Review of Traffic Management Systems—Current Practice

PUBLICATION NO. FHWA-HRT-23-051 JULY 2023

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
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FOREWORD

Traffic management systems (TMSs) and their centers are critical resources that offer agencies the potential to improve the safety and mobility of travel on the surface transportation system. TMSs also assist agencies in fulfilling the ever-increasing transportation needs of travelers (e.g., travel times), service providers (e.g., transit, emergency services), other agencies, and the public (e.g., incidents). Agencies continue to be challenged with improving the performance of their TMSs, expanding the geographical area they serve, expanding or enhancing services, and providing the funding and staffing needed to manage, operate, and maintain the systems.

This report accentuates the current practices, new methods, emerging technologies, and approaches agencies are using to improve or prepare for the next generation of their TMSs. It highlights the basic functions, operational strategies, motivation for different capabilities, and the range of opportunities agencies have considered to improve the active management, operation, and performance of these systems. The practices and methods captured in this report should assist agencies when they plan, design, procure, develop, implement, test, operate, and evaluate possible improvements to legacy or the next generation of their TMSs.

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-23-051	2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Review of Traffic Management Systems—Current Practice			5. Report Date July 2023 6. Performing Organization Code	
7. Author(s) Steve Kuciemba, Les Jacobson, Arianne Mizuta, and David Nguyen			8. Performing Organization Report No.	
9. Performing Organization Name and Address WSP Under contract to: Cambridge Systematics, Inc. 3 Bethesda Metro Center, Suite 1200 Bethesda, Maryland 20814			10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-16-D-00051	
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration Office of Operations (HOP) 1200 New Jersey Avenue, SE Washington, DC 20590			13. Type of Report and Period Covered Final Report; October 2018—May 2021 14. Sponsoring Agency Code HRSO-50	
15. Supplementary Notes The contracting officer's representative was Jon Obenberger (HRSO-50; ORCID: 0000-0001-9307-847X).				
16. Abstract The purpose of this report is to provide an appreciation of the current practices, new methods, emerging technologies, and approaches to improve the active management and operation of a traffic management system (TMS). As agencies plan to implement or explore improving a TMS, they are facing a number of challenges, such as performance, costs for expanding system coverage, costs for enhancing supported services, costs for operating and maintaining the system, and demands on staff resources and their capabilities to operate and maintain the system. This report examines the basic functions of TMSs and supported operational strategies to identify how their current system compares to others; the range of capabilities existing in their practice; the motivation for agencies making investments in TMS functions or capabilities; the challenges and lessons learned from other agencies; and how to help agencies identify potential areas of improvement for their systems.				
17. Key Words Traffic management systems, operations, functions, capabilities, system monitoring, performance measures		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. https://www.ntis.gov		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified		21. No. of Pages 143	22. Price N/A

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

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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS AND ACRONYMS

ADVISE	Adverse Visibility Information System
AMS	analysis, modeling, and simulation
API	application programming interface
ARM	adaptive ramp metering
ATC	Advanced Traffic Controller
ATDM	active transportation and demand management
ATM	active traffic management
ATMS	Advanced Traffic Management System
ATSPM	Automated Traffic Signal Performance Measures
Caltrans	California Department of Transportation
CAV	connected and automated vehicle
CCTV	closed-circuit television
CHART	Coordinated Highway Action Response Team
CMF	capability maturity framework
CMM	capability maturity model
ConOps	concept of operations
DART	Dallas Area Rapid Transit
DB	design-build
DBB	design-bid-build
DMA	dynamic mobility application
DLUC	dynamic lane use control
DMS	dynamic message sign
DOT	department of transportation
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
HAR	highway advisory radio
HOV	high-occupancy vehicle
HOT	high-occupancy toll
https	hypertext transfer protocol secure
ICM	integrated corridor management
IMTMS	Intermodal Transportation Management System
INDOT	Indiana Department of Transportation
IoT	Internet of Things
IP	Internet Protocol
IRIS	Intelligent Roadway Information System
IT	information technology
ITSs	intelligent transportation systems
JTMC	joint traffic management center
KC Scout	Kansas City Scout
KDOT	Kansas Department of Transportation
LADOT	Los Angeles Department of Transportation
LCS	lane control sign
LPR	license plate reader

MDOT	Maryland Department of Transportation
MMITSS	multimodal intelligent traffic signal system
MoDOT	Missouri Department of Transportation
MnDOT	Minnesota Department of Transportation
MPO	metropolitan planning organization
MTP	metropolitan transportation plan
NITTEC	Niagara International Transportation Technology Coalition
NWS	National Weather Service
QW	queue warning
RAMS	Regional Arterial Management System
ROF	Regional Operations Forum
RTOP	Regional Transportation Operations Program
RTP	regional transportation plan
SANDAG	San Diego Association of Governments
SDOT	Seattle Department of Transportation
SHA	State Highway Administration
STMC	Satellite Transportation Management Center
SOC	Statewide Operations Center
SOP	standard operating procedure
SWIFT	Southwest Florida Interagency Facility for Transportation
TIM	traffic incident management
TIP	Transportation Improvement Program
TMC	Traffic Management Center
TMS	traffic management system
TRB	Transportation Research Board
TSMO	transportation system management and operations
TSP	transit signal priority
TxDOT	Texas Department of Transportation
UDOT	Utah Department of Transportation
VPN	virtual private network
VSL	variable speed limit
VCTMC	Virtual Corridor Traffic Management Center
VDOT	Virginia Department of Transportation
WSDOT	Washington State Department of Transportation
WYDOT	Wyoming Department of Transportation

CHAPTER 1. INTRODUCTION

PURPOSE AND FOCUS

The purpose of this report is to provide an appreciation of the current practices, new methods, emerging technologies, and approaches to improve the active management and operation of a traffic management system (TMS). Primarily, this report focused on what agencies are doing today with some consideration of how those practices will need to evolve in the future.

The specific goals of this document include the following actions:

- Identify current practices for the active management and operations of TMSs.
- Identify innovative methods and technologies being used.
- Identify agencies' processes for assessing, evaluating, and reporting on the TMS performance.
- Identify how agencies are planning, designing, developing, and implementing enhancements to or replacements of their TMSs.

INTENDED AUDIENCE

As agencies plan to implement or explore improving a TMS, they are facing a number of challenges, such as performance, costs for expanding system coverage, costs for enhancing services supported, costs for operating and maintaining the system, and demands on staff resources and their capabilities to operate and maintain the system.

TMSs rely on technologies, software and software applications, services, and transportation data to manage and support roadway operations, maintenance, planning, and design. Agencies that have operated TMSs in somewhat of a controlled or manual environment in the past are adjusting to the evolution of the capabilities of the newer system, the evolution of new data sources and data platforms, and how these systems can be proactively managed and operated.

Proprietary products add more challenges and integration issues when using shared data or cloud-based software platforms in a more dynamic and automated environment normally used to improve operations. Integration issues of proprietary products also impact the need to support standards and interoperability.

However, with those challenges come new opportunities for agencies to improve TMS operations by more actively managing and monitoring the system using emerging technologies and data sources. Designing and using different architectures that incorporate these technologies can improve the capabilities of the system and support a variety of operational strategies, especially around data-sharing services with other systems or service providers. Increasing agency awareness, planning on how to address, and early preparation for these challenges will help position agencies for expected changes in the capabilities and how to operate the next generation of TMSs; for instance, in a connected and automated vehicle (CAV) and connected traveler environment.

This report will benefit a wide range of practitioners, who may be responsible for support or make decisions that might influence or may be impacted by TMS' capabilities or how they are managed or operated. This report is intended for a variety of users because it will familiarize the audience with the current state of the practice, key concepts, challenges, and lessons learned pertaining to TMSs. Understanding current practices and lessons learned will provide readers with a basis to improve the understanding of TMS capabilities, how those capabilities are being managed and operated, and their potential to improve safety and mobility on the facilities they manage and support.

This report examines the basic functions of TMSs; reviews their operational support strategies; identifies how their current system compares to others; explores the range of capabilities existing in their practices; analyzes the motivation for agencies making investments in TMS functions or capabilities, challenges, and lessons learned from other agencies; and helps agencies identify potential areas of improvement for their systems. Individuals who would benefit from reading this report include anyone involved in or responsible for providing resources to TMSs or involved with managing, operating, evaluating, planning, designing, developing, and implementing TMSs. This group of practitioners includes representatives from State departments of transportation (DOT), local agencies, metropolitan planning organizations (MPOs), regional authorities, toll authorities, or other groups involved with or who support TMSs. In addition, consultants, contractors, and researchers also will benefit from reading this report.

CONTEXT OF TMS

Roadway congestion and safety problems increased significantly after World War II, when land development and economic growth accelerated, which led to the launch of nationwide transportation facilities under an interstate highway program in 1956.[(1)] Safety became a recognized problem when the frequency and severity of collisions increased substantially due to the rapid increase in driving.

Agencies initially served as *providers* and *maintainers* of the transportation network but have been experiencing a shift in mission statements, especially for agencies that manage traffic in dense urban areas. Agencies have realized that to continually improve the performance and reliability of their transportation network, they need to expand their mission statements to include *management* and *operations*. Successful management and operations of the network rely on the integration of TMSs into the management and use of different operational strategies, which also might include coordinating with other agencies and TMSs to pursue common support services and other key management processes and activities.

One of the first successful management and operational strategies to address capacity and demand was deployed on freeway ramps in the early 1960s. Ramp metering is one example of an operational strategy supported by a TMS that has steadily grown in deployment in metropolitan areas to improve the safety and operation of travel on freeways and adjoining surface streets. Operational strategies strive to find a balance between using physical roadway capacity restraints, maintaining public agency budgets, needing to improve safety and operations, and implementing and using sustainable transportation solutions (e.g., operational strategies) as means for good stewardship.

A key aspect of effective traffic management is active management. Active management of a TMS provides dynamic and adaptive adjustments to changing current and future conditions. Active management offers agencies a way to incrementally improve their TMS implementations by monitoring the performance of the TMS, assessing its effectiveness, developing and selecting actions to improve its performance, and implementing the selected action(s). This cycle starts again with monitoring the performance of the TMS. This active management cycle is illustrated in figure 1.

Source: Federal Highway Administration (FHWA).

Figure 1. Diagram. The active management cycle.[(2)]

Active management involves the following actions:

- Focuses on the present and immediate future (planning horizons).
- Recognizes that conditions vary and may not be "typical."
- Centers on customers and their service needs.
- Focuses on performance outcomes instead of outputs.
- Emphasizes system management over system development.
- Operates 24/7.
- Scales to trips instead of jurisdictions.

An effective TMS is one that has the active management concept embedded in it. A TMS is a system that comprises a complex, integrated blend of hardware, software, processes, and people performing a range of functions and actions. TMSs are focused on improving the efficiency, safety, and predictability of travel on the surface transportation network. For the latter half of the 20th century and the beginning of the 21st, TMSs have been deployed to fulfill the ever-increasing transportation needs of society. These needs have evolved from solely reporting travel times to a wide range of needs, including reporting on various types of traveler information, detecting incidents, managing the use of operational strategies in response to changing conditions, and improving safety and travel on facilities being managed. Modern TMSs are very complex systems, combining field equipment, operations personnel, and advanced communications and information technology (IT) to meet their missions.

The more complex TMSs comprise multiple subsystems. A subsystem is a group of self-contained and interactive components that support one or more operational strategies as a part of a TMS. For example, a statewide TMS may be composed of multiple smaller subsystems working together to meet agency goals and implement operational strategies. Examples of common subsystems that make up a complex statewide TMS include ramp metering, traffic signal control, dynamic message sign (DMS), data, and communication. TMSs and subsystems have become more complex as the technology and components that make up these systems have evolved. These components are devices or hardware elements that serve a purpose as part of a larger subsystem or TMS. As technologies and components have evolved, so too has the operation, management, and maintenance of these systems.

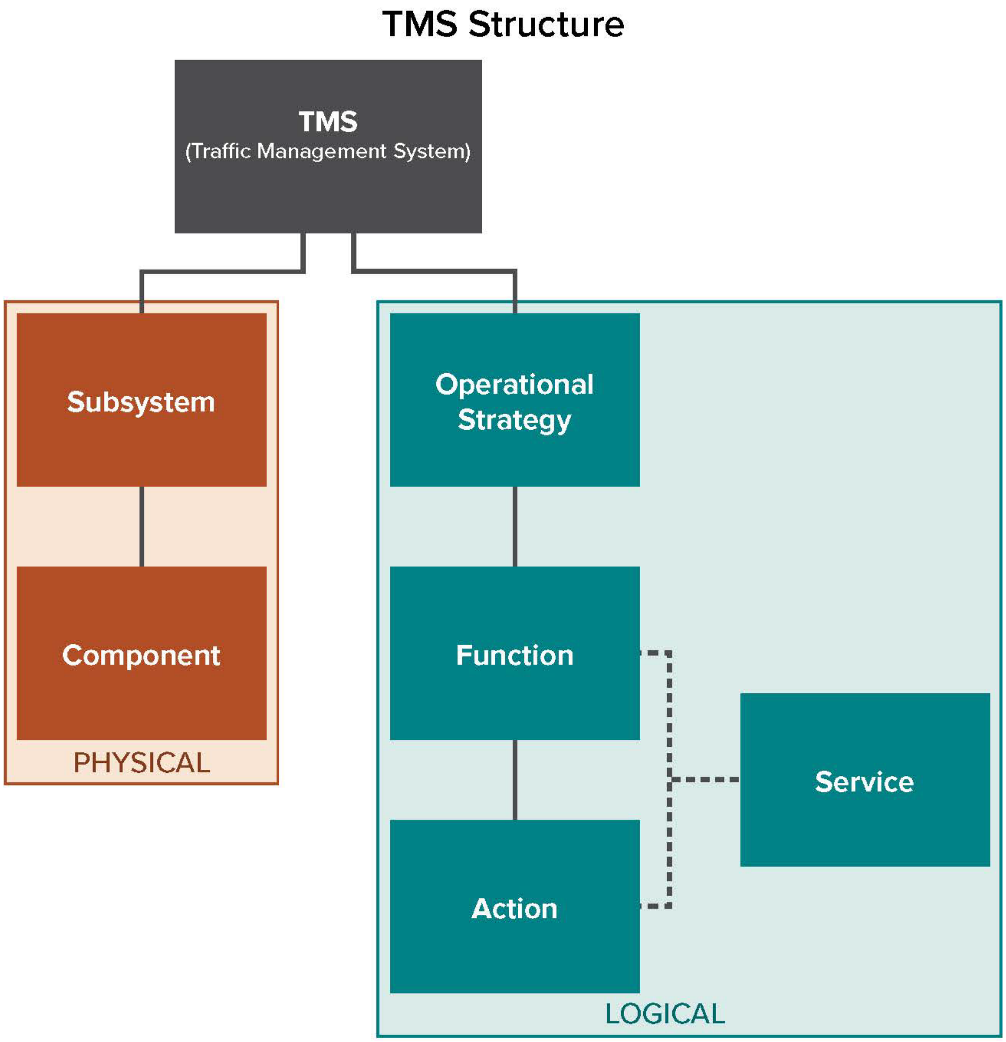
Operational Strategies are a set of functions and combinations of actions that achieve transportation agency objectives, which are often related to safety, mobility, and reliability. Using a suite of operational strategies—such as active traffic management (ATM) and road weather management—can enhance the safety and performance of an existing roadway by improving management of the roadway operations and controlling user demand for the facility. They can also enhance the user experience by improving travel reliability, reducing delays, enhancing mobility, and making safety improvements that reduce the likelihood and severity of crashes.

As agencies implement operational strategies, specific functions, actions, and services that are required to support these strategies should be considered. An action is a basic, singular task of a component or a person. A function is a series or combination of actions that support an operational strategy. A service is a set of functions and/or actions that support system operations. An example of a service could pertain to an external system or subsystem or an internal system (e.g., agency data hub) that would need to connect to the TMS through a mechanism, such as an application programming interface (API).

A Traffic Management Center (TMC) is often an important component of operating a TMS, because it is typically located where the physical elements of the TMS connect to each other and to communications and computing power. Therefore, a TMC is often a highlighted element in planning for a TMS. The TMC operation should support the TMS vision, goals, and objectives. TMC staff members are key stakeholders because they are knowledgeable in their daily management of TMSs and can provide valuable input.

For example, in a TMS that is actively managed, TMC operators are constantly monitoring the transportation infrastructure for incidents or other sources of degradation in operations and traffic flow. TMC operators and managers have firsthand experience with the huge impact that incidents have on the performance of TMSs that individuals outside of the TMC may not consider. In addition, TMC staff can provide input into the operational planning for the TMS, including integration with established regional intelligent transportation systems (ITSs) architectures and ITS strategic plans.

The design or structure of a TMS can be broken down into its physical elements and its logical elements. The physical elements include the subsystem and the components. The logical elements are the operational strategies, functions, actions, and services. A visual representation of the TMS structure is shown in figure 2.



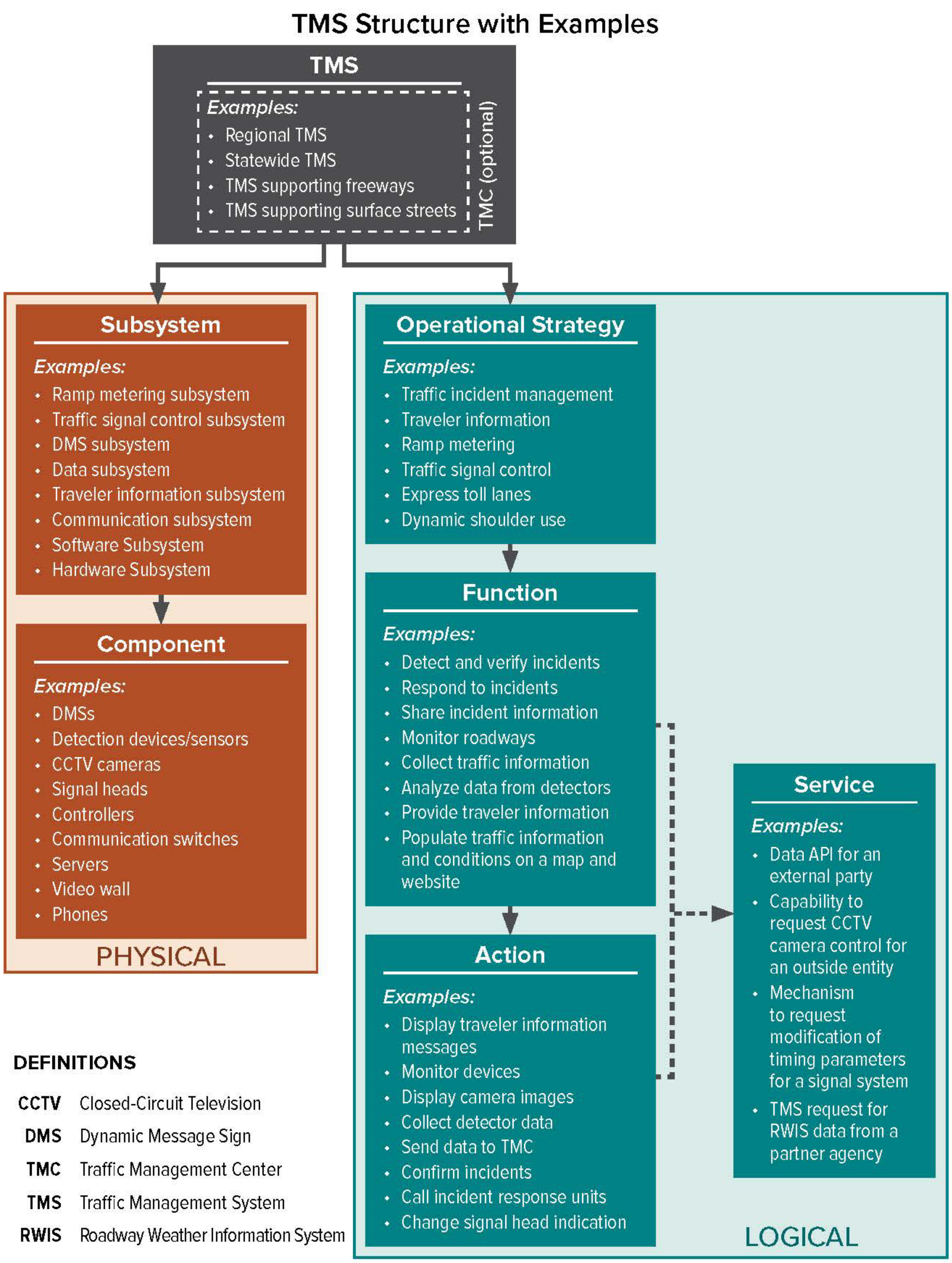
Source: FHWA.

Figure 2. Flowchart. General TMS structure.

The lines in figure 2 depict the relationship in the structure for both the physical side and the logical side of TMS. The lines do not depict a flow of data or information.

EXAMPLE TMS STRUCTURE OR ARCHITECTURE

Figure 3 provides examples for each of the logical and physical elements of a TMS.



Source: FHWA.

Figure 3. Flowchart. TMS structure with examples.

The examples shown in this diagram are not meant to be all inclusive of every element that may exist in a TMS, but rather it is meant to highlight some common elements that agencies may encounter in their own systems. This diagram does not show the relationship between the logical side and the physical side. To explain that relationship, this section presents two use cases:

1. Controlling closed-circuit television (CCTV) and displaying CCTV images.
2. Commanding and controlling ramp metering.

Use Case: Controlling CCTV and Displaying CCTV Images

Physical Side

In a CCTV subsystem, common components include CCTV cameras, controllers, service cabinets, communication switches, servers, and others. In an environment where CCTV is a standalone system, the CCTV system would be considered the TMS. In many cases, CCTV is not standalone, rather, it is just one subsystem in a more complex TMS.

Logical Side

In this example of a CCTV TMS or a TMS that includes a CCTV subsystem, common operational strategies that agencies implement may include traffic incident management (TIM), traveler information, traffic signal control, and other approaches. These operational strategies support agency objectives by performing functions such as detecting and verifying incidents, responding to incidents, sharing incident information, monitoring roadways, collecting traffic information, providing traveler information, and other activities. To achieve these functions, some necessary actions may include monitoring components, displaying camera images, sending data to the TMC, confirming incidents, calling incident responder units, and other actions. Often, agencies will use their TMS to provide services to external parties. In a TMS that involves CCTV, services may include a data API for external parties to access or a mechanism to request CCTV camera control.

The Relationship Between Physical and Logical

When considering the relationship between the logical side and the physical side of a TMS, the clearest relationship is between operational strategies and subsystems. It is easier to understand this relationship because subsystems are generally created to implement operational strategies, which are developed to meet agency goals. When implementing an operational strategy such as TIM, a CCTV subsystem is critical for success in terms of detecting, verifying, and monitoring incidents. It becomes more difficult for an agency to implement the TIM strategy without a CCTV subsystem in place. CCTV subsystems also may be used to support other operational strategies, such as traveler information and traffic signal control.

Traveler information and traffic signal control are examples of strategies that may not always include CCTV subsystems, but they may be enhanced by CCTV when used. Obtaining traveler information may be accomplished by using other subsystems that involve detection and analysis of information, but for this example, CCTV may also provide traveler information via images and visual evidence of travel conditions. Traffic signal control is an operational strategy that is implemented through a traffic signal control TMS/subsystem. However, some traffic signal control subsystems may be enhanced by a CCTV subsystem. One example is pretimed signal control strategies, whereby live CCTV image feeds from CCTV systems can provide visual cues for signal timing engineers to modify their timing schemes. Operational strategies can be carried out by subsystems with the help of personnel, but generally not by an individual component on their own. For example, a CCTV camera will not be able to implement the TIM strategy, but the entirety of the CCTV subsystem with personnel working together can.

The relationship between the logical and physical sides becomes more complex when comparing the functions and actions (logical side) to the subsystems and components (physical side). When examining the TIM strategy, one of the included functions is detecting, verifying, and responding to incidents. Actions related to that strategy and function include monitoring components, displaying camera images, and confirming incidents. As some operational strategies can be carried out by subsystems, functions and actions also can be completed using subsystems. In this example, the CCTV subsystem can carry out the aforementioned functions and actions. However, these relationships will vary on a case-by-case basis. For example, many actions can only be completed by a human operator or engineer.

When examining these functions and actions and comparing them to CCTV components, the relationship is not fully clear. For the most part, the functions cannot be carried out by components, such as a camera, alone. The functions that support operational strategies typically are performed at the subsystem level. Certain actions, such as collecting traffic condition images and transmitting the images to the TMC, can be carried out by a CCTV camera (component). In this case, actions are more closely related to components, and functions are more closely related to subsystems. For example, to achieve the function of detecting and verifying incidents, additional actions that are not performed by a single component, such as a CCTV camera in this example, need to be taken.

These actions may include monitoring components, confirming incidents, and calling incident responder units. These actions are all likely to be performed by a person or operator rather than by a component of the TMS. All these processes together comprise a TMS or a subsystem. In some cases, CCTV cameras have the capability to analyze images and use algorithms to detect and confirm incidents without the need for an operator. In such cases, certain functions can be carried out by components. Components serve a certain purpose as a part of a TMS/subsystem, and that purpose may support one or more operational strategies.

The relationship between services and subsystems or components will vary case by case, but services would most likely be implemented at the system or subsystem level with an appropriate connection and protocol, such as an API, to an external system. For example, a service such as allowing third parties to access images and request control of cameras could be provided through a physical communication connection and an API. An application could connect the external system to the CCTV subsystem to access images or video streams. Control can be enabled through an API.

Use Case: Commanding and Controlling Ramp Metering

Physical Side

In a ramp metering subsystem, common components include signal heads, load switches, detection components, controllers, flashing beacons, service cabinets, communication switches, servers, and others. Like the CCTV example, ramp metering may comprise a TMS if it is an isolated system, but it is typically a subsystem within a complex TMS.

Logical Side

In this example of a ramp metering TMS/subsystem, the most obvious operational strategy agencies implement is ramp metering. The ramp metering strategy is embodied within the ramp metering subsystem. The operational strategy is the logical representation of what happens within the subsystem, which makes it easier to understand the relationship between a subsystem and operational strategy. This operational strategy supports agency objectives by performing functions, such as controlling entrance ramp flows, monitoring ramps, collecting traffic information, analyzing data, and others. To achieve these functions, some actions needed may include monitoring components, gathering volumes from detectors, sending data to the TMC, changing the signal head indication, and other purposes. Agencies may use their TMS to provide services to external parties. From the ramp metering perspective, a service may include a data API that transmits detector data or ramp metering status to external systems, such as traffic signal subsystems or traveler information subsystems operated by neighboring jurisdictions.

The Relationship Between the Physical and Logical

As with the CCTV example, and especially for this example, it is relatively easy to understand the relationship between the subsystem and the operational strategy. The ramp metering subsystem is created for the purpose of implementing the strategy of controlling the flow of traffic onto the freeway mainline. In this example, implementing a ramp metering strategy is not possible without a ramp metering subsystem. A ramp metering subsystem also may be used to support other operational strategies, such as traveler information and traffic signal control. Traveler information and traffic signal control are examples of strategies that may not directly be implemented by a ramp metering subsystem, but these strategies can be enhanced or supported by the subsystem in a complex TMS. Traveler information can be accomplished by another subsystem, such as DMS, but can use the detection components on mainline freeway facilities that are connected to the ramp metering subsystem to collect mainline data, such as volume, speed, and occupancy. These data can be analyzed and used to display information on the DMSs to implement a traveler information strategy.

Traffic signal control is another operational strategy that can be supported by a ramp metering subsystem. Coordination between ramp metering and nearby signalized intersections can make a difference in the success of implementing the traffic signal control strategy efficiently. By coordinating timing schemes between ramp metering subsystems and traffic signal control subsystems, traffic flow can be optimized at a larger scale. Operational strategies can be carried out by subsystems with additional human actions but not by an individual component on its own. For example, a ramp meter controller alone will not be able to implement the ramp metering strategy because other components are needed, such as ramp meter signal heads. It takes the complete ramp meter subsystem, possibly with human interaction, to implement the strategy.

The functions that support operational strategies are typically performed at the subsystem level, perhaps with the help of operators and engineers. When examining the ramp metering strategy, some of the functions include controlling entrance ramp flows, monitoring ramps, collecting traffic information, and analyzing data. These functions are carried out at the subsystem level. For the most part, functions are not carried out by a single component on its own.

Actions related to ramp metering functions include monitoring components, gathering volumes from detectors, sending data to the TMC, and commanding a change to the signal head indication. All these actions can be carried out by the controller (a component).

Services may be implemented at the system (TMS) level as well as at the subsystem level, as described for the CCTV subsystem. For example, if an external system needs traffic volume information that is collected by the ramp metering subsystem, it may be most appropriate for the service to access the data management subsystem that stores and manages the data that includes data from the ramp metering subsystem.

REPORT ORGANIZATION

This report identifies current and successful practices where existing TMS operational strategies can be enhanced or modified by improving TMS components or expanding TMS functions to support new services and information sharing. This report also identifies issues and evolving technologies or methods for agencies to consider when evaluating TMS capabilities and performance for improvement. The content of this report leverages important findings from a review of published literature from industry publications, association websites, governmental websites, material from workshops, and various journals and reports. Additional key findings emerged from work being done on related projects, such as the Leveraging and Coordinating Technology Resources for Transportation Systems Management and Operations and the Active Management Cycle project.[(3)] Relevant findings from the recent Transportation Research Board (TRB) 2020 Workshop 1030: Vision, Concepts, and Capabilities for the Next Generation of TMSs, also have been incorporated in this document, as appropriate.[(4)] The bibliography provides a list of the literature referenced in the preparation of this report.

This report includes seven main chapters and is organized as follows:

- **Chapter 1. Introduction**. This chapter presents the purpose of the report, introductory information on the TMS, the general structure of the TMS, the benefits of using this report, who would benefit from reading this document, and the overall organization of the report.
- **Chapter 2. TMSs: Logical Elements**. This chapter provides examples of TMS structure, history and evolution of operational strategies, and logical elements of the TMS as it relates to different operating environments.

- **Chapter 3. TMSs: Physical Elements**. This chapter dives into the history and evolution of TMS subsystems and their components and how these subsystems are used to achieve operational strategies in different operating environments, and it provides a summary of current practices' successful implementation of TMSs and operational strategies.

- **Chapter 4. Planning and Developing TMSs or Specific Enhancements**. This chapter walks through the process of planning, developing, and implementing a system, agency policies, and industry trends and practices.

- **Chapter 5. Assessing and Reporting on TMS Capabilities and Performance**. This chapter focuses on the state of the practice in terms of assessing and reporting on system performance, including discussions on operational goals, knowledge gaps in practice, and emerging trends.

