Decision Support Methods and Tools for Traffic Management Systems

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FOREWORD

New and emerging data sources generated from travelers using mobile devices, vehicles, infrastructure, and other sources will provide agencies with opportunities to change how they manage traffic and their transportation systems. These data sources offer agencies with traffic management systems (TMSs) the challenge of enhancing or developing capabilities to collect, compile, save, use, and share this data.

The Federal Highway Administration Office of Safety and Operations Research and Development is pleased to present *Decision Support Methods and Tools for Traffic Management Systems*. This report provides support to public agencies in planning, developing, and maximizing the benefits of decision-support methods and tools (DSTs) in TMSs. It also identifies the possible processes and potential issues agencies may want to consider when planning, designing, developing, operating, maintaining, and integrating DSTs within a TMS. DSTs assist with processing and using data collected or received from connected vehicles, connected mobile devices, and other sources to help improve the capabilities and performance of TMSs and allow for more information than ever before to be more readily shared with other systems, service providers, and the traveling public. Many DSTs can also greatly aid in decisionmaking and predict possible outcomes of decisions. This report aims to assist transportation agencies in choosing and implementing DSTs to prepare for or build the next generation of TMSs and traffic management centers.

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Director, FHWA Office of Safety and Operations Research and Development

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16. Abstract

Traffic management systems (TMSs) and their operating centers, known as traffic management centers (TMCs), support real-time and offline functions, services, actions, activities, and related tasks or decisions (e.g., administrative and operational). In this context, decision-support tools (DSTs) are not generally used as stand-alone solutions; rather, DSTs are deployed and integrated with specific subsystems (e.g., software subsystems and data subsystems) of a TMS. (Depending on the requirements and how a TMS uses a tool, it may be integrated with the software of a specific subsystem, component, or device.) This report supports agencies in planning, developing, and improving their use of DSTs and decision-support methods already in use or being considered for the next generation of TMSs and TMCs. It identifies issues and opportunities for agencies to consider in exploring potential opportunities for the use of DSTs in enhancing the capability and performance of TMSs and supporting information sharing with other systems, agencies, and service providers and the traveling public.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 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

ACP20	Transportation Research Board Committee on Freeway Operations
API	application programming interface
CHART	Coordinated Highways Action Response Team
ConOps	concept of operations
CV	connected vehicle
DMS	dynamic message sign
DOT	department of transportation
DSS	decision-support system
DST	decision-support tool
DTA	dynamic traffic assignment
ERE	expert rules engine
ETL	extract, transform, and load
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GEH	Geoffrey E. Havers
GUI	graphical user interface
HCM	*Highway Capacity Manual*
HCS	Highway Capacity Software™
IaaS	infrastructure-as-a-service
IEC	International Electrotechnical Commission
ICM	integrated corridor management
INCOSE	International Council on Systems Engineering
ISO	International Organization for Standardization
IT	information technology
ITB	invitation to bid
ITN	invitation to negotiate
ITS	intelligent transportation systems
KPI	key performance indicator
LOS	level of service
ML	machine learning
NCHRP	National Cooperative Highway Research Program
NOAA	National Oceanic and Atmospheric Administration
PaaS	platform-as-a-service
RFP	request for proposal
R–ICMS	regional integrated corridor management system
RMSE	root mean square error
RTM	requirements traceability matrix
SaaS	software-as-a-service
SME	subject matter expert
TMC	traffic management center
TMS	traffic management system
TRB	Transportation Research Board
TxDOT	Texas Department of Transportation
UI	user interface
USDOT	U.S. Department of Transportation

CHAPTER 1. INTRODUCTION

Traffic management systems (TMSs) are complex operational systems. They combine field equipment, advanced information technology (IT) and communications, and software tools. They collect and synthesize traffic data, integrate external systems, and enable command and control of intelligent transportation system (ITS) field devices. They enable human operators to perform functions that support improving the efficiency, safety, and predictability of travel on the surface transportation network.

The ever-increasing availability of traffic data and the expanding operational strategies available to agencies are increasing the complexity of making operations-related decisions in realtime. Decision-support tools (DSTs), including computer-based and noncomputer-based tools, support a range of decisions. Examples of noncomputer-based DSTs are paper-based decision trees and decision tables that can be printed and collated into reference information. Computer-based DSTs can potentially play a key role in improving the real-time decisionmaking of traffic operations personnel by complementing and enhancing the operational capabilities of TMSs.

For the purpose of this report, computer-based DSTs are tools that process vast amounts of data, capture the operational processes of an agency, and potentially mimic the real-time decisionmaking of traffic management center (TMC) or TMS operators. DSTs can aid operations personnel in monitoring and assessing conditions (e.g., environment, facility, and network), detecting and verifying adverse conditions, and identifying and evaluating appropriate response strategies to planned and unplanned events. DSTs can also help agencies achieve more consistent and understandable decisionmaking across their transportation management staff.

This report explores implementing DSTs and processes to improve TMSs. State departments of transportation (DOTs) and local agencies may use the concepts and processes discussed for developing practices to plan, design, operate, monitor, evaluate, and report on the performance of decisionmaking with a TMC. Additionally, this report seeks to do the following:

- Examine current practices and trends among agencies using or planning to implement DSTs to improve the capabilities and performance of staff and TMSs.
- Discuss types of available DSTs, how they might benefit operational personnel, and how they can be integrated into a TMS to support or carry out real-time decisionmaking.

The objectives of this report are as follows:

- To present types of available DSTs, thus facilitating and improving agencies' management and operation of their TMSs.
- To identify issues for consideration when assessing the decision-support needs and capabilities of a TMS.
- To frame issues of consideration when incorporating different types of DSTs into the management and operation of a TMS.

- To identify opportunities for the potential use of DSTs during any phase of the TMS lifecycle (e.g., planning, design, maintenance, and operation).

