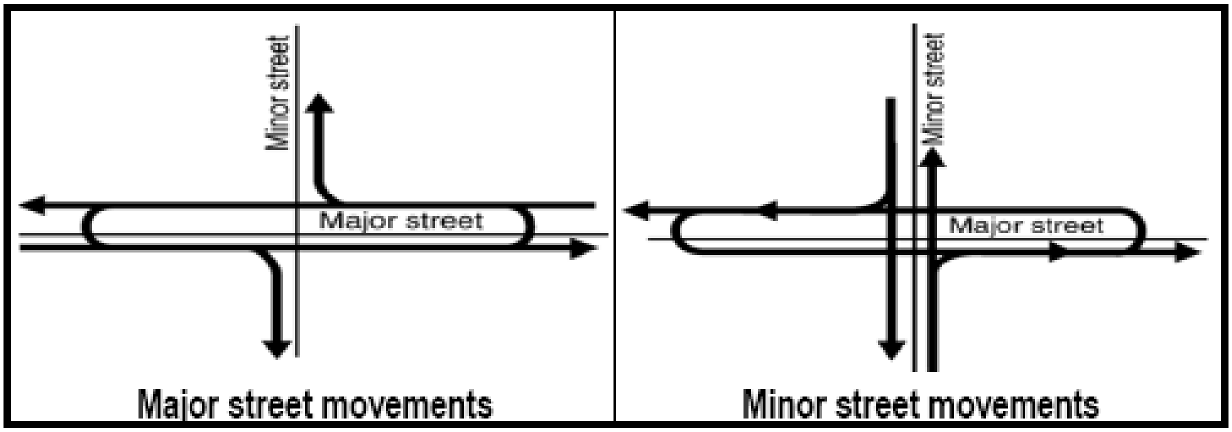
Figure 67. Graphic. Illustration of a left-turn crossover in a full DLT intersection.(16)

Median U-Turn Intersection

The median U-turn (MUT) intersection (also referred to as Michigan lefts) has been used extensively in Michigan. (16) At MUT intersections, left turns are not allowed at the major intersection. Rather, drivers turning left from the major approach must first proceed through the intersection and make a U-turn several hundred feet downstream of the major intersection. Figure 68 illustrates the pathway of left-turning vehicles at a MUT intersection. A MUT treatment is most effective on boulevard type streets with wide medians of between 60 to 100 feet.

The MUT intersection can be either a partial MUT intersection or a full MUT intersection. At a partial MUT intersection, the side road approaches operate like the side road approaches at conventional intersections, where left turns occur from the left-most lane on the side road approaches. For partial MUT intersections, left turns from the major road are generally prohibited. Agencies may prohibit left turns from both the major and intersecting side roads at full MUT intersections.

If considering a MUT intersection, agencies should implement them as a left-turn treatment for the entire corridor. Research recommends against mixing different types of left-turn treatments at signalized intersections along a corridor.(16)



Source: Federal Highway Administration.

Figure 68. Graphic. Illustration of MUT left-turn movements.(16)

INTERCHANGES CONTROL

Freeway to arterial street interchanges represents another situation where agencies might need to implement advance control signal operations. Typically, the most common types of interchanges where agencies tend to use advance control concepts include diamond interchanges, signal point urban interchanges, and diverging diamond interchanges.

Diamond Interchanges

The primary objective of timing a diamond interchange is to provide safe and efficient operations for all interchange users. A diamond interchange is unique in comparison to a regular signalized intersection because it serves as a junction of a freeway and a surface street. Diamond interchanges consist of two intersections where the ramps from the freeways intersect with the arterial. In cases where the intersections are closely spaced, agencies might consider operating the two intersections as a single, coordinated intersection.