- **Chapter 6. Challenges and Effective Practices: Improving TMSs**. This chapter discusses challenges and opportunities involved in making improvements to—or complete replacement of—TMSs. This section includes a discussion on a global perspective of TMSs and evolving trends and issues.

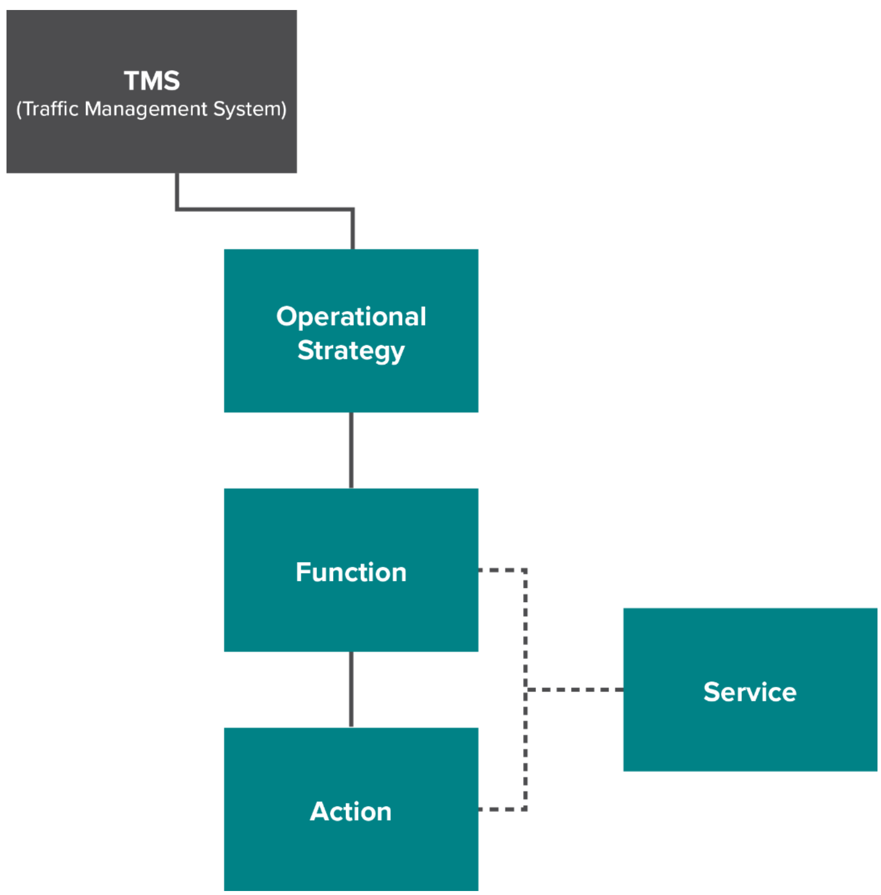
- **Chapter 7. Emerging Operational Strategies and Data Sources**. This chapter summarizes some of the emerging issues and knowledge gaps facing agencies today, including third-party data providers, shared TMSs, and CAVs.

CHAPTER 2. TMSs: LOGICAL ELEMENTS

The objective of this chapter is to provide the reader with a clear understanding of the logical side of a TMS and how operational strategies, functions, actions, and services are implemented and may perform in different environments. In computer terminology, a logical element converts inputs into appropriate outputs. In the same context as a TMS, the logical element takes input from physical components and executes operational strategies that have a direct output meant to satisfy a functional or operational need. How these logical elements are implemented is based on the type of roadway being managed and on the agency's need and the geographical extent of their jurisdiction.

By providing some context of the logical side and examining how these strategies have evolved over time, we can better understand the changing needs of an agency and how they have evolved to meet present-day needs.

Figure 4 displays the logical side of the TMS structure.



Source: FHWA.

Figure 4. Flowchart. General TMS structure: logical side.

TMS OPERATIONAL CHARACTERISTICS

Various defining characteristics of a TMS from an operational or logical perspective include the following aspects:

- Active management.
- Operational goals, performance measures, and reporting.
- Operating environment, describing the type of facility in which the TMS is implemented. The major environments covered in this report include integrated management of freeways, surface streets, and travel on multiple facilities or corridors.
- Operational strategies implemented by the system, which includes the functions, actions, and services that support these strategies.
- Operation deployment model, which describes the type of operational implementation model for a TMS. The models covered in this report are centralized, distributed, virtual, hybrid, and temporary.
- Geographic extent the TMS covers, which describes the area in which a TMS serves.
- Number and type of agencies involved in the operations.

More detailed explanations of these TMS operational characteristics are presented in the following subsections.

Active Management

For TMS operational strategies to maintain a high level of effectiveness, agencies need to introduce improvements incorporating the active management cycle. The active management cycle includes tailoring and adjusting strategies to directly address current or anticipated future conditions in realtime. The level of active management corresponds with how agencies adjust individual strategies in realtime to respond to current and future traffic conditions in both recurring and nonrecurring congestion. Incremental improvement can increase responsiveness to operating conditions. The following stages are levels of responsiveness in the active management context:

- **Static**—Strategy responses to variations in conditions are preset and updated based on the calendar.
- **Reactive**—Strategy responses occur when problems are observed with the static plans, requiring real-time monitoring.
- **Responsive**—Strategy responses to variations in conditions occur in realtime after they are detected.
- **Proactive**—Strategy responses are adjusted in anticipation of future conditions.

In the past, most agencies implemented operational strategies at the static level. The evolution of technology and data management functionality has allowed agencies to move toward reactive, responsive, and proactive levels of operational strategy implementation.

From a TMS perspective, active management includes the following actions:

- Executing or changing operational strategies according to current or anticipated conditions.
- Sharing information in realtime.
- Affecting specific control plans, initiating actions, and coordinating actions.
- Applying these concepts, through enhanced coordination, across geographic boundaries or linking with service providers and systems.
- Collaborating with partner agencies.

Operational Goals, Performance Measures, and Reporting

Clear and well-defined operational goals and objectives are core to having a successful TMS and to assessing the performance of the TMS. Agencies must define the system performance that they are trying to achieve relative to those goals. The data collected to monitor the performance of the TMS can serve as statistical or empirical evidence that describes the current progress toward achieving those goals. Unambiguous performance measures allow for identifying needs and deficiencies in the system. Agencies can also use performance measures to track the impacts of a TMS, report progress to stakeholders, and inform better transportation decisions. These transportation decisions could include modifying operational strategies, refining existing tools, or even adjusting objectives.

Operating Environment

TMSs and their subsystems are the physical embodiment of the operating environment, operational strategies, functions, and actions that an agency may implement. The operational strategies implemented, actions taken, coordination conducted, and actions taken can vary based on the operating environments in which they operate. The operating environment includes the physical environment and the institutional environment. The institutional environment includes policies, resources, and agency capabilities, all of which affect the operation of the TMS. This report will focus on the following three physical environments that operational strategies, functions, and actions support:

- Freeways.
- Surface streets.
- Multiple facilities, corridors, or regions.

A TMS may span multiple operating environments and types of facilities (e.g., event sites, corridors, and regions), and in situations in which multiple agencies are involved, the complexity increases significantly. However, for the purposes of this report, separating TMSs into specific operating environments will allow the authors to provide more context on specific TMS operational strategies, functions, actions, and services. Readers will recognize where their individual environment might lie across the spectrum of possibilities and extract relevant lessons learned.

Operational Strategies

As described in the TMS structure use cases, the physical elements of a TMS are deployed with the intent of implementing operational strategies. The type of operational strategies that a system implements is a way to characterize TMSs. A list of common, but not all inclusive, operational strategies are presented in table 1. The table also highlights whether the operational strategy typically serves freeways, surface streets, or both, while describing some of the common functions of those strategies.

Table 1. TMS operational strategies.

Activity	Operational Strategy	Operating Environment: Freeways	Operating Environment: Surface Streets	Description of Functions
System monitoring	Network surveillance	✓	✓	• Monitor real-time network conditions. • Collect data on traffic flow and roadway performance.
System management and traffic control	Managed lane	✓	✓	• Provide traveler information regarding lane access eligibility (e.g., express lanes, truck-only, or HOV/bus-only lanes). • Provide traveler information regarding pricing of lane use (e.g., express toll lanes and HOT lanes).
System management and traffic control	Traffic signal control	—	✓	• Control the flow of vehicles at an intersection. • Collect intersection performance information. • Adjust the phasing and timing along a corridor to accommodate changing traffic patterns and ease traffic congestion (adaptive signal control).
System management and traffic control	VSL/display	✓	—	• Collect traffic, weather, or construction/maintenance information. • Provide traveler information in the form of recommended safe speeds: ○ In an urban area, the speed information typically is a part of a larger traffic management strategy. ○ In rural areas, the speed information typically is a part of a weather management strategy.
System management and traffic control	Speed warning	✓	✓	• Detect the presence of a vehicle. • Provide traveler information in the form of recommended safe speeds. This information is used to target a specific vehicle or vehicle type traveling too fast for conditions.

Activity	Operational Strategy	Operating Environment: Freeways	Operating Environment: Surface Streets	Description of Functions
System management and traffic control	Ramp metering	✓	—	• Collect data on ramp performance. • Manage and control the type (e.g., preemption and priority control) and rate of vehicles entering a freeway or expressway facility. • Balance freeway demand and capacity.
System management and traffic control	QW	✓	✓	• Detect the presence of a queue or significant slowdown. • Provide traveler information in the form of a warning message regarding the upstream queue.
System management and traffic control	Signal priority and preemption control	—	✓	• Detect transit, emergency, and other types of priority vehicles approaching an intersection. • Modify normal traffic signal timing or phasing to give priority to vehicles (e.g., transit, emergency) approaching an intersection. Priority strategies can include passive (e.g., areawide for corridors with transit routes) and active priority on facilities approaching traffic signals detecting these vehicles. • Interrupt the existing signal operations to shorten or extend the signal phasing to allow emergency vehicles to pass through the intersection (emergency vehicle preemption). • This concept can also be applied to trucks on important freight routes, managed lanes, or CAVs.

Activity	Operational Strategy	Operating Environment: Freeways	Operating Environment: Surface Streets	Description of Functions
System management and traffic control	Lane use control and reversible lane control	✓	✓	• Lane use control: ○ Monitor traffic lanes. ○ Control access to individual traffic lanes. ○ Provide traveler information in the form of advance warning of the closure(s) to safely merge traffic into adjoining lanes. ○ In an active management approach, the network is continuously monitored. Real-time incident and congestion data are used to control the lane use ahead of the lane closure(s) and dynamically manage the location to reduce rear-end and other secondary crashes. • Reversible lane control: ○ Monitor roadways. ○ Provide traveler information in the form of closure of the lanes by direction. ○ Control the direction of travel for traffic lanes. The purpose is to allocate the capacity of congested roads, thereby, allowing capacity to better match traffic demand throughout the day. ○ In an active management approach, the control of lane directionality is updated dynamically in response to or in advance of anticipated traffic conditions.
System management and traffic control	Hard shoulder running/ part-time shoulder use	✓	—	• Monitor roadways. • Provide traveler information on shoulder use availability. • Active management and operation of the shoulder as a travel lane opening based on schedule (e.g., timed daily schedule (static)) or conditions (e.g., congestion trigger (dynamic)).
System management and traffic control	Roadway closure management	✓	—	• Monitor roadways and confirm closures. • Control access to roadway segments (can be done automatically or manually). • Provide traveler information on closures.

Activity	Operational Strategy	Operating Environment: Freeways	Operating Environment: Surface Streets	Description of Functions
System management and traffic control	Parking management	—	✓	• Detect the presence of parked vehicles in parking spots or parking facilities (e.g., trucks, cars). • Provide traveler information in the form of parking availability.
Incident and event management	TIM	✓	✓	• Monitor roadways. • Coordinate with relevant agencies. • Detect, verify, and respond to incidents. Responding to incidents may include clearing disabled vehicles and debris to restore roadway capacity. • Provide traveler information regarding the incident. This information could include the effects of the incident on travel conditions. • Use predetermined business rules, operational strategies, procedures, and actions in response to changing conditions due to incidents (e.g., congestion thresholds as triggers), supplanting the normal day-to-day operation and oversight for other types of irregular or atypical events.
Incident and event management	Emergency management	✓	✓	• Monitor roadways. • Coordinate with relevant agencies. • Detect, verify, and respond to the emergency or disaster. Responding to the emergency may include sending response units or coordinating with law enforcement. • Provide traveler information regarding the emergency. This information could include alternative routes for travelers.

Activity	Operational Strategy	Operating Environment: Freeways	Operating Environment: Surface Streets	Description of Functions
Incident and event management	Special event traffic management	✓	✓	• Actively manage the TMS addressing the conditions resulting from the special event. This task includes coordinating and collaborating with other systems, agencies, and service providers based on the impacts of events on travelers. • Monitor roadways. • Provide traveler information regarding the special event. This information could include the effects of the event on travel conditions. • Manage and operate TMSs in response to changing demand and network conditions based on an event. Use or adjust operational strategies in response to or anticipation of these changing demands and conditions.
Incident and event management	Work zone management	✓	✓	• Actively manage the TMS addressing the conditions resulting from the work zone. This activity includes coordinating and collaborating with other systems, agencies, and service providers based on the impacts of events on travelers. • Provide traveler information on construction impacts to travel and closures. • Provide traveler information in the form of speed advisories or VSLs. • Manage and operate TMSs in response to changing demand and network conditions based on the work zone and work zone activities. Use or adjust operational strategies in response to or anticipation of these changing demands and conditions.

Activity	Operational Strategy	Operating Environment: Freeways	Operating Environment: Surface Streets	Description of Functions
Incident and event management	Road weather management	✓	—	• Collect weather and roadway condition data. • Provide advisory traveler information on weather and roadway conditions. • Control (restrict or regulate traffic flow) based on weather and roadway information. • Perform treatment on roadways (application of resources to minimize weather impacts). An example application includes an agency deploying snow and ice treatments and determining the amount needed to minimize travel impacts.
Information dissemination	Traveler information	✓	✓	• Collect and analyze traffic information and conditions. • Provide traveler information. This information can be used to help inform travelers and influence their choice of travel mode, route, and departure times—both pretrip and en route.

—No data.
HOT = high-occupancy toll; HOV = high-occupancy vehicle; QW = queue warning; VSL = variable speed limit.
Note: ✓ indicates the operating environment for which the TMS activity is applicable.

For more detailed information on the history and evolution of some of these operational strategies, please refer to the History and Evolution of Operational Strategies section.

Operation Deployment Model

In addition to operational strategies, the operating model is another characteristic of a TMS. Some of the most common TMS operating models in the United States include the following system types:

- Centralized.
- Distributed.
- Virtual.
- Hybrid.
- Temporary.

Centralized

The centralized operating model includes a central location or facility in which the TMS resides. This central location or facility is typically a TMC. Generally, a single entity manages the TMS, and straightforward lines of authority are established. This model's operational focus is usually on local issues, but coordination with nearby agencies may still be necessary depending on interagency agreements. This model can be deployed in a region (e.g., statewide TMS), or it can be deployed in multiple regions whereby each region oversees its own area.

Distributed

The distributed model, which can also be called the decentralized model, involves the TMS and staff residing in multiple locations or TMCs. This model is often a joint program whereby various agencies reach an agreement on policies, funding, structure, asset sharing, roles, and staffing. In this model, certain TMS functions are distributed or shared among the locations/TMCs. This model allows for an agency to maximize their resources, share costs, improve working relationships, and increase efficiency. This model is typically applied to larger metropolitan areas that cross jurisdictional boundaries.

Virtual

The virtual model involves the use of communication, computing, and software technology to manage and operate TMSs without a physical nerve center or TMC. The most common approaches to applying this model include being staffed and operated by a single entity or being managed by a single entity with support from other partner agencies. Depending on the scale of which this model is applied in terms of jurisdiction, geographical area, operational strategies, and scope, it may require extensive coordination from participating agencies. An interagency agreement may be required. Access to this virtual system may be available to both agency and interagency personnel. By using the virtual model, participating agencies can either share costs or the virtual TMC can be funded by a single entity.

Hybrid

The hybrid model is essentially a mixture of the virtual model with the centralized and distributed models. Therefore, this model can be further categorized into hybrid centralized and hybrid distributed. The focus of this model can apply to an extended geographical area, including urban and rural regions. The hybrid centralized submodel has a single entity, and all users within that entity share the same network. This network can be accessed via an Intranet or a virtual private network (VPN). The hybrid distributed submodel has multiple participating entities that access the TMS on the Internet using the hypertext transfer protocol secure (https) communications protocol. In other words, users can access the system from any location if they have Internet connectivity. Typically, some level of restrictions exists for the type of access allowed for specific groups of users and specific functionalities. Currently, many TMSs in the United States have virtual capabilities. However, these capabilities are typically established for emergency and backup operations rather than as primary standalone hybrid models.

Temporary

The temporary TMS can be deployed to serve an immediate, short-term need. An example of this TMS is a portable work zone ITS, which comprises components such as portable CCTV or other surveillance components, "smart" construction drums with speed detection capability, portable DMSs, and other mechanisms. Drums with speed detection capabilities collect data that are used to warn drivers when speeds are excessive in the work zone. Agencies can link these portable technologies and temporary systems to their permanent infrastructure to help support management of the larger network.

Geographic Extent

TMSs may serve individual facilities, jurisdictions, metropolitan areas, a region, an entire State, or groups of States. Jurisdictions comprise a range of geographic areas, such as a city, a county, or a State. TMS models based on geographic areas can be grouped into these common approaches:

- **Single facility**. This model is the simplest one described in this section. A single facility TMS serves a single corridor, highway, or surface street. It may or may not have a central system or TMC. It may be composed of multiple single-facility TMSs operating separately within a larger geographic area, either controlled by the same jurisdiction or multiple jurisdictions. Examples include a toll facility, a freeway that is isolated from other freeway TMSs, or a traffic signal TMS along a State highway or similar surface street in a geographic area without parallel signal systems controlled by the same agency.

- **Single jurisdiction**. These TMSs typically serve a single city or county and are often operated out of a central location or TMC. They may be composed of multiple single-jurisdiction TMSs operating separately in a metropolitan area with multiple jurisdictions.

- **Multiple jurisdictions**. This model involves a TMS that is usually controlled in a central location or a TMC that includes subsystems and components in multiple jurisdictions (e.g., cities and counties). Typically, the scale of the TMS is larger than that of a single jurisdiction TMS.

- **Regional or district**. This model is similar to the multiple jurisdiction model, except it expands the area of coverage to include nonmetropolitan areas, such as counties and State facilities. These TMSs typically operate on freeways and rural highway facilities. They may also include urban arterial traffic management.

- **Statewide**. These TMSs are usually managed and operated by a State department of transportation (DOT). The coverage of this system encompasses the entirety of the State and is usually controlled from a TMC. Many of these TMSs are operated by a single agency. In terms of geographic scale, statewide TMSs cover more areas than regional or district TMSs.

- **Multistate**. These larger systems can be formed when agencies with common operational goals and objectives pool their resources and form partnerships to cover a wider geographic network. One key consideration with such integrated systems is to establish a shared concept of operations (ConOps) document with key agency stakeholders that ensures that identified common core functions and services are maintained across jurisdictional boundaries.

Number of Agencies

The number of agencies involved in the operations is another characteristic of a TMS. Agencies involved in TMS operations may include State, city, or county transportation agencies; transit agencies; tolling agencies; and other public safety agencies. The number and type of agencies involved can significantly impact the operations and functions of a TMS. The following TMS types are a few common models:

- **Single agency**. This model is the most common type of a TMS. Typically, a single agency TMS will serve a single city, county, or State. Often, a single agency TMS is the same as a single jurisdiction TMS.

- **Multiple transportation agencies**. This model includes multiple agencies working together to operate a single TMS. One example of this model would be two regional DOTs coming together to manage their TMSs under one TMC.

- **Multiple agencies and disciplines**. This model is the most complex compared to the previous two models. This model includes involvement from other disciplines outside of transportation/traffic. It may include a combination of transportation, public safety, emergency management, or transit agencies sharing a common facility. These agencies may even be from different jurisdictions. The most common combination of these agencies includes the collocation of a transportation department with a public safety agency within a single TMC. This model can play a valuable role in managing and restoring operations after unplanned events (such as lane-blocking incidents) and planned special events (like professional sports or concerts), which put additional pressure on the arterial network due to increased demand and require management of vehicles as well as transit and pedestrian traffic, parking, and other street uses. Arterial-to-arterial diversion is often required to address these events, and this diversion will usually span jurisdictional boundaries. A multiagency TMS is based on a coalition of agencies that share technologies and data, often through an overarching Web-based system that collects information from all partners in one location. Procuring and installing big data technologies and tools can be challenging for the multiagency system if issues with integrating multiple vendor systems exist.

HISTORY AND EVOLUTION OF OPERATIONAL STRATEGIES

This section presents a general summary of the history and evolution of operational strategies, functions, actions, and services that are implemented by TMSs, and how they may have changed throughout the years as their needs and goals have changed. This discussion focuses on a sample of the most widely used operational strategies and is not an all-inclusive discussion of operational strategies. The strategies discussed are widely implemented and provide a good representation of the evolution of operational strategies. Most of these strategies were originally implemented using TMSs to optimize the performance of the facility in which they were deployed. Some agencies may have started their strategies with a focus on improving vehicular traffic flow but then evolved to improve performance from a multimodal perspective (e.g., person carrying capacity versus number of vehicles per hour, travel time reliability versus average speed). Other agencies may have focused their strategies on improvements within their own jurisdictions but then evolved to cross jurisdictional boundaries through coordination and interagency agreements.

Ramp Management and Control

Ramp management and control was one of the first operational strategies deployed by TMSs in metropolitan areas. This strategy was utilized to minimize congestion and improve safety by managing traffic entering the freeway on entrance ramps. Starting with the Eisenhower Expressway in Chicago in the 1960s, major cities experimented with different metering strategies and techniques to achieve their respective agency priorities and needs.(5) Although some metering algorithms and control strategies have not changed much from local or fixed-time control, an increasing number of systems have evolved to adopt responsive systemwide control. Responsive strategies and systemwide control allow agencies to modify when and how they manage and operate freeway ramps based on new control algorithms and, in some cases, new data sources and types.

Agencies now have more methods of collecting traffic data and other roadway information. With better access to data and advanced metering algorithms, agencies can improve how they manage and operate ramp meters. Ramp metering systems can perform functions along a facility or corridor, independent from other systems, or work with other operational strategies managed by the TMSs. Combined systems may help agencies manage preferential or special-use lanes in a corridor or geographic area. As agencies look to implement more responsive ramp metering strategies that require more data, the costs of implementing these strategies may be a concern. However, agencies may quickly realize that the initial costs to deploy these strategies will be well worth the overall long-term benefits of minimizing congestion and improving safety within the system.

Managed Lanes

Using managed lanes to address increasing traffic congestion has become an increasingly popular strategy. Many variations of the managed lane strategy are flexible in that they can adjust over time in response to changing needs.

The three primary types of lane management strategies are:

1. Pricing—such as tolling, congestion pricing, etc.
2. Vehicle eligibility—such as vehicle occupancy, bus or truck only, special permit, etc.
3. Access control—such as reversible lanes, time-of-day permissions, etc.

Traditionally, managed lane treatments consisted of static markings and signage for high-occupancy vehicle (HOV) lanes. The managed lane strategy has evolved from a static and isolated approach that focuses only on the management of a single lane to an approach that employs a holistic philosophy of managing an entire facility, using many tools, to optimize traffic flow.(6) Agencies can use the managed lane philosophy to actively manage demand by applying new or modifying existing strategies that respond to changing conditions in realtime. While the static approach to the managed lane strategy is still widely used, actively managing lanes in realtime to changing conditions is becoming increasingly popular.

These strategies often embrace many other tools, such as variable speed display or several sets of traffic data, to manage the facility. A common example of managed lanes that has evolved to become more active and allow for flexibility in freeway demand is the high-occupancy toll (HOT) lane strategy.(7) This strategy uses variable toll rates that can change based on demand or by time of day. Access to these lanes is often available free of charge to HOVs and other eligible vehicle types.

As urban congestion continues to grow, agencies are looking toward incorporating managed lane systems on surface streets. By continually focusing on integrating transit operations into major corridors, agencies can implement dedicated transit facilities and exclusive busways, which are commonly used to manage lanes on surface streets.

On surface streets where transit vehicles operate in a shared space with general-purpose vehicles, bus-only queue jump lanes may be strategically placed along a corridor, repurposing existing right-turn lanes that could be used during peak periods only to maintain transit travel time reliability. Bus-only queue jump applications utilize transit signal priority (TSP) to manage and coordinate traffic within a corridor. The exclusive busway could be part of the general roadway or operated in a separate, parallel right-of-way or as part of a bus rapid transit system. Managed arterials may also include a priced lane strategy (e.g., applying a strategy similar to the HOT lane strategy on freeways), whereby paying drivers can use underpasses or overpasses at major intersections to experience more reliable and predictable travel times for their trips. Exclusive truck-only lanes may also be implemented to improve the efficiency of the movement of goods and increase overall roadway safety by reducing the mixing of traffic of heavy freight and light vehicles. As the managed lane strategy continues to evolve, agencies have a broad range of strategies to choose from that would best meet their needs.

Traffic Signal Control

Traffic signal control is the primary management and operations strategy agencies use to assign right-of-way and to control traffic flow on surface streets, with the current goals of improving safety, improving traffic flow, and reducing delays. To help meet these goals, transportation operating agencies use interconnected signals along a corridor to control traffic flow and collect and analyze arterial traffic data. When implementing an interconnected traffic signal control strategy, flexible and adaptive adjustments are initiated with central control to provide optimum vehicle progression and minimize delays.

Control schemes include responsive and adaptive functions, which use real-time inputs from roadway sensors to make dynamic changes to phasing and timing plans specific to the conditions at each connected signalized intersection. Examples of centrally controlled adaptive systems are the Split, Cycle, and Offset Optimization Technique and the Sydney Coordinated Adaptive Traffic System.[(8)]

Many major metropolitan areas have adopted adaptive and interconnected traffic signal control strategies to maximize performance and improve traffic flow on their surface street facilities. These adaptive and interconnected traffic signal strategies include functions such as reacting to variations in traffic conditions, thereby allowing central control to recommend changes in the signal timing plans (e.g., change cycle length, phase lengths, and coordination with other signals) at each intersection to improve operations. In comparison, fixed-time and actuated-coordinated systems are more limited in their functions to react to changes in realtime; or to optimize a larger, complex urban signal network. In the past, it was difficult for agencies to implement adaptive control strategies due to the high costs to install, operate, and maintain (e.g., detectors, communication between signals, and communication with central control) these systems. However, with newer adaptive control algorithms that require less detection and decreasing costs of detection and communication technology, the implementation of strategies that use adaptive systems has increased in recent years.

Signal Priority

Signal priority solutions have emerged to improve right-of-way for eligible vehicles. The initial application of signal priority was used to provide signal preemption for emergency vehicles. The success of emergency vehicle preemption, coupled with advancements in technology, provided the opportunity to apply the concept of providing priority to a class of vehicles. The first class of vehicle widely considered for signal priority was transit. Transit priority strategies emerged as agencies transitioned to more traffic-responsive systems, and greater emphasis was placed on improved corridor progression and travel reliability for transit. The TSP strategy includes the function of adjusting signal timing at intersections to better accommodate transit vehicles approaching the signal.

Generally, a priority request is transmitted either from the transit vehicle or from central control to a traffic signal controller. The signal controller receives the request and applies logic rules to decide whether to provide priority to the transit vehicle or not. Early adoption of TSP strategies used signal controllers operating independently that decide priority without considering the state of any other signal controller in the network or corridor.

As the technology improved over time, TSP strategies also improved, allowing for more sophisticated implementation. These strategies include central priority management functions, which allow for more complex rules and schemes that incorporate real-time feedback from the signal controller before determining priority.

An extension of the traditional TSP implementation that is gaining acceptance is the use of connected vehicle technology—an example of which includes the multimodal intelligent traffic signal system (MMITSS).(9) This system comprises multiple subsystems and applications that allow for real-time traffic signal monitoring. MMITSS grants transit priority based on several additional factors, such as passenger counts; transit service type (e.g., local or express); and scheduled and actual arrival times. These inputs are transmitted from onboard vehicle components to roadside equipment. MMITSS provides enhanced TSP and supports more complex corridor management strategies.

The signal priority concept has evolved to consider a broader set of vehicles than just emergency vehicles and transit vehicles. An even broader set of conditions under which priority is given can also be considered. For example, in locations that have large freight movements, priority could be given to trucks during times of heavy truck movement. Priority may also be given near the end of the normal green phase to reduce the likelihood that a truck will need to stop. By providing priority to trucks, freight movement may be made more efficient, signal operations may be more efficient by reducing startup time for trucks from a stopped condition, and emissions may be reduced from trucks starting from a stopped condition. Other classes of vehicles can also be considered for priority treatment, depending on regional and agency goals.

TIM

TIM focuses on the improving safety and reducing the disruption caused by traffic incidents. Clearing traffic incidents quickly and efficiently was a quick solution to reduce the likelihood of secondary collisions and prolonged traffic congestion.

TIM has traditionally relied on various physical assets (such as speed detection and CCTV) to facilitate the functions of detecting and verifying incidents. Improvements in technology and new data sources have enabled the TIM functions to be carried out in a more efficient manner. For example, CCTV cameras have higher resolution and postprocessing capabilities that allow agencies to detect and verify incidents more easily.

TIM strategies are now more complex, and they incorporate various events or activities, which may be planned or unplanned, and may spot problems or regional issues, including weather or man-made incidents. TIM strategies also have improved over the years due to enhanced interagency communications that enable better responses to clear the incident and restore traffic flow.

The number of TMSs that support integrating TIM with other operational strategies is growing. For example, transportation agencies may integrate TMS functions and staff with incident and emergency responders. Agencies may colocate staff and integrate TMS with response systems (e.g., computer-aided dispatch) from multiple agencies to improve the timeliness and accuracy of information sharing, which ultimately decreases response times. In addition to interagency communication, data sharing, and technology, TIM strategies can be further improved with effective traveler information. Informing travelers of incidents can influence their trip behavior and route choice, thereby diverting traffic flow away from the incident. Depending on the complexity of the operating environment, the size and scope of TIM challenges, and the capabilities of the operating agencies, a continuum of traveler information strategies are available to support TIM. These strategies range from only providing information about the incident to including the likely extent and impact of the incident to providing travel options to those affected by the incident.

Some agencies today are still operating independently with limited interagency coordination. However, with continued growth in technology, data sharing, and system integration, and with the clear benefits becoming more widely known, interagency coordination will likely increase as time goes on and TIM evolves.