DECISIONMAKING AND TRAFFIC MANAGEMENT SYSTEMS

Improving the timeliness and effectiveness of decisionmaking is a focus for agencies exploring opportunities to improve how they manage and operate TMSs. Traffic management relies on timely decisionmaking for monitoring traffic conditions, detecting and managing unplanned events, scheduling and managing planned events, improving signal timing, assessing and planning for adverse weather, and managing critical infrastructure. Decisionmaking relies on the real-time management and operation of a TMS, which involves unique knowledge, skills, and experience. These capabilities include the following five aspects:

1. Possessing knowledge of the transportation system.

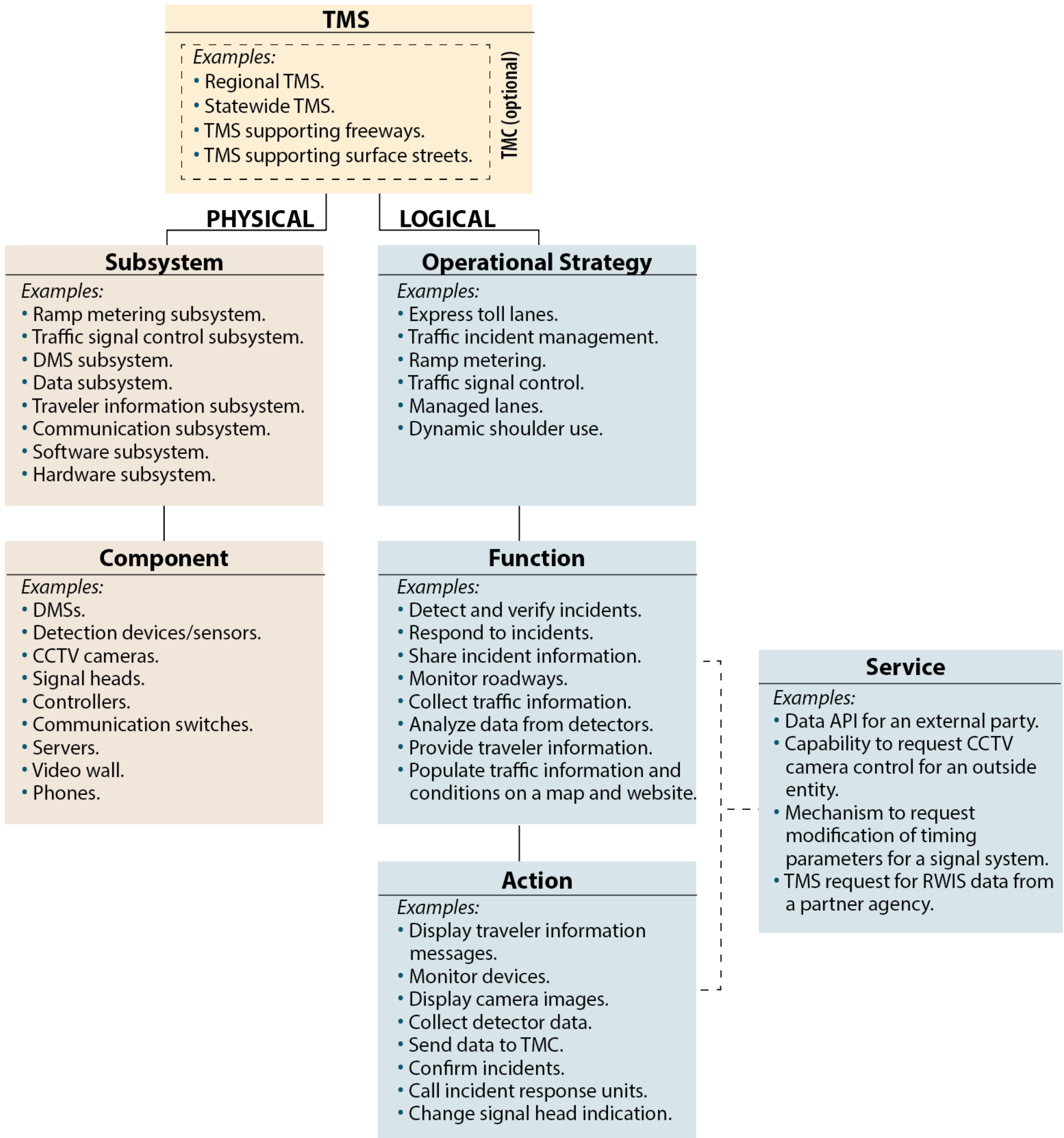
2. Understanding agency policies and operational procedures.

3. Applying policies and procedures in realtime based on changing conditions and different events.

4. Processing wide ranges of data and information and assimilating them.

5. Anticipating implications of implementing or changing the operation of different operational strategies or control plans.

TMSs provide the software platforms or subsystems that agencies and TMCs rely on to support operations. Figure 1 illustrates the physical and logical components of a TMS and examples of these components. Operational decisionmaking is associated with the logical elements of the TMS structure—operational strategies the TMS is designed to support, functions supported by the TMS, control plans that may be used, and actions to be executed.



Source: FHWA.
API = application programming interface; CCTV = closed-circuit television; DMS = dynamic message sign; RWIS = road weather information system.

Figure 1. Diagram. TMS structure with examples (Miller et al. 2021).

The decisionmaking framework associated with traffic management, shown in figure 2, involves four stages:

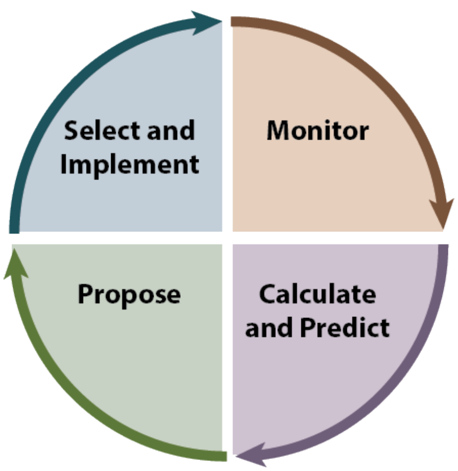
- Monitor: Collect and process data from various field devices, third-party data sources, and partners to evaluate the current conditions of the transportation network.

- Calculate and predict: Apply advanced data processing that combines current and historical information to predict the future state of the network and increased risk of impactful events. This phase also involves detecting/predicting events that will adversely impact traffic performance and warrant an operational response.

- Propose: Generate one or more response plans (i.e., sets of operational strategies, functions, and actions) to mitigate the effects of the traffic event.

- Select and implement: Select and execute the response plan most likely to best improve performance.

Early generations of TMSs typically relied on users to manually perform the activities associated with the four decision stages. Today, the availability of computer-based DSTs can reduce the burden on operations staff. DSTs can facilitate data processing, automating forecasting, and prediction. They can provide visualization tools to improve how TMSs monitor current conditions and predict future conditions. They can also make recommendations to maximize the use of operational strategies, functions, and actions. As such, they can be integrated with TMSs to fully or partially automate processing and decisionmaking activities that may occur across these four stages.