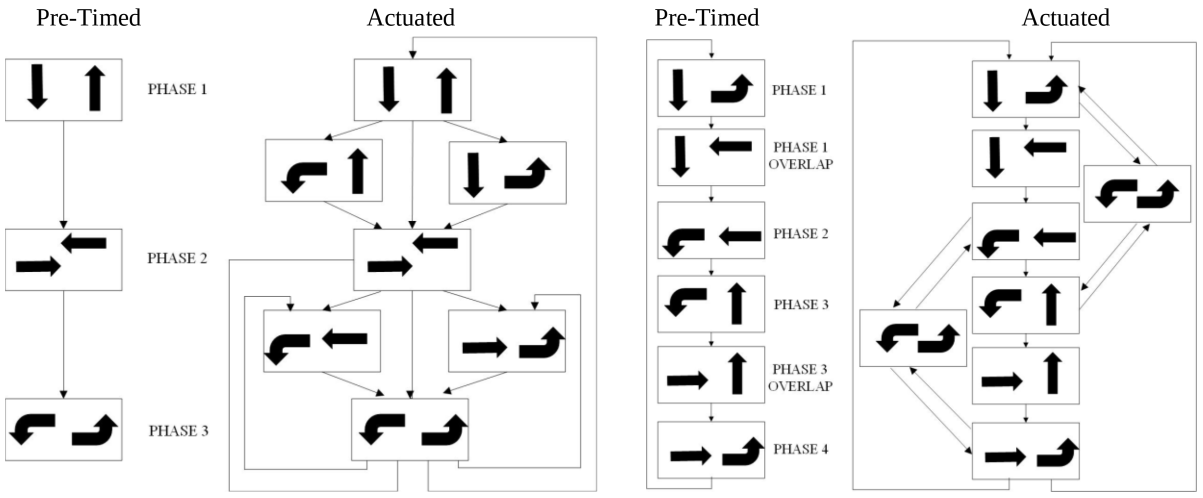
Signal Timing Operational Strategies

Even though a diamond interchange comprises two signals, it is desirable to operate the interchange using a single traffic signal controller. The single controller configuration allows agencies to operate in a fully actuated mode while maintaining the smooth flow of traffic between the two intersections of the interchange. The first decision to be made in the operation of the interchange is selecting the phasing sequence. The selection of the phasing sequence depends on the interchange spacing as well as the traffic patterns. The second decision to be made is whether to operate the interchange in a coordinated or fully actuated mode. The operating mode decision primarily depends on the proximity of other traffic signals that can influence the operations at the interchange. Figure 69 shows two common signal phase sequences used at diamond interchanges.

Many agencies use traffic signal controllers that have a special routine designed specifically for diamond interchanges. This routine makes it easy for an agency to configure the controller. These controllers usually can operate a diamond interchange with three types of phasing sequence: three-phase, four-phase, and separate intersection phasing sequences. Apart from these three phasing sequences, some engineers use two-phase and the non-diamond mode phasing sequences to operate diamond interchanges.

Detection for Diamond Interchange Control

Detector placement at a diamond interchange depends on the phasing sequence. Some agencies may decide to change the phasing sequence by time of day to accommodate significant variability in traffic patterns. Traffic signal controllers that are designed to operate diamond interchanges have built-in logic to automatically assign detectors to the appropriate channels based on the selected operational strategy. Figure 70 illustrates a recommended detector layout for operating a diamond interchange.