Traveler Information

Traveler information includes new collection methods that provide data to agencies. Traditionally, agencies obtained information by directly observing roadway conditions through physical assets (e.g., speed detection or CCTV cameras) or through human observation (from service patrols driving on the freeways). Traffic information was often communicated to motorists via commercial radio stations, warning them of unusual driving conditions. As data sharing grew more common, traveler information strategies became more prevalent and sophisticated.

Traveler information strategies include disseminating information on roadway conditions or events to travelers via a variety of methods. The type of information that was disseminated during the early onset of TMSs was mostly static (e.g., information on upcoming closures, special events, hours of operations of HOV lanes, and vehicle restrictions). Improvements in technology-enabled agencies to capture more information about their facilities and systems and, consequently, transform their traveler information operational strategies. The type of information made available to travelers grew to include more dynamic and real-time information (e.g., roadway travel conditions, potential alternative routes, weather advisories, traffic incidents, and parking availability).

Traveler information strategies have also evolved based on how information is disseminated. Traditionally, information has been made available to travelers through physical assets, such as agency-deployed roadside DMSs and highway advisory radio (HAR) communications and, as the tools evolved, through 511 phone options or Web-based systems. Although many of these methods are still widely used today, the evolution and proliferation of social media platforms have provided agencies with a broader variety of additional ways to deliver traveler information, such as mobile applications that can provide both pretrip and en route traveler information. As technology continues to change, agencies have the opportunity to use these technologies to shape the transportation field. However, agencies are challenged with determining where, what, why, and how to apply these technologies to improve the capabilities of their TMSs to improve safe and efficient operations within their available resources.

OPERATIONAL STRATEGIES THAT SUPPORT FREEWAYS

This section discusses the commonly used operational strategies incorporated in TMSs to achieve agency goals and objectives for managing freeways. Traffic operational strategies encompass a set of functions and actions to improve the management and operation of the roadway network, optimize performance, and improve safety. Deployment of operational strategies is informed by agency goals, policies, procedures, and associated performance metrics.

In the past, freeway-focused operational strategies performed by TMSs primarily focused on performing basic functions, such as monitoring traffic conditions and collecting traffic data. As time went on, agencies started using those data to enhance their operational strategies. Functions evolved from basic monitoring and collecting data to regulating access, managing incidents, providing traveler information, and other activities.

As technology continues to evolve, so too has the functionality to collect and manage more complex forms of data. This evolution shapes the way agencies implement operational strategies because they can leverage more data to make informed decisions.

Active Management

As agencies upgrade their components and software, the timeframe for decisionmaking and responding to changing conditions has improved. The ability to actively manage operational strategies also has improved, allowing agencies to progress through the levels of active management.

An example of an operational strategy in the freeway environment that is deployed at the static level is time-of-day ramp metering (i.e., preset ramp metering rates that change based on timeframes set by an agency). As agencies install detection devices to monitor volumes on the ramps and mainline, they can use those data to automatically change their operational strategy to become reactive and responsive to changing conditions. An agency that operates ramp metering at the proactive level can use both real-time and historic data to predict future conditions and implement ramp metering in anticipation of those conditions.

As data collection and management functionality continues to improve, so has the range of available data. For example, crowdsourced data enable agencies to provide better traveler information and to more effectively and actively manage operational strategies to respond to reported or anticipated congestion, incidents, and weather conditions.

Operating Environment

Freeway operational strategies may range from one freeway through an urban or rural area to several freeways throughout an urban or rural area to one or more freeways throughout an entire State. The institutional environment for operational strategies that support freeways may emphasize policies. Objectives support policies, and policies often formalize objectives. The main objectives of a TMS that supports freeway operational strategies are to maximize traveler safety, eliminate or minimize the duration of congestion, reduce travel time impacts, reduce the severity of or eliminate traffic incidents, and provide drivers with the information necessary to make informed travel decisions. Policies often address the need for and manner of coordination and collaboration with partner agencies, especially those agencies that operate the surface street system that borders and crosses freeways.

TMSs in the freeway environment are not limited to managing recurring conditions within a single agency network. The systems also can support a range of functions related to short-term objectives, such as temporary systems, or several objectives shared by multiple agencies, such as multiagency systems and statewide systems. TMSs can even support objectives shared across State lines, such as multistate systems.

Operational Strategies

Operational strategies are designed to achieve specific goals or objectives that can be clearly identified and measured. The performance of an operational strategy can be measured to determine the effectiveness of reaching the intended objectives. Often, a suite of operational strategies is needed to reach these goals. Many operational strategies that agencies can use deploy to support freeway operations are available. The following approaches are some of the more common strategies:

- Network surveillance.
- Ramp metering.
- Managed lanes.
- Variable speed limit (VSL).
- Dynamic speed advisory/harmonization.
- TIM.
- Part-time shoulder use.
- Traveler information.
- Road weather management.
- Queue warning (QW).
- Work zone management.

Functions

Operational strategies are enabled by specific functions and actions. Functions that can be implemented to support these operational strategies include:

- Monitoring roadway conditions.
- Collecting weather information.
- Performing roadway weather maintenance.
- Analyzing the collected data.
- Disseminating traveler information.
- Deploying speed limit reductions or advisory speeds.
- Using predictive decision-support software to guide operators in system adjustments and overrides.
- Providing traffic detection and surveillance.
- Managing incidents and special events.
- Managing freeway ramps.
- Managing preferential and priced lanes.
- Providing coordination among agencies.
- Monitoring and evaluating system performance.

Actions

These functions are composed of basic and singular actions that are performed by a person or a TMS component. The following list of actions can be performed:

- Monitoring components.
- Collecting data from detectors, including traffic and roadway conditions data.
- Collecting weather data.
- Sending data to storage.
- Sending data to another system or party.
- Sending data to a TMC.
- Displaying traveler information and public advisories on DMSs.
- Displaying speed advisories on lane control signs (LCSs).
- Broadcasting travel advisories or anticipated travel delays using HAR.
- Displaying CCTV camera images on a video wall or website.
- Providing information or conditions to invoke a decision, action, or sharing of information.
- Confirming incidents.
- Calling incident response units.
- Calling maintenance crews.
- Changing the ramp meter signal head indication.

Services

Operational strategies also are typically supported by services. These services, with the help of communication mediums and mechanisms, can be described as a set of functions and actions that allows for system access to be enabled for external parties. The following examples of services can be implemented for operational strategies in the freeway environment:

- A cellphone application that connects to traveler information and data management subsystems can allow travelers using the application to contribute information related to reporting incidents and hazardous roadway conditions. This service can supplement the incident management and traveler information operational strategies by providing additional information to be shared with other travelers.

- A mechanism that allows for onboard connected vehicle equipment to be installed on freight vehicles to communicate with the road weather management and data management subsystems can allow for speed advisories to be displayed within the vehicle when weather conditions limit visibility. This service can also supplement the dynamic speed advisory operational strategy.

- An interface that allows for data and information to be exchanged between the road weather information systems and a regional or agency TMS can be installed. Most road weather information systems are separate from a TMS, and this service can help facilitate that data exchange. This service can support the road weather management strategy.

- A method that allows for data exchange between the road weather TMS and the National Weather Service (NWS) can be implemented. This service can support the road weather management strategy.

- A method (e.g., software, algorithms) that allows agencies to monitor, assess, and provide multiple optional responses. The agency can then select the best alternative. This service is often referred to as a decision-support method.

OPERATIONAL STRATEGIES THAT SUPPORT SURFACE STREETS

This section examines the commonly used operational strategies incorporated in TMSs to achieve agency goals and objectives for managing surface streets. These operational strategies may be integrated into a TMS that could include responsibilities for a region or corridor, and the systems may include interconnection with other TMSs.

Active Management

In the past, strategies such as traffic signal control had the basic function of regulating and controlling traffic movements at an intersection. Then, much like operational strategies deployed in freeway environments, strategies in the surface street environment began to leverage the increases in available data, data collection methods, and communication technologies to enhance their strategies, actively manage them, expand their functionality, and progress through the levels of active management.

Operational strategies, such as traffic signal control, evolved from using pretimed and time-of-day functions to collecting real-time data to implement adaptive signal control functions. The degree of data collection and management functionality of a system dictates the types of surface street operational strategies an agency implements and how actively it can manage them. The improved data collection capabilities of the systems allowed strategies to become enhanced with improved functions related to traffic management, traveler information, incident management, coordination, and performance measurement. For example, many traffic signal control strategies that use real-time signal controller data can revise signal timing schemes (or notify an operator to modify schemes) in response to or in anticipation of changing traffic conditions and inform agency personnel on the performance of the system before and after the changes. In essence, this strategy embodies the active management steps (monitor, assess, develop, and recommend alternatives and then implement the selected alternative).

Operating Environment

Traffic signal control is one of the primary strategies that local agencies deploy to manage traffic on surface streets. However, TMS deployment has expanded to include a range of operational strategies, functions, and actions to support regional mobility and access objectives for a rapidly expanding population and growing economy.

The physical environment for surface street operational strategies may range from local streets to high-volume, high-speed primary arterials. The institutional environment for operational strategies that supports surface streets may be quite diverse. Policies may range from promoting traffic calming and moving pedestrians, bicycles, or transit vehicles to promoting the efficient movement of vehicles. The primary objectives of a TMS that supports surface street operational strategies may be similarly diverse. As with the freeway environment, coordination and collaboration with partner agencies are important for the operating environment.

Operational Strategies

Many operational strategies that agencies can deploy to support surface street operations are available. Some of the common operational strategies include the following approaches:

- Network surveillance.
- Traveler information.
- Traffic signal control.
- TIM.
- TSP.
- Emergency vehicle preemption or priority.
- Managed lanes.
- Parking management.
- Special event management.
- Emergency management.

Functions

Operational strategies comprise specific functions and actions. Some functions that can be implemented to support these operational strategies include the following actions:

- Collecting traffic information.
- Analyzing the collected data.
- Disseminating traveler information.
- Providing traffic detection and surveillance.
- Providing priority for transit vehicles at signalized intersections.
- Providing preemption for emergency vehicles at signalized intersections.
- Managing incidents and special events.
- Collecting parking availability information.
- Providing coordination among agencies.
- Monitoring and evaluating system performance.

Actions

These functions are made up of basic and singular actions that are performed by a person or a TMS component. The following list summarizes some of the actions that comprise these functions:

- Monitoring components and traffic signal equipment.
- Collecting data from detectors.
- Sending data to storage.
- Sending data to another system or party.
- Sending data to a TMC.
- Displaying traveler information on a DMS.
- Displaying CCTV camera images on a video wall or website.
- Confirming incidents.
- Calling incident response units.
- Calling maintenance crews.
- Changing the traffic signal head indication.

Services

Similar to the freeway operating environment, operational strategies in the surface street environment are often supported or enhanced by services. These services, facilitated through communication mediums, comprise a suite of functions and actions that allow for data exchange to occur with external systems. The following examples of services can be implemented in the surface street environment:

- A mechanism can allow for a third-party traveler information provider to exchange data with the agency's traveler information and data management subsystem. This method enables the agency and third party to leverage data from both subsystems to provide travelers with more comprehensive information. This service can also supplement TIM, emergency management, and special event management strategies.

- An interface can allow for data and information to be exchanged between a local agency operating in a surface street environment and a State agency operating in a freeway environment. Many operational strategies are applied to surface streets and freeway facilities separately due to systems operating within their respected jurisdictions. This service can enable these agencies and strategies to be coordinated to improve effectiveness at a larger scale. This service may support traveler information, TIM, special event management, and emergency management strategies.

- A method that enables communication between onboard equipment installed on transit vehicles to communicate with the traffic signal control subsystem can enhance TSP functionality. This service can support the TSP and traffic signal control operational strategies.

- An API can allow enforcement agencies to access data from the parking management subsystem. This service can enhance the parking management strategy by providing enforcement agencies information on potential parking violators when facilities are near capacity. This service can also supplement special event management and emergency management operational strategies.

COORDINATED TRAFFIC MANAGEMENT AND OPERATION TO SUPPORT MULTIPLE FACILITIES, CORRIDORS, OR REGIONS

The key to coordinating traffic management and operation across multiple facilities is to integrate the process of the various TMSs operating in each facility. The basic premise behind such an integrated approach is to actively manage and operate individual TMSs in a more coordinated manner. This process contrasts with the traditional approach, which applies individual systems and operational improvements independently without considering how they can work together to improve operations in a synergistic way.

The integration of multiple systems can be accomplished through a multijurisdictional, multiagency, or multifunctional system structure. Examples of systems that could be integrated include TMSs that support surface street operations, freeway operations, transit operations, and other processes. As more importance is placed on the coordination and management of activities among agencies, especially in dense urban areas, managing the transportation system holistically will allow operating agencies to enhance their ability to monitor conditions on their facilities as well as on other agencies' facilities to implement coordinated operational strategies.

The specifics of how an integrated system will operate depend primarily on the current conditions of the systems and on the existing TMSs and operational strategies. Understanding the users of the facility, corridor, or region—and the unique characteristics of the types of travelers and how they access information—will help determine possible operational strategies that may be effective to deploy in an integrated manner.

Active Management

To effectively manage traffic and coordinate the operation of multiple facilities, an integrated implementation of complementary strategies and actions, rather than a single strategy along a single corridor or even a suite of strategies applied to each facility, is required. A cornerstone in the effective operation of a set of complementary strategies is to actively manage all strategies in the set. Agency stakeholders will need to identify potential areas of interconnection between different roadway facilities and modes of travel and then determine how best to manage the systems that support this interconnection. Stakeholders across the systems and the agencies involved will need to monitor the entire network of facilities. Common evaluation methods by each agency stakeholder to assess their systems and integration alternatives will be key for both selecting operational strategies that support agency operations and for assessing the effectiveness of the operation of those strategies. This process will lead to selecting actions that will, in turn, help with achieving the shared vision and objectives for the multiple facilities that are being integrated, such as improved travel time, improved system/corridor reliability, or reduced recurring peak-period congestion.

Actively managing TMSs across multiple facilities, corridors, or even regions is equally important as actively managing TMSs on a single facility or type of facility. The basic concepts are the same, as discussed in the previous sections regarding operational strategies that support freeways or surface streets. The operational strategies that support freeways or surface streets can also be applied to multiple facilities, corridors, or regions. The primary additional challenge when addressing multiple facilities is the need for coordination with multiple operating agencies. The challenge for active management is that all the agencies involved in the TMSs across the various facilities need to have a commitment to and the resources for actively managing the systems they operate.

Operating Environment

TMSs that operate in a multiple-facility environment need to address various facility types, such as freeways and surface streets, and numerous jurisdictions and jurisdiction types. For the most part, the operational strategies used in a multiple-facility environment will be the same as those used in freeway and surface street environments. The physical environment will be a combination of freeways and surface streets. However, the institutional environment will be more complex. Policies will have to balance the objectives that are in place for each of the facility types and each of the jurisdictions involved. It will be critically important to balance these objectives, which could include mobility, reliability, and safety in a multimodal, multiple-facility environment. The movement of people and goods will need to be balanced with traffic calming and the movement of pedestrians, bicycles, or transit vehicles. The primary objectives of a TMS that supports coordinated, multiple-facility operational strategies may be similarly diverse. Coordination and collaboration with partner agencies will be even more important than discussed in other operating environments.

Of particular importance is the need to plan, develop, implement, and operate in a multijurisdictional environment. The operational strategies selected will need to be integrated from technical and institutional perspectives. The individual TMS included will need to share information and operate in an integrated fashion.

Operational Strategies

Operational strategies are designed to achieve specific goals or objectives that can be clearly identified and measured. When addressing a broader facility, corridor, or region, these goals and objectives may differ from operational strategies that serve individual roadways. As such, operational strategies will have to be modified to serve multiple goals and procedures. Potential operational strategies will be implemented and operated in an integrated and coordinated manner. The full array of operational strategies presented for freeways and for surface streets is appropriate to consider in a multiple-facility environment. The following operational strategies have a higher level of importance:

- Network surveillance across all facilities included.
- TIM.
- Emergency management.
- Special event management.
- Information or conditions invoking a decision, action, or sharing of information.

Functions

Functions that can be implemented to support the multiple-facility environment are the same as those that support the freeway or surface street environments for the operational strategies included. Some functions that will be of particular emphasis include the following actions:

- Performing interagency coordination.
- Monitoring roadway conditions across the variety of facilities included.
- Analyzing collected data from a multimodal, multijurisdictional perspective.
- Disseminating multimodal traveler information.
- Using predictive decision-support software that supports operation across multiple facilities and modes.
- Monitoring and evaluating system performance across facilities and jurisdictions.

Actions

A set of basic and singular actions that is performed by a person or a TMS component comprises a function. Actions in a multiple-facility environment are similar to those for freeways and surface street environments. The following actions are particularly important in a multiple-facility environment:

- Sending data to multiple systems and agencies.
- Communicating with multiple response agencies.
- Collecting data from multiple sources, including streets, freeways, and transit systems.
- Incorporating transit information in traveler information dissemination.
- Displaying traveler information and public advisories on DMSs.

Services

Services can support and enhance operational strategies. Services are implemented with the help of communication medians and mechanisms that facilitate data exchange between separate systems. The following examples of services can be implemented for operational strategies in a multiple-facility environment:

- A mechanism that facilitates data exchange between an integrated TMS with a road weather management system can enable rapid response to inclement roadway conditions on both surface streets and freeways while improving public advisories. This service can support road weather management and traveler information operational strategies.

- Data exchanges between TMSs and a third-party traveler information provider can provide information on travel times and incidents on integrated corridors. The integrated TMS could comprise subsystems that support freeways and surface streets. This service can support the traveler information, incident management, and other operational strategies.

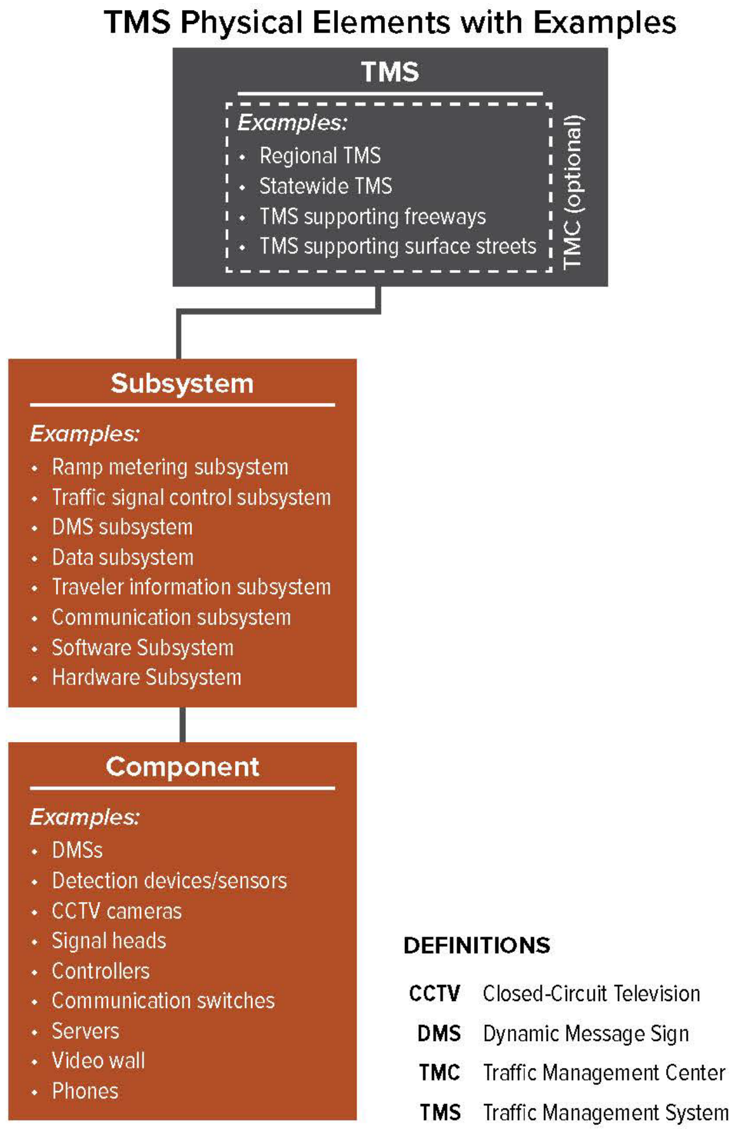
- TMSs can share information on available parking spots at a park-and-ride facility and transit arrival times. This service can leverage data from the parking subsystem and the transit subsystem, which would usually operate independently, to provide relevant information to travelers in one location. This service can supplement the parking management and traveler information operational strategies.

CHAPTER 3. TMSs: PHYSICAL ELEMENTS

This chapter provides the reader with a close look at the physical side of the TMS, including the subsystems and components that are commonly used by agencies. By considering individual parts of the system, agencies can evaluate how systems are carrying out needed functions, overall system performance, and (if necessary) the need to make changes in how a TMS is actively managed and operated. Additionally, agencies can modify how operational strategies or services are being deployed and upgrade or replace individual components or the entire system, as needed.

In addition to providing some context and examining how these systems have evolved over time, this chapter also includes examples and current practices of successful implementations of TMSs that carry out operational strategies. By presenting examples of how these subsystems and their components are supposed to operate, or how they are intended to perform, agencies can better understand where their current capabilities lie (and if improvements should be made).

The focus of this chapter is on the subsystems and components (and their interfaces) that comprise a TMS from a physical standpoint. Many TMSs have a physical TMC that acts as the nerve center of the system, whereas others do not and may never have one. Regardless of whether a TMS is controlled by a TMC, modern TMSs are complex systems and are typically made up of a suite of subsystems. The subsystems are often made up of an integrated collection of components or ITS components. Figure 5 depicts a visual representation of the physical side of the TMS.



Source: FHWA.

Figure 5. Flowchart. General TMS structure: physical side.

Subsystems are often deployed together to enable various operational strategies that are intended to meet agency goals. Components from these subsystems can include DMSs, detection components, CCTV cameras, signal heads, controllers, communication switches, and other computer technologies. These components may work in isolation from one another, or they may work in concert with components serving other subsystems to perform functions to achieve the overall objectives of the system.

The selection of ITS components and technologies can be guided by what operational strategies an agency is trying to implement; the subsystem architecture and how the components are linked to the subsystems; and how the architecture, components, and subsystems all work together to meet overall agency goals, objectives, and performance measures.

HISTORY AND EVOLUTION OF SUBSYSTEMS

This section summarizes several TMSs and subsystems that support operational strategies. This section also describes some of the components that comprise these subsystems and how they may have changed over the years as agency needs and goals have changed. The TMSs and subsystems are implemented to optimize the performance of the facility in which they are deployed. Many have evolved from systems that perform basic traffic control functions to complex data management and performance-based systems.

TMS subsystems include software, hardware, data, communication, traveler information, and CCTV to name a few. These examples are described in more detail in the following paragraphs.

Software

Software subsystems include the programs that support the operational strategies and services of the TMS. The following types of software products are included in every TMS:

- Operating system.
- Database software.
- Security applications.
- User interface.

Other common types of software contained within a TMS include algorithms, simulation packaging, and rules control programs. APIs provide the interfaces between software packages and between the software subsystem and TMS services. An API is a description of the routines, protocols, and tools for interfacing and exchanging data with a software application or program. An API specifies how software programs should interact, the data they exchange, and how the data are exchanged (i.e., format and type).

Hardware

Hardware subsystems reflect the purpose and location of the TMS. Hardware subsystems include servers, data storage devices, and network communication equipment (e.g., routers and switches). Most agencies use standard IT servers to host the software and data subsystems. The capacity and performance of the hardware subsystem will depend on the functionality of the TMS, the processing power needed, and the amount of data involved.

Data

Data subsystems comprise components and technology that carry out specific functions and actions. Examples of supported functions and actions include transmitting, processing, analyzing, interpreting, reporting, and archiving the data. Data subsystems use detectors and other data collected by other components to obtain data for use in TMSs and for other purposes. Data collected by many TMSs involve the use of data stations that consist of loop detectors in each lane.

New detector technologies, such as radar, video, infrared, and even vehicle probes (e.g., wireless local area network/wireless technology detection), are available to address some of the maintenance issues that are inherent to loop detectors. Regardless of the technology, detector components measure volume, occupancy, and speed, generally, on a 20-second basis. The data are usually collected, saved by lane, and sent to the data subsystem for processing and use by the TMS. In some subsystems, the field controller also performs a series of checks and verifications to detect failures. These processes have been operating for decades and continue to do so at many locations throughout the world.

The data subsystem has traditionally used either agency-owned or leased wireline communications to transfer data between field components and a TMS or a field master controller. For traffic signal operations in the past, a field master controller was a critical interface and was connected to all the signalized intersections in a given geographic area or on a given arterial to coordinate operations within the system. When agencies wanted to adjust the signal control parameters, they would make those changes through the field master controller, which communicated to the other connected controllers.

As more advanced forms of communication media became more readily available (e.g., fiber optics), field master controllers became less common in traffic signal subsystems. In addition, the evolution of wireless technologies and the increasing availability and prevalence of mobile data, other sources of data, and cloud-based management solutions provide opportunities for agencies to further modernize their field equipment and increase their coverage of data collection on their roadway networks. Formal data-sharing agreements and the availability of data collected and made available from third-party sources provide the opportunity to integrate additional types of data into the TMS subsystem. These additional data sources allow for additional analysis tools and new information to be integrated into the management and operation of specific operational strategies or the TMS. The use of these emerging data sources (both internal to the agency and from a third party) supports the continued evolution of data sharing and coordination.

Data subsystems comprise components and technology that carry out specific functions and actions. Examples of supported functions and actions include transmitting, processing, analyzing, interpreting, reporting, and archiving the data. Some of these functions can be carried out by specific components with the help of communication media; for example, transmitting volume data from a traffic signal controller to the TMS via fiber-optic cables. When the data have been transmitted to the TMS, they can be analyzed and interpreted in a way that is useful to the agency.

The storage and processing of data for an agency's TMS have traditionally been completed in-house on dedicated equipment. In recent years, however, databases located in different locations where the TMS might have access to the data via the Internet and enable the telecommunication connection have become more common. Having this ability allows TMSs to work with an agency's enterprise IT to procure the storage and capabilities needed to manage data as a contracted service provided by a commercial vendor or databases provided by the agency.

Data subsystems are becoming increasingly virtualized and more accessible from any place with Internet connectivity. For example, cloud storage and cloud computing are becoming more popular as agency IT departments reduce physical components within their TMSs. Cloud storage involves storing data in remote servers that are accessed via the Internet. The servers are maintained by a cloud storage service provider. By using cloud storage and cloud computing as an alternative to local servers and workstations, hardware and software development and acquisition can be reduced and maintenance costs can be lowered.

Software, hardware, and data subsystems are key subsystems to support the decisionmaking required for a TMC, operational strategies, functions, actions, or other activities of the TMS. Programs included in a software subsystem that is installed on a hardware subsystem support the decisionmaking needs of managing and using a TMS and its operational strategies, functions, and services using data from the data subsystem. These three subsystems work in concert to support essentially every operational strategy in a TMS.

Communication

Communication subsystems have evolved with technology trends in bandwidth, speed, and wireless technology. Communication media are used to transmit data and act as the foundation for most TMS subsystems. Therefore, the evolution of many TMSs and subsystems occurred with the advancements in communication technologies. Historically, twisted copper pair (serial) cables and dial-up communication methods were used for early TMSs. Such communications media have inherent and severe limitations on backhaul capacity and data transmission speeds, but at the time, they were readily available and affordable.

Even to this day, some agencies do not have a communications infrastructure in place that can meet their current or future needs. However, tradeoffs are often made in pursuit of satisfying an operational need to deploy components and technology to support a function or service, even though they might not have the complete communication infrastructure to enable all their current or future capabilities. In such cases, the agencies may store the data on computers within the local vicinity of the data collection components and make periodic field visits to manually pull the data.

In general, however, higher-performing communication options have become more readily available and affordable, such as fiber optics, digital subscriber lines, cellular, and other wireless communications. These newer methods of communication allow for faster deliveries of data and higher densities of data to be transmitted.

Modern standards of the last 15 years rely on Internet Protocol (IP) communications using fiber-optic cables, high-speed wireless systems, and IP over copper. Such communications media, particularly fiber-optic cabling, have more growth potential for higher data transmission capacity. Agencies often use a combination of new communication media within their TMSs.

Many agencies today use a fiber-based communication subsystem to transfer data from local TMS components and controllers to a TMC for processing, archiving, and analysis. Recent technology development has made fiber more and more affordable, resulting in more agencies transferring high volumes of more complex forms of data than ever before.

With more complex data being transferred at higher volumes and at faster speeds, new issues arise, including privacy and security of the data collected. Therefore, a dedicated communications subsystem that can securely transmit data is an important aspect of TMSs.

Agencies may elect to use a VPN as a component of their interface when their subsystems do not communicate over a dedicated network. Agencies may use encryption techniques, such as a VPN, to hide any sensitive or personal information that may be collected from travelers. An example of the need to encrypt data is license plate readers (LPRs) used for travel time processing. Agencies encrypt the license plate numbers collected with a unique identification code to ensure that if a security breach occurs, a hacker would be unable to trace the license plate numbers back to the drivers' more personal information.

As more agencies incorporate modern communication subsystems into their TMSs, the capabilities of these systems to collect more complex forms of data are enhanced. Whether it is designing a new system or making gradual improvements to parts of the system, the widespread availability of communication media, such as fiber optics, allows for the TMSs to be designed with higher capacity for data management than ever before.

Many agencies today also are planning to upgrade (or actively upgrading) their TMSs and communication subsystems to prepare for the influx of high-density connected vehicle data that are anticipated to become available in the near future.

Many systems today are controlled from a central location, which inherently limits the design of the systems in terms of costs. As agencies look to design or improve their systems, the costs to expand their coverage may be restrictive. However, as hardware, software, and computing power continue to evolve, the costs for field components and controllers with enhanced capabilities offer the potential to change how agencies design and operate TMSs. Wireless communications and onboard analytics are examples of these enhanced capabilities. Being able to process data without needing to send the data back to a central location may lead to more distributed systems. The coverage area, type of data, and costs to build an adequate communications subsystem are all direct factors in the design of a TMS and how it will be operated.

Traveler Information

Traveler information subsystems use data collection components to obtain data on roadway conditions and disseminate relevant information to travelers. Traveler information subsystems grew in sophistication alongside advancements in data collection technologies and communication media. Common traveler information components used to communicate to travelers include roadside DMSs, HAR, 511 phone systems, and Web-based interfaces.

HAR is used to disseminate information to travelers via broadcast radio. Typical HAR operates in the AM broadcast band (530 kHz) to 1700 kHz) and has a coverage radius of 3 km. Some States have purchased FM broadcast rights to use for targeted travel information broadcasts that have a wider reach than traditional AM signals might.