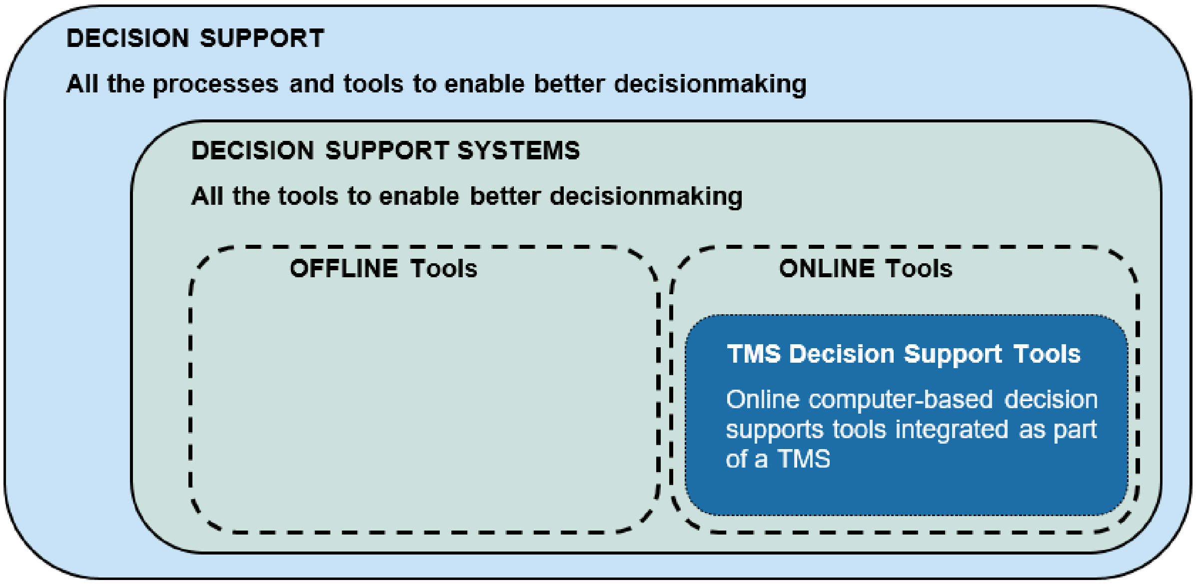


Source: FHWA.

Figure 2. Diagram. Traffic management decisionmaking (Miller et al. 2021).

WHAT IS A DSS?

Decision support is an overarching concept that embraces all the processes and tools that enable better, faster, and more consistent decisionmaking. Computer-based decision-support systems (DSSs) are used in several industries to improve business operations. Figure 3 depicts the taxonomy of DSTs adopted for this report. The report focuses on the “TMS Decision Support Tools” box within the diagram.



Source: FHWA.

Figure 3. Diagram. Taxonomy of decision support (Miller et al. 2021).

DSTs

DSTs include online computer-based tools and offline noncomputer-based tools. Examples of offline tools are paper-based decision trees and decision tables that can be printed and collated into reference information.

DSSs

DSSs are computer-based tools that support business or operational decisionmaking. They encompass technologies and solutions used for online or offline decisionmaking as follows:

- Online DSS are real-time, computer-based DSSs that support real-time traffic management and operational decisionmaking.
- Offline DSSs are typically used to support both short-term and long-term planning.

Examples of online tools that support real-time management and operation of TMSs include the following:

- Real-time traffic analysis tools have the potential to analyze data such as traffic conditions, weather, and transit system performance. The data can be integrated into the decisionmaking of how a TMS is managed and operated. For example, these tools can analyze data to enable improved decisionmaking for traffic signal timing.
- Look-up tables for traffic operational strategies and control plans simplify selecting operational strategies (e.g., ramp metering and lane control), control plans (e.g., time of day or demand responsive, open or closed), and actions to be implemented (e.g., incident response plans) based on conditions detected or projected to occur. While incident

response plans may be offline tools, look-up tables enable a simplified real-time process for selecting the appropriate plans.

Examples of offline tools for TMSs include the following:

- Maintenance DSSs and pavement management DSSs are examples of offline systems that agencies use to support maintenance activities.

- Incident response plans provide instructions for preestablished responses (e.g., plans and procedures) to different types of incidents, including processes for coordinating efforts among agencies and service providers. Agencies typically have plans developed to respond to a wide range of potential incidents, where the actions taken will vary based on location, time of day, severity, and conditions (e.g., traffic demand and weather). These plans enable consistent, rapid decisions, and they define how agencies and service providers respond to different types of incidents.

- Decision trees allow an operator to complete a structured process to reach a decision consistent with the organization's policies and accepted procedures. Through a series of questions, which usually have a few limited answers, operators can arrive at a decision regarding a specific issue.

- Performance monitoring, measuring, and reporting tools (e.g., spreadsheets and algorithms) generate individual measures of performance or summaries of overall performance based on current observed conditions and historical data. Examples of individual measures include travel time and travel delay indices. Examples of summaries include dashboards and reports that provide a snapshot of how the operation is performing based on industry-recognized measures. These summaries are typically generated by TMSs in realtime or on a daily, monthly, or annual basis. Such information enables policy makers and agency leaders to make better long-term decisions and helps the public understand how the system is performing.

DST INTEGRATION: ASSESSING, PLANNING, AND DESIGNING

As agencies continue to plan for next-generation TMSs, they are considering what enhancements may be needed and what may be reasonable and feasible to implement to improve TMS performance and decisionmaking and enable the automation of decisions (e.g., tasks, functions). As many existing subsystems and components can be modified to support TMS integration, agencies may want to evaluate whether their current TMSs can be modified to enhance functionality. Based on this evaluation, an agency can decide whether it will reuse and modify an existing TMS or design and build a new TMS. The following questions can be examined during such evaluations:

- What technologies may be appropriate to select?

- What may be needed to support the integration and use of these new technologies?

- What data may be needed for different functions or services?

- What translations (e.g., format changes) may be needed to enable data to be used for different functions or services?
- What tools and accompanying software, if any, can be stand-alone or can be integrated into the software subsystem of the TMS?
- What commercial off-the-shelf or open-source software products are acceptable, or would a commercial or proprietary product would be more appropriate?

Once the requirements and capabilities of an existing TMS have been established and compared to desired requirements and capabilities, an agency can evaluate available products and technologies. If the agency concludes that no commercial off-the-shelf products or internal reusable product components are suitable, the agency can consider building its own TMS. Staff can identify and assess the potential build/buy/reuse decision alternatives (e.g., commercial off-the-shelf, open source, or proprietary) for each component of the TMS that may need to be revised. After staff conduct an analysis and reach decisions, staff can document recommended selections for technologies and products for each component. This process can be considered part of the system design.

These issues and technologies are just some of the factors that agencies may consider. These decisions are further discussed in chapter 5, which includes details on the specific evaluations and decisions some agencies have made when integrating DSTs into their TMSs as examples.