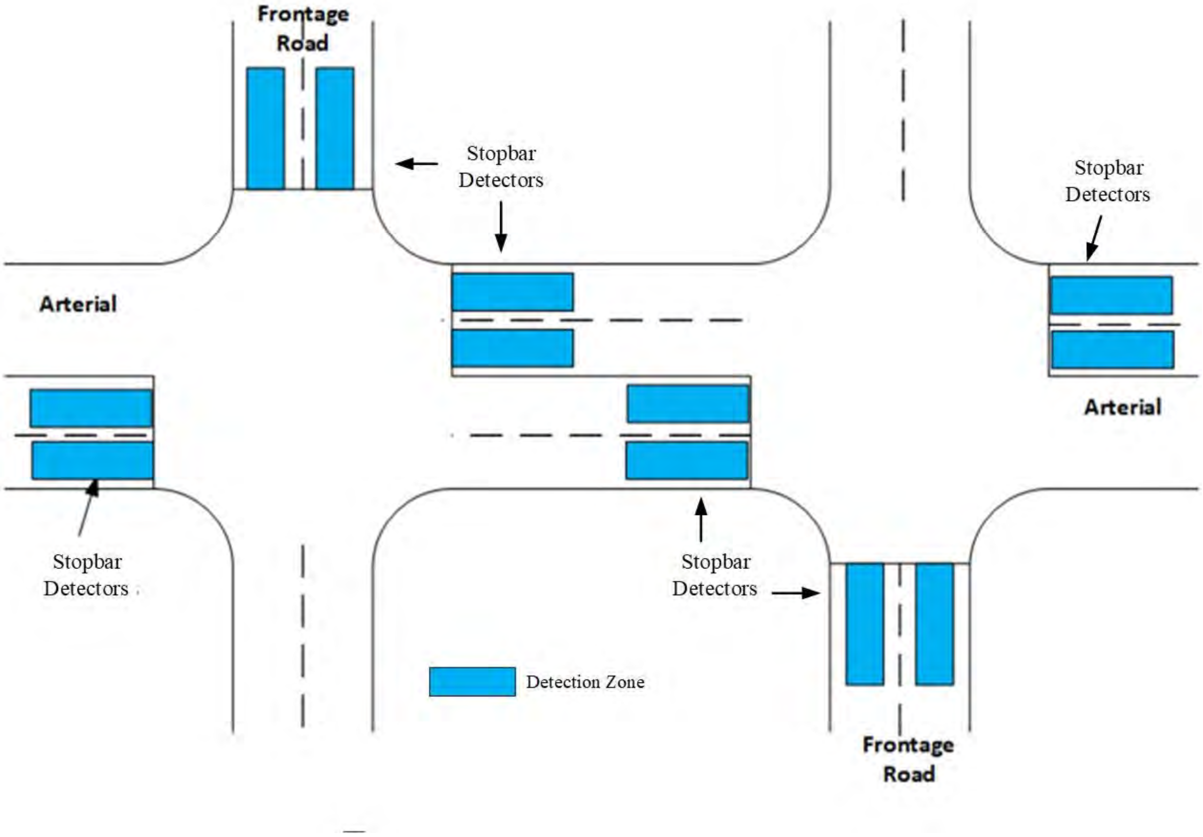


Three-Phase Diamond Control

Four-Phase Diamond Control

Source: Federal Highway Administration.

Figure 69. Graphic. Common Diamond Interchange Phase Sequences

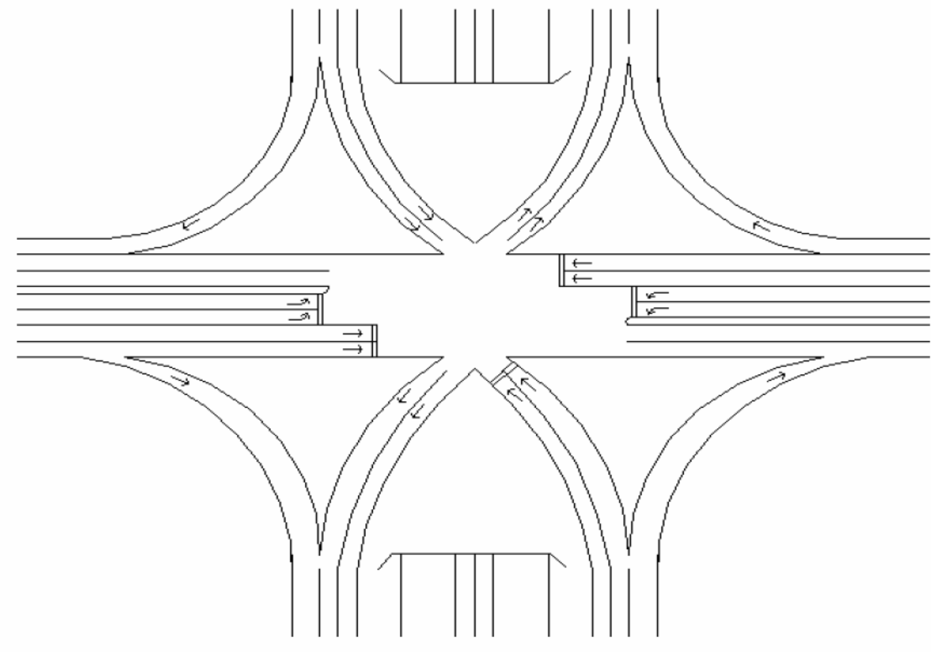


Source: Texas A&M Transportation Institute

Figure 70. Graphic. Recommended detector layout for diamond interchanges.

Signal Point Urban Interchanges

In the 1970s, agencies began using a new type of interchange called a single-point urban interchange (SPUI) to overcome some limitations of diamond interchanges. The SPUI (also called a single signal interchange, a single point diamond, and an urban interchange, among others) uses a single signal instead of two signals in a conventional diamond interchange. Having a single intersection instead of two reduces the number of vehicle phases, which improves signal efficiency. Figure 71 illustrates an example of a SPUI interchange.