In the year 2000, the Federal Communications Commission designated 511 as a nationwide traveler information telephone number to be made available for States and local jurisdictions in the United States.(10) Dozens of State and local agencies began to create 511 telephone systems to provide varying levels of traffic conditions or travel access information. Many 511 subsystems have expanded to disseminate information on agency websites and display a variety of real-time information relating to incidents, construction, special events, weather, and other travel issues. In many cases, the agencies have branded their online sites as 511 to coincide with their telephonically delivered systems—and some have stopped using the telephone systems altogether.

DMSs are one of the fundamental components used for en route traveler information strategies and subsystems. Typically, these components are signs that are permanently installed adjacent to or over the roadway. In other cases, temporary and portable DMSs are used to support work zone management, emergency management, and special event management strategies in areas where permanent installations are not needed. Early models of DMSs were only capable of displaying a fixed number of messages. Examples include conventional fold-out signs, rotating drum signs, and neon or blank-out signs. The type of message displayed on these signs was predetermined before manufacturing; therefore, the signs were used to display messages relating to recurring events and conditions. An example is a fold-out sign that enables access to express lanes based on the time of day.

As technology evolved, DMSs gained the ability to display an unlimited number of messages. These modern DMSs allow for flexibility in the messages that can be displayed because they are made up of a matrix of pixels that can be customized in realtime by the agency.

Coinciding with increased technical capability, the type of messages displayed from agencies have also evolved from static and time-of-day messages to broader messages that are dynamic and based on real-time data. Today, DMSs continue to be one of the commonly used components by agencies to support many operational strategies and subsystems.

In addition to deploying and maintaining devices, agencies have been increasingly disseminating traveler information through "portals" or services that allow any number of private sector websites and cellphone applications to be created. These services allow a large volume of information to be shared among a wide range of organizations. In addition, these services allow private applications that provide travel time and roadway condition information; and in some instances, they result in newer customized solutions for personalized pretrip and en route traveler information for users of connected mobile devices.

APIs are the interfaces that support these services. APIs and services can support a much broader range of information than travel time and roadway conditions. By sharing as much operational data as possible, third-party providers have better situational awareness about current and future conditions. They can develop innovative approaches to providing travel-related information for a variety of purposes that can consider the potential strategies and tactics by operational stakeholders to meet the needs of their customers.

CCTV

CCTV subsystems are one of the most commonly used systems used by transportation agencies for roadway monitoring purposes and supporting operational strategies. Legacy CCTV subsystems were developed using analog technologies, which forced agencies to implement a centralized architecture of field cameras connecting to a central video switch at a TMC. If recording was permitted (not all agencies allowed recordings), these analog CCTV subsystems used tape-based recording components to save and archive video feeds.

As technology advanced, CCTV subsystems started to transition toward digital cameras and IP-based technology. This technological advancement simplified the process of sharing and sending video feeds across different agencies—and even media partners. This process also allowed for more distributed functional capabilities, whereby operators could access the video from multiple destinations, such as video walls, workstations, network storages, mobile devices, or even remote TMCs.

As advancements continued to occur in communication media, archiving capabilities (e.g., storage capacity and video compression techniques), and digital and IP technologies, CCTV subsystems also continued to improve. Newer generations of CCTV cameras that were introduced to the market came with enhanced capabilities that previously required external subsystems and components. Some of the key improvements in CCTV cameras in recent times include enhanced video resolution, thermal capabilities, low-light or night-vision capabilities, onboard video analytic capabilities, and onboard video recording.

Some of the most common types of data that modern CCTV cameras are capable of collecting and producing include vehicle, pedestrian, and bicyclist volumes. These cameras can detect the presence of vehicles, pedestrians, and bicyclists by programming in detection zones where volume is expected. For example, a CCTV camera monitoring an intersection approach would have detection zones developed in each lane close to the stop bar, simulating the detection zones created by traditional induction loops. When a vehicle enters that detection zone, the camera can detect the vehicle's presence by the disruption of the image in that zone and record that data as a single vehicle volume count.

Systems that Support Freeways

This section discusses the commonly deployed TMSs and subsystems that serve the freeway operating environment. Subsystems encompass a set of physical components that work together to improve the management and operation of the roadway network, optimize performance, and improve safety. TMSs can carry out operational strategies, functions, actions, and services.

Initial freeway-focused TMSs consisted primarily of equipment and technologies that focused on performing basic functions, such as monitoring traffic conditions and collecting traffic data. Agency TMSs then used the traffic data to perform other functions, such as regulating access to the freeway, dispatching safety service patrols, managing incidents, and providing information on traffic conditions to the public to fulfill operational strategies. The traffic data output collected by the system was a means for agencies to achieve their goals pertaining to these functions.

As TMSs, subsystems, and components evolved, real-time monitoring and extensive data collection became more common for agencies. Upgrades in physical components and software algorithms allowed for subsystems to evolve from implementing reactive and time-of-day strategies to more proactive and predictive approaches. The degree of data collection and management capabilities of the subsystems and components dictates what type of operational strategies and systems an agency decides to deploy.

Emerging technologies allow for improved capabilities to perform functions and actions to support operational strategies. These technologies also allow for improved coordination among agencies. Interagency coordination and communication are important elements that support any strategy. Close working relationships improve responses and productivity. Linked lines of communication enhance system capabilities and mitigation strategies.

Subsystems

Many TMS subsystems physically embody the operational strategies they were designed to implement. They were designed to carry out a specific operational strategy (e.g., ramp metering subsystems). Other subsystems were designed to support multiple subsystems and supplement operational strategies (e.g., data management subsystems and CCTV subsystems). Although the range of subsystems that operate in the freeway environment is vast, the following subsystems are the most common:

- Software.
- Hardware.
- Ramp metering.
- CCTV display and control.
- DMS control.
- Vehicle detection.
- Traveler information.
- VSL.
- Lane use control.
- Part-time shoulder use.
- QW.
- Environmental sensor stations.
- Weigh-in-motion.
- Communication.
- Data.

Components

Subsystems comprise individual components that serve a purpose as a part of the subsystem or TMS. The following components serve a purpose as a part of the subsystems listed in the previous set of bullets:

- Ramp meter signal heads.
- Ramp meter controllers.
- ITS controllers.
- Vehicle induction loops.
- CCTV cameras.
- Video walls.
- Workstations.
- DMS.
- LCSs.

- Radar vehicle detection sensors.
- HAR stations and signs.
- Environmental sensors.
- Communication switches.
- Servers.
- Phones.

These subsystems and components are used by agencies to implement operational strategies and functions. The next section summarizes agency TMSs' current practices and operational strategies deployed in the freeway environment.

Current Practices in the Freeway Environment

Many agencies have incorporated interesting and advanced new approaches to implementing operational strategies through a suite of subsystems to manage their facilities and maximize their roadway capacity. A few examples of successful subsystem implementations and operational strategies by agencies are highlighted in the following paragraphs. These examples do not represent an exhaustive list of applications and active deployments.

The Washington State DOT (WSDOT) implements operational strategies related to traffic incidents, traveler information, and freeway management through their TMS.(11) Their TMS comprises a variety of subsystems to support their operational strategies. WSDOT's goals through these implementations are to reduce collisions associated with congestion and blocked lanes and to improve traffic flow through key corridors adjacent to downtown Seattle, WA.

The following subsystems within WSDOT's TMS support these operational strategies:

- Ramp metering.
- VSL.
- Lane use control.
- QW.
- Part-time shoulder use.

The following key components are used within WSDOT's TMS and subsystems:

- Ramp meter signal heads.
- Ramp meter controllers.
- Vehicle detectors (e.g., inductive loops and radar detectors).
- DMSs.
- Lane use control signs.

By actively managing their TMS and operational strategies, WSDOT improves traffic flow and reduces the likelihood of secondary collisions and panicked braking by dynamically displaying enforceable speed limits on their DMSs when congestion is detected downstream. As shown in figure 6, speed limits are reduced in advance of traffic slowdowns to reduce speed differentials and reduce crashes. Messages are displayed on an overhead or a shoulder-mounted DMS to warn drivers of congestion or collisions downstream with specific lane or distance information. The

WSDOT TMS also deploys adaptive ramp metering (ARM) throughout the Seattle region and dynamic part-time shoulder use along one portion of I–405.

Source: FHWA.

Figure 6. Photograph. ATM deployed on I–5 in Seattle, WA.[(12)]

WSDOT's success in the active management of these subsystems and operational strategies resulted in reduced speed differentials across lanes, frequency of "stop and go" and abrupt evasive maneuvers, frequency of collisions, collision severity, and increased throughput for approaching onramps. The success of their implementation also provided some valuable lessons learned. One of these lessons learned includes providing enhanced education on active management strategies and technology, particularly within the managing agency, which can increase the potential for the project's success. Another lesson learned is to procure durable and high-quality DMSs, which are a foundational component to many subsystems and active management strategies.

The Utah DOT (UDOT) manages a TMS that is focused on a road weather management operational strategy.[(13)] Their solution provides both operators and motorists with more accurate and timelier road weather and travel impact condition information and forecasts. By providing this information, UDOT is progressing toward their goals of improved safety and mobility during weather events.

The following subsystems support this operational strategy:

- Traveler information.
- Environmental sensor stations.
- Data.

These subsystems comprise several key components:

- Environmental sensors.
- DMSs.
- HAR stations.

UDOT initially deployed the pilot Adverse Visibility Information System (ADVISE) on a fog-prone area along I–215 during the 1995–2000 winter seasons to notify motorists of safe travel speeds.[14] The warning system was installed on a low-lying, 2-mile segment in Salt Lake City, UT, where multivehicle, fog-related crashes occur. Visibility sensors and detection sensors provided data to a subsystem that constantly evaluated the roadway and visibility conditions and traffic volumes. The data were transmitted to a central computer that monitored threats and automatically displayed a warning message and a recommended safe speed on the DMS. The ADVISE system has evolved into the current road weather subsystem that involves meteorologists housed in the TMC to support road weather forecasts.

One of the unique elements of the UDOT TMS is their citizen reporting service. Motorist volunteers are enlisted to provide information regarding weather conditions along specific roadway segments through UDOT's own traffic smartphone application. The citizen reporting service supplements UDOT's data subsystem by filling in gaps in the existing road condition reports and supporting more timely and accurate forecasts. The service was especially beneficial for UDOT in rural areas that lacked adequate road weather data acquisition coverage. The citizen reporting service proved to be a viable and useful source of road weather information to supplement their primary data collection methods. One major lesson the agency learned from implementing their citizen reporting service was to provide adequate training and support for citizens who are not experienced in transportation operational strategies to ensure reporting functions smoothly and meets expectations.

Kansas City Scout (KC Scout) is Kansas City's bi-State TMS, jointly operated and funded by the Kansas DOT (KDOT) and Missouri DOT (MoDOT).[15] KDOT and MoDOT use KC Scout to manage and operate traffic on more than 100 miles of freeway corridor and across State lines in the greater Kansas City metropolitan area. KC Scout encompasses the jurisdictional boundaries of Cass, Clay, and Jackson Counties in Missouri, and Johnson County and Wyandotte County in Kansas. KC Scout was designed to decrease congestion, improve rush-hour speeds, increase safety by reducing rush-hour accidents, and improve emergency and incident response. KC Scout is used to implement operational strategies in the freeway environment, including TIM, emergency management, traveler information, special event management, work zone management, and road weather management.

The following subsystems support the KC Scout operational strategies:

- Ramp metering.
- Traveler information.
- Environmental sensor stations.
- Data.

The subsystems use the following key components:

- Ramp meter signal heads.
- Ramp meter controllers.
- CCTV cameras.
- DMSs.
- Vehicle detectors.
- HAR stations.

The KC Scout TMS disseminates information obtained through the subsystems and components to facilitate coordination with public agencies and service providers as they respond to incidents and adverse weather impacting the roadways. All the data collected within the network are centrally accessible in the TMC. The TMC accommodates operators, emergency response personnel, and the media for a coordinated approach to implementing operational strategies. By leveraging shared resources and data, KC Scout is able to provide timely information in regard to traffic incidents, scheduled events (e.g., roadway construction), special events (e.g., heavy traffic stadium and concert events), traffic congestion, and road weather information.

A valuable lesson from KC Scout is its successful integration of a road weather information subsystem with the preexisting traffic management capabilities of KC Scout. By upgrading their TMSs, Kansas and Missouri were able to integrate weather information into the operator's user interface as another "layer," utilizing the data available from external weather information sources, such as National Oceanic and Atmospheric Administration, NWS' National Digital Forecast Database, and Meridian-511 providers.

Furthermore, during winter storm events, MoDOT's traffic department operates a workstation that is used solely for monitoring road conditions and reporting on the snowplow activity within its coverage area. This information is particularly useful because it can be used to disseminate traveler information in advance, which can help operators clear lanes that would otherwise be impeding snowplowing activities. The integration of a weather information subsystem helps KC Scout reach their goals by providing timelier messaging to motorists, thereby improving highway performance and enhancing safety.

The Georgia NaviGAtor system is a TMS that uses a variety of technologies to monitor, manage, and operate the State's freeway facilities.[(16)] The Georgia DOT (GDOT) implemented their TMS with the goals of improving traffic flow efficiency, safety, and response times to traffic incidents and for disseminating accurate and timely traveler information. To achieve these goals, GDOT uses the NaviGAtor TMS to implement a variety of operational strategies, including traveler information, ramp metering, TIM, special event management, and work zone management.

The Georgia NaviGAtor TMS includes the following subsystems:

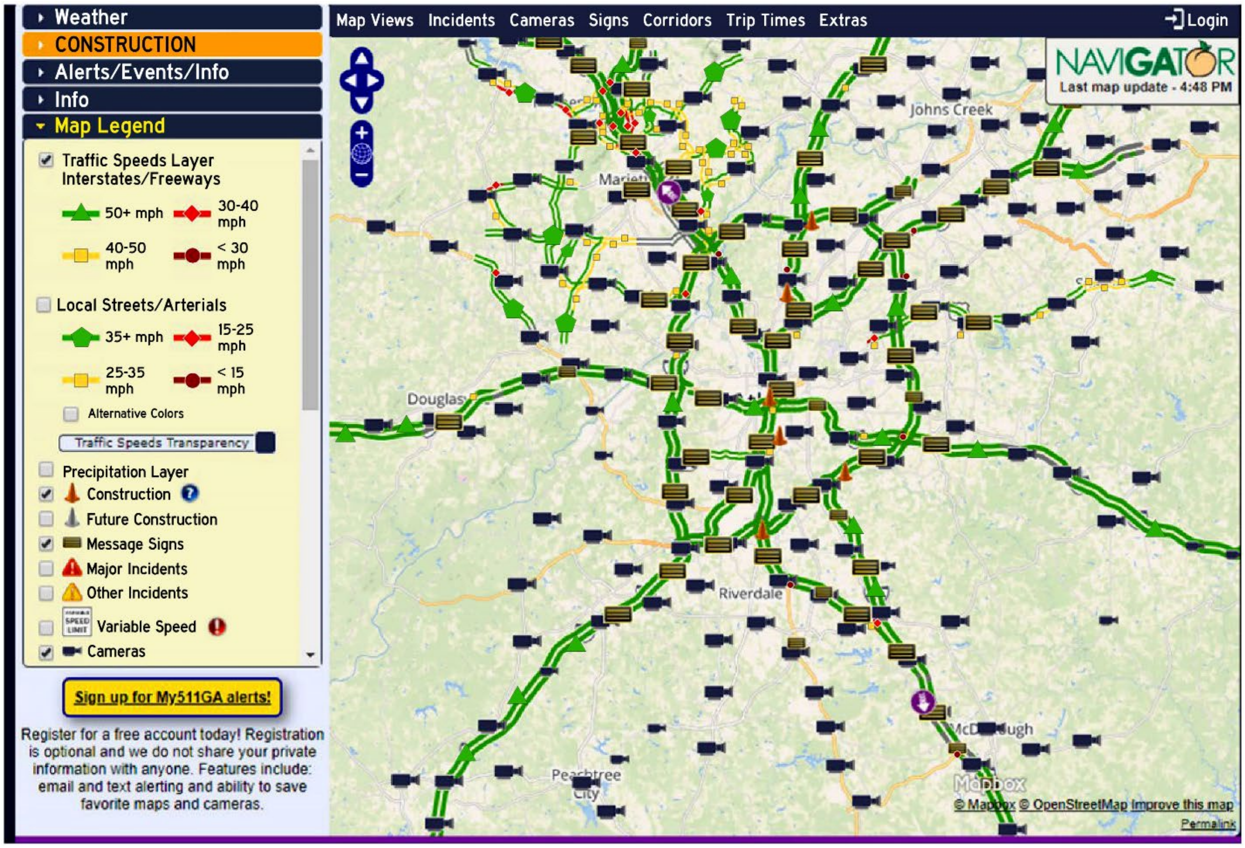
- Traveler information.
- Ramp metering.
- VSL.
- Traffic signal control.
- Data.

The subsystems comprise the following key components:

- Ramp meter signal heads.
- Ramp meter controllers.
- CCTV cameras.
- Vehicle detectors.
- DMS.

One of the primary goals of the GDOT TMS is to better manage traffic flow. One major TMS function to achieve that goal is to provide real-time traffic information to improve transportation decisions and public information. The TMS collects data through components—such as CCTV cameras, video detectors, and radar detectors—and a communication subsystem that transmits the data back to the TMC via fiber-optic cables. The TMS then enables operators to manage traffic incidents and congestion by controlling ramp meters, traffic signals, and DMSs. GDOT uses the collected information to display pretrip and en route traveler information, assist in dispatching incident responders, and provide services to transit agencies to help them manage their operations around changing road conditions.

As shown in figure 7, the data are used to populate a map of real-time traffic and roadway conditions—including travel times, incidents, speeds, and camera views—on GDOT's website and display messaging on roadside DMSs.



Original map © 2020 Mapbox and OpenStreetMap. Screenshot © GDOT.

Figure 7. Screenshot. GDOT NaviGAtor website (2020).[(16)]

The Georgia NaviGAtor TMS uses video detection cameras as its primary source of real-time traffic flow information rather than the traditional induction loop or a radar detection unit. Therefore, NaviGAtor is a great example of successful implementation of video detection technology as the foundation for traffic management and operations.

The video detection cameras are installed along most major interstates around Atlanta, GA, and can provide continuous speed and volume data, which the TMS uses to generate travel times that can be disseminated to DMSs. However, generating travel time data from video detection components can require significant levels of evaluation and quality control processing compared to more established and traditional detection components, such as induction loops. GDOT also uses video detection cameras from different vendors, which can be an additional barrier for data processing.

An example of processing complications includes inconsistent sampling rates (i.e., varying reporting frequencies by component type). This inconsistency can result in an inaccurate aggregation of raw data if an agency assumes consistent sampling rates across components from different vendors. Considerations for agencies implementing subsystems that use video detection components include standardizing the data sampling rate when procuring components or purchasing the same model of components from a single vendor.

SYSTEMS THAT SUPPORT SURFACE STREETS

This section examines the commonly used TMSs and subsystems used to implement operational strategies to achieve agency goals and objectives for managing surface streets.

Similar to systems that serve the freeway environment, physical components and technologies shape the systems that serve surface street environments. TMSs that support surface streets evolved from fixed-time traffic signal subsystems to responsive subsystems, to, most recently, adaptive signal control subsystems.

Technology is used to improve signal operation along arterials. Technology enabled the introduction of field master controllers. Field master controllers were located at one intersection and interconnected to nearby traffic signal controllers within the system. This process allowed for coordinating the operation of the traffic signals at adjoining intersections through a telecommunication media (e.g., copper wire, leased phone line with a low-speed modem). When an agency or operator at a TMC wanted to observe the operating status of a traffic signal controller or make modifications to control parameters at one or all of the traffic signals controlled by the master, a connection was made to the field master, which communicated with local controllers to retrieve data and send the data back to the TMC.

As technology continues to improve, data collection and communication capabilities also improve. Agencies are realizing the benefits of leveraging data to improve their operations and system performance. As the need for more data increases, agencies are upgrading their data collection and communication subsystems to be able to handle more complex forms of data. For example, newer communication media—such as fiber-optic, wireless, and IP communication systems and video-based detection technologies—have become more widespread, and legacy field master controllers are being phased out.

As agencies integrate traffic signal control systems into the management of the overall surface street network, functions from other systems that were previously operated in a singular or isolated manner are being incorporated as a function of multiple subsystems within a region. Regional integration allows agencies to achieve synergy through shared systems and the exchange of data and information. Furthermore, in the absence of central control and monitoring capabilities, systems are isolated, perform independently along a corridor, and are unable to be integrated and coordinated with real-time information to achieve agency (or interagency) goals and objectives.

Subsystems

Advanced surface street management strategies and the implementation of new and evolving subsystems rely on a strong communications and data subsystem. As communications and data capabilities evolve, so do surface street operational strategies and subsystems. The following subsystems operate in the surface street environment:

- Traffic signal control.
- Vehicle detection.
- Traveler information.

- Lane use control.
- DMS control.
- CCTV display and control.
- Communication.
- Environmental sensor stations.
- Data.

Components

With the evolution of detection technology and the range of data that comes with it, signal controllers have, in turn, evolved to handle the processing needs of that new technology. Surface street systems have also evolved to encompass more than just traffic signal control subsystems and strategies. The following components make up this growing range of surface street subsystems:

- Traffic signals.
- Traffic signal controllers.
- ITS device controllers.
- Vehicle detectors.
- Wireless local area network/communication using wireless technology roadside detectors.
- TSP signal detectors.
- Emergency vehicle preemption detectors.
- Environmental sensors.
- DMS.
- CCTV cameras.
- Communication switches.
- Servers.
- Phones.

The following section summarizes the current practices of agencies that have successfully deployed TMSs, subsystems, components, and operational strategies that serve the surface street environment.

Current Practices in the Surface Street Environment

The examples that follow illustrate how agencies have deployed TMSs and operational strategies that meet the needs of the agency and support the active management of these systems. The examples are at the forefront of the practice and illustrate either current or future trends.

The San Diego, CA, area Regional Arterial Management System (RAMS) was completed in late 2008, with the primary goal of coordinating traffic signals to optimize traffic flow along interjurisdictional surface street corridors.(17) Before RAMS was implemented, neighboring agencies in the San Diego region managed their traffic signals, components, and software independently.

The RAMS enabled these neighboring jurisdictions to coordinate traffic signal management activities using common resources. The San Diego RAMS interconnection among the various interjurisdictional traffic signal subsystems is called the Intermodal Transportation Management System (IMTMS). The IMTMS links the subsystems through a regional network and comprises the communications across the subsystems that facilitate shared information and services and the communications between subsystem components and software. With the integration of interjurisdictional subsystems, the RAMS deploys operational strategies, including traveler information, special event management, transit management, and traffic signal control.

The RAMS deploys the following subsystems to support these operational strategies:

- Traveler information.
- Traffic signal control.
- Transit management.
- Data.
- Communication.

The following key components comprise these subsystems:

- Traffic signal heads.
- Traffic signal controllers.
- DMSs.
- CCTV cameras.
- Vehicle detectors.
- Regional integrated workstation.

The RAMS consists of multiple subsystems that utilize a common communication subsystem for integration. This TMS is supported by a software package that supports management and interjurisdictional signal coordination efforts. The traffic signal optimization software was installed at the participating agency facilities, where operators coordinate signal changes through a map-based user interface on a regional integrated workstation. This TMS allows agencies to view signals from neighboring agencies—including signal status, controlled time, timing, and coordination information—and implement regional timing plans for both their own signals and preselected signals from neighboring agencies.

Additionally, the RAMS supports shared functions among the stakeholder agencies, such as interjurisdictional signal timing, regional timing plan implementation, field component control management, incident and event management, and resource management. Agencies can set the amount of information and control functions that are shared.

The RAMS is a complex TMS that encountered numerous delays during project deployment. Primarily, these delays could be attributed to disagreements among partners, difficulties with moving from planning to deployment, a lack of alternative support for the software system, and staff turnover that required refamiliarization with the project. Based on this project, the lessons learned that could be applied to other integration projects include adopting project management standards with a structured deliverable document review process, making proper workload adjustments for public agency staff responsible for technology project management, allocating time for project managers to attain technical expertise regarding the system, developing procedures and policies, and including operations staff throughout the planning and design phases of the project.

The Seattle DOT (SDOT) manages an ITS-based TMS that serves the surface street environment in the Seattle, WA, metropolitan area.(18) The goal of this TMS is to improve multimodal travel in terms of safety and efficiency. To accomplish these goals, SDOT leverages ITS and technology to enhance their TMS and implement operational strategies. These operational strategies include traffic signal control, traveler information, TIM, work zone management, special event management, and traffic signal priority.

The following subsystems comprise SDOT's TMS and support their operational strategies:

- Traveler information.
- Traffic signal control.
- Data.

The following key components comprise these subsystems:

- CCTV cameras.
- DMSs.
- Traffic signal heads.
- Traffic signal controllers.
- TSP detectors.
- Vehicle detectors.
- Wireless local area network detectors.
- Bicycle detectors.
- Environmental sensor stations.

In 2014, SDOT became an early adopter of integrating wireless local area network detectors into their traveler information and data management subsystems to measure travel times on congested corridors within the city. SDOT also uses these detectors to support their TIM operational strategy. By detecting anomalies in travel times, operators can verify incidents using their CCTV cameras and respond to them in a timelier manner. Additionally, these wireless local area network detectors are also used to support their traveler information operational strategy by providing real-time travel time data to the travel public on DMSs and their public travelers website.

SDOT's implementation of detectors into their TMS is a good example of leveraging emerging technology to support operations within the surface street environment. Before the wireless local area network detectors were installed, SDOT relied on LPRs to collect travel time data. However, LPRs were expensive to procure and maintain, and they raised privacy concerns by collecting license plate information that could be traced back to personal driver information. These wireless local area network detectors do not have the same issues as LPRs because they are cheaper to procure and maintain, and they collect data from mobile devices that are securely encrypted and anonymized. As data collection continues to grow in prevalence across the transportation field, issues such as data privacy and data security will become a significant factor in the type of subsystems and components agencies decide to deploy. A lesson learned from SDOT's example is to consider these emerging issues that come with improved technology when planning to deploy these subsystems and components.

The city of Fort Worth, TX, manages a TMS within the surface street environment with the goals of reducing congestion, improving air quality, improving safety, and moving traffic.[(19)] To progress toward these goals, the city implements operational strategies, such as traffic signal control, traveler information, TSP, emergency management, and road weather management.

The city deploys the following subsystems to address these operational strategies:

- Traveler information.
- Traffic signal control.
- Environmental sensor stations.
- Data.

The following key components make up these subsystems:

- Traffic signal heads.
- Traffic signal controllers.
- Vehicle detectors.
- Bicycle detectors.
- TSP detectors.
- High-water flashing beacons.
- Environmental sensors.

One of the subsystems managed by the city that stands out is the flood-warning subsystem. The high-water warning subsystem relies on data collected from rain and water level gauges at low-water crossings and weather stations. The data collected from these weather stations are transmitted to the subsystem in realtime to determine whether the allowable threshold has been breached. When a breach occurs, the subsystem activates roadside flashing beacons with static signage to immediately warn drivers of a flood hazard. In addition to activating these components, alerts are simultaneously sent to first responders and incorporated into travel condition information that is made available to the public.

The flood-warning subsystem relies on the communication subsystem to transmit the data to the data management subsystem. Flood warning messages are pushed out to other agency stakeholders, social media platforms, and the media. Flood-warning information is also made available on the city's website with interactive filters and graphical displays related to a wide range of data metrics (e.g., rainfall amounts, hail intensity, dew points, reservoir storage status, flood status, flashing beacon status, gate position, and many other factors).

SYSTEMS THAT SUPPORT MULTIPLE FACILITIES, CORRIDORS, OR REGIONS

This section discusses the commonly used TMSs and subsystems that enable operational strategies in multiple environments, such as facilities, corridors, or regional environments.

The integration of multiple systems can be accomplished through a variety of operational models, including multijurisdictional and multiagency. Examples of systems that could be integrated include TMSs that support surface street operations, freeway operations, transit operations, and other processes. As more importance is placed on interagency coordination, especially in dense urban areas, managing corridors in an integrated manner allows for benefits, such as shared resources, more efficient communications, faster response times, and saved costs.

The specifics of how an integrated system will operate depend primarily on the conditions that occur in the corridor in which the integrated system is installed and existing TMSs and operational strategies that are in place in the corridor. Understanding the users of the facility, corridor, or region and the unique characteristics of the types of travelers and how they access information will help determine possible operational strategies that may be effective to deploy in an integrated manner.

Effective regional or corridor management will involve implementing multiple complementary and cohesive strategies, rather than a single strategy along the corridor, or even applying a suite of strategies to different modes of travel. Agency stakeholders will need to spot potential areas of interconnection between different roadway facilities and modes of travel. Each agency stakeholder will need common evaluation methods to assess their systems and evaluate integration alternatives, which will be essential for selecting operational strategies that support agency operations, and, in turn, help with achieving the shared vision and objectives for the integrated corridor, such as improved travel time, improved system/corridor reliability, or reduced recurring peak-period congestion.

Subsystems

Advanced operational strategies and implementation of new and evolving subsystems rely on a strong communications subsystem, which also supports and facilitates data and information sharing between agencies. These functions give the agency capabilities they might not have had previously, such as the ability to monitor regional traffic conditions and coordinate effective regional response plans, including traveler information dissemination for planned and unplanned events that span both freeway and surface street environments. These coordinated systems improve operations, safety, and travel time reliability while using resources more efficiently. The following examples of potential subsystems could be applied to an integrated management environment of facilities, corridors, or regions:

- Data.
- Ramp metering.
- Traffic signal control.
- Traveler information.
- Vehicle detection.
- Lane use control.
- QW.
- Environmental sensor stations.
- CCTV display and control.
- Communication.

Components

Subsystems comprise individual components that serve a purpose as a part of the subsystem or TMS. The following components serve a purpose as a part of the subsystems listed in the previous set of bullets:

- Ramp meter signal heads.
- Ramp meter controllers.
- Traffic signals.
- Traffic signal controllers.
- ITS controllers.
- Vehicle induction loops.
- Wireless local area network/communication using wireless technology roadside detectors.
- TSP signal detectors.
- Emergency vehicle preemption detectors.
- CCTV cameras.
- Workstations.
- DMSs.
- Vehicle detectors.
- Environmental sensors.
- Communication switches.
- Servers.
- Phones.

Current Practices in Facility, Corridor, or Regional Environment

The examples presented in this section illustrate successful agency-deployed TMSs and subsystems that provide a multimodal, multifacility, and multijurisdictional set of operational strategies.