HOW TO USE THIS REPORT

This report explores the application of DSTs and processes for improving TMSs. State DOTs and local agencies may use the concepts and processes in this report to develop practices to plan, design, operate, monitor, evaluate, and report on the performance of decisionmaking with a TMC. Each chapter discusses key concepts of DSTs, lessons learned from case studies from the state of practice for DSTs, and the three common types of DSTs useful for traffic management: knowledge-driven DSTs, data-driven DSTs, and model-driven DSTs.

The intended audience for this report is public agency staff, academia, and contractors involved in planning, designing, implementing, maintaining, managing, and operating TMSs. This report aims to help readers understand different types of tools that have the potential to improve the decisionmaking capabilities and performance of a TMS. Readers are assumed to have a general awareness of ITS technologies and TMSs.

REPORT OVERVIEW

This report provides an overview of practices to consider when integrating DSTs into the real-time management and operation of a TMS. Additionally, it outlines issues to plan for when integrating DSTs into existing or new systems, requirements of DSTs and TMSs, and what to consider when integrating a DST with a TMS.

For this report, the study team conducted literature searches on existing research, TMS deployments, DSTs used in the transportation industry, and other resources for transportation agencies (e.g., the Federal Highway Administration (FHWA) ITS program (FHWA 2021)). Information was also provided to the study team by individuals and agencies, as follows:

- During the 2018 Transportation Research Board (TRB) Workshop on DSTs for the Next-Generation of TMS (National Operations Center of Excellence 2018).
- During the associated sessions and meetings of the TRB Committee on Freeway Operations (ACP20) (ACP20 2018).
- From National Cooperative Highway Research Program (NCHRP) reports (Horowitz et al. 2014; Margiotta et al 2007).

This report is organized as follows:

- Chapter 1: Introduction—Introduces the concepts of TMSs and DSTs and provides an overview.
- Chapter 2: Overview of DSTs—Discusses some of the DSTs used within a TMC for operations and planning.
- Chapter 3: Decision Support and TMSs—Discusses the real-time decision-support subsystems used within a TMS.
- Chapter 4: TMS Decision-Support Needs—Describes the process of identifying agency needs a DST can meet. This process can be done early in the planning stages. The agency defines what the project will accomplish, establishes that the project is necessary, and provides the means to validate the success of the project.
- Chapter 5: Using DSTs—Describes the process of assessing an agency's capabilities and existing DSTs (e.g., processes, procedures, business rules, noncomputer-based tools, datasets). Gathering this information allows an agency to identify DSTs that meet its needs. Additionally, agencies can use this process to identify how to improve TMS management, operations, and capabilities. This identification will form the basis for the new DST to be implemented. Agencies may decide how and when to reuse existing DSTs, what modifications may be needed to create a new DST, and when and how to retire existing DSTs.
- Chapter 6: Selecting a DST for Traffic Management—Outlines the requirement and design phases, which take the project from understanding system and user needs to beginning system development. Major decisions about strategy and the integration approach are made during these phases. Begins with a discussion of the set of stages that encompass these phases.
- Chapter 7: Procuring and Implementing DSTs—Introduces issues agencies may consider when procuring a DST. Discusses how integration strategies influence procurement options, the procurement options best suited to meet an agency's goals, and what types of products are compatible with agency policies and procedures.

- Chapter 8: Initiating the Use of DSTs—Provides an overview of the steps for preparing to operate and evaluate a DST once it has been developed, configured, deployed, and integrated into the TMS.

- Chapter 9: Monitoring, Evaluating, and Using a DST—Presents a discussion of effective practices and provides recommendations to agencies for validating and calibrating DSTs once they are deployed and operational. Discusses the process of continually monitoring and evaluating DSTs to ensure they are meeting the goals, objectives, and performance metrics established by the agency.

- Chapter 10: Using and Maintaining DSTs—Provides an overview of the ongoing operations, monitoring, and maintenance of a DST once it has become operational. Outlines routine maintenance activities for each type of DST technology.

CHAPTER 2. DECISIONMAKING AND DECISION-SUPPORT TOOLS

This chapter introduces the range of different types of DSTs agencies may use to sustain their traffic operations programs, including planning for day-to-day traffic operations, planning traffic management, and managing and operating TMSs. It summarizes the key factors that influence decisionmaking, describes the concept of decision support, and highlights the types of DSTs typically used by agencies. Additionally, it examines how DSTs are used offline and online and how operational policies and procedures may affect the design and use of a DST by a TMS.

This report focuses on the use of online DSTs to support the management and operation of a TMS. However, understanding the more general concepts associated with decision support and the range of tools at an agency's disposal provides the reader with a clearer context of the potential benefits to enhance the next generation of TMSs.

The objectives of this chapter are to describe the following:

- What factors influence decisionmaking.
- How operations-related policies and procedures affect an agency's decisions about the design or operation of a TMS.
- How different types of DSTs can be used for various types of decisions, tasks, or functions carried out within a TMS.
- What types of offline and online DSTs can be used within TMSs.

This chapter helps the reader understand the concept of decision support and the tools used to assist in making operations-related decisions. Additionally, it discusses the types of tools that may be appropriate to integrate into the day-to-day operation of a TMS and provides examples of how these tools have been integrated and used by TMSs. Subsequently, chapter 3 will discuss how these tools and processes are integrated and used to automate or improve specific tasks, functions, and operations of a TMS.

TRAFFIC MANAGEMENT SYSTEMS

TMSs are the tool that agencies use to improve the management and operation of the surface transportation system. TMSs also share information with and support other traffic systems management and operations programs or initiatives. TMSs provide the functions, services, and capabilities for agencies to manage traffic, control ITS field devices, manage incidents and planned events, coordinate with stakeholders in response to these events, and provide information on travel conditions.

A key feature of TMSs is helping operators make faster and more effective decisions in response to current and projected conditions (e.g., traffic, roadway infrastructure, weather, and events). Decision-support capabilities have expanded to support or automate functions, decisions, and actions that TMS operators carry out or implement (e.g., ramp metering and identifying travel times). Recently designed TMSs can provide responses to multiple events. With increased focus on integrated corridor management (ICM), newer TMSs have also begun the transition from managing, controlling, or coordinating travel on one type of facility to supporting several facilities (e.g., freeways, surface streets, and traffic signals).