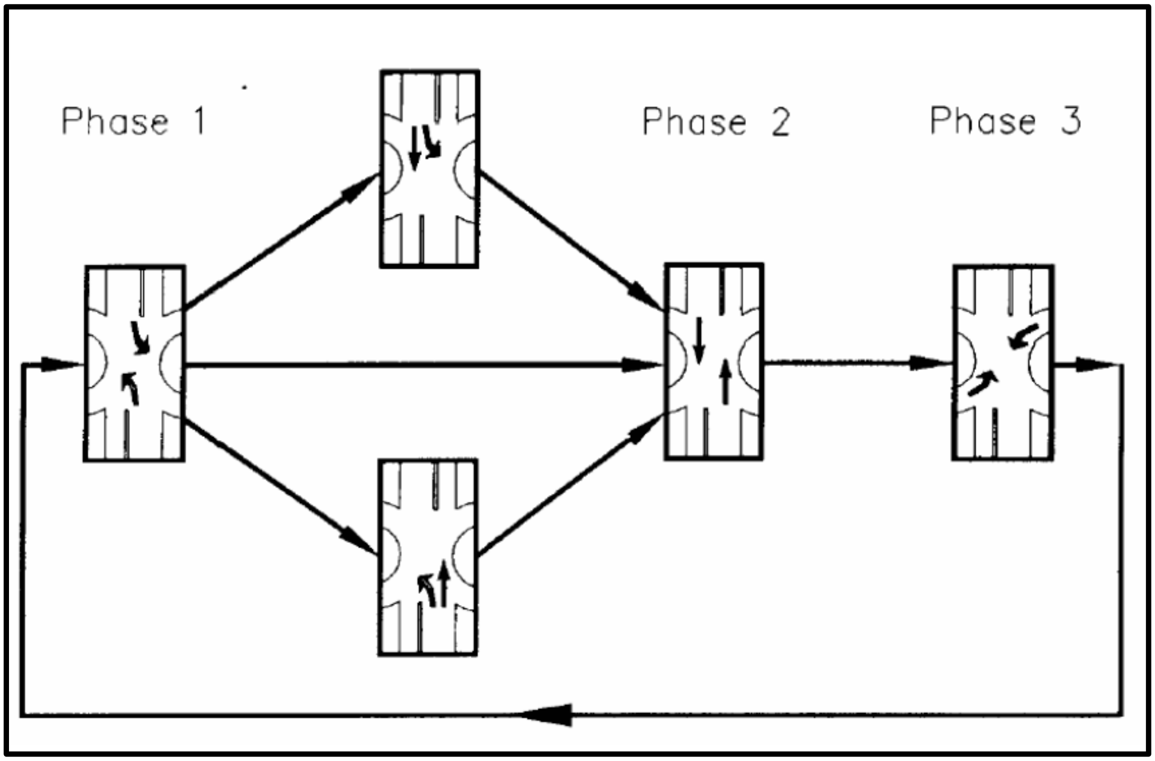


Source: Federal Highway Administration.

Figure 71. Graphic. Illustration of a SPUI.(16)

SPUIs tend to require less ROW than even a tight diamond. SPUIs operate more efficiently under higher volumes of between 20,000 and 35,000 average daily traffic on the arterials.(16) Because SPUIs use a single traffic signal, coordinating SPUIs with adjacent intersections is more straightforward than coordinating a diamond interchange, and SPUIs have a more straightforward phasing pattern (see Figure 72figure 72).

SPUIs do have some limitations. It is not very easy to provide service to pedestrians at a SPUI. While several strategies to service the pedestrians exist, most are not pedestrian-friendly, inefficient for vehicle operations, or too costly for agencies to implement. Another limitation of SPUIs is the cost to construct the interchange.



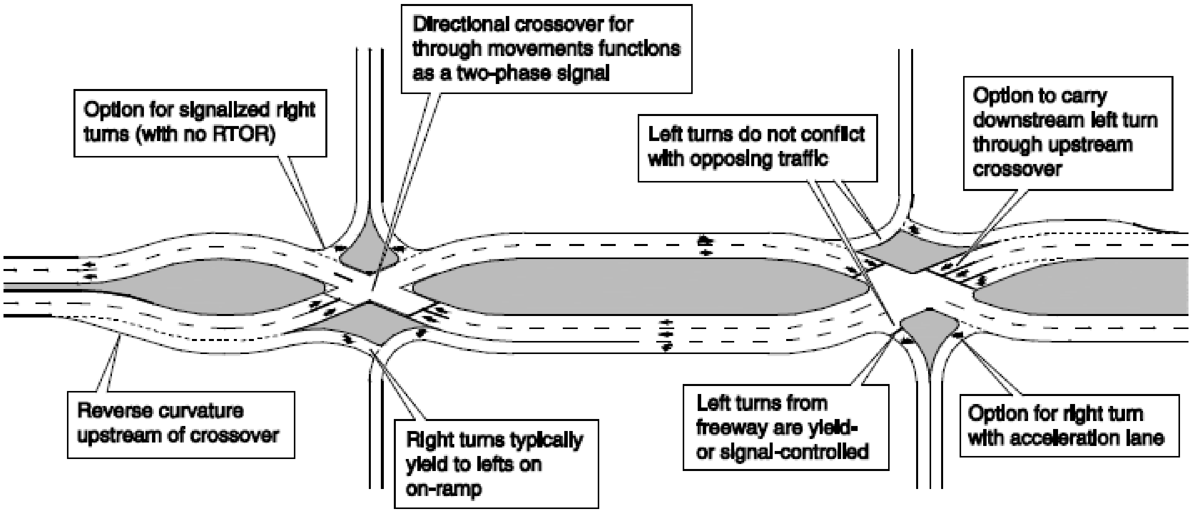
Source: Federal Highway Administration.