The Dallas, TX, U.S. 75 integrated corridor management (ICM) system was designed to achieve the goals of increasing corridor throughput, improving travel time reliability, improving incident management, and enabling intermodal travel decisions.[(20)] The Dallas Area Rapid Transit (DART) is leading this TMS, which provides participating agencies with an integrated platform for managing traffic, incidents, and construction within the corridor. In addition to DART, participating agencies include city of Dallas, city of Richardson, city of Plano, town of Highland Park, city of University Park, North Central Texas Council of Governments, North Texas Tollway Authority, and Texas DOT (TxDOT). Subsystems from participating agencies are interconnected in this TMS to facilitate data sharing, communication, and operational strategies.

Operational strategies were selected and broken out by network type, ranging from TSP, TIM, special event management, managed lanes, traveler information, traffic signal control, parking management, and ramp metering.

The following subsystems were integrated to implement these operational strategies:

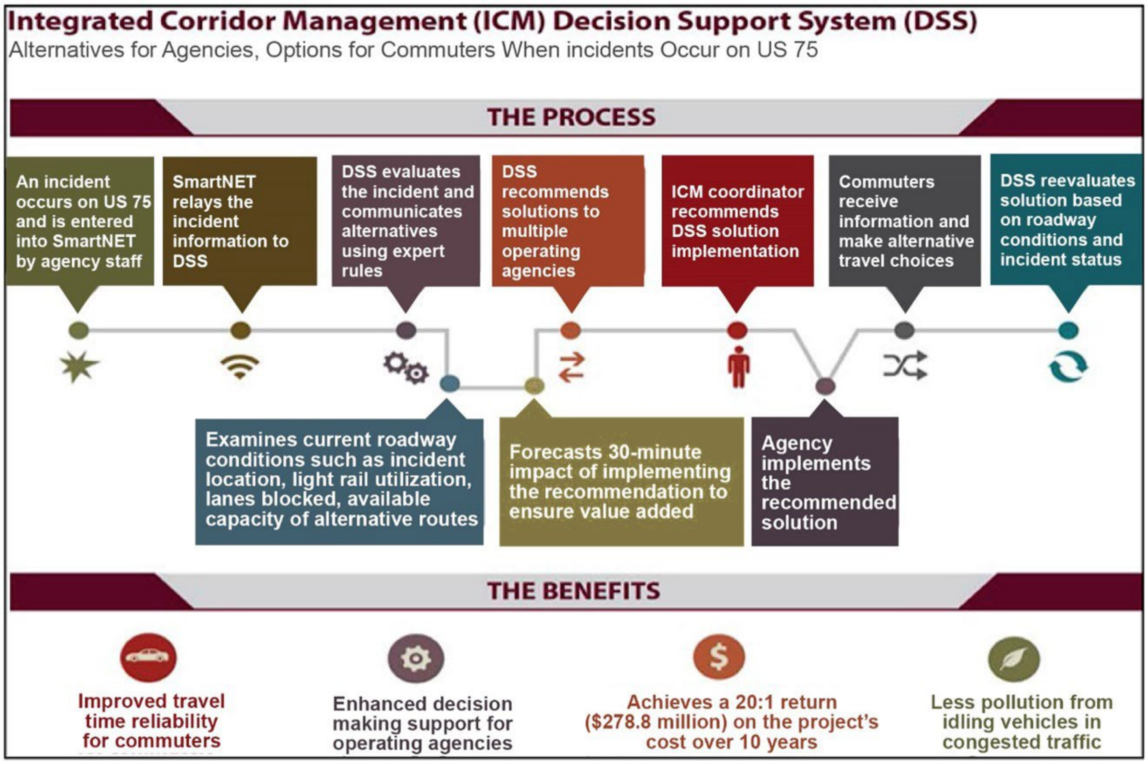
- Traffic signal control.
- Traveler information.
- Transit management.
- Data.

This TMS includes the following key components:

- Traffic signal heads.
- Traffic signal controllers.
- Ramp meter signal heads.
- Ramp meter controllers.
- TSP signal detectors.
- CCTV cameras.
- DMSs.
- Vehicle detectors.
- Smart parking detectors.

The U.S. 75 TMS integrates multiple subsystems that support sharing internal and external incident, construction, special event, transit, and traffic data. The TMS utilizes a decision-support subsystem to provide operational planning and evaluation data through a center-to-center interface that communicates to various agency systems. The decision-support subsystem is also used to facilitate operational strategies. The TMS uses a Web-based graphical user interface that allows agency subsystems and centers to share important information with each other, such as location and status of incidents, resources deployed, planned events, and construction areas. The TMS also uses a data fusion engine to manage the data from the various subsystems, and it allows those data to be shared with external parties through their 511 traveler information subsystem.

The daily operation of the corridor is an expansion of the existing relationships and operations of the stakeholder agencies within the region, but with additional coordination, communication, and responses. All the operations through the ICM are coordinated through the decision-support subsystem. Figure 8 illustrates the interactions of the functions and processes of the U.S. 75 system in Dallas.



Source: FHWA.

Figure 8. Diagram. U.S. 75 ICM decision support in Dallas, TX.[20]

The U.S. 75 is a good example of a TMS that serves an integrated corridor. This TMS fundamentally changed how transportation agencies in the U.S. 75 corridor collaborate to move people and vehicles through the corridor and implement coordinated operational strategies, such as TIM and traveler information. TMSs and operational strategies that serve the integrated corridor environment are fundamentally focused on interagency coordination. As such, the lessons learned from the deployment of the U.S. 75 TMS are focused on interagency coordination as well.

Participating agencies confirmed that integrated approaches to TMSs and operational strategies should build on existing institutional arrangements because starting with existing relationships is the key to building consensus. Institutional issues that may arise in the early parts of the project can be mitigated by setting expectations and defining roles and responsibilities.

Furthermore, the key to successful integrated corridor TMS operations is data sharing. Planning for the operation of the current system, as well as planning for future expansions, are important. The geographic region, systems involved, agencies involved, and applications that may be needed in the future should also be considered. One way to ensure success is to include the integrated corridor TMS in the regional ITS strategic plan, so that agencies are committed to the deployment in the region.

The San Diego, CA, I–15 Corridor ICM is led by the San Diego Association of Governments (SANDAG).[21] Major stakeholders involved in the development and operations of the TMS include California DOT (Caltrans), California Highway Patrol, Metropolitan Transit System, North County Transit District, city of San Diego, city of Poway, and city of Escondido.

The goals of the San Diego ICM initiative are to grow multimodal travel, improve safety, provide traveler information, provide integrated approaches to problems, and manage the corridor holistically. To achieve these goals, operational strategies are implemented in coordinated and integrated ways. These strategies include ramp metering, traffic signal control, TSP, traveler information, TIM, priced managed lanes, and multimodal electronic payment.

The following subsystems are within the I–15 ICM that support these operational strategies:

- Traffic signal control.
- Ramp metering.
- Traveler information.
- Data.

These subsystems are composed of the following key components:

- Traffic signal heads.
- Traffic signal controllers.
- Ramp meter signal heads.
- Ramp meter controllers.
- CCTV cameras.
- Vehicle detectors.
- DMS.
- TSP detectors.
- Electronic toll collectors.

The operational strategies of the integrated corridor and critical coordination among agencies is accomplished through a Virtual Corridor TMC (VCTMC), which manages the ICM system and infrastructure. The VCTMC allows for further integration of the agency subsystems and functions. By integrating subsystems together, participating agencies are able to provide seamless traveler information, such as travel times; incident information; and expected delays through the DMSs, 511 mobile phone application, and other sources.

Like the Dallas system, this TMS also integrates a decision-support subsystem that uses real-time simulation, predictive algorithms, and analysis to evaluate potential congestion mitigation strategies and suggest an optimal combination of those strategies for the corridor.

The coordinated effort resulted in improved joint agency action plans for traveler information, traffic signal timing, ramp metering, and managed lanes. The integrated subsystems also allowed for enhanced management across the different facilities, including shared control and coordination across jurisdictions for field components.

The successful deployment of the I–15 integrated corridor TMS encourages agencies to manage their transportation corridors as an integrated and multimodal system rather than individual systems. The use of analysis, modeling, simulation, and performance measures to make informed decisions and shape operational strategies was a large factor in the success of the I–15 TMS.

The success of the system was also enhanced by interagency coordination and an interagency decision-support subsystem. These are all items that agencies should consider when planning and designing an integrated corridor system.

The city of Houston is home to the Houston TranStar TMS. The Houston TranStar is a unique partnership of four agencies: city of Houston, Harris County, METRO, and TxDOT. The goal of this TMS is to keep motorists informed, roadways clear, and lives safe within the Houston metropolitan area.(22)

The TranStar TMC houses representatives from all the participating agencies, which enables the sharing of resources and exchanging of information within one physical location. The collaborative nature of this TMS allows for an integrated approach to implementing operational strategies. Some of the operational strategies implemented by TranStar include traffic signal control, ramp metering, TIM, emergency management, traveler information, road weather management, and work zone management, which are applied to both freeways and surface streets.

The following subsystems comprise the TranStar TMS:

- Traveler information.
- Ramp metering.
- Traffic control signal.
- Transit management.
- Environmental sensor stations.
- Data.

The TranStar subsystems are composed of the following key components:

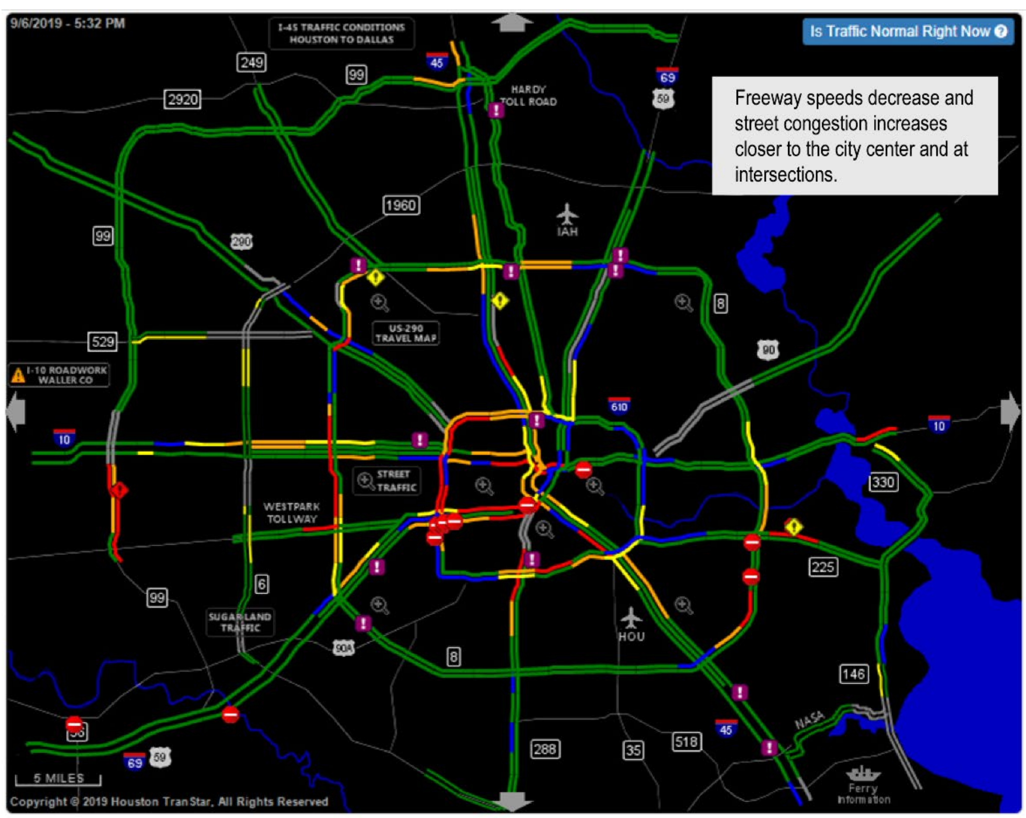
- Traffic signal heads.
- Traffic signal controllers.
- Ramp meter heads.
- Ramp meter controllers.
- CCTV cameras.
- DMS.
- HAR stations.
- Environmental sensors.
- Vehicle detectors.

This collocation of agencies and technologies under one roof allows for subsystems and components to be pooled together, thus establishing familiarity among the participating personnel for an effective operational strategy implementation, such as shared access to the CCTV cameras and DMSs for effective incident management and traveler information dissemination across different operating environments.

This integrated TMS also enables operations staff to effectively dispatch vehicles to remove debris and communicate with emergency vehicles about the most direct routes to an incident where the route may include both freeways and surface streets.

TransStar can inform travelers of conditions through real-time traffic maps and by posting traffic alerts to the TranStar Twitter account.

Houston is known for its many heavy rainfall events, making flooding a concern for travelers within the region.(23) TranStar leverages Harris County's flood control district warning subsystem to alert travelers where flooding may be a risk during heavy rain events. Figure 9 provides a snapshot at the Houston TranStar website, which shows vital travel information, including flood warning indications, travel times, and incidents.



© 2020 Houston TranStar.

Figure 9. Screenshot. Houston, TX, TranStar traffic map (2020).(22)

TranStar was one of the first TMSs to integrate transportation and emergency management in the United States. The emergency operations center, which resides within the same building as the transportation operations center, is where Harris County takes the lead role in emergency response. Harris County is responsible for improving public safety during disasters caused by human beings and natural disasters. Depending on the disaster, coordination efforts also may include the U.S. Army, Salvation Army, Harris County Toll Road Authority, Amateur Radio operator volunteers, the American Red Cross, and local governments. The automated flood warning system, Doppler radar imagery, satellite weather maps, roadway flood warning systems, and the Regional Incident Management System are some of the tools used during emergency response.

TranStar is a great example of a TMS that operates within an integrated corridor that is also multimodal, multifacility, and multijurisdictional.

CHAPTER 4. PLANNING AND DEVELOPING TMSs OR SPECIFIC ENHANCEMENTS

This chapter addresses the range of possible projects, processes, and steps associated with planning, developing, and implementing TMS. This chapter also addresses the issues to consider and practices with planning for and developing specific improvements (e.g., software platform, data subsystems, telecommunication media) for a TMS. Challenges, lessons learned, and other issues encountered by agencies who have already taken steps to replace or enhance their systems or specific improvements also are covered.

Many agencies do not conduct feasibility studies for a TMS, and many may not have multiyear transportation management strategic plans to lay the groundwork to build TMS plans upon. It is critical to develop and integrate plans for TMS into existing agency planning efforts, especially transportation system management and operations (TSMO) plans and ITS strategic plans. Leveraging existing planning efforts and plans is crucial when planning TMSs and assessing the aspects of a TMS that may need improving to meet the needs of an agency, region, or any specific geographical area. Stakeholders often start from scratch when they begin exploring options to pursue or plan for improving TMSs because nationally developed resources are still being developed to assist with these studies. This chapter discusses a series of assessment efforts that can be conducted in support of planning for the next generation of TMSs.

By reviewing information presented in the previous chapters on how subsystems and their components can be used to fulfill operational strategies, agencies can capture how their current system is performing, assess and document its functions, and explore options to improve performance or plan for the next generation of TMS. The information in this chapter supports the topics on system monitoring and performance reporting covered in chapter 5.

PLANNING FOR TMS

This section identifies some of the topics that agencies need to address when planning for TMSs. Current agency practices and plans (e.g., strategic plans, regional operations plans, and ConOps) should be used as a preliminary framework to assess TMS performance and contribute to planning a TMS. This section addresses the importance of integrating TMS planning efforts with agency or regional plans, conducting feasibility studies (especially with new TMSs or adding new operational strategies to a TMS), and developing a plan for a TMS. Issues to consider during the process, with examples of current practices, are also included.

Connecting Planning for a TMS to Agency or Regional Plans

Before a TMS can be developed and implemented, an agency needs to go through a planning process. Planning for developing, installing, and operating a TMS is a process that is most effective when driven by objectives and desired outcomes. The rationale behind this idea is to link planning processes and traffic operations so that the performance of the network is enhanced in an efficient manner to meet agency, regional, or State goals. When planning for a TMS, agencies and stakeholders should consider appropriate performance measures that can show the progress made toward reaching these goals. The performance measures selected need to reflect the data that can be collected by the system or acquired from other systems or parties.

Planning Considerations

TSMO activities are at the core of transportation agencies' mission to provide safe and efficient transportation. TMSs enable many of the TSMO activities that support agencies' missions. Planning helps agencies identify how the TMS will operate and aids in identifying how the TMS will be structured, including any services that will be provided to external entities. Agencies can then integrate the requirements needed for a TMS into their capital program, TSMO program, or regional transportation plan (RTP) at the level of detail applicable to that program or plan. Documenting the TMS requirements in a plan formalizes the planning process and can help guide future system enhancements.

Scenario planning is often integrated into the long-range transportation planning process. Long-range scenario planning involves addressing strategic, high-level questions about major changes in the external operating environment, such as changes in the economy, demographics, technology, and the environment. The goal of scenario planning is to ensure that whatever system is built, it will be adaptable to potential future changes, and the agency can use these scenarios to get a clearer idea of the implications of major changes. Short-term scenario planning is much more operational in nature and centers around how the TMS will be operated and managed under different conditions, such as planned events (e.g., sporting events, construction work zones), incidents (e.g., closed lanes or inclement weather), and typical day-to-day operations. The use of modeling and simulation tools can facilitate the assessment of the TMS in various scenarios and help agencies determine the best range or combination of scenarios to include and use as the basis around which the planning evolves. The integration of scenario planning into long-range planning processes is especially important for prioritizing the needs for future investments of operations in transportation. The six-step scenario planning process defined in the Federal Highway Administration (FHWA) 2011 FHWA Scenario Planning Guidebook can be modified for TMSs and operational strategies to address the following questions:(24)

- How should we get started?
  - Scope the effort.
  - Engage partners.
- Where are we now?
  - Establish baseline analysis.
  - Identify factors ad trends that affect the State, region, community, or study area.
- Who are we, and where do we want to go? Establish future goals and aspirations based on values of the State, region, community, or study area.
- What could the future look like?
  - Create baseline scenarios.
  - Produce alternative scenarios.
- What impacts will scenarios have? Access scenario impacts, influences, and effects.

- How will we reach our desired future?
    - Craft the comprehensive vision.
    - Identify strategic actions and performance measures.

Results of agencies' planning work can also be captured in a multiyear TMS plan that identifies resources, future projects, and procurement methods. The TMS plan, or elements of the plan, can be included in agency transportation or TSMO plans, capital programs, and budgets. Key elements of the plan should include identifying linkages among the agency's TSMO plans and long-range scenario plans, MPO long-range plans, and other agency plans. The document should be used as decisions are made regarding the design and development of the TMS, integration of projects, and allocation of funds in future budgets to provide the resources needed for the agency to implement the plan. The multiyear plan should identify any enhancements or improvements that may be needed over a 5- to 10-year period, ongoing operations and maintenance requirements, and administration needed to support the TMS over the planning phase of the study.

Experience also has shown that an RTP, normally produced by an MPO, can serve as a blueprint for transportation system investments within the region across all modes. The RTP ensures that transportation projects are completed collaboratively across various agencies and jurisdictions. The RTP examines the regional transportation system by looking into the future for 20 years or more, and it includes both short-range and long-range strategies that lead to the development of an integrated multimodal system.

Planning in subareas and corridors entails accounting for the impacts of using a range of operational strategies and TMS with the required functional capabilities at varying geographical scales. A subarea is a smaller portion of the region. Planning for a smaller scale geographical area will require an agency to perform planning activities in greater detail, including conducting an analysis and a system feasibility assessment. Examples of subareas include a downtown area, a municipality, an activity center, or another type of area within a region. A corridor typically is a group of routes that runs parallel either through or is contained within a region. Compared to a subarea, this region has a larger scale travel space. When agencies are considering implementing a TMS at a regional level, it is important to understand what range of operational strategies may be used and where they may be implemented. Agencies can then determine the capabilities needed by a TMS to assess how it may impact mobility at the subregional levels. By doing so, the planning process will better reveal specific elements in these systems that support mobility goals.

The use of data during planning phases is essential, because accurate and reliable data will enhance an agency's ability to estimate the potential benefits to the transportation network from implementing a TMS, actively managing and operating traffic, using new operational strategies, or expanding the services currently provided. Therefore, the data will help agencies determine which type of TMS operational strategies and functions will be most beneficial.

Programming and Budgeting

At the programming level, securing funding is a competitive process due to limited resources and a high demand for other projects. Programming and funding processes can vary from State to State. Generally, a TMS can be included in transportation improvement plans, long-range plans, and short-range plans if it can support the plan's goals and objectives. However, TMS implementation projects will have to compete with other projects to be approved for funding. TSMO managers must understand their agencies' budgeting and project programming processes to get TMS projects funded.

During the programming and budgeting process, proposed TMS enhancements (e.g., add functionality), expansion (e.g., area of coverage), new capabilities, or entire replacement of a TMS need to be integrated into the multiyear budget plans. Defining all the needs and identifying supporting projects in a TMS study would help to bolster the prioritization, justification, definition, and scope necessary to support a project being integrated into an agency's multiyear plan and budgets for all capital or operational expenditures (e.g., MPO Transportation Improvement Program (TIP)).

A key element of the programming process is project prioritization. Traditional prioritization processes may not have the ability to accurately assess the benefits that are often accrued by a TMS. TSMO managers should advocate for updates to the prioritization process to account for these benefits. One of the most important benefits of TMSs is that they improve travel time reliability. Standard assessment techniques that estimate benefits based on average roadway conditions and average traffic flows do not consider fluctuations that can dramatically affect travel time reliability. Analytical techniques that incorporate measured benefits or those that accurately model stochastic fluctuations in travel conditions are examples of methods that can more accurately assess TMS benefits. Active participation in the programming process is an effective way to ensure that benefit assessments used for project prioritization accurately reflect the benefits that a TMS can deliver.

Effective Practice: Prioritize Operations at the Programmatic Level

Many of the challenges with implementing TMSs and improving operational strategies can be addressed at the programmatic level. Caltrans is working to improve their operational strategies by advancing their TSMO program. In 2013, Caltrans utilized an FHWA Regional Operations Forum (ROF) and capability maturity model (CMM) assessment to identify organization gaps and a tailored approach for statewide implementation.[25] Additionally, TSMO was integrated into the 2015–2020 Caltrans Strategic Management Plan as a major component that was tied to the State's goals.[26] Caltrans placed a strong emphasis on improving operations and performed the following additional actions to advance TSMO and ICM in California:

- Identified the top strategic corridors in California.
- Conducted a connected corridors pilot in Los Angeles.
- Created a statewide connected corridors program.

- Created 3-day ROF and CMM self-assessments that focused on corridor operations that included local partnering agencies. This process resulted in corridor-level implementation plans that led to improved coordination and more effective TSMO in those corridors.

To continue the emphasis on TSMO implementation, Caltrans also created a TSMO ROF website with information from all the ROFs that have taken place.(27) This website includes information on topics, such as TIM, corridor issues and challenges, planning and programming for operations, work zones, safety, freight and connected vehicles, and CMM self-evaluation.

Effective Practice: Plan for Operations

Developing robust practices to include operational strategies in planning and programming processes is another method that can ensure a successful rollout of a TMS. WSDOT implemented and expanded their TMS on I–5, SR 520, and I–90 within the past few decades.(28) WSDOT deployed a variety of operational strategies, including ARM, dynamic lane use control (DLUC), dynamic shoulder lanes, dynamic speed limits, and QW. WSDOT intended these various deployments to reduce crashes, improve travel time, and improve travel time reliability. Their DLUC operational strategy, for example, includes VSLs and lane status information to warn drivers of downstream backups as they approach significant congestion, a lane-blocking incident, or a work zone.

WSDOT successfully implemented this substantial set of operational strategies by making active management a priority in their business processes, such as planning and budgeting. Including the enhancements to their TMS into the traditional planning process, within the context of regional goals, helped WSDOT secure funding for the project.

In general, agencies can incorporate operational strategies and the development of a new or improved TMS by widely distributing basic concepts about the TMS and its operational scenarios and by explaining the benefits of deploying such a system. During the feasibility study for their I–5 ATM deployment, WSDOT engaged representatives from FHWA, Washington State Patrol, Puget Sound Regional Council, elected officials, decisionmakers, and local agencies in workshops and forums to spread information about the system and gain support for the development and implementation of the system.

Assessing the Capabilities of a TMS

Initial activities for agencies to consider when planning a new TMS or improving, upgrading, or replacing an existing TMS are to conduct feasibility studies either for the system or for specific components. Feasibility studies include a number of steps:

- Recognize that improving, revising, replacing, or planning a new system could apply to any system component and does not necessarily mean that the entire system has to be enhanced at once. A feasibility study can be conducted on an entire system or on just the proposed enhancements/expansion of the existing system. Agencies may elect not to deploy an entirely new system due to constraints, such as lack of resources, or they may elect to "pilot" a new function along a specific corridor, road facility, or district. Recognizing that specific components of a TMS can be enhanced to gain adequate benefits enables an agency to improve incrementally and at a pace that is feasible.

- Consider certain elements as part of the feasibility study when implementing a TMS or updating specific components of a TMS. Major elements should include budgeting for the effort and planning for interoperability with existing systems. Updating specific aspects of a TMS could include working with software platforms, computing platforms, data management subsystems, user interfaces, and field components; expanding areas of service; enhancing the operational strategies and services or functions of the system; and other possibilities. Agencies should consider the requirements to implement these changes in the feasibility study.

- Include projects to enhance or expand current TMS operational strategies or functions, or implement a new TMS, as part of the planning processes. A feasibility study or assessment should be completed as part of, or in parallel with, the planning process and completed before agencies move forward with developing the TMS concept. This process includes diving into the risks associated with performing these enhancements and improvements, meeting with various stakeholders to fully understand their needs, and sketching a rough system design to identify challenges as well as proposed benefits. Considering the rapid pace of technology advancements and the associated impacts on TMSs is imperative to understanding what factors drive the risk and feasibility of a TMS project and how that may change in the future.

Planning a TMS to address current needs and future functions within the context of addressing congestion issues as part of the congestion management plan can help agencies focus on the strategic planning of a TMS. Agencies that consider the goals, objectives, and operational strategies developed as part of the congestion management plan, which targets improving systemwide performance and reliability, have the potential to gain more effective allocation of limited transportation funding to apply toward a TMS plan that is integrated with the broader agency and regional plans. The integration of TMS planning can also be included as part of a metropolitan transportation plan (MTP) and TIP for an MPO or as part of a TSMO plan, as mentioned earlier in this section. Integrated planning processes might often require a slightly different focus and applicable level of detail to describe the influence of the TMS to enable the wide range of operational strategies and services it may be expected to support. In some cases, the plan may only be a description of the TMS, listing its capabilities, noting the operational strategies that would be provided, and identifying resources needed over a planning horizon to enable the TMS to operate in that environment. By providing this planning information within an integrated plan, agencies can identify support placeholders early—including any necessary operations staff and funding needed to move forward—for the effective implementation of a TMS.

As transportation issues continue to arise, the realization of the importance of addressing these issues at the institutional and programmatic levels has emerged. Tools to help agencies address these issues and assess their readiness to make improvements are available. Common examples of these tools are the CMM process and the capability maturity framework (CMF) tool—both of which are frequently used in the planning process to help agencies assess their capability to deploy TMSs at a more formal and programmatic level.

The CMM was adapted as a process to increase the effectiveness of TSMO at the programmatic level, as determined by the Strategic Highway Research Program.[(29)] Based on the CMM approach, the CMF tool was developed to assist transportation agencies as they self-evaluate their organization's current transportation operations and management processes with respect to specific operational strategies or bundles of strategies. The CMM process and the CMF tool can be used to assess an agency's current TMS operations and identify areas of improvement with respect to program effectiveness.

Additionally, the CMM and CMF can help guide the development of institutional architectures into a more formal program to support TMSs. In other words, the CMM and CMF can be used to help agencies address the nontechnological challenges in developing a program centered on actively managed TMSs, and help with the adoption of these systems. CMM and CMF processes are valuable during the planning and assessment stages of identifying future needs. Agencies can embark upon the usually longer-term process of ensuring they have adequate resources available to make the identified improvements, assuming their prioritization shows it to be beneficial enough to expend the required funds.

It is important to note that no CMF specifically addresses TMSs, but models that cover the important policies, procedures, and general support for using operational strategies that make up a TMS are available. However, the information captured in this report provides an overview of the type of issues to assess for a TMS, if an agency were to begin assessing their TMS.

Using Modeling and Analysis Tools

Modeling and analysis tools can be used during the planning phases of developing a TMS. These tools are used to provide insights into the mobility impacts of different approaches. Planners use a variety of modeling tools to simulate various TMSs and operational strategies. These tools can be categorized as microscopic, mesoscopic, or macroscopic. The appropriate modeling tool depends on the type of TMS and the scale of the impacts desired to be simulated.

Although many challenges, gaps, and issues with linking planning and operations using analysis tools and methods exist, opportunities to use the existing tools more innovatively to help simulate different types of TMSs exist. Safety, environmental, and benefit-cost impacts are all considerations for planning a TMS that typical traffic modeling tools may not incorporate in a straightforward manner. A safety analysis can be completed by using crash and incident data. However, crash reports and incident data typically lack location-specific information with enough fidelity to be useful for evaluating many TMSs, making safety analysis a challenging task. The environmental impacts of a TMS can be assessed by using mobile sources emissions models. Benefit-cost analysis allows an agency to consider the financial perspective of implementing a TMS. FHWA developed the Tool for Operations Benefit-Cost Analysis to help users estimate the costs and benefits of implementing various TSMO strategies, which is inclusive of operational strategies deployed by TMSs.(30) The browser-based benefit/cost analysis tool user's manual is FHWA's *BCA.Net—Highway Project Benefit–Cost Analysis System*.(31) The FHWA traffic analysis tools provide additional guidance on analysis methods that will help agencies select the most appropriate tool(s) for their planning needs in analyzing various TMS-deployed operational strategies, such as ramp metering, traffic signal coordination, and TIM.(32)

Effective Practice: Feasibility Assessment

In 2011, a feasibility and cost assessment was performed for a metropolitan planning area joint TMC (JTMC) in Albuquerque, NM.(33) The JTMC would be shared by staff from the city of Albuquerque, Bernalillo County, and State agencies that have transportation operations responsibilities.

The primary purposes of the assessment were to determine the feasibility of implementing a joint TMC, or JTMC, and the costs associated with that implementation. The assessment identified requirements for the JTMC (including staff, facility, and site requirements); site and building constraints; potential site and building opportunities for the JTMC's immediate move in and future growth; security analysis; potential near-term and long-term enhancements to the site and building for transportation operations; and costs. The assessment effort also included an analysis of the ConOps that describes the planned operations for the JTMC.