FACTORS INFLUENCING DECISIONMAKING

Decisionmaking is often inherently complex. The challenges of decisionmaking may be compounded by decisionmakers' experience levels, societal pressures, cultural norms, fatigue, and inherent biases. These factors also impact the quality of the policies, procedures, programs, actions, services, and operational performances that result from the decisions. The effects of these limitations can become even more pronounced as systems grow in complexity, when decisions need to be made quickly, or when there is insufficient data or insufficient time to assess an incomprehensible amount of data. DSTs are designed to address these limitations, and over the years, these tools and associated processes have demonstrated their effectiveness across a variety of fields (e.g., medical diagnoses and emergency response).

As transportation networks have grown more complex and congested, decision support has played a greater role in optimizing the efficiency and safety of the movement of people and goods. As the amount of information available for these networks continues to grow, DSTs can help process data and improve the quality of the decisions made, which will influence the performance of these complex systems.

The use of established processes and logical aids can offset some of the typical biases that arise when making decisions. Robinson et al. (2017) found that DSTs can minimize the influence of biases (e.g., confirmation bias) on decisions, ensure consideration of alternatives, and encourage quantitative assessment of options. However, the same study also found potential disadvantages to overly relying on DSTs, such as discounting intuition and experience. Despite these pitfalls, properly designed and implemented DSTs can be valuable assets to an operator in a TMS. Lukasik et al. (2011) found that the use of DSTs in transportation can leverage and improve on several recent advances in realtime traffic management and operation.

The Decision Support Concept

The concept of decision support emerged from theoretical studies of organizational decisionmaking. Initially, decision support generally focused on higher-level strategic decisions, and then expanded to include tools for supporting all types of decisions. The following three key computer-based DSSs eventually emerged, accompanied by an evolution from single-user to multiple-user approaches:

- Executive information systems—Ran on mainframe computers to package a company's data and provide sales performance or market research statistics for decisionmakers. The intent was to develop computer applications that highlighted information to satisfy the company's strategic and program-planning needs. Typically, an executive information system would only provide high-level data that supported these decisions.

- Group DSSs—Evolved from single-user to multiple-user computer-based systems. Group DSSs were designed to use inputs from numerous users simultaneously interacting with the system to arrive at a decision as a group.

- Organizational DSSs—Focused on coordinating and disseminating decisionmaking across functional areas and hierarchical layers. A key goal was to ensure that decisions were congruent with the organization's goals and with management's shared interpretation of the competitive environment.

Since decision support's continued evolution as a field of study and practice during the 1980s, computing hardware has become more powerful—and, as more data have become available, DSSs have continued to evolve and improve. Today, many commercial products are available to build DSTs and provide decision-support functions across multiple industries. For example, many systems in the financial and medical industries have evolved since the early research. These systems assist decisionmakers across numerous topics, including loan processes, which financial instruments to purchase, and which medicines to prescribe.

TYPES OF DECISION-SUPPORT TOOLS

DSTs used within a TMS may be classified across two dimensions: the type of interaction and the approach used in the tool. The type of interaction refers to the level of human interaction with the DST—how decisions are made (manual or automated) and the degree to which the DST involves the decisionmaker (interactive or automated). Table 1 shows common approaches used in DSTs for traffic management.

Table 1. DSTs mapped to decision-support classifications.

Approach	Incident Response Plans (Offline)	Decision Trees (Offline)	Performance Measurement Tools (Offline)	Real-Time Traffic Analysis Tools (Online)	Look-Up Tables (Online)
Knowledge-driven	Yes	Yes	No	Yes	Yes
Data-driven	No	Yes	Yes	Yes	Yes
Model-driven	No	No	Yes	Yes	No

Three common approaches are used in DSTs for traffic management, as follows:

- Knowledge-driven DSTs provide specialized problem-solving expertise based on the processing of stored facts, rules, procedures, and similar forms of knowledge. They attempt to emulate human reasoning but with more consistent results. Expert systems are the best-known type. They use databases of knowledge generated by previous expert users and a system's business rules to emulate the decisionmaking capabilities of an expert user of the system. Based on this knowledge, such tools recommend actions to traffic operators. Knowledge-driven tools are different from table-based tools (e.g., decision tables) in the way knowledge is extracted, processed, and presented. The knowledge-driven DST attempts to emulate human reasoning; the table-based tool responds to all events in a predefined manner. The following are primary characteristics of knowledge-driven DSTs:

    - Provide recommendations based on human knowledge.
    - Apply a heuristic (i.e., practical, rule-of-thumb) technique for problem solving.

- Data-driven DSTs use data to aid in the decisionmaking process. Data-driven DSTs use data from databases that can be queried and enable the processing and analysis of data to develop insights that support decisionmaking. One example is statistical analysis software, which is one of the most common types of DSTs. The effectiveness of a data-driven DST depends on the quality of the data gathered and the effectiveness of the decisionmaker's analysis and interpretation. With many of the data analysis tools in use by the industry, transportation agencies can customize dashboards to display the data they want to see and run custom reports. Ongoing advances in how data can be accessed, analyzed, and visualized enable agency staff who do not have a technology background to work with analytical tools, analyze data, and make more informed decisions. The following are primary characteristics of data-driven DSTs:

    - Summarize data into usable information.

    - Use large amounts of data and query and visualize the results of the analyses conducted in well-organized ways.

    - Offer flexible reporting and analytical capabilities.

- Model-driven DSTs use mathematical models and simulation tools that express the theoretical relationships among data elements or key variables of interest for an analysis being conducted. These tools can be used (online or offline) to simulate the behavior of a transportation system (or parts of the system) using different values for certain parameters. Model-driven DSTs use different types of analysis tools (e.g., statistical software and traffic analysis software) to assess the available data, evaluate the data, and report on conditions. Traffic analysis tools that use data captured by a TMS can be used offline or online to assess how the transportation network will perform based on various potential actions. Model-driven DSTs can be used in realtime as part of a TMS to predict the possible outcomes of actions a TMS is considering implementing, thereby allowing agencies to assess impacts on key metrics like travel time, environmental impacts, and person and vehicle throughput. The following are primary characteristics of model-driven DSTs:

    - Provide what-if analysis based on historical and assumed (e.g., scenario-based) data.

    - Leverage algorithms and simulation and optimization tools to provide decision support.

    - Use data and parameters provided by decisionmakers to help analyze situations without the need for intense amounts of data input.

DSSs are computer-based tools that support business or operational decisionmaking activities. This term encompasses a wide range of technologies and solutions used for online or offline decisionmaking. Within the framework of knowledge-driven, data-driven, and model-driven, TMSs commonly use a number of DSTs. These DSTs can be offline or online.