Figure 72. Graphic. Typical phasing diagram for a SPUI without frontage roads.(16)

Diverging Diamond Interchange

A diverging diamond interchange (DDI), also known as a double crossover diamond, is an alternative to conventional diamond interchanges. As shown in Figure 73figure 73, the primary difference between a DDI and a conventional diamond interchange is the design of directional crossovers on either side of the interchange.(17) Directional crossovers eliminate the need for left-turning vehicles to cross the paths of approaching through vehicles. DDIs improve traffic flow for motorist turning left onto the freeway. By moving through traffic to the left side of the street between the crossovers, left-turn movements onto the freeway do not conflict with opposing traffic.(17)

Agencies generally operate their DDIs using a single traffic signal controller; however, in some cases, agencies may need to use two controllers to manage the DDI signal timing. With a single controller, an agency can use overlaps to control several movements in multiple rings. Using a single controller also helps to maintain progression through the two intersections during high demand periods. Using two controllers, on the other hand, allows more flexibility and design transparency, and agencies can modify the offsets between the two intersections more easily to adjust progression priorities throughout the day. Controlling the DDI with two controllers also simplifies developing the timing plans for the interchange and the programming of the signal controller and wiring in the cabinets. The two-controller design is also often more readily understood by operators and technicians. Agencies can mitigate some of the operational downsides of using two controllers by using fixed operations and GPS units to synchronize the controller clocks. Table 50 lists the pros and cons of using one and two traffic signal controllers to manage a DDI. Agencies can find more information about signal timing strategies for diverging diamond intersections in the *Diverging Diamond Interchange Informational Guide*.(17)



Source: *Federal Highway Administration.*

Figure 73. Graphic. Key characteristics of a DDI.(17)

Table 50. Pros and cons of operating a DDI using one and two traffic signal controllers.(17)

Single Signal Controller	Two Signal Controllers
+ Reduced hardware costs. + Helps to maintain progression through the two intersections during high demand periods + Avoids the need to set up communication between controllers. + Improved flow during free-running signal operation (late night). − Increased need for wiring across DDI. − More complicated signal design and cabinet setup.	+ Can use simpler timing plans + Ability to better control offsets. + More flexibility because all turns are signalized. + Easier for operators to understand signal design and cabinet setup. − Need for controllers to communicate. − Additional hardware and installation cost. − May result in undesirable gap out situations during low-volume periods.

Note: Pros are shown with a (+) and cons with a (−).

Source: Federal Highway Administration.

PLANNED SPECIAL EVENT AND INCIDENT SIGNAL TIMINGS

Planned event or incident signal timing synchronizes groups of traffic signals to favor traffic entering and exiting a special event venue or area in order to minimize congestion. It can also be used to divert traffic around an unplanned event, such as an incident or a region-wide evacuation. Implementing signal timing control for planned and unplanned events involves the following:(2)

- *Cooperation and coordination between agencies*—Event managers, traffic agencies, public transportation agencies, and law enforcement should work together to identify which vehicles and routes will need priority, organize communications during the event, and coordinate how to respond to unexpected incidents.

- *Real-time Monitoring*—Actual traffic conditions can be difficult to predict for planned events or incidents. For planned events, the start and end times vary and the popularity of the event impacts the number of people who will attend. For unplanned events, predicting the time an incident occurs is impossible. Therefore, an agency will typically monitor the event or incident traffic in real time and adjust the signal timings to match the actual conditions. This process often requires agency staff to work outside regular business hours to implement the planned event or incident signal timings.

- *Special event signal timing plans*—Planned event or incident signal timing plans are turned on and off manually by a person monitoring the traffic conditions. However, if traffic detectors are available, they can control event signal timings automatically. These detectors can measure an increase in traffic, time of day, or the number of parked vehicles in order to automatically activate a signal timing plan.

From a systems and technology standpoint, planned event or incident signal timing strategies involves the following needs:

- Communications from traffic signals to a central operations center.

- Central traffic signal software.

- Vehicle detection to measure traffic volumes.

- Video surveillance for detection and monitoring.

For more information on the use of signal timing strategies for planned and unplanned event traffic, the reader should consult the *Signal Timing Manual, 2nd Edition.*(2)

REGIONAL TRAFFIC SIGNAL OPERATIONS PROGRAM

A regional traffic signal operations program (RTSOP) provides partner agencies with a formal framework for discussing cooperative control of traffic signal operations across jurisdictional boundaries, planning for network-wide consistency in operations, and sharing experiences among multiple agency operations personnel.(18) Common issues and activities RTSOPs can address include the following:(19)

- Consistency in signal timing practices (e.g., setting clearance intervals, intersection configurations, and pedestrian timing and policies).
- Reporting and responding to citizen complaints and providing travelers information.
- Regional priorities and corridors of significance.
- Region-wide performance goals and performance measurement.
- Outreach to the public and decision-makers.
- Cross-jurisdictional timing.
- Region-wide transit signal priority.
- Implementation of incident management plans.
- Implementation of severe weather plans.
- Adaptive traffic signal control.

Table 51 lists some of the key activities and issues that RTSOPs typically address.