The requirements for the JTMC were developed from the participating agency's input for both the near-term implementation period and 10 years and beyond. An examination of the existing site and building conditions was conducted to determine any challenges to developing a JTMC and where opportunities for enhancements can be made. The JTMC was planned to be operational 24 hours a day, 7 days a week with both transportation management and emergency event public safety communications functions. Due to the nature of the JTMC, security was a major item of emphasis in the feasibility assessment efforts. A security strategy, which identified various security components required to ensure uninterrupted operations, was developed for the JTMC. The security component requirements included items such as access card readers, security cameras, bullet/impact resistance building components, alarms, backup power, information security tools, motion detectors, and other implements. A major component of the feasibility assessment was the program-level cost estimate performed. The rough order of magnitude cost estimate for the proposed JTMC provided budgetary information needed to determine the feasibility of developing the new facility and to maintain operations. Elements factored into the cost estimate included construction costs, contractor fees, building components, electrical components, design costs, and other items.

The feasibility study provided the participating agencies with assurance that the JTMC implementation was possible and reasonable. This feasibility study allowed for the agencies to proceed with a more detailed needs assessment, schematic design efforts, and the development of more detailed budget allocations and phasing plans.

Developing a TMS Plan

A TMS business plan or implementation plan can be used as a roadmap for agencies to follow to establish and link their strategic direction, vision, and goals to the TMS. Planning documents, such as the regional ITS architecture, TSMO strategic plan, ConOps, and operations plan, provide valuable input into an agency's TMS plan. One of the greatest benefits of this exercise is its role in linking ITS programs to regional objectives and funding sources. The contents of a TMS business or implementation plan may vary slightly from agency to agency, but the following elements comprise the five core components of the plan:

1. **Business concept**. It outlines at a high level both existing and desired functions and services of the TMS, including its relationships (both technical and institutional), its role in the regional context, and its operational objectives and goals, and it presents the overall vision for the TMS.

2. **Sets of strategies**. They define the actions and activities required to achieve the vision of the TMS, which could include implementations of new systems, upgrades or enhancements to existing systems, and integration activities. Additionally, these sets of strategies identify the implementation timeframe and responsibilities related to these actions.

3. **Value proposition/benefit**. It outlines the anticipated benefits resulting from the achievement of the goals and objectives identified in the business concept. This component is critical for the TMC plan for the purposes of garnering support from key decisionmakers, leaders, and partnering agencies.

4. **Organization and management structure**. This component defines the roles and responsibilities of partner agencies. It includes identifying the owners, managers, and participants in TMS activities and operations. Furthermore, it documents the organization of the TMC, including personnel and staffing. The TMS' relationship to other agencies and the relationships within the agency that owns the TMS are defined within this element as well.

5. **Financial plan and funding strategy**. It covers the budget for capital expenses and operations and management costs for the TMS. This component includes the discussion of timeframes for expenditures, potential funding sources, and strategies for working within regional funding and programming processes. It also covers the procurement issues and requirements.

Business Processes Should Be Considered When Planning For a TMS

When developing a TMS plan, it is important to determine whether a system that relates to the system planning goals and objectives already exists, and if so, what components may be available from the original design upon which the plan can build or improve. The TMS plan can be used to align with other agency plans—such as an MTP or TSMO plan—and build from already established regional transportation goals, investment and funding packages, and stakeholder relationships.

TMC's Role in TMSs

As mentioned in chapter 1, a TMC is a key element of a TMS. The TMC generally houses key subsystems of a TMS. Operations staff that control, manage, and monitor the TMS are located in the TMC. Key functions of a TMS—such as detecting and verifying incidents, monitoring roadways, and analyzing data—are carried out at the TMC. When planning for a TMC, agencies should consider the need for a TMC, whether the TMC needs to be physical or virtual, and whether it needs to be monitored at one physical location or can be distributed or operated remotely. Consideration also should be given to a full range of systems and functions outside a TMS that should be incorporated in the TMC.

TMC operators and managers have a firsthand experience on the huge impact that incidents have on the performance of TMSs that individuals outside of the TMC may not consider. TMC staff can provide input into the operational planning for the TMS, including integration with established regional ITS architectures and ITS strategic plans. TMC staff can provide valuable TIM perspectives when planning for TMSs. The TMC can also play a key role in the development of operations plans, maintenance plans, TIM programs, and other documents that will be used for a TMS.

High-Level Issues to Consider

High-level issues that should be considered when planning for a TMS are applicable institutional policies and regulations and the feasibility of increasing operations personnel. These issues should be identified and resolved before taking the next step toward designing the system. The stakeholder engagement activities around the preparation of the ConOps document during systems engineering may be the appropriate place to uncover and come to a consensus on any future challenges that may arise in implementing the TMS.

Legal issues may pose potential challenges to planning TMSs or operational strategies. For example, VSLs may have legal and enforcement implications. When implementing a variable speed display subsystem, the agency should understand the laws and policies within the region and its impact on the operation of their strategy. In the case of VSLs, the agency should assess the legal authority to establish and enforce VSLs, as well as the willingness of enforcement entities to support the subsystem. Policies and regulations vary by location and can impact the operations of a VSL subsystem. For example, regulations in Missouri presented an operational challenge for MoDOT by restricting their deployed VSL subsystem from displaying speeds below the minimum posted speed limit within that area. If VSLs are not allowed in a State, a variable speed advisory subsystem may be equally effective.

The complex nature of actively operating TMSs may pose an additional challenge to implementing TMSs or subsystems. Agencies may need additional staffing to ensure successful implementation of a TMS or an operational strategy. One example of this need can be seen in the operations of dynamic part-time shoulder use. Additional law enforcement and patrol vehicles may be used to ensure timely incident response and verification when the shoulder lane is open to traffic. Furthermore, additional operators and staff are needed to monitor the facility (usually through the use of CCTV cameras) to ensure that the part-time shoulder lane is free of blockages from incidents and debris that will impact the performance of the system.

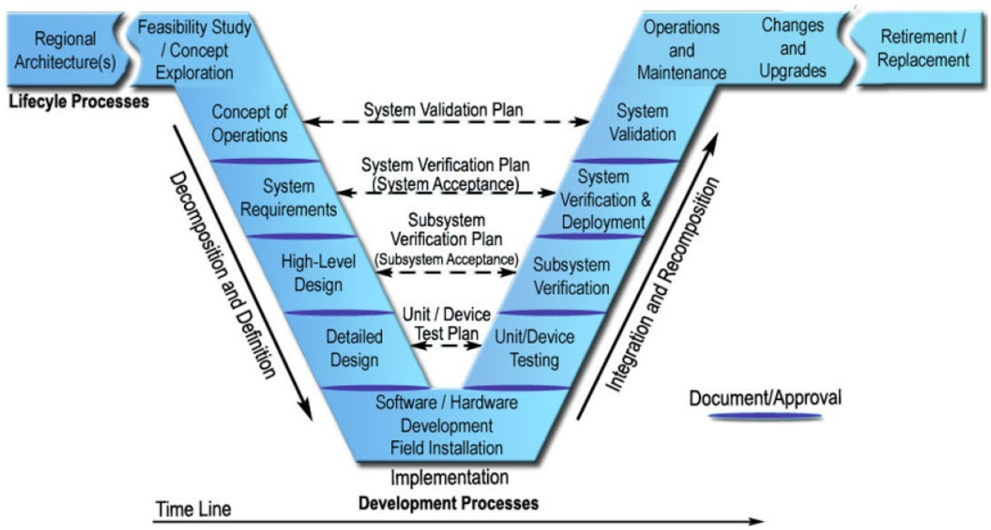
DEVELOPING A TMS PROJECT

After a TMS plan is in place, the next step is to develop a project or set of projects to implement the plan. Specific steps in developing a project or set of projects are needed to further develop what the system will do and how it will perform. Project development includes the systems engineering process, including developing the concept of the system, identifying system requirements, and creating the design process. Project development also includes obtaining resources needed to design, develop, implement, and initiate operation and pursuing a procurement method that supports the development. Agencies can refer to planning documents, such as long-range scenario planning, or previously conducted feasibility studies that may have incorporated an assessment of their current systems, as covered in the previous section for guidance on the established development progression. Agencies can refer to an already established process to develop the TMS and to determine which physical system elements, such as other subsystems and the necessary components, to procure.

Procurement methods may differ from what is procured for design services versus what is procured for development and deployment of ITS-based systems. Agencies have options to mix and match procurement methods. Agencies should be aware of challenges and issues when assessing their ability to procure services, such as nonengineering or professional, or to maintain components with different procurement practices. Agencies should weigh the benefits of these options when making the appropriate selections for back-end software systems, including using open-source or commercial off-the-shelf products against choosing a proprietary or in-house designed software package, or maybe even considering integrating aspects of both. Procurement methods are discussed in more detail in the following section.

The "Development" Portion of the Systems Engineering Process

When ITS components are included in a TMS, the systems engineering process should be applied.(34) The systems engineering process can be best conceptualized by the "V diagram," which visually addresses the lifecycle of an engineered system. Figure 10 presents the "V diagram." This model is one of several systems engineering models that are effective in systems engineering analysis, depending on the characteristics of the project and TMS being evaluated.



Source: FHWA.

Figure 10. Diagram. Systems engineering "V" diagram.[(34)]

Three critical steps in the systems engineering process support project development:

1. **Regional architecture**. For ITS-related projects, agencies develop regional ITS architectures to support the region's objectives and transportation planning. Regional ITS architectures act as a framework that outlines existing and planned operational transportation systems in a particular region and how they interact with one another and how they should be integrated. Regional ITS architectures enable agencies to efficiently plan for transportation systems by organizing their existing transportation operation systems at a high level, piecing together how new systems may fit in, revealing how data may flow among the different systems, identifying services those systems can provide together, and displaying how those systems support agency goals. Many regions and agencies develop an ITS strategic plan to complement a regional ITS architecture. The ITS strategic plan is sometimes known as the ITS deployment plan, which includes priorities and strategies regarding the research, development, and adaptation of technology-based transportation systems. The ITS architecture is developed before the TMS plan is developed and provides key inputs to the following steps of the systems engineering process and the project development process:

    a. Identifies regional integration needs.

    b. Indicates needed interfaces and how the target TMS will operate with other systems.

    c. Identifies standards that will ensure interoperability and be useful in the design and procurement processes.

    d. Enables disparate systems from multiple systems to work together.

2. **Feasibility study**. A feasibility study may also be undertaken before a TMS project is identified. It may be the first step in the planning process, or it may be the first step in the project development process. The feasibility study is a stand-alone document that presents a business case for the potential deployment of a TMS. This process assesses the technical, economic, and political feasibility of the TMS while presenting alternative TMS concepts that meet the project's purpose and need.

3. **ConOps**. This document describes how a system will be used and identifies the fundamental needs of all stakeholders involved throughout the lifecycle of a system. It also considers different use cases or scenarios for how the system will operate. A ConOps is essential to success because it serves as the repository of needs and helps ensure that all aspects of the system lifecycle—from design, implementation, maintenance, and upgrades—support those needs. The ConOps allows for stakeholders to understand how the system is to be developed, maintained, and operated. It also identifies users and system capabilities in an easy-to-understand format.

If following the traditional systems engineering "V diagram," the ConOps document sets up the foundation for the development and design of the TMS. It is important that this exercise ties back to the vision, goals, and measures of this foundation. Once the ConOps document has been developed, requirements for the system need to be defined. The requirements lay out the groundwork for the development of the technological components of a TMS and include both functional requirements (i.e., what the system is supposed to do) and performance requirements (i.e., how well the system carries out its functions). Proper alignment with the vision and measures early in the document should allow for later connectivity as the requirements phase of the ConOps is developed.

System Requirements

The requirements development step is important because an agency uses these requirements to communicate what the system should do. Requirements serve as a reference point to verify that the system was built correctly. An agency also should establish environmental and nonfunctional requirements that define under what conditions the system is required to function to meet performance goals.

Identifying system requirements can be at the discrete component level or at a higher level that can encompass certain systems, such as virtual TMSs, active TMSs, temporary TMSs, testing programs, and procedures.

The example in the callout box shows what functional requirements can look like when developing a TMS. Functional requirements define what the system should do; therefore, developing these requirements early in the process can help all stakeholders clearly understand how the system will operate in its environment. The Maryland DOT (MDOT) State Highway Administration (SHA) Coordinated Highway Action Response Team (CHART) manages and operates both freeway and surface street TMSs in the State. One function of their TMS is to generate reports summarizing the data collected from their subsystems. The excerpt in the callout box provides a snippet of a few system requirements for the report generation function.

CHART II System Requirements Excerpt

3.1.4 Report Generation. This section lists requirements for the generation of reports from the CHART system and archive data.

3.1.4.1 The system shall provide the capability to generate reports from online and archived data.

3.1.4.2 The system shall support the generation of operational reports.

3.1.4.2.1 The system shall support the generation of center situation reports.

3.1.4.2.2 The system shall support the generation of disabled vehicle event reports.

3.1.4.2.3 The system shall support the generation of incident event reports.

3.1.4.2.4 The system shall support the generation of traffic volume reports.

Following the establishment of the system requirements are the system design phases. The design phases are broken out into the "high-level design" phase followed by the "detailed design" phase, and both phases are critical steps in the development of an engineered system. In the high-level design phase, the overall system framework is defined, including subsystems and components. For a TMS, this phase includes the process of defining software, components, and interfaces. During the detailed design phase, specifications of the software, hardware, and communication components are defined. These specifications detail how the components will be developed to meet the system requirements defined in the prior phases.

High-Level Design Phase

During the high-level design phase, one key consideration designers need to account for is whether to purchase, reuse, or develop system software from scratch. The specific project may prefer the purchase of certain off-the-shelf software or hardware, or the purchase may be required due to the unique aspects of the project or system. Some projects have design constraints that require using a specific product. For example, an agency is expanding its TSP subsystem to cover more key transit corridors. Their existing subsystem includes existing detection components that communicate with proprietary central control software to implement the TSP strategy. This specific subsystem design constraint requires the agency purchase components that have interoperability with the in-place central software. The results of the high-level design phase include identifying subsystem components and their relationships, describing the subsystem behavior, identifying the subsystem interfaces, describing the standards to be used, and defining the information that will be managed by the subsystem, integration plans, verification plans, and subsystem acceptance plans.

When developing an active TMS, such as a variable speed display system, the system design components can be broken down into two primary categories: civil and technology elements.

Core civil design elements specific to variable speed display include overhead gantry and/or side-mounted signs and static signage. Other TMSs may have other civil design elements, such as roadway geometry elements, pavement markings, emergency pull-off areas, etc. Core technology design elements specific to variable speed displays include the control software, detection components, CCTV cameras, communication hardware, and DMS (to display speeds and to inform drivers why they should slow down). Other technology design elements that may be applicable to other TMSs include signal controllers, controller upgrades; access control subsystems (e.g., subsystem to prevent wrong-way movements), overhead warning beacons, and other implements.

As with other ITS-based systems, the communications subsystem and central equipment located at a central operations center to control the field components are also technology design elements that need to be defined. Central equipment and communication components may include servers, hardware racks, local networks, and communication media that interconnect hardware components. Communication media include fiber-optic cables, wireless radio links, cellular links, and other communication lines.

Detailed Design Phase

During the detailed design phase, hardware and software specialists develop the detailed design for the subsystems and components identified from the high-level design phase. The results of this phase include hardware and software designed for the system components to support development and/or off-the-shelf product procurement, component verification plans, and technical review documentation. A TMS should be able to operate with high levels of automation. A critical component of the design phase is to assess the capabilities of the existing software to operate the new TMS and evaluate the potential required modifications.

Once the design phases conclude, software and hardware developments take place based on the components identified in the design phases. The developments may include procuring off-the-shelf items and/or building custom software.

Developing Specialized Systems—A Virtual TMS

The following callout box describes some of the items that should be considered when developing a specialized system, in this case, a virtual TMS.

Developing a Virtual Traffic Management System

When developing a specialized system, such as a virtual TMS, guidelines and processes for developing a typical TMS (e.g., centralized TMS) are similar. Some of these similar processes include performing a needs assessment, developing a ConOps, preparing security design, developing a communications framework, establishing standard operating procedures (SOPs), creating a training plan, performing risk assessment, and other activities. Due to the inherent nature of a virtual TMS, extra emphasis should be placed on preparing a system security design and developing a communications framework.

A virtual TMS has unique security challenges created by a lack of a physical control facility, complex multilocation architecture, user mobility, and requirements to deploy a variety of subsystems and applications. Therefore, virtual TMS developers need to consider layered security methods, such as deploying network and applications firewalls, using technology that detects and responds to threats in an adaptive manner, establishing specialized firewall functionality to protect critical devices within the virtual TMS, and protecting mobile devices that are on external networks.

Developing an effective communications subsystem can be challenging for a virtual TMS. With advancements in communications technology, this challenge can be overcome. TMCs are used as the central hub for communications with ITS field components. The challenge for a virtual TMS, which lacks a physical control hub to communicate with field components, is that most existing communication subsystems have been designed with a traditional physical TMC as the heart of the system. Agencies have several options to facilitate communications within a virtual TMS with a physical field component:

- Establishing a hosted TMS model using hosted services.
- Modifying an existing communications subsystem to enable communications from a virtual position.
- Establishing a center-to-field communications hub where virtual communications can be established using secure communications (e.g., firewalls, VPN).

Incorporating TIM in a TMS

How the system fits into an agency's TIM program should be considered when developing a TMS. One of the primary goals of a TMS is to regulate traffic flow in an efficient and safe manner, and an incident can have adverse impacts on reaching that goal. The management of incidents goes hand-in-hand with the management of traffic. A TMS that is impacted by incidents to a larger degree compared to others is a TMS that is focused on implementing the dynamic managed lane operational strategy. TMSs that implement dynamically priced managed lanes are typically operated by a TMC and are uniquely affected by incidents from a financial standpoint because such incidents will likely result in revenue loss if tolls are suspended or if the facility must be closed. Additionally, the method of separating the managed lanes from general-purpose lanes can pose a unique challenge for TIM because some facilities use physical barriers that can limit access for responders. Other managed lane implementations may use flexible posts, moveable barriers, or simply dedicated pavement marking that will not be as physically limiting for incident responders. The use of ITS to detect congestion and incidents is especially critical in the development of a TMS that implements managed lanes. As such, managed lane facilities operated by a TMC will typically have robust technologies and communication capabilities to detect incidents and disseminate information.

Outside of the technical considerations, special considerations exist that are involved with the development of a TMS to support the interaction of two strategies, such as TIM and managed lanes for example. TMSs that implement dynamic managed lanes should include agency policy considerations, especially when also accounting for TIM. A TMS that implements dynamic managed lanes is a great example because TIM and robust technology and communication capabilities are integral parts of that system. The capability to detect incidents and deficiencies in performance will enhance interagency coordination and data sharing. When developing a TMS that implements dynamic managed lanes, data-sharing agreements and communication protocols should be established for both normal traffic management and incident management situations. These agreements should include applicable transportation operating agencies in addition to incident response and enforcement agencies, and the roles and responsibilities of each participating agency should be clearly defined with points of contact established for both planning and operating matters. These protocols will enable effective coordination, data sharing, TIM, and general traffic management.

IMPLEMENTING A TMS

The previous sections covered the preliminary phases of planning, developing, and designing a TMS. The next phase is implementing or deploying a TMS. Successful deployment is dependent on the design, development, testing, acceptance, and startup required leading up to this phase. Agencies have utilized many different project delivery methods to deploy their TMS projects. Some examples of different project delivery methods that could be used for TMS projects are summarized in table 2.

Table 2. Project delivery methods.

Delivery Methods	Pros	Cons
DBB	Allows the owner to control the quality of the design and construction of the project.	Longer delivery schedule compared to DB since construction must occur after design has been completed.
DB	Project is developed from the start to meet both design and budget needs. The contractor's cost and pricing are transparent.	Expectations must be clearly communicated through a Request for Proposals.
Design-build-operate-maintain	Method includes integrated procurement through a single contract, therefore, increasing efficiency.	Owner does not have as much control of the project compared to the traditional DBB method.

Delivery Methods	Pros	Cons
Construction management at risk	Beneficial when transportation improvements are needed in a timely manner as construction elements can be accelerated.	Can be costly to the owner.
Public–private partnership	Provides alternative funding sources.	Proposal process is expensive.

DB = design-build; DBB = design-bid-build.

Each project delivery method will have its advantages and disadvantages, and the most effective method will vary with each project.

Effective Practices in Implementing TMSs

Regardless of the project delivery method, early and continuous attention to coordination, scheduling, and risk management during the implementation phase are considered effective practice. The following recommendations exemplify effective practices:

- The contractor should take a leading role in fostering collaboration among the stakeholders. Coordination efforts should be reflected in the project schedule to ensure that it has high priority in the implementation process. Consideration should be given to forming a committee to maintain information sharing, risk management, and outreach and to resolve any issues during construction if such a committee does not already exist. Note: There may be existing committees—such as ITS, transportation demand management, and incident management committees—that can be leveraged to facilitate coordination efforts for TMS implementation.

- Effective scheduling is critical for a successful rollout of a TMS, as with any other project. When implementing a more complex system, such as ones that deploy ATM strategies (which tend to have more civil components compared to a typical ITS project), daily operations of the existing facility can be affected by delays in the civil improvements required by the system. Effective practice for scheduling should include coordination to address issues, systems operations and maintenance training within the schedule, SOPs development, education and outreach; and timely integration of software integration into operations (including testing, debugging, and training). For example, an agency implementing dynamic part-time shoulder use lanes may require modifications to the facility's geometric properties, pavement markings, and static signage. Delays in these changes may directly impact the agency's ability to maintain existing operation of the facility. Therefore, schedule adherence and risk monitoring should be priorities when implementing solutions that are inherently more complex, such as ATM, than traditional transportation projects.

- Effective risk management practices should include establishing an augmented risk regime (developing documentation that quantifies risks, ranking the probability of risk occurrence, and assessing the effects of risk occurrence); developing a risk response plan; performing risk analysis; and ensuring that the risk management plan is revisited and updated throughout the project implementation process.

Stakeholder Engagement During TMS Implementation

During the planning phases, stakeholder engagement and public outreach are important to educate the intended audiences on the basic concepts of a new TMS. This helps to build confidence in investments and garners support for the implementation of these systems. Gaining stakeholder and public support will help to ensure that an agency's TMS deployment occurs successfully. During TMS deployment and implementation, smaller working groups can be established to provide opportunities for input and participation and to generally keep agency stakeholders informed on current progress. If involved stakeholders have a common understanding of the purposes, objectives, and benefits of a new TMS, they can do a better job of educating the public to gain their support.

Effective Practice: Stakeholder Engagement

Stakeholder engagement is extremely important to ensure successful implementation of a TMS. The Wyoming DOT (WYDOT) developed a VSL subsystem along a stretch of the I–80 corridor in 2009.(35) This subsystem was implemented to address weather-related closures and to reduce speeds during inclement weather conditions. The subsystem comprises cameras and road and wind sensors to monitor visibility and weather conditions along the corridor. Additionally, a weather station is placed in the middle of the project corridor to collect atmospheric conditions data, and pavement sensors are used to monitor vehicle speeds along the highway. Operators in the TMC control the speed displayed on the VSL signs based on the visibility, surface conditions, current vehicle speeds, and roadway and weather conditions reported from the detection components. Engineers and Wyoming highway patrol have the authority to lower the speed limits. No requirements exist on how often the speeds can be changed or how long the modified speeds must be displayed.

Stakeholder engagement and public outreach were major elements in the successful rollout of the WYDOT VSL subsystem. WYDOT used a variety of outreach methods and communication avenues to spread information about the project, ranging from press releases to frequently asked question documentation and educational videos. Due to the nature of their subsystem, WYDOT had to make sure that their subsystem would fit within the existing legal and policy framework relating to speed limits and enforcement. WYDOT was proactive in their engagement with policy decisionmakers and law enforcement agencies to get their support and buy-in for the authority to modify speed limits within the corridor.

Lessons Learned from TMS Implementation

In recent years, agencies that have deployed advanced TMSs have learned about the importance of sharing lessons learned. The following callout box lists a few lessons learned from other agency TMS deployments; for additional resources documenting lessons learned, refer to the National Operations Center of Excellence Knowledge Center.(36)

Develop a strong system acceptance testing program.

Developing a strong system provides reassurance that existing or new TMS components will meet intended functional requirements; and for TMSs that have a software elements, the system acceptance would include system support documentation.

Establish a clear, specific vision of the functional objectives of the TMS, and communicate that vision throughout the project.

Establishing a clear vision minimizes potential confusion and is especially important when a TMS involves a partnership of agencies and other jurisdictional stakeholders.

Strong public outreach and awareness efforts in both pre- and postimplementation.

Establishing strong public outreach and awareness primarily helps to promote the TMS system and its benefits and to educate travelers on the proper usage of the new system and gain public acceptance.

In 2017, the Minnesota DOT (MnDOT) developed an active QW subsystem along their I–94 and I–35 West corridors.[37] The subsystem's purpose was to detect traffic conditions that may result in higher risks for crashes and send warning messages to upstream drivers to increase their awareness and potentially decrease the frequency of crashes. The system was developed to interface with the existing ATM subsystems already operating within the area. Prior to full implementation, the subsystem was thoroughly tested and validated to ensure it functioned properly. MnDOT also facilitated a broad range of outreach techniques, including group presentations, workshops, forums, individual meetings, advertisements, newsletters, and emails to inform travelers and policymakers on the new subsystem. Agencies that had successful outreach efforts realized that messages about safety benefits resonated more than technical terminology, such as speed harmonization benefits. Additionally, reviewing outreach information regarding the successful implementation of related projects can lay the foundation for future projects.

CHAPTER 5. ASSESSING AND REPORTING ON TMS CAPABILITIES AND PERFORMANCE

The previous chapter presented processes associated with planning, developing, and implementing a TMS. This chapter builds on the previous chapter and discusses operational goals, objectives, and current practices to define, assess, and continually improve system performance. This chapter also addresses monitoring and reporting TMS performance and provides examples of effective practices. By reviewing information provided in this chapter on what agencies have developed in the past regarding performance monitoring and reporting, agencies can examine the challenges and best practices that are most relatable to their systems and organization.

Some of the key issues covered in this chapter include gaps in system coverage, data latency, costs, jurisdictional stovepipes, data from multiple sources, and real-time data incorporation. The availability and condition of an agency's physical assets—that is, whether they are working correctly—are especially important.

This chapter also summarizes the challenges agencies are facing with assessing, benchmarking, and determining how this information can support exploring options to improve TMS performance; documenting how it supports the traffic operations program and/or business; and identifying opportunities provided by evolving technologies and methods.

Chapter 4 discussed how agencies can assess the capabilities and performance of their current system, document the results, and explore options to improve performance. This chapter builds on that knowledge to support the system performance monitoring, evaluation, and reporting topics. Performance reporting can serve as a benchmark for future TMS performance monitoring and assist in guiding an agency's operational objectives for systemwide performance. This discussion supports chapter 6 on what agencies should consider when assessing the feasibility of expanding, enhancing, and improving their current TMS.

SYSTEM MONITORING AND PERFORMANCE MEASUREMENT

Performance monitoring is important as agencies recognize the importance of using a suite of strategies to achieve safety and mobility goals. The emphasis on implementing a combination of strategies increased the importance of reporting metrics on travel reliability, incident response rate, and other areas that are of interest to the public. Performance monitoring activities are highly important for the successful implementation of TMS operational strategies to achieve agency goals and objectives. In addition to the benefits of monitoring and measuring performance, there also are common challenges, such as the lack of comprehensive real-time system data that span the entire roadway network and the need to collect and manage data in a way that allows them to be easily accessed for performance measurement activities.

Furthermore, performance measures can be used to support future planning efforts. The process of performance measurement allows agencies to collect and evaluate data about their systems with the purpose of measuring progress toward specific goals. These goals typically relate to improving safety, increasing efficiency, and meeting customer expectations. Performance measurement aims to answer the following questions:

- Are transportation goals being met?
- Are resources being used efficiently?
- How well are roadways being managed and operated?
- Are there areas where efforts for improvements can be focused?
- Are data being used effectively for decisionmaking?
- Are there any trends to note?
- Are the customers/travelers satisfied?

When operational objectives are well defined, agencies can target specific performance measures that fit those objectives, and resource requirements can be effectively allocated. Agency business processes need to be developed to a level of detail that accommodates efficient and effective system monitoring and performance assessment.

When looking at traffic signal control subsystems, many agencies today are well experienced in designing detector layouts based on various operational use cases. However, for some agencies, designing detection layouts for data collection, system monitoring, and performance measurement may be a relatively new idea, and there may be a gap in institutional knowledge of effective designs for such purposes. For example, an agency desires to have stop bar occupancy data collected, but their signalized intersections are only equipped with advanced detection for the purposes of dilemma zone protection. In this case, the agency's business processes should prioritize new detector layouts so that resources can be allocated for the installation of stop bar detection and data visualization for performance measurement.

Data Collection

Many agencies use traditional system components to monitor their system, such as CCTV cameras, traffic detectors, and environmental sensors. By using these traditional components, agencies can detect and respond to traffic incidents, traffic congestion, and weather conditions after they occur. Agencies often obtain information on incidents through 911 calls or crowdsourcing. Some agencies have been successful with using automated incident detection algorithms, in conjunction with surveillance cameras, for specific situations; however, to date, this method has not been widely deployed.

Monitoring a transportation system is not limited to collecting traffic flow data; weather and work zone data can also support an agency in monitoring their facilities. Road weather sensors, temperature data probe sensors, and visibility sensors are some of the components used to monitor weather data associated with the transportation system. Work zone data can be obtained with portable ITS components that monitor traffic conditions during construction that can be redeployed as the work zone configuration changes.

Asset inventory and asset management also factor into data collection. Including asset performance and condition in the overall assessment of a TMS is important. Some of the asset information needed includes the system's inventory, status, configuration, lifecycle, and repair or replacement history.

Historically, most traffic signal controllers were only capable of providing volume and occupancy data. External advanced control applications were required to obtain data at a more detailed level. With improved technology, high-resolution signal event data have become more common, and more signal controllers are capable of collecting and storing these data.

Agencies have begun incorporating nontraditional, but emerging, technology-based data collection methods by using probe vehicles and roadside technology capable of component identification, such as wireless technology and wireless local area network readers. These means of data collection enable agencies to collect travel time data along a corridor to support system-level performance evaluation with acceptable latency.