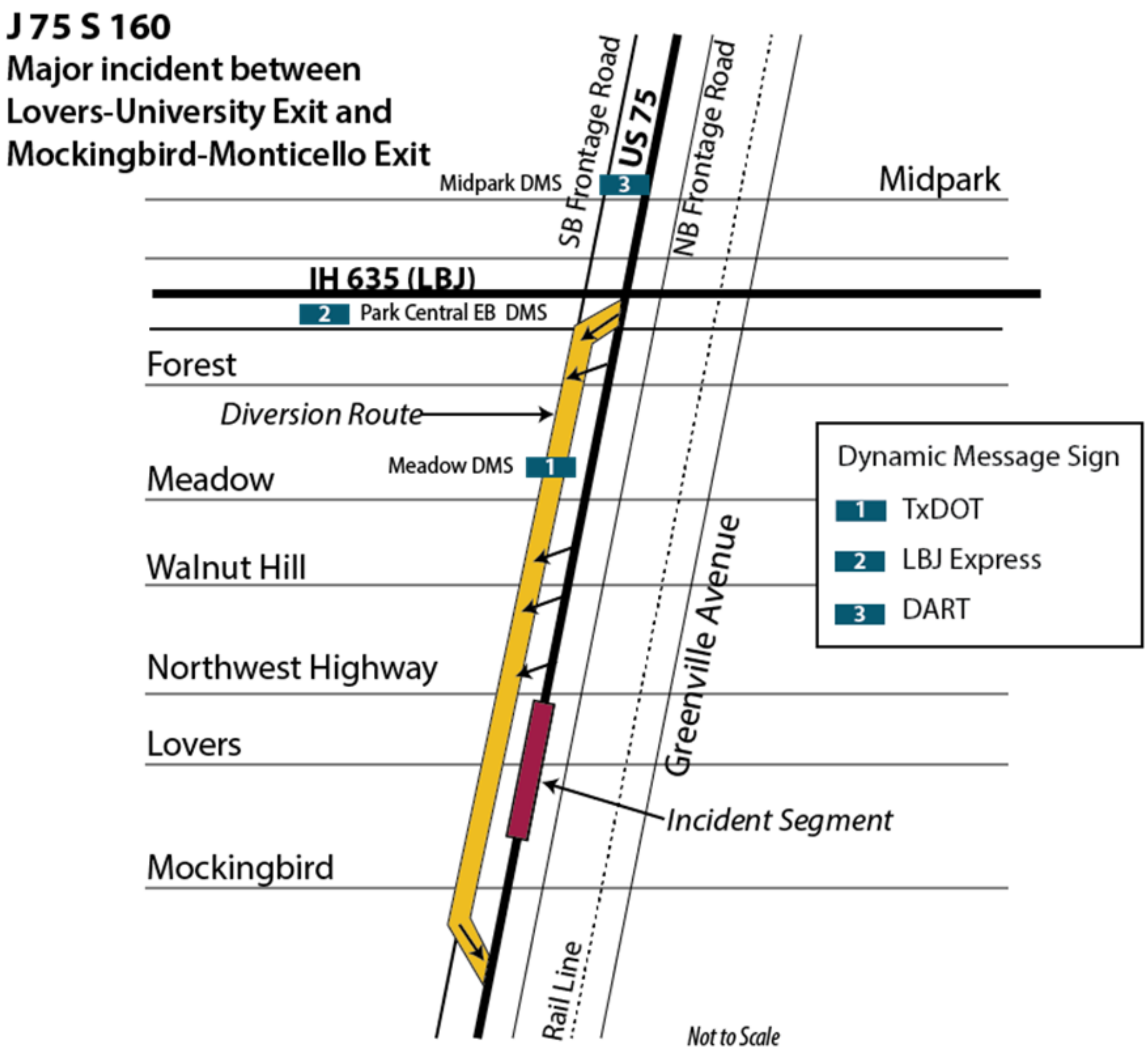
Offline DSTs

Offline DSTs are typically used to support short-term and long-term activities related to transportation system management and operation planning, programming, and policy. Maintenance DSSs and pavement management DSSs are examples of offline systems that agencies use to support maintenance activities. The following sections describe examples of offline DSTs used in TMSs.

Incident Response Plans

An incident response plan is a predefined set of actions an agency performs based on the location, type, and expected impact of an incident (e.g., vehicle on shoulder and one or two lanes blocked). Within a TMS, the use of these plans as an offline tool may involve an operator viewing a plan from a printed document and implementing actions within a TMS. Many TMSs have incident response plan books that are developed based on experience. These plans provide operators with a playbook for how to respond to a particular incident. The responses will prescribe appropriate actions (e.g., temporary detours and traffic signal changes) and identify resources needed. Incident response plans are usually selected using a process in which operators monitor data from the TMS and manually select the response plan based on variables such as incident location, time of day, level of congestion (e.g., length of queue), and availability of detour routes; some TMSs have converted these offline tools into online tools. Either way, these incident response plans are static documents, either electronic or printed, that the operator uses to respond to an event.

Within some TMSs, the software recommends to an operator which incident response to use based on business rules. Response plans might be based on the location, time of day, and severity of an incident. These plans are usually not integrated into the TMS, but a reference to the incident response plan is provided within the software. The TMS has basic business rules integrated into the software, which then selects the appropriate incident response plan based on the rules. Figure 4 shows a sample response for a major incident, including various field infrastructure and a suggested diversion route.



DART = Dallas Area Rapid Transit; EB = eastbound; LBJ Express = Lyndon Baines Johnson Expressway; NTTA = North Texas Tollway Authority; SB = southbound; TxDOT = Texas Department of Transportation; WB = westbound.

Figure 4. Illustration. Overview of a major incident response plan (Miller et al. 2021).

Based on the incident in figure 4, the incident response plan further defines the overall response plan and suggests individual agency actions (figure 5).

Dallas

- Frontage road: activate signal timing signal plan #32 and monitor every 15 min.

Native Signal ID	Name	SmartNet Signal ID	DIRECT Signal ID
3455	CENTRAL @ UNIVERSITY	1010139110	2053
3449	CENTRAL @ MOCKINGBIRD	1010139040	2061
3453	CENTRAL @ SMU	1010139090	2081
3468	CENTRAL @ SOUTHWESTERN	1010139240	2112
3465	CENTRAL @ LOVERS	1010139210	2113
3473	CARUTH HAVEN @ CENTRAL	1010139290	2126
3496	CENTRAL SBFR @ WALNUT HILL	1010139520	2159
3491	CENTRAL SBFR @ PARK LN	1010139470	2160
3489	CENTRAL SBFR @ NORTHPARK S.C.	1010139450	2167
3501	CENTRAL SBFR @ MEADOW	1010139570	2178
5634	Central SB @ Churchill	1010142330	3141
3766	FOREST LN @ CENTRAL SBSR	1010142280	3166
3505	ROYAL LN @ CENTRAL SBSR	1010139610	583

- CCTV: monitor traffic conditions on Southbound US 75 Frontage Rd. every 15 min.