Examples of regions that have implemented regional traffic signal operations programs include the following:(18)

- Denver, Colorado—Denver Regional Council of Governments.
- Kansas City, Missouri—Mid-America Regional Council.
- Las Vegas, Nevada—Regional Transportation Commission of Southern Nevada.
- Reno, Nevada—Washoe County Regional Transportation Commission.
- Atlanta, Georgia—Georgia Department of Transportation.
- Los Angeles, California—Los Angeles County Metropolitan Transportation Authority.
- Orange County, California—Orange County Transportation Authority.

Table 51. Key areas of collaboration for regional traffic signal operations programs.[19]

Area of Collaboration	Issues
Operations	• Optimization and coordination of signals within and between agencies, such as State, local, county, and transit agencies. • Optimization and coordination of traffic signals with highway systems, such as interchange ramp termini and ramp metering. • Altering arterial signal timing during freeway and arterial incidents. • Sharing data on arterials during performance measure reporting, freeway and arterial incidents, and traveler advisories. • Sharing maintenance practices and resources. • Communication to both the public and elected officials with a consistent message. • Documentation of practices and procedures. • Training and development opportunities.
Policy, Agreements, and Institutional	• Establish different objectives and policies for varying arterial types, such as arterials within the central business district (or downtown), suburban, and rural areas. Objectives may vary depending on the type of land uses, travel patterns, travel speeds, and vehicle characteristics. An operations program should address these variations to maintain regional consistency. • Establish a regional working group comprised of key stakeholders and a champion to lead the group in being responsible for traffic signal management and maintenance within the region. • Develop the vision, goals, objectives, and performance measures for traffic signal management and operations in the region. • Develop a regional traffic signal management Concept of Operations to identify high-level policies and plans needed to support individual arterials' plans and procedures. Such high-level policies should include: o Balancing major street throughput and average network/intersection delay. o Vehicle clearance times (yellow and all red). o Left-turn movement treatments (leading, lead-lag, lagging). o Pedestrian treatments (rest in walk, leading walk, recall, clearance times, etc.). o Signal timing monitoring and plan updates. o Intersection hardware maintenance. • Identify information and resource sharing needs on a regional level (e.g., whether local agencies can access and view freeway detector and CCTV cameras). • Propose technology and ITS needs to support corridor traffic signal management and maintenance at a regional level. • Assess and establish the needs and qualifications of engineering and maintenance staffing.

Source: Federal Highway Administration.

The reader should consult the following key references for more information on regional traffic signal operations:

- *Regional Traffic Operation Program* Website, FHWA.(18)
- *Regional Traffic Signal Operations Programs: An Overview.*(19)
- *Operational and Institutional Agreements that Facilitate Regional Traffic Signal Operations.*(20)
- *Best Practices in Regional, Multiagency Traffic Signal Operations Management.*(21)

CONNECTED VEHICLE TECHNOLOGY

Connected vehicle technology refers to systems in which vehicles and infrastructure communicate information about vehicle locations and roadway conditions for the traveler's benefit. Connected vehicle technology involves the transmission and reception of this information, additional vehicle applications, and the infrastructure to utilize the available information. These applications may focus on safety-related features, such as forward collision avoidance or red-light running violation warnings, or operational features, such as transit signal priority or advisory speeds for avoiding congestion on a freeway or arterial. All information shared via connected vehicle technology is anonymous, meaning it does not tie any identifying information to the vehicle. Vehicle-to-vehicle communication refers to messages sent between vehicles, while vehicle-to-infrastructure (V2I) communication refers to messages sent between vehicles and the infrastructure (such as the traffic signal cabinet).

The International Society of Automotive Engineers (SAE International) developed a standard (J2735) to allow data transmission interoperability between different vendors of connected vehicle technologies.(22) This section discusses the three most common standardized messages: the basic safety message (BSM), the signal phase and timing (SPaT) message, and the intersection geometry (MAP) data message. The BSM is a message sent by a vehicle, and the SPaT and MAP are messages sent by the infrastructure for the benefit of vehicles on the facility. Each message has a message count and a timestamp to help applications identify if the data are recent enough to be relevant.

Basic Safety Message (BSM)

A connected vehicle sends a BSM for other devices (vehicles and infrastructure) to know its location and velocity. Vehicles broadcast their BSM at 10 Hz. The BSM has two parts. Part I of the BSM contains the core data, which includes the latitude, longitude, elevation, speed, heading, acceleration, and some vehicle operation data like transmission state and braking state. Part I is always included to enable other vehicles to avoid collisions or drive cooperatively. Infrastructure applications can use the BSM information for a wide variety of applications, such as red-light running violation warnings, signal timing, or even performance monitoring of a facility.

Part II of the BSM is sent conditionally, such as when the antilock brake system activates. Part II contains information to describe a disabled vehicle's status, special vehicle information (for emergency vehicles and trucks), and other miscellaneous information.