Data Processing

Once data are collected, they need to be processed and archived. Raw and unprocessed data need to be aggregated, cleaned (i.e., removing outliers and bad data), and translated into a usable format that describes the current conditions of the facility. For example, an agency installs a series of wireless local area network detectors along a corridor to monitor congestion using travel times. The sensors detect the presence of mobile devices carried by travelers. They can collect and store the unique identification tag (media access control address) of wireless local area network-enabled mobile devices, the location of the detections, and the time of detection. Agencies need to convert these raw data into travel times before they become useful. To convert the data, agencies match identification tags at various locations and then use the time the mobile devices were detected and the distance between detections to calculate travel times. Additionally, small sample sizes can often be an issue during periods of low traffic volumes. Processing the data can involve filling in gaps where information is lacking and checking for potential errors in the data. For monitoring corridor congestion, and especially for assessing system performance, the unprocessed data are generally insufficient. With the processed data, and sometimes combined with other surveillance/verification methods, transportation agencies can more effectively assess system performance.

Data Management

Archiving allows agencies to revisit the collected data, query the data, and develop historic trends regarding system performance. Traditionally, agencies access archived historic data to inform current TMS operations based on past performance. For example, agencies would use historic data to determine that congestion typically occurs at a certain time of day and use that data to inform the implementation of ramp metering strategies to control traffic flow. As agencies begin to shift their focus more toward actively managing their TMSs, the use of real-time data becomes more prevalent in operations. The use of historic and real-time data, in conjunction with modeling tools, is an emerging practice that enables future traffic conditions to be forecasted. By forecasting future traffic conditions, agencies can proactively manage traffic by modifying system operations and strategies before a breakdown occurs.

Challenges to Successful Performance Monitoring

As agencies shift their focus from monitoring and advising toward more active management of their systems, they must overcome challenges that are rooted in establishing and maintaining real-time monitoring processes. The lack of real-time monitoring can hinder advancements toward optimal active management practices. The following callout box highlights five primary challenges facing agencies that use real-time monitoring.

1. **Handling gaps in coverage**: Freeways are typically monitored at spaced intervals in urban regions, resulting in potential gaps in between sensors.
2. **Addressing latency in data collection**: Jurisdictional issues, staffing limitations, and data latencies mean that agencies typically react after congestion has already formed; and sometimes they react after secondary incidents have occurred.
3. **Building out and maintaining field devices and assets/costs to build out and maintain field equipment**:
    a. Assessing build out costs.
    b. Managing the assets overall.
    c. Obtaining field components, such as roadway sensors and CCTV cameras, which are costly to procure and maintain, resulting in significant gaps in geographic coverage and inconsistent functionality.
4. **Consolidating data from multiple sources**: Obtaining data from multiple sources can be challenging due to format differences, nonuniformity in geographical and temporal granularity of data, different data schema used by participating agencies, and methods of addressing multimodality of trips.
5. **Linking real-time data to modeling tools**: Combining historic and real-time data in modeling tools requires the resources skilled enough to develop the model and incorporate nontraditional data, such as weather and incidents into the model.

These challenges reduce an agency's ability to operate the system efficiently and in a cost-effective manner. For example, an incident occurs on a parallel arterial, causing backups onto the freeway. In most cases, the State DOT will not be aware of the issue until the backup reaches the freeway. At this point, it is typically too late to take the most effective corrective actions. As technology continues to grow and broader forms of data emerge, this challenge becomes more prevalent. By using historic and real-time data, combined with modeling tools, agencies can simulate future conditions to proactively manage traffic before congestion occurs.

Effective Practices

Agencies should make a significant effort to prioritize performance monitoring needs, focusing on needs that are current and near term that will attract the attention of decisionmakers. Identifying near-term monitoring needs is one key effective practice for TMS performance monitoring that enables agencies to prioritize the desired functions of their system. One example is when senior management or decisionmakers consistently send requests regarding a specific type of data at certain locations. Prioritizing these key specific needs will help make an agency's monitoring efforts more useful in the near-term. Often, the focus on long-term needs can be daunting for agencies as they try to achieve their goals for an optimal system, especially those agencies in their infant stages of monitoring. Agencies do not need to have a perfect and comprehensive data collection and monitoring subsystem to produce useful results. By focusing more on near-term needs, agencies can incrementally improve and produce beneficial results on the way toward developing their ideal system.

Detailed and fine-grained data metrics provide more options for assessing system performance. Agencies that do not yet have the capability to collect more fine-grained data should start with what they have and increase their capabilities incrementally, as feasible. Typically, the data agencies are already collecting are a good indicator of what is most important to the agency at that time and are a good starting point. Adding real-time data from multiple sources allow agencies to incorporate additional metrics, build the foundation for predictive algorithms to enable a more proactive response, and ultimately provide a more comprehensive view of the system.

The condition of the TMS assets also should be integrated into the inventory and information collected and compiled for these assets. This includes physical condition (e.g., wear and tear); logical condition (e.g., firmware or software versions); and, for many devices, backhaul communications (e.g., reliability, capability for future enhancements). Once this inventory and condition information are available, an assessment of the remaining lifecycle of the asset and supports future planning for replacements or an assessment of the TMS' capabilities can be conducted.

Agencies need data presented in meaningful, understandable, and useful formats. The collection of aggregated data could come in the form of a dashboard or a data visualization tool that allows the system operator to easily view the conditions of the system. Archiving the collected data is a good practice because it enables agencies to analyze historical trends to make informed future decisions.

ASSESSMENT AND REPORTING

The assessment of the capabilities and performance of the TMS will include a combination of qualitative and quantitative information. Subjectively, any assessment must cover an agency's specific environment—geographical, political, environmental, and financial. Although many of those factors are not typically covered in basic performance management evaluations, considering an agency's specific situation is important.

Objectively, assessing system performance entails analyzing and transforming data into measurable metrics that describe the state of the system and the operational progress toward transportation system objectives. Agencies can then report notable trends in the data by using emerging technologies and visualization methods. This information allows agencies to make informed decisions to improve or enhance system performance and to identify any issues that might result in inefficient system performance.

Performance metrics can be investment oriented or outcome oriented. Investment-oriented performance metrics are centered around the resources spent on the system. The resources could include staff hours, cost of third-party services, or money spent on upgrades. The higher the investment spent, the higher the expectations related to performance of the system. In contrast, outcome-oriented metrics revolve around measuring data related to the results of the system operations. The data are used to evaluate the quality of the service provided by the TMS. As such, the resources spent on maintenance and procurement can be prioritized based on this information.

Assessment: Typical TMS Performance Measures

Agencies should identify and develop performance measures that match TMC objectives to agency and regional goals. The performance measures for a TMS should be developed to support the purpose and context of the TMS. A few examples of typical key performance measures for analyzing functions of a TMS are included in table 3. For a more comprehensive list, refer to the TMC Performance Monitoring, Evaluation, and Reporting Handbook (2005) Web page.(38)

Table 3. Typical TMS performance measures.

TMS Function Category	Performance Metrics
Mobility	• Delay due to congestion. • Vehicle miles traveled by congestion level. • Level of service. • Travel time reliability.
Safety	• Total number of crashes. • Number of secondary crashes. • Construction-related fatalities.
Incident management	• Number of responded crashes versus total number of crashes. • Incident detection rate. • Roadway coverage.
Information dissemination	• Frequency of data sharing. • Extent of real-time information. • Number of agencies that receive information. • Reduced overall travel time.
Asset and configuration management	• Uptime of equipment. • Mean time between failures. • Average downtime for repairs.

The performance measures for any given TMS will be somewhat unique to match the needs the TMS is addressing, its operational strategies and functions, the environment in which it operates, the agency or agencies it serves, and the region it manages.

A TMS and its operational strategies and functions require regular monitoring to identify ways it can more effectively meet overall program goals. The type of data collected to support performance metrics is dependent on the performance measures selected, but it often relates to the availability of quality data and the type of TMS operating environment, such as freeways, surface streets, or integrated multiple facilities. The system's capability to collect the raw data and process those data into a format that can then be analyzed according to the desired performance measures should be considered. The analysis to assess performance may be undertaken by other functions within the agency outside the TMS.

Reporting: Analysis and Performance Reporting

The primary use of the performance assessment results is to identify ways to improve the performance of the TMS. (See chapter 6, Focus on Constantly Improving Operations and Capabilities, and the discussion of the active management cycle.) The performance assessment results should also be used to plan and design other TMSs or the enhancement of the TMS that is the subject of the assessment. The performance assessment results will provide insight into the operational strategies and highlight functions that are performing well and those that need improving. The results can also indicate how the operational strategies could be improved to better meet the objectives of the TMS. The lessons learned from the performance of an existing TMS can be applied to the planning and design of a new TMS or used to enhance the existing TMS.

Performance assessment reports should be designed to fit with the performance assessments of the agency and the region outside the TMS. Reports that are consistent with agency and region performance reporting enable valuable information about the TMS and its performance to be communicated to agency decisionmakers, stakeholders, and the public. Regardless of how the reporting is completed, the results should be clearly and concisely communicated. The frequency of reporting performance assessment results should also be considered. Performance reports should be designed to meet the various uses of performance monitoring, from providing direct feedback to operations staff in realtime, to daily assessments, to trend analyses, to providing one aspect of the performance of an entire agency.

The content and context of a report will depend on its purpose. The information provided should be in a format suitable for the intended audience, whether it is an informal document for internal agency decisionmakers or a formal document intended for external stakeholders or the public. Displaying performance measures in a text format is the simplest and often the least expensive method. In smaller scale use cases or with simpler performance measures, the use of text to display performance measures can be sufficient to convey the information on performance. Some of the challenges to displaying performance measures in a text format include a lack of clarity, conciseness, and effectiveness.

Reports should be presented in a comprehensive manner and should make the best use of visual displays of data that show trends, performance, and interaction between datasets. Graphical representations of performance measures can be achieved through various means, such as using the chart features in spreadsheet software; data visualization application user interfaces; and cloud applications, such as online mapping portals, custom software, or various combinations of software modules. These data visualization software solutions and methods are linked with new challenges, such as higher costs, steeper learning curves, more difficult implementation, and potential compatibility issues with existing data systems. Some software solutions to data visualization can be intensive in terms of software development or license fees, resulting in higher costs. However, the benefits typically outweigh the costs as graphical interpretations of performance measures are more accessible to a wider range of people because the data are portrayed in a way that is both interesting and easily understandable. Relevant and easy-to-understand graphics are more likely to be shared, thereby reaching a wider audience.

If performance reporting is developed as a Web-based application, multiple users can access the information from different locations. When Web-based reporting incorporates interactive graphical representations, whereby the viewer can choose to overlay trends or manipulate time periods, more complex data messages can be communicated.

An increasing number of agencies is reporting on system performance in realtime by collecting and analyzing data using methodologies that have no latency in data output, such as a dashboard or a data metric visualization tool, and providing TMC operators with the information they need to make decisions in a timely manner.

Challenges to Successful Reporting

The primary challenges that agencies might encounter when assessing and reporting on the performance of their transportation systems include:

- **Availability of data.** The presence and absence of required data and lack of real-time data and data analytics are limitations to both system monitoring and assessment. The ongoing and systematic collection of both automated and manual data can be resource intensive.

- **Completeness of data.** If data collection results in missing data elements or if a particular data measurement is not collected properly, performing an analysis and the concluding results would be incomplete or misleading.

- **Quality of data.** Data collected from unreliable and faulty equipment can produce poor-quality data, causing agencies to work with an inaccurate view of the system performance. Sustaining a robust maintenance system for essential TMS components and establishing a data validation process are important. Data collected from a single source, a small number of components, or collected infrequently will result in a low quantity of data and subsequent performance measures that might provide an inaccurate view of a system's performance. The data collection equipment might be working but not working correctly. As we begin to use more sophisticated data collection tools, a simple "heartbeat" of the equipment is not enough. It is necessary to know whether the equipment is transmitting "good data" that can be used or data that could be useless.

- **Limited data fusion.** Incomplete or inadequate data fusion activities result in a one-dimensional approach to assessing system performance. This challenge may reflect a lack of resources to monitor the system comprehensively or limited multijurisdictional coordination. Data fusion allows an agency to review the state of the system from the perspective of different modes and/or different jurisdictions, depending on the data sources. If a State DOT only assesses the system using freeway loop data stations, the agency cannot get a clear view of the entire transportation ecosystem. For example, coordination with a transit agency allows the State DOT to account for transit vehicle performance and its impacts on the system in conjunction with loop data performance measures.

- **Standardization of measurement techniques.** Definitions of the same data, as well as units of the data collected, may be different from one agency to another. Standardizing the uniformity of data collection among agencies and within regions can promote data sharing and future data comparisons of the same metrics.

- **Presentation of performance data.** Determining the most effective way of presenting particular performance measures in a way that is understandable, with the appropriate amount of detail, to the right audience is a challenge. In general, data presented to external agencies and the public should follow the golden rule of "less is more," whereas internal agency decisionmakers and operations staff prefer to see detailed charts, tables, and figures with greater amounts of information.

Effective Practices

According to the *Handbook for Developing a TMC Operations Manual*, agencies that are proficient in their performance measurement process generally perform the following steps.(39) (Note: This process is an iterative one that agencies must refine to best suit their needs.):(39)

- Identify the critical activity.
- Identify the goals and objectives of the activity.
- Identify and develop a set of performance measures that relate to the goals and objectives.
- Establish performance targets that meet those goals and objectives.
- Identify the uses of the performance measures and who comprises the audience of those measures.

- Identify the data needed to calculate the performance measures, including the analytical tools required.
- Establish the data collection and evaluation procedures.
- Establish procedures for ensuring data collection methods produce "good data."
- Evaluate the performance measures in comparison to the performance targets.
- Determine corrective actions or progress needed to achieve the targets.
- Determine performance metrics reporting or presentation formats.

The measures and metrics are at the center of this process. An agency can select from thousands of potential measures that their TMS can use to assess performance. Agencies will want to select the measures that can effectively gauge the progress toward their goals based on their current resources. If the identified measures are able to assess current progress well, but the agency does not have the capacity to continuously collect and analyze the data, those measures are not effective. A good measure typically has five main traits:

1. Be realistic with respect to the capacity and resources of the agency. If the required data are expensive to collect and analyze, the measure is likely to be unsuccessful.

2. Measure the correct item, such that it focuses on defined goals and objectives set by the agency. Performance measures can apply to areas outside operations as well.

3. Be mindful that the presentation of the information should ultimately be simple, understandable, and meaningful to the customer. Changing the measure to be more tailored toward different audiences may be more effective.

4. Be responsive to changing conditions. A performance measure that does not accurately capture events or major changes cannot adequately show progress toward goals.

5. Be appropriate for the timeframe and location of the TMS. The geographic extent of the TMS may dictate what is an appropriate measure.

Agencies with successful performance measurement programs embrace several effective practices. The following effective practices are not meant to be rigid; they are more general guidelines that have worked well for agencies in the past:

- Keep the number of measures manageable. Agencies that are successful with the performance measure tend to focus on the most significant measures, and they do not include measures just because they seem interesting. For agencies that have limited resources or are just starting to assess and report on performance metrics, this approach could mean starting with what they can report and incrementally adding more measures as capacity allows.

- Be flexible. To find the measures that are most significant, an agency should not refrain from testing new measures to find the set of measures that are most appropriate or to drop measures that turn out to be hard to collect/analyze/output.

- Go beyond the basic sets of measures. Although simplicity is often desirable, the more difficult issues may require measures that are more complex. Recognizing this necessity may help an agency grow and provide better service to the customers.

- Use a balance of measures. The measures being assessed should include the broad range of responsibilities and tasks performed by an agency. Additionally, an agency may have a wide range of audiences, which can dictate which of the measures are the most effective.

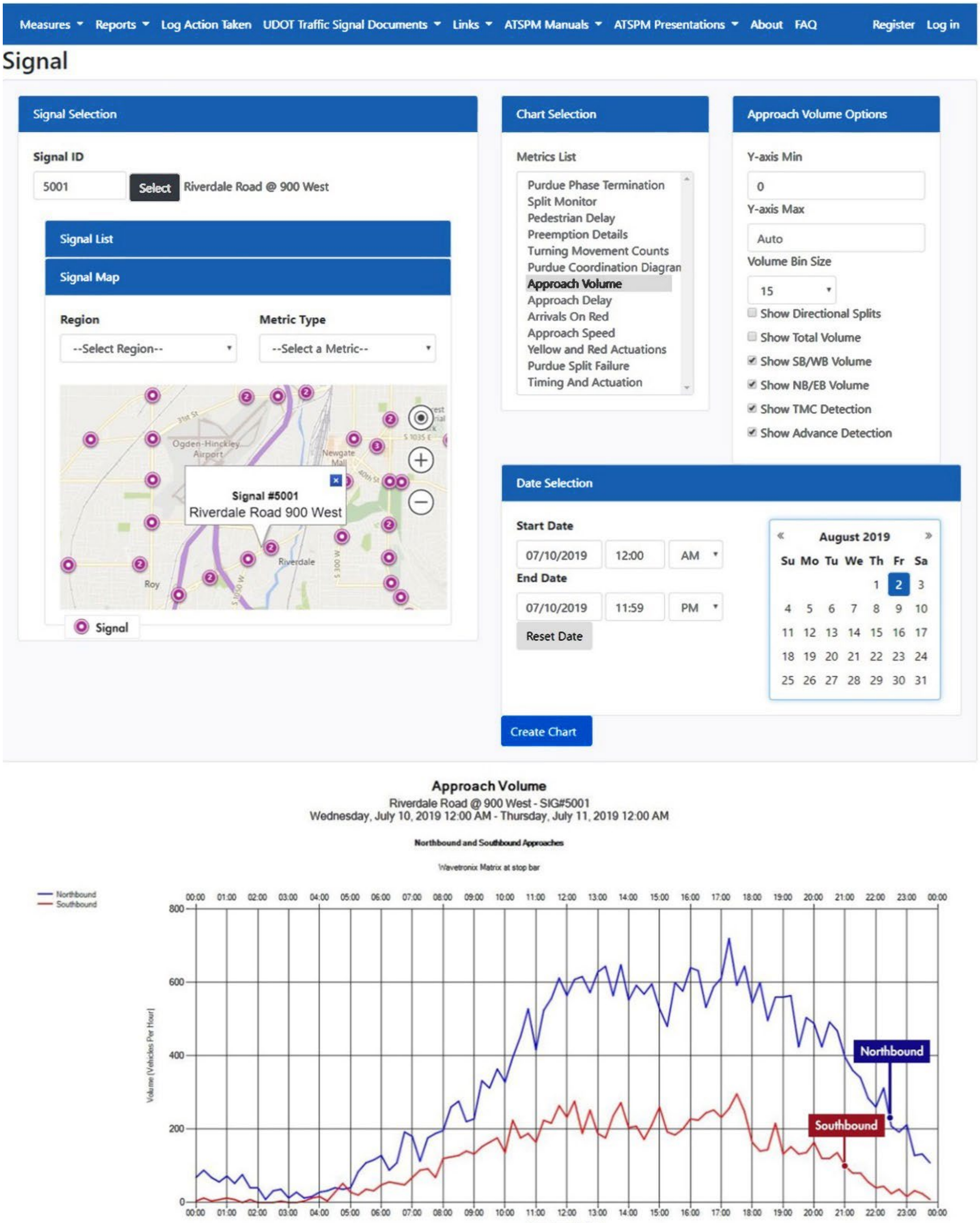
- Use reporting language that meets the audience's needs. An agency may have a wide range of audiences, which means they may have to communicate the performance results in language that best fits the audience. This communication may simply mean using different words to describe the outcome. When explaining performance to a less technically versed group, such as the general public, using more generally understood terms and more graphics to get the idea across is more effective.

- Establish regular reviews. The performance monitoring process should be kept up-to-date with any changes to current operations and needs.

Agency Practices of Performance Monitoring and Reporting

One example of an agency reporting on the performance of their freeway system is the Indiana DOT (INDOT) via the State Performance Dashboard—Indiana.(40) This reporting method, which includes a type of traffic ticker, is a relatively new concept to visualize system performance using probe vehicle data. INDOT is able to use vehicle probe data to report on congestion and speed in realtime for their interstate highway system in Indiana.

UDOT is another agency that has invested resources into the development of performance measures and reporting.(41) Their performance reporting system, which uses signal control high-resolution event data, logs events every 1/10th of a second with a time stamp, such as the beginning of a green phase, the beginning of a yellow phase, a detector activation, etc. Similar to the INDOT system, UDOT has developed an Automated Traffic Signal Performance Measures (ATSPM) website that has rapidly grown to include metrics for more than 1,000 monitored intersections.(41) UDOT's system is a great example of a performance measurement and reporting system that can be deployed in a relatively short period when an adequate data infrastructure is in place. Their ATSPM website allows for customizable date ranges and metrics for each intersection. Some of their metrics include Purdue phase termination, turning movement counts, approach volumes, arrivals on red, and many other measures. Figure 11 shows a screenshot of the UDOT's ATSPM website.(41)



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ID = identification; SIG = signal; SB = southbound; WB = westbound; NB = northbound; EB = eastbound.

Figure 11. Screenshot. Example UDOT ATSPM website (2019).[41]

The WSDOT *Gray Notebook* is a quarterly performance and accountability report featuring quarterly and annual updates on key agency functions and providing in-depth analyses of topics aligned with the agency's strategic plan and legislative funding priorities.[(42)] The subject index covers a wide variety of subjects—such as progress on topics related to mobility, safety, and infrastructure conditions—and explains the agency's planning process and rationale behind different actions. Table 4 shows articles in the *Gray Notebook* on each of the individual subjects.

Table 4. Performance measure reporting accountability effective practice: WSDOT *Gray Notebook* subject articles per reporting period.[(42)]

Quarter 1 March	Quarter 2 June	Quarter 3 September	Quarter 4 December
Active transportation: safety	Bridges	Active transportation: mobility	Environmental compliance
Commercial vehicle information systems networks	Fish passage barriers	Aviation	Freight (rail)
Noise quality	Freight (multimodal)	Capital facilities	Highway maintenance
Safety rest areas	General environmental permits	Corridor capacity report	Pavement
Transportation and the economy	Highway safety	Ferries vessels and terminals	Practical solutions
Travel information	Inclusion	Water quality	Public transit safety
Wetlands protection	—	—	Tolling
Workforce development	—	—	Worker safety

—No data.

The *Gray Notebook* has been a model for other agencies looking to improve their project and program transparency and accountability.[(42)] The *Gray Notebook* engages the reader by using colors and varying the use of text and graphics—such as charts, tables, and maps—thus making the data more readily accessible to the public audience.

Considerations for Future Efforts

With technological improvements of individual components and emerging advancements in TMS performance, data collection methods also are expanding. As new technology allows for more high-resolution data from various sources, engineers and researchers will be able to find new applications for performance measurement and reporting. While procurement of the data infrastructure required for performance measurement and reporting capabilities can still be expensive (despite lowering costs of technology), newer methods are constantly evolving that improve the availability of data from a variety of sources abide beyond physical installations.

If large procurements are not feasible, the agency can still implement high-resolution data collection incrementally at a lower cost that is more in line with the agency's routine maintenance and equipment replacement. The data that can be retrieved from new infrastructure will improve operational activities and can enable an automated performance monitoring process. In turn, this process will result in more efficient use of an agency's resources to focus on improvements in areas that need it more.

With the increase in available data collection methods and expanding TMS infrastructure, agencies should focus on keeping their assets, TMSs, and components in good condition to ensure they are performing optimally throughout their lifecycles. By establishing an internal organizational TMS management structure with distinct management groups—one focused on improving lifecycle performance of a TMS and another on functional uptime performance of the components, for instance—an agency can work toward improving the performance monitoring program overall. Agencies that adopt and implement these more proactive measures to assess TMS performance are better positioned to achieve their performance objectives and prioritize their resources based on actual system performance metrics.

CHAPTER 6. CHALLENGES AND EFFECTIVE PRACTICES: IMPROVING TMSs

This chapter addresses challenges and opportunities that arise in developing the next-generation TMS. The following key issues, as related to enhancing TMSs, are covered in this chapter:

- Planning, designing, and operating the TMS so it can be actively managed.
- Conducting performance measurement activities that can be used to plan, design, and actively manage the TMS.
- Addressing institutional and programmatic issues, including issues related to shifts in philosophy, planning for operations, security, system failures, political constraints, and funding.

The challenges agencies face when improving their TMSs, successful strategies to overcome those challenges, and emerging trends related to TMSs provide foundational knowledge on the current state of the practice and how to move forward toward the next-generation TMS.

This chapter also presents an international look at countries outside the United States that have implemented TMSs. Providing guidance on how agencies can overcome challenges and adapt to evolving trends in system improvements enables early identification of emerging issues and challenges that can be addressed. Chapter 7 covers emerging operational strategies and data sources from which agencies can garner knowledge and identify the approaches and resources that are most applicable to them.

FOCUS ON CONSTANTLY IMPROVING OPERATIONS AND CAPABILITIES

As travel demand and congestion increases, transportation agencies are tasked with the increasingly difficult job of managing traffic flow and maintaining an acceptable level of system performance. Furthermore, limitations—such as right-of-way constraints, lack of funding, increasing construction costs, environmental concerns, and societal impacts—contribute to the escalating challenges of constructing new capacity as a solution to meet demand. As such, there has been a recent shift in philosophy, from a design and construct ideology to a more formal and programmatic approach to an efficient and proactive operation of facilities. "Active management" and TSMO are growing concepts that align with this shift in philosophy. TSMO, as discussed in chapter 4, involves implementing a set of strategies that improves an agency's existing transportation system performance, without a major capacity expansion, and enables an agency to operate the available transportation assets at a high rate of efficiency.

Active management is the idea that an agency can improve system performance by operating and managing transportation systems in a way that is dynamic and adaptive to current and future conditions rather than with a fixed strategy. Figure 12 depicts the four steps in the active management cycle:

1. **Monitor the system.** Track the transportation system status using real-time and historic data and analysis tools.
2. **Assess system performance.** Measure system performance using the collected data and analysis tools to determine if system performance is at the desired level.
3. **Identify and recommend dynamic actions.** Identify appropriate dynamic actions to improve the level of active management.
4. **Implement dynamic actions.** Implement the recommended actions and continue to monitor the system.

Source: FHWA.

Figure 12. Diagram. The active management cycle.[(2)]

When it is applied to a TMS, the active management cycle provides a model for continually improving the performance of the TMS. The cycle allows the agency and the traveling public to get the most out of the TMS and the transportation system of which it is a part. However, implementing new TMSs or improving existing TMS operations can involve challenges, including the need for advanced systems management and operations capabilities, adequate business processes, required technology, and sufficient staffing.

Operations staff, often housed in a TMC, play a critical role in managing a TMS that deploys active management strategies, such as dynamic managed lanes. Close monitoring and coordinating need to occur to assess the impacts of functions and actions that are part of the operational strategy. For example, what is the impact on overall TMS performance objectives of opening the managed lane when incidents occur? Was the method of opening the lane effective? Did it improve performance? The use of patrol vehicles that continuously traverse the facility may allow for speedy incident detection and efficient response, therefore, minimizing downtime and reducing revenue loss on priced managed lanes. Does this function improve the overall performance of the TMS? If not, what improvements can be made?

The answers to the aforementioned questions are examples of the types of information needed during the TMS planning and design processes. An effective performance monitoring effort will allow operations staff, planners, and designers to determine what changes could be made to improve the performance of the TMS. Even though most of these questions directly address operational decisions, assessing the effectiveness of implementing these decisions can point to changes in physical design, operational protocols, or TMS enhancements or adjustments. Linking the results of the performance assessment to planning and design processes will ensure that the operational lessons learned will be carried over to enhancements to the TMS or to the plans for developing a new TMS.

Effective Practice: TMS Planning and Design

When planning and designing TMSs, agencies should consider making decisions that focus on needs, system performance, and development of cost-effective solutions. The performance measurement and assessment concepts presented in chapter 5 are inherent to the TMS planning and design activities. Assessing system performance supports active management in realtime and helps identify methods to improve the ability to actively manage a TMS through the planning and design process.

Improving traffic management and operations is often accomplished by implementing the right suite of operational strategies and technologies or by assembling a TMC workforce with the appropriate level of knowledge, skills, and abilities to inform operational decisions. However, an element of the TMC that is often overlooked is workspace layout. Although a lot of thought often goes into the plans for a new center that is still being designed, reevaluations of existing floor plans or workstation layouts, and how they relate to efficient operations, often are not conducted.

The MDOT SHA implemented a complete reconfiguration of the CHART Statewide Operations Center (SOC) to modernize the facility in support of their current and future planned traffic management capabilities.[(43)] This redesign was prompted because the original SOC was designed using common practices from the 1990s, which were not applicable to current evolving demands and functions. The dichotomy was in the state-of-the-art system software and field infrastructure against an outdated physical layout that did not fully support new operational goals. The new configuration of the operations floor plan centered on locating functional areas and personnel together, reducing the time to share information and prioritizing collaboration. Through this operations-oriented design approach, the SOC could provide more effective, efficient, and reliable service to the traveling public. In this example, the planning exercise was focused primarily on the facility (SOC). While the SOC operational planning provided a valuable benchmark for redesigning a TMC facility, a larger-scale TMS strategic planning exercise would have covered a wide variety of support services and the integration of future needs for TMS services more adequately. This plan would have also fed more naturally into budgeting, programming, and planning exercises that were conducted specifically for the facility redesign but were not necessarily considered for the broader TMS overall.

CHALLENGES TO IMPROVING TMS

Transportation agencies are faced with many unique challenges that impact how they implement TMSs or improve operational strategies. These challenges will likely vary based on the level of maturity of the existing system. Identifying challenges could be an important evaluation metric and starting point for an agency to implement improvements. Although organizational issues require a top-down commitment to change, there also are several technical and operational challenges that an agency should evaluate in its pursuit toward enhancing their TMS and assessing the ability to improve their TMS. Challenges in improving TMSs, as well as challenges agencies face as part of their normal operations, are included in table 5. Table 5 also presents strategies that have proven effective in overcoming the challenges shown and improving the capabilities and performance of TMSs.

Table 5. TMS challenges and strategies.

Challenge	Strategies to Overcome Challenges	Strategy Description
Emphasis has traditionally been on capacity expansion instead of efficiency improvement.	Develop a multiyear strategic plan for the system and integrate it into agency plans.	• Use an ITS strategic plan as a roadmap for the research, development, and adaptation of technology-based transportation systems. Also use the plan as a guide for investments into the TMS and technology and operations-focused solutions. • Inform interested stakeholders about the benefits of implementing the system. • Integrate multiyear plans or feasibility plans into these planning processes to ensure consistency at various planning levels and help elevate the TMS implementation. • Assess and report on legacy TMS capabilities and compare them to the benchmark of planned capabilities in 5 or 10 years.
Emphasis has traditionally been on capacity expansion instead of efficiency improvement.	Move away from the design and construction philosophy.	• Implement a TMS to help shift focus toward operations. • Define operational benefits in a way that is meaningful and easy to understand for TMS managers, staff, operators, and policymakers. • Communicate how operations can address issues and help achieve goals related to mobility/reliability and safety.
Lack of understanding of TMS objectives from elected officials and decisionmakers.	Coordinate with other agencies and political entities.	• Coordinate technical resources. • Consult with legal entities, enabling legislation. • Form formal agreements with enforcement agencies.