TxDOT

- DMS:

Message ID	Name	SmartNet ID
2	75_SB Meadow	5074420

LBJ Express

- DMS:

Message ID	Name	SmartNet ID
2	HOV 635_EB_Park Central	5074220

DART

- DMS:

Message ID	Name	SmartNet ID
2	HOV 75_SB Midpark	5074900

Rd = road.

Figure 5. Screenshot. Agency actions in a response plan for a major incident (Miller et al. 2021).

Decision Trees

A decision tree is an offline tool that enables an operator to work through a formalized process to reach a decision consistent with an agency's accepted procedures and policies. Users answer questions that usually have a few limited answers to arrive at a decision about a specific issue. Decision trees are mostly used for planning, selecting additional equipment, and deploying specific technologies. Some decision trees are developed to assist operators in consistently predicting incident durations. These decision trees provide a process with decision points and options; the operator then works through each decision point to reach a conclusion or action at the end. The decision tree is basically a series of questions with potential answers that are linked together to create a decision once the questions have been answered.

For example, for a decision tree used in the Maryland Coordinated Highways Action Response Team (CHART) system, when a TMS operator is notified of an incident, the DST asks the operator a series of questions to help determine an approximate incident duration. The DST then provides the operator with an expected duration, which is entered into traffic management software. Table 2 and table 3 show the variables and outputs of part of the decision tree and the relations between incident clearance times and their associated factors. These relations and factors were derived from experience and historical data.

Table 2. Maryland CHART incident duration decision tree.

No.	Description of Classifier			Clearance Time (Min)
1	IF	(road=I895 & incident_type=disabled) or (noTT=0 & noSDsh=0 & incident_type=disabled) or (noTT=0 & road=US50 & incident_type=disabled)	THEN	Minor (<30)
2	ELSE-IF	(OC=TOC3 & noLane=13 & county=MO & incident_type=cpd) or (noTT=0 & road=I495 & incident_type=disabled & pavement=dry) or (chart=1 & noLane=12 & road=I95 & incident_type=disabled)	THEN	Minor (<30)
3	ELSE-IF	(OC=TOC3 & SDBmain=minor & pavement=unspecified) or (OC=AOC_South & noLane=12 & road=US50) or (weekday & incident_type=disabled & detection=CHART)	THEN	Minor (<30)
4	ELSE-IF	(totalveh=2 & incident_type=fatality) or (night=0 & road=other & incident_type=fatality)	THEN	Major (>120)
5	ELSE-IF	(noTT=0 & county=3 & incident_type=disabled) or (OC=TOC3 & noSDBmain=0 & incident_type=cpd)	THEN	Minor (<30)
6	ELSE-IF	(noSUT=0 & non-holiday & exit=22 on I495, I270, I695, and US50) or (SDBmain=minor & county=MO & detection=CHART) or (noSDsh=2 & noSDBmain=0 & noODBsh=0 & incident_type=disabled)	THEN	Minor (<30)
7	ELSE-IF	(night=0 & noODBsh=0 & exit=31 on I495, I270, I695, and I83) or (noODmain=3 & SDBmain=minor & county=Anne Arundel) or (chart=1 & noLane=13 & noSDBmain=0 & peakhr=PMpk)	THEN	Minor (<30)
8	ELSE-IF	(noLane=12 & SDBmain=minor & road=I495 & incident_type=cpd) or (totalveh=2 & noSDBmain=0 & county=Frederick & incident_type=cpd) or (noLane=12 & noSDBsh=1 & incident_type=cpd & peakhr=PMpk)	THEN	Minor (<30)
9	ELSE-IF	(region=Baltimore & incident_type=cpi & detection=CCTV) or (county=BC & incident_type=cpi & pavement=unspecified & detection =MDTA) or (OC=AOC_Central & totalveh=3 & incident_type=cpi & non-holiday)	THEN	Intermediate (30−120)

BC = Baltimore City; MDTA = Maryland Transportation Authority; MO = Montgomery; PG = Prince George's.

Table 3. Descriptions of variables in an incident duration decision tree.