Signal Phase and Timing (SPaT)

SPaT messages contain information about the current status of the signal operations at a signalized intersection. The intersection transmits SPaT messages at 10 Hz with information about the intersection operation, phase status, and when the signal indications status expects to change. Producing SPaT messages involves converting NTCIP 1202 messages from the traffic signal controller into the SAE J2735 standard format.(22) The J2735 format includes the intersection status so vehicles will know if the intersection is in fixed timing, preemption, or failure mode. The SPaT provides the signal state status and time change details for all the signal groups at the intersection. The intersection identification number in the SPaT must correspond with the intersection identification number in the MAP message.

The signal status has 10 options to handle different unavailable statuses and different behaviors expected for green, yellow, and red indications.(22) For example, the SPaT has different values for flashing red operations where the behavior expected is stop-then-proceed if safe and a solid red indication where the behavior is stop-and-remain.

Signal groups denote lane movement controlled by the same signal state. The signal state is a required data element for the SPaT message. If movements vary throughout the day, the SPaT message identifies which lane IDs, corresponding to lanes described in the MAP message, are active at a given time. For example, suppose a signal is near a school with a one-way street during part of the day and two-way traffic at other times. In that case, the MAP message contains lane IDs for both the one-way street and two-way operations, and the SPaT message identifies which of those lanes, by ID, are operational at the current time.

SPaT messages also contain optional time-to-change details provided by the NTCIP 1202 data given by the controller. If the SPaT has time-to-change details, the minimum end time parameter is required. The minimum end time describes the earliest possible time (in tenths of a second) that a signal group's state expects to change in the current or next hour using coordinated universal time, excluding unpredictable events like preemption. The SPaT may contain a maximum end time parameter that conveys the latest time the phase can change. The standards permit other signal timing information, such as the time change of the phase start time and likely time to change, to be included in the SPaT message. The controller cannot estimate time change parameters like the maximum end time and likely time accurately in traffic-dependent operations when some or all the phases are actuated.

Intersection Geometry (MAP) Data

The MAP message contains information about roadway geometry to enable vehicle applications to identify their location on a facility. The MAP message may describe road segments, high-speed curves, work zones, or intersections. MAP messages are transmitted once per second, which is not as frequent as other messages. The MAP message is a static description of the vector geometries of the intersection approaches. The vehicle system compares the GPS location readings against the MAP message to determine which leg of the intersection the vehicle is approaching.(23)

The MAP message usually describes intersections. It describes the area of interest in a frame called *Intersection Geometry*. The MAP message can hold as many as 32 of these *Intersection Geometry* frames, but many CV deployments provide a single MAP message for each intersection. The primary reason MAP messages describe one intersection is to manage the size of the transmitted message. If the MAP message is too large, the equipment will not transmit the message over standardized ports. The MAP message provides roadway geometry data for the intersection in three dimensions with a 1 cm resolution. Lanes in the MAP have different use types to describe their acceptable uses (e.g., motor vehicles, pedestrians, medians, bike lanes, trains, etc.). Lanes in a MAP are described by a centerline and widths to save space in the message. Every lane with a stop line requires a data frame for *Connects To* information, which describes which lanes can accept users. The *Connects To* data frame describes connections between lanes and contains the signal group identification number corresponding to the SPaT message. The MAP contains data elements to describe which maneuvers are acceptable on or between lanes.

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APPENDIX. SCOPE OF WORK TEMPLATE FOR CONDUCTING SYSTEMS ENGINEERING ANALYSIS

The following is a model scope of work document that agencies can use for conducting a comprehensive systems engineering analysis. As stated in Chapter 4, this outline is descriptive, not prescriptive, and there are many ways to effectively engage and document a systems engineering process to reduce project risk.

TASK 1. CONCEPT OF OPERATIONS

Task 1a. Existing Documentation

- Identify existing systems engineering documents for related, interfaced, or similar systems within the agency.
- Identify planning documents that define the operational activity (e.g., TSMO Plan, TSMP, Regional ITS Architecture).
- Note and document from planning documents the purpose for undertaking the system project (related to achieving organization goals and objectives, also defined during planning process).
- Deliverables: Chapters 1 and 2 of Concept of Operations (following the American National Standards Institute outline).

Task 1b. User Needs for Existing Activities

- Identify system users (those personnel who will perform tasks using or being supported by the system).
- Document user activities with current system (in one or more meetings with users).
- Include all needed categories: operations, maintenance, configuration management, support, performance measurement, security, and more.
- Document how current system does not properly support activities (and, if using the model documents, add to Chapter 3).
- Document specific use cases and needs by users to carry out those activities. When using the model documents, select the desired use cases and user needs from the model Concept of Operations.
- Deliverables: Chapters 3 and 4 of Concept of Operations.

Task 1c. User Needs for New Activities

- Document need for new activities: What operational problem or deficiency will be solved by instituting these new activities?