Challenge	Strategies to Overcome Challenges	Strategy Description
Lack of coordination between multiple stakeholders.	Set up communication protocols and ongoing coordination.	• Develop methods to involve and retain nontraditional partners by focusing on common issues and building on initial successes. • Encourage ongoing cooperation around events and activities. • Increase transportation agency presence in existing or new public safety forums (e.g., governor's office of emergency management). • Form multiagency committees at multiple working levels.
Lack of funding and resource constraints.	Pursue innovative funding mechanisms and prioritize operations in planning.	• Integrate the managing condition of TMS assets into the assessment of TMS capabilities and plan for future improvements to obtain a better sense of long-term resource needs. • Pursue innovative funding mechanisms or other sources of funding, such as new user taxes, dedicated local sales taxes, toll revenues, or economic development funds. • Establish relationships with policy decisionmakers and legislators to benefit from earmarked funds and encourage resource sharing from other departments. • Include TMS improvements and operations-focused projects in agency planning documents. • Develop plans for meeting future staffing needs that evolve with desired capabilities of the TMS.

Challenge	Strategies to Overcome Challenges	Strategy Description
Rapidly changing technology requires updates to outdated or legacy systems.	Assess the existing system capabilities.	• Evaluate the capacity of the current systems to support adaptation and integration with evolving technologies. • Develop requirements for the new system, whether any components can be maintained, and identify data archiving capabilities and needs. • Focus on the evolution of capabilities for specific subsystems to allow for incremental changes and updates (i.e., do not always need one large replacement of TMS). • Establish ongoing maintenance and support for the existing system while transitioning to a new system (this is a critical step). • Coordinate with both internal agency departments and external agencies to determine overlaps in data and technologies that can be streamlined and shared. • Assess personnel roles to determine skill sets and if any adjustments need to be made to match the vision of the new system and its operations.
Integration issues with new and existing systems.	Engage system integrators and vendors early.	• Include system integrators and vendors in conversations during the planning process to discuss interoperability and to ascertain options to issues that may be unique to each system.

Challenge	Strategies to Overcome Challenges	Strategy Description
Lack of ability to collect and manage large amounts of data.	Plan for data collection and data management.	• Create processes that consider data acquisition, governance, storage, and analysis: o For acquisition, the capacity of the existing system to collect large amounts of data should be assessed for both the near term and the long term, along with procurement options. Latency in data collection should also be considered and will vary based on the agency's needs. o For governance, explore opportunities for which data collection can serve multiple purposes. This step should also address privacy, security, and management concerns. o For storage, agencies need to consider the barriers to using private or public cloud services. The variety and type of data to be stored, the duration of time the data are anticipated to be stored, and the granularity of the data will affect the storage requirements. • For data analysis and processing, an assessment on the system's current data analysis and management capabilities should be performed. The required analysis tools and staff skill sets should be reviewed.

Consider these challenges when planning and designing a TMS and when developing a performance monitoring program to assess its performance is important. Strategies to overcome these challenges can be addressed during the planning and design processes and later during the operation of the TMS.

INTERNATIONAL INFLUENCES

One of the emerging strategies to improve TMS performance is to operate these systems using an active management philosophy. ATM strategies have been used internationally for years with proven success. As a result, the FHWA-sponsored international technology studies in 2006 and 2010 focused on ATM.(44) These studies focused on gathering information on how agencies outside the United States managed traffic congestion using ATM operational strategies at various levels of scale. European countries were found to be at the forefront of a wide range of early ATM strategy deployments. A few examples of successful and well-known references of ATM strategies deployed outside of the United States are included in table 6.

Table 6. Operational strategies deployed outside of the United States.

Operational Strategy	Country	Year Deployed
VSLs	United Kingdom	Early 1990s
VSLs Dynamic route information panels	Netherlands	Early 1990s
Full ATM concepts implemented	United Kingdom	Early 2000s
DLUC VSLs	Australia	2010

In the early 2000s, the United Kingdom's Highways Agency, which manages the roadways, implemented VSLs, lane use control, QW, hard shoulder running, and other ATM strategies on the M42 outside of Birmingham.(45) This implementation was the most widely referenced global example of early ATM deployment. The objective was to reduce congestion by utilizing the hard shoulder running concept during peak periods of travel. Since then, other similar active management system projects have been implemented under the banner of "Managed Motorways."

Australia is another country that is a leader in ATM deployment. The DOT for the State of Victoria (VicRoads) implemented an improvement on the British concept of Managed Motorways.(46) The VicRoads-managed motorway concept includes TMSs that integrate real-time data into its algorithms to predict traffic conditions and mitigate congestion in a proactive manner. The early deployment of Managed Motorways was on the M1 motorway in Melbourne in the late 2000s, which transitioned into a fully managed motorway in 2010, and included integrated speed and lane control and coordinated ramp metering along the entire 75 km corridor.

European and Australian approaches to improving TMS capabilities and performance are concentrated on the ideology of active management. These European examples and the scanning tour completed by U.S. transportation agency leaders in the mid-2000s helped give the agency leaders successful examples to refer to when considering ATM implementations in their own regions. The international experience with ATM has laid out the groundwork for the United States to move toward a more active way of thinking when managing traffic.

CHAPTER 7. EMERGING OPERATIONAL STRATEGIES AND DATA SOURCES

Building on chapter 6 regarding challenges and opportunities to implement strategies to successfully implement a next-generation TMS, this chapter summarizes some of the emerging operational issues, data sources, and knowledge gaps agencies face today.

This chapter also touches on agencies that are at the forefront of implementing emerging operational strategies. The effective practices, along with lessons learned from agencies that have deployed emerging technologies, are presented with the goal of helping agencies learn from the best practices that are most applicable to them.

EMERGING OPERATIONAL STRATEGIES

New technologies and data collection methods offer the potential to advance TMS capabilities and offer entirely new functions or services. These new opportunities can position agencies to implement emerging operational strategies and prepare for automation and next-generation TMSs.

Active Transportation and Demand Management

Active transportation and demand management (ATDM) strategies can help address safety and congestion by supporting new and emerging implementation approaches, but this process relies on agencies, and therefore TMSs, doing more with existing components and technologies. The next section describes a sample of effective practices that address ATDM.

Effective Practice: ATDM—City of Chicago

Freeways and arterials in the downtown Chicago area were among the facilities selected as a testbed for their analysis, modeling, and simulation (AMS) capability.(47) The extracted network for the Chicago Testbed included 150 freeway links, 47 highways, 247 ramps (including 59 metered ramps), and more than 4,300 arterial links. The testbed also had nearly 545 signalized intersections and simulated 24-hour demand at a 5-minute resolution, totaling more than 1 million vehicles in each simulation period. The testbed was developed and analyzed using the enhanced, weather-sensitive DYNASMART platform, in conjunction with a special-purpose microsimulation tool for the dynamic mobility application (DMA) bundle in a connected vehicle environment.(47) To evaluate the effectiveness of the ATDM strategies, various operational conditions were defined through a data-driven method that used the historical traffic flow, weather, and incident data. The operational conditions were varied to represent specific daily scenarios pertaining to different levels of travel demand and weather events. These conditions were designed to address research questions and evaluate the system-wide impacts and effectiveness of the individual and logical combinations of the proposed ATDM strategies and DMA bundles when prediction and active management are combined with data capture and communication technologies.

The analysis was primarily aimed at answering the impact of connected vehicle technology and data on the DMA applications versus the impact of data from legacy systems. Since the Chicago Testbed was an AMS testbed, the operational conditions modeled were not directly connected to field TMSs, but they were made as close to real-world conditions as possible by modeling the actual transportation system on a virtual computer-based environment. Three connected vehicle scenarios were considered:

1. The impact of the connected environment under low, medium, and high demands and under 10 percent, 50 percent, and 90 percent market penetrations.
2. The impact of speed harmonization without connectivity on the different operational conditions.
3. The impact of speed harmonization in a connected environment for different operational conditions and under different market penetrations.

Observations showed that a highly connected environment has the potential to help a congested network recover from a breakdown in free flow conditions, and the effects of connected vehicles—such as improved travel time reliability and improved system performance—become more realized as demand increases.

Expansion and Evolution of TMSs

New and emerging data sources do not necessarily mean a reduced need for TMSs and operations personnel to interpret and act. In fact, new sources could mean just the opposite, whereby TMC operators are now dealing with a larger geographic footprint, more real-time capabilities, and an overall increased workload. Regional operations could mean additional personnel from different agencies sharing the same space—which could result in more proactive management decisions being made on the TMC floor—or could even be realized through a public–private partnership sharing in the collection and manipulation of data, actions, and outputs all through the framework of one TMS.

Technology will enable virtual sharing of data, operational capabilities, and policy decisionmaking. Greater data availability and quality will enable more proactive management of existing transportation facilities. The roles and responsibilities of the TMS, the TMC, and the TMC operator will likely evolve several times over the next several decades.

Regularly revisiting an agency's ITS strategic plan or TSMO strategic plan has been proclaimed by many agencies as an important activity to help ensure they are keeping up with these changes—and can adapt to them—while simultaneously keeping their focus on minimizing interruptions in service and maximizing safety and mobility benefits for customers.

Shared TMSs

This section presents the types of systems that may be implemented to manage, control, and operate facilities that cross jurisdictions and span geographical boundaries of one agency or types of facilities (e.g., freeways, tollroads, surface streets). These shared systems also could manage functions within an agency, such as those systems that support incident management and response, planned special events, traveler information, road condition information, and other strategies that may or may not be integrated into a TMS. Agencies that adopt shared goals and implement common operational strategies for integrated corridor operations are well positioned for the future smart city. A general summary of the evolution of the systems and their range of functions and capabilities are included.

Effective Practice: Multiagency Signal Operations—GDOT

GDOT initiated their Regional Transportation Operations Program (RTOP) in 2010, with the overall goal of improving signal operations to increase throughput, minimize congestion, and reduce delays along commuter corridors.(48) Maintaining and operating the traffic signals in the region is the responsibility of GDOT and local agencies, depending on jurisdictional boundaries and the availability of resources for local agencies. In the case that local agencies do not have sufficient resources to operate and maintain signals, GDOT assumes that responsibility.

Before the development of the RTOP, GDOT recognized the importance of optimizing operations and made significant investments in improving their signalized systems.(48) In the early 1990s, GDOT created a program to standardize traffic signal equipment to simplify procurement efforts and help maintain a common platform for agencies in the State. In 2002, GDOT adopted the next-generation 2070/Advanced Traffic Controller (ATC) standard; and the efforts included deployment of central software, training, and upgraded controllers for agencies within the State.(49) In 2004, GDOT launched the Fast Forward Congestion Relief Program, which included investments in traffic signal upgrades and synchronization. This program helped to further standardize signal control equipment and reduce maintenance costs for GDOT and local agencies. In 2005, GDOT established the Metro Atlanta Signal Timing Program to further focus on signal timing improvements in the Atlanta metro region. The retiming efforts resulted in significant improvements to travel times, reductions in delays, and reductions in fuel consumption and emissions. Additionally, the Office of Traffic Operations maintains several signal maintenance contracts to supplement the signal maintenance efforts of GDOT and local agencies.

Although significant investments have been made in signal improvement programs, GDOT recognizes that existing long-term barriers must be overcome to achieve optimal signal operations. These long-term barriers include routine equipment maintenance, active management of signals, and cross-jurisdictional coordination. Cross-jurisdictional coordination has been a barrier for GDOT because most major arterials in the region cross one or more jurisdictional boundaries. GDOT recognizes that inconsistencies exist in the operating plans across these boundaries due to agencies only operating and maintaining signals within their individual jurisdictions. The RTOP tackles this barrier by establishing a partnership between GDOT and local agencies to operate and manage the traffic signals systems as a collective.

Through this program, GDOT supplements local agencies by providing personnel to support operations and maintenance efforts and develop strategies for improvements. The local agencies with fewer resources depend more on GDOT's support for their signal operations. Due to the varying need for GDOT support, two levels of RTOP participation were developed:

- **GDOT lead.** For TMSs where GDOT is the designated lead agency, GDOT takes primary responsibility for operating and maintaining the system. The local agency is only responsible for incident response and major system repairs.

- **Local lead.** For TMSs where the local agency is the designated lead agency, the local agency assumes primary responsibility for operating and maintaining the system. GDOT assigns a corridor manager to perform routine analyses of the system operations and adjust signal timing. The local agency then reviews these routine tasks before they are implemented.

Effective Practice: Data-Sharing System—Virginia DOT

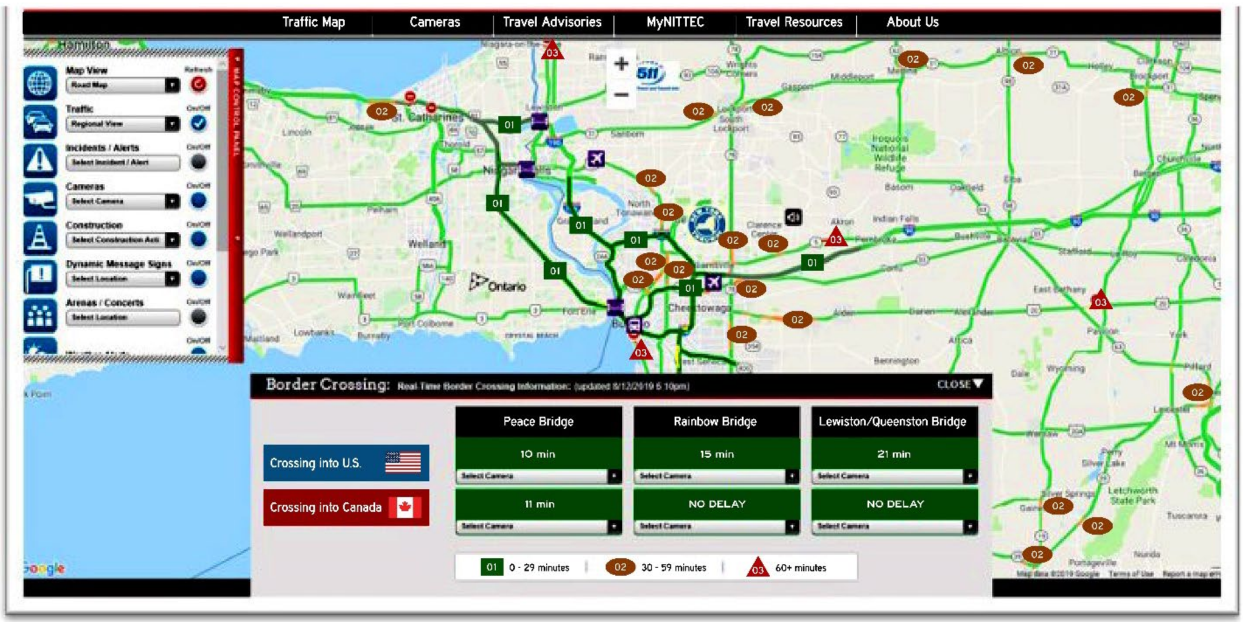
The Virginia DOT (VDOT) has taken steps to integrate five of their TMCs.[50] Through this integration, VDOT can create a cohesive traffic and emergency communications subsystem, integrate data and emerging technologies, and implement the sharing of systems. These actions are in anticipation that CAVs will collect and share data about traffic and road conditions, and that it is critical for TMCs to coordinate and share data through the various communications capabilities. By utilizing integrated data collection and sharing systems, agencies will be able to efficiently send messages to digital signs related to weather, incidents, or work zones. The data will be shared by VDOT, Virginia State Police, and emergency operation centers. The concept for data sharing and integration will be based on the Virginia Connected Corridor cloud computing environment, which will connect to roadside equipment that will collect data obtained from CAVs. VDOT also created a data portal called SmarterRoads, which is a cloud-based portal that contains data from various sources related to incidents, work zones, road conditions, and road signs.[51] SmarterRoads can be accessed by users online, and it continuously connects to different datasets, which are made available to the users.

Effective Practice: Shared TMS Functions—Caltrans

Caltrans is the first agency outside Minnesota to embrace the Advanced TMS (ATMS) Intelligent Roadway Information System (IRIS) software and make use of its collaborative and open-source feature.[52] IRIS was originally developed by the MnDOT, but was made free to the public in 2007. IRIS was enhanced to be compatible with Caltrans District 10 infrastructure and field components, and it was adapted to match the district's operations. Caltrans District 10 focused on shared TMS functions for DMS, CCTV cameras, incident feeds, and traffic data to start, with additional enhancements and functions planned for future deployments in other districts. The open-source ATMS software substantially lowers costs compared with proprietary systems, and the system provides significant capabilities, improved safety, lower personnel maintenance needs, and higher reliability. The collaborative nature of the open-source IRIS system supports transportation technology innovation at a much lower cost and facilitates knowledge management and transfer to other agencies. Efficient development, implementation, and funding of innovation can be shared across agencies.

Effective Practice: Shared Traffic Information System—Niagara International Transportation Technology Coalition

The Niagara International Transportation Technology Coalition (NITTEC) is a coalition of 14 member agencies and multiple stakeholder agencies in Western New York and Southern Ontario, Canada, that comprise the road management system used in the Buffalo–Niagara Falls region.[53] NITTEC was formed in 1995 with shared goals for improving traffic mobility, reliability, and safety across the U.S.–Canada border. NITTEC allows transportation agencies to collaborate and manage their multimodal transportation systems, while facilitating coordination and communication. Each of the stakeholder agencies has specific roles and responsibilities they perform, which are outlined in a memorandum of understanding that establishes each stakeholder's willingness to cooperate and coordinate with each other to improve regional and cross-border mobility. NITTEC collects and disseminates real-time traffic information, including border crossing wait times and information on incidents along the Buffalo–Niagara Integrated Corridor. (An example is shown in figure 13.)



Original map: © 2018 Google. Screenshot © 2020 NITTEC.

Figure 13. Screenshot. Example NITTEC traffic map (2020).[(54)]

EMERGING DATA SOURCES

Presently, TMSs tend to utilize traditional infrastructure-based detection technology to operate and optimize performance. This section discusses emerging data sources that agencies can adopt to enable a wide range of operational strategies and system functions. TMSs that implement operational strategies, such as TIM, traffic signal controls, ramp metering, VSLs, and managed lanes, can all be improved through enhanced data sources. The opportunity to electronically collect and share information from these emerging sources requires agencies to consider what additional technologies, strategies, and communication capabilities may be necessary to enable this information sharing.

Some emerging systems are starting to use other sources of data, such as probe vehicle data. The anticipated entry of CAVs to the U.S. transportation network holds the promise to provide new forms of data, and, accordingly, the operation of TMSs will evolve. Early FHWA research has indicated the TMSs can function in the connected vehicle environment, and the new sources of CAV data can enhance the operations of these systems.

Preparing for Emerging Data Sources

Current roadside hardware—such as ramp meters, DMS controllers, and traffic signals—often has little or no additional processing capabilities or data storage available to perform additional functions. As emerging collection methods for data become more and more available for TMSs to capture and use, agencies will need to integrate this information into their roadside equipment and systems. This step will require agencies to reimagine and potentially develop the databases, central computer hardware and software platforms, decision-support subsystems, communication subsystems, software interfaces, and other TMS components that can handle a rapidly expanding data universe.

Connected vehicles and connected travelers (i.e., mobile devices) are already starting to result in a significant change in how agencies' systems are designed to collect, compile, use, and share information with these sources. The geographical coverage of travel condition information provided by emerging data sources will dramatically increase compared to data historically collected via point detection and CCTV surveillance at key locations along the network. If future TMSs can be flexible in accepting both point detection technologies and future mobile methods, they have the potential to substantially expand their service areas and overall functionality.

However, the massive amount of probe data that could potentially be collected from connected vehicles and travelers may require agencies to incorporate a new set of data tools, workforce skills, and network technologies into their TMC operations.

Agencies will need to develop a comprehensive plan for leveraging emerging data sources and incorporating new data tools and technologies into their traffic management practices and TMCs. The comprehensive plan should discuss high-priority functions that align with agency goals and objectives; regions and sites for the deployment of field equipment and communications; TMC equipment updates, changes, and augmentations; and plans for collaboration, partnering, and data sharing and exchanges.

In addition to new data types, agencies will also be dealing with new data resources, such as third-party providers. Private companies, academic institutions, or even private citizens (via crowdsourcing) could become integral data sources for agencies as new and innovative methods for collecting, storing, and transmitting data emerge.

Using Third-Party and Service Provider Data

A growing number of agencies is using innovative and emerging technologies to monitor their systems to advance their TMS and operations. One example is the use of mobile devices and Global Positioning System to collect traffic data to describe the current state of the system with minimal latency. These technologies, coupled with organizational and cultural changes, provide an opportunity to improve system monitoring and response. Examples of these emerging technologies include decision-support systems, the Internet of Things (IoT), cloud computing, big data, machine learning, crowdsourcing, and CAVs. These recent innovations provide a broad range of tools that can help agency TSMO programs reach their maximum potential by improving operational strategies to become more proactive and data driven.

Crowdsourcing is an emerging methodology that can overcome some of the known challenges of real-time system monitoring when it is integrated with an agency's existing efforts. Crowdsourcing utilizes technology to collect data from a large number of people to address a need or problem. Crowdsourcing is based on the following three common methods:

- Data extracted from social media platforms.
- Data acquired from third-party data providers.
- Data acquired from mobile applications developed for transportation needs.

The different types of crowdsourced data and the metrics they could yield are as follows:

- Probe—speed and travel time.
- Event—crashes, stalled vehicles, weather, etc.
- Travel behavior—where, when, and how people travel.
- Social media—public sentiment about roadways and agency performance.
- Vehicular—heavy breaking, wiper on/off, temperature, and more from connected vehicles.
- Mobile infrastructure/IoT—connected work zone cones sharing location and surrounding vehicle speed.

One agency that has been using crowdsourcing to improve their TSMO applications is UDOT. In 2013, UDOT launched the Citizen Reporter Program, which allows users to report current road weather conditions along specific roadway segments.[(55)] Users can download a mobile application, which provides travelers with a consistent method to report conditions on the go, especially in rural areas. UDOT uses these reports to improve winter maintenance activities and distribute traveler information.

Another agency utilizing crowdsourcing is the Kentucky Transportation Cabinet. The Kentucky Transportation Cabinet uses data from third-party providers to create automated email alerts for TMC staff.[(56)] These alerts enable staff to verify data in realtime and improve roadway maintenance activities. Operations staff use this real-time data to expedite and improve traveler information dissemination.

The District DOT (Washington, DC) is using crowdsourced data to assess the performance of arterials and signalized intersections.[(57)] The data are used to create a Web-based performance measures dashboard, which enables operators and engineers to optimize signal retiming strategies in a proactive manner.

Other Preparations for CAVs

Technology companies, automotive manufacturers, and infrastructure owners/operators are all investing heavily to develop connected and automated features for vehicles with the goal of reducing human error during the driving task. The timely and safe deployment of CAVs and associated technologies can be affected by advances in infrastructure design and practices (e.g., machine-readable markings and signs, quick response codes, and weather information). As noted in the emerging data section, the deployment of CAVs will also begin to rapidly impact TMS functions and operations. With CAV technologies on the rise, State and local infrastructure owners and operators seek new approaches to designing, constructing, operating, managing, and maintaining highway infrastructure.

When considering the challenges of resources and funding, some incremental improvements or activities agencies can be implemented in the short term to start preparing TMSs and infrastructure for CAVs. Agencies are already implementing many of these improvements or activities through transportation projects and routine maintenance

Pavement Markings

Pavement markings are an important part of CAV implementation because CAV systems use cameras and image processing to identify markings to correctly position vehicles within lanes. CAV testing results have shown that inconsistent and unmaintained pavement markings may cause CAV performance to suffer. Additionally, automakers have indicated that pavement marking consistency is one of the most immediate infrastructure needs for successful CAV rollout. Agencies already update and maintain pavement markings for human drivers, but more frequent attention may be required as they prepare for CAVs. The use of consistent pavement markings is also important for successful CAV operations. The use of wide (6-inch) lane, edge, and center lines with high levels of retroreflectivity will help CAVs detect lane lines more easily. Although standards have not been developed for line markings for CAVs, California has started installing 6-inch lane lines in preparation.[58] The use of reflective tape for pavement marking lines is another option to improve visibility for both human and CAV detection.

Signing

Signing is another key infrastructure for CAV operations. CAV systems may run into difficulty trying to read signs that are damaged, faded, or noncompliant. Agencies can maintain signs to make sure that they are in good condition and have high levels of retroreflectivity. Ensuring that signs are not blocked and can be detected by CAVs is another simple activity that agencies may perform. In the future, standardized digital infrastructure and traffic regulation information that CAVs and other automated detection systems can understand will need to be developed.

Maintenance

Agencies are already conducting maintenance activities that can help them prepare for CAVs. As alluded to in the discussion for pavement markings and signing, timely and continual maintenance of these infrastructures will help to ensure smooth operations of CAVs. Another traffic system element agencies should maintain is the roadway because significantly degraded roadway surface conditions may pose a concern for CAV sensing systems. Whether additional maintenance activities will be needed to accommodate CAVs in the future is unclear at present.

Consistency and Standardization

Agencies can use consistency and standardization on signs and pavement markings to help CAVs operate better on roadways. Standardizing should include the type, placement, and application of pavement markings and signs. Current CAV technology uses machine learning and neural networks to identify objects using a library of images. Therefore, CAVs may struggle when noncompliant signs or pavement markings are used.

Traffic Signals

CAVs will need to identify and detect traffic signals. Ultimately, traffic signal controllers would send signal timing and phasing data to CAVs, allowing the CAVs to move effectively through signalized intersections. Due to proprietary concerns, vehicle manufacturers do not disclose the algorithms and technologies used in their vehicles, which makes it difficult for agencies to properly prepare their traffic signal control systems. For now, agencies may procure traffic signal controller cabinets that have extra space to allow for future equipment and upgrades.

Inventory of Traffic Components

An inventory of traffic components or features that are likely to be utilized by CAVs will be useful for data sharing and communication applications in the future. It is anticipated that CAVs will collect and share data on road conditions with other vehicles or with the corresponding transportation agency. For example, if a CAV detects debris on the roadway, it can share that information with another vehicle, so the second vehicle can react accordingly. Transportation agencies may be able to capture the data created by CAVs to enhance their TMSs. Agencies may inventory all the features that are most likely to be affected by CAVs. For commercial CAVs and truck platooning, these features may include bridge heights, speed limits, truck routes, and load restrictions. For general traffic and safety applications, agencies may inventory traffic signals, speed limits, signs, roadway curvature, crosswalks, etc. It is important to document how data were collected, as well as the accuracy of the data and its reporting. For example, an inventory entry of a sign with unknown exact location should account for a location range of where the sign may be located. A CAV system will be able to deal with inaccuracies better if inaccuracies are known.

Communication Infrastructure

Agencies can make improvements to their communication infrastructure to help TMSs prepare for the influx of complex data that will be made available by CAVs. To communicate and share data with CAVs, it is anticipated that roadside units will communicate with a CAV's onboard system. A complete communications system may include roadside units, onboard units, controllers, a TMC, and communication links. Agencies may consider future communication needs, upgrades, and maintenance in highway plans. Currently, many agencies own and operate extensive fiber-optic networks to transfer significant amounts of data reliably and securely. Fiber optics can also be used for a broad range of applications, including ITS-based TMSs and CAV data transfers.

High-Resolution Mapping

High-resolution maps help CAVs identify their location within a three-dimensional (3D) environment. High-resolution mapping involves creating a 3D map that includes information about the physical environments, such as medians, poles, curbs, surfaces, etc. However, the costs of collecting data for high-resolution maps are significant. Therefore, agencies are unlikely to develop high-resolution maps until CAV technology is better understood.

Effective Practice: Planning for CAVs—Los Angeles

CAV-related activities in Los Angeles are mainly planning related at this time. Agencies within the Los Angeles County region formed an organization called the Coalition for Transportation Technology. This group developed a strategic action plan to prepare for new technologies, and to take advantage of the opportunities that may emerge from them.(59) The organization consists of Caltrans, Los Angeles DOT (LADOT), Los Angeles County Metropolitan Transportation Authority, County of Los Angeles Public Works Department, and Southern California Association of Governments. CAV-related preparations include some of the following ongoing and planned activities:

- Identifying short, medium, and long-term needs.
- Updating the regional ITS architecture.
- Identifying and pursuing funding opportunities for pilot projects and equipment procurement.
- Creating dedicated positions focused on CAV technology.
- Cataloging available data sources.
- Investing in lane markings.
- Resurfacing roadways.
- Installing ATC cabinets that are CAV technology ready.

Although no lessons learned have yet been identified from these activities, the partnership and collaboration of agencies in the region have emerged as a best practice in preparing for new technologies such as CAV.

KNOWLEDGE GAPS FOR NEXT-GENERATION SYSTEMS

This section highlights a few emerging gaps in knowledge related to data management, control algorithms, and data science, which apply to agencies as they move toward preparing for next-generation TMSs:

- How to handle incoming data from a variety of data sources?
    - Incoming data will include data from third-party data providers, a mix of reported data and crowdsourced data, and soon, data transmitted from connected vehicles.
    - Existing systems are not equipped to handle the full range of data that they may have access to in the future. Having the most up-to-date data analytics platforms can help prepare for this issue.

- How to integrate data availability from traditional and emerging sources, such as probe data, with traditional system control algorithms?
    - Most of the control algorithms are based on traffic flow theory data types, which require data metrics on different points of the roadway. The data are collected from traditional sources and include point measures, such as speed, density, and volume obtained from roadway sensors.

- The most cost-effective data source is probe data, which provides information on individual trips rather than data at specific locations. Algorithms that rely more on probe or trip-based data than on point data may need to be developed.

Agencies interested in adapting control algorithms for traffic signals and ramp metering currently lack an established protocol for incorporating probe data, once it is validated for accuracy and completeness, to improve operations.

How can transportation agencies fill their data science gap?:

- Traditional transportation engineering programs do not train engineers in data management and governance, but data scientists who can perform data analysis in the transportation field are increasingly in high demand.

- Unless agencies are in a jurisdiction that recognizes better pay and has a defined career path for these data scientists, it will be difficult to acquire and retain engineers and data scientists with these needed skills.

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Recommended citation: Federal Highway Administration,
Review of Traffic Management Systems—Current Practice
(Washington, DC: 2023) https://doi.org/10.21949/1521996

HRSO-50/07-23(WEB)E