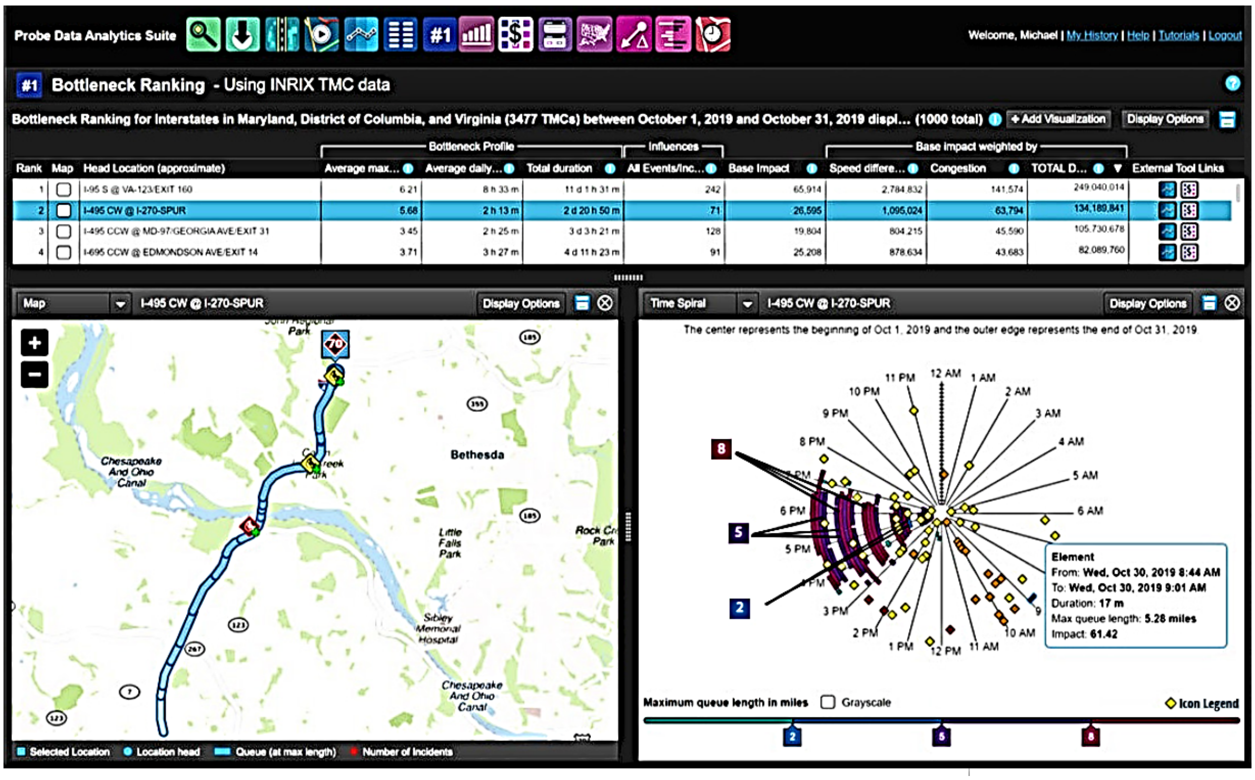
Variable	Description
Incident_type	Type of incidents: • Disabled: disabled vehicles. • Cpi: collision with personal injury. • Cpd: collision with property damage. • Fatality: collision with fatality. • Fire: vehicle on fire. • Unknown: no specific information available.
noTT	Number of tractor trailers involved with incident
noPVS	Number of pickup trucks, vans, and sports utility vehicles involved with incident
noSUT	Number of single-unit trucks involved with incident
Totalveh	Total number of vehicles involved with incident
noLane	Number of lanes on both directions (including shoulders and medians)
noSDASH	Number of shoulder lanes on the same direction as where an incident occurred
noSDBsh	Number of blocked shoulder lanes on the same direction as where an incident occurred
noODsh	Number of shoulder lanes on the opposite direction as where an incident occurred
noODBsh	Number of blocked shoulder lanes on the opposite direction from where an incident occurred
noSDmain	Number of main lanes on the same direction as where an incident occurred
noSDBmain	Number of blocked main lanes on the same direction as where an incident occurred
SDBmain	Ratio of number of blocked lanes to total number of lanes on the same direction as where an incident occurred
noODmain	Number of main lanes on the opposite direction as where an incident occurred
noODBmain	Number of blocked main lanes on the opposite direction as where an incident occurred
ODBmain	Ratio of number of blocked lanes to total number of lanes on the opposite direction from where an incident occurred
OC	Responsible operation center
Pavement	Pavement conditions: dry, wet, snow/ice, chemical wet, and unspecified
Chart	If CHART is involved in the clearance, 1; otherwise, 0
Detection	Incident detection sources
Night	If an incident occurs between 8 p.m. and 6 a.m., 1.
Peakhr	• AMpk: a.m. peak periods (7–9:30 a.m.) • PMpk: p.m. peak periods (4–6:30 p.m.) • Non-pk: off-peak periods
Region	• Washington: Fredrick, Montgomery, Prince George’s, District of Columbia. • Baltimore: Anne Arundel, Baltimore City, Baltimore, Carroll, Harford, Howard. • Eastern: Caroline, Cecil, Dorchester, Kent, Queen Anne’s, Somerset, Talbot, Wicomico, Worcester. • Southern: Calvert, Charles, Saint Mary’s. • Western: Allegany, Garrett, Washington.

AM = morning; PM = evening.

Through the combination of these variables and associated questions, the decision tree provides the operator with an expected duration after answering questions provided by the DST.

Performance Measurement Tools

Performance measurement tools (e.g., monitoring and reports) provide regularly scheduled performance indicators for various aspects of the surface transportation system. Performance monitoring tools generate individual measures of performance or summaries of overall performance based on the monitoring of current conditions and historical data. Performance measures or reports (e.g., dashboard summaries) can be used by TMSs as an offline DST, as shown in figure 6. They can assist operators in identifying bottlenecks and areas of recurring incidents that may need further investigation for mitigation strategies (e.g., signing, marking, and roadway cross-section changes).



Note: Screenshot created by CATT Lab using the Bottleneck Ranking Tool from the Regional Integrated Transportation Information System Probe Data Analytics Suite.

Figure 6. Screenshot. Top 1,000 ranked bottleneck locations in Maryland, District of Columbia, and Virginia between October 1 and October 31, 2019 (Miller et al. 2021).

Online DSTs

Online DSTs are real-time computer-based tools that support real-time traffic management and operational decisionmaking. These tools can be separate from or fully integrated with a TMS. The following are examples of online DSTs that are used in TMSs and can be fully integrated into the real-time operation of a TMS.

Real-Time Traffic Analysis Tools

As stated in *Traffic Analysis Toolbox Volume I: Traffic Analysis Tools Primer*, "Traffic analysis tools are designed to assist transportation professionals in evaluating the strategies that best address the transportation needs of their jurisdiction" (Alexiadis et al. 2004, 5).

Traffic analysis tools are designed to help evaluate the strategies used to address the transportation needs of a jurisdiction. The term is collective and describes both software-based analytical procedures and methodologies that support aspects of traffic and transportation analyses. Methodologies include sketch planning, travel demand modeling, traffic signal optimization, and traffic simulation. Collectively, traffic analysis tools can help practitioners do the following:

- Improve process of decisionmaking and help practitioners arrive at better planning and engineering decisions for complex transportation problems. They can estimate the impact of traffic management and other strategies after deployment and help to set priorities among competing projects. They can also provide a consistent approach for comparing potential improvements or alternatives.

- Improve outcomes of decisionmaking. They can estimate the impacts of various strategies and help decisionmakers set priorities among competing projects. Traffic analysis tools can also provide a consistent approach for comparing potential improvements or alternatives.

- Reduce disruptions to traffic. Traffic management and control strategies come in many forms and options. Analytical tools provide a way to estimate the effects prior to full deployment of the management strategy. They may be used to initially test new TMS concepts without the inconvenience of a field experiment.

- Facilitate evaluations to prioritize planning and operational alternatives. This aspect typically involves comparing no-build conditions with alternatives that include various types of potential improvements. The impacts are reported as performance measures and are defined as the difference between the no-build and alternative scenarios. The results can be used to select the best alternative or prioritize improvements, with the goal of increasing the odds of a successful deployment.

- Make improvements in design and evaluation time and cost. Traffic analysis tools are relatively less costly when compared to pilot studies, field experiments, or full implementation costs. Furthermore, analytical tools can be used to assess multiple deployment combinations or other complex scenarios in a relatively short time.

- Illustrate strategies to stakeholders and the public. Some traffic analysis tools have graphic and animation displays that can be used as tools to show what-if scenarios to stakeholders and