- Document user activities to be supported by proposed system (in one or more meetings with users).

- Include all need categories: operations, maintenance, configuration management, support, performance measurement, security, and the like.

- Document specific use cases and needs by users to carry out those activities. When using the model documents, select the desired use cases and user needs from the model Concept of Operations. If the model does not support the proposed activity, it will need to be documented in whole.

- Deliverables: Chapters 3 and 4 of Concept of Operations.

Task 1d. System Concept

- Document basic subsystems and architecture. Select and tailor the appropriate statements from the model documents and refer to the Model Documents Reference Architecture.

- Evaluate conceptual alternatives.

- Identify interfaces and standards between modules.

- Extract project architecture from regional architecture.

- Deliverable: Chapter 5 of Concept of Operations.

Task 1e. Environment

- Document the operational environment (How do users access system? How is the system placed before them? Where is the system located?).

- Document the support environment (Who maintains the system? Who will do configuration management?).

- Document operations and maintenance resource activities and requirements for staffing, equipment, and tools.

- Deliverables: Chapters 6 and 7 of Concept of Operations.

Task 1f. Scenarios

- Document examples of system application (Scenarios) that show how needs and activities are carried out to address problems to be solved. Follow the examples in the model documents.
- Deliverable: Chapter 8 of Concept of Operations.

TASK 2. VALIDATION PLAN

- Combine the user needs into validation cases (e.g., user needs that coalesce around common procedures and activities), as suggested generally using the model documents.
- Identify the method needed to evaluate validation cases.
- Identify who will conduct validation at what stages of the project (validation of requirements, conceptual and preliminary designs, final designs, implementation phases, post-acceptance operation, etc.).
- Deliverable: Validation Plan.

TASK 3. REQUIREMENTS

- Extract requirements from user needs. If using the model documents, these requirements are provided and already associated with each user need. Select as necessary for the needs that have been selected.
- Organize requirements by system function (use needs are organized by use case). The model documents' requirements are already organized.
- Develop Needs-to-Requirements Traceability Table (provided in the model documents).
- Check requirements traceability (built into the use of the model documents).
- Validate requirements using Validation Plan (consistency). The model documents' requirements have already been checked for consistency with the user needs.
- Conduct requirements walk-through. In this meeting, the systems engineer presents each requirement and demonstrates that it traces to user needs and is consistent with user needs. The time required for such a meeting is worth it—it takes the place of document reviews that may never be fully undertaken.
- Revise requirements if necessary after the walk-through (requires revalidation).
- Deliverable: Validated Requirements Document.

TASK 4. VERIFICATION PLAN

- Combine requirements into verification cases (e.g., requirements that coalesce into common system functionalities). The model documents already suggest verification cases.
- Identify the method needed to evaluate requirements fulfillment (provided in the model documents).
- Identify who will conduct verification at what stages (verification of conceptual and preliminary designs, final designs, implementation phases, final acceptance).
- Deliverable: Verification Plan.

TASK 5. DEVELOP SYSTEMS ENGINEERING ANALYSIS

This analysis must be developed per FHWA requirement, but note that FHWA's documentation processes are differently in each State in the Stewardship Agreement that governs how States perform oversight tasks delegated to them.

- Document architecture compliance (from Concept of Operations).
- Document agency roles and responsibilities (from Concept of Operations).
- Document requirements (from Requirements Document).
- Document alternatives (from Concept of Operations).
- Develop and document procurement approach (which still needs to be done; see below).
- Identify standards (provided in the Concept of Operations from the regional ITS architecture) and testing (Verification Plan).
- Identify operations/management resources. This process remains a challenge. An agency undertaking an activity needs staff, equipment for the staff to use, facilities to house the staff, and infrastructure. Systems engineering is applied to the infrastructure implementation, but the operations planning documents that provide the foundation for systems engineering should identify the staffing, equipment, and facilities needed for the activity. Thus, this documentation comes from operations planning documents, unless they do not exist. See below.
- Deliverable: Systems engineering analysis.

TASK 6. PROCUREMENT OPTIONS

- Qualifications vs. cost vs. sole-source for selection.
- Request for proposal vs. design-bid-build vs. design-build, and so forth.

- Who will fill what role?
  - Agency.
  - Systems engineer.
  - Designer.
  - Contractor.
  - Vendor.
  - Tester.
- Who will provide training, maintenance, support, and warranty?
- Deliverable: Relevant portion of systems engineering analysis.

TASK 7. RESOURCE REQUIREMENTS

- Staffing needed to carry out activities described in Concept of Operations.
- Staffing gap analysis (numbers and skills).
- Plan for filling staffing gaps.
- Identify equipment needed for operations and maintenance.
- Plan for providing equipment.
- Identify facilities needed to house activity.
- Plan for providing facilities.
- Deliverable: Relevant portion of systems engineering analysis.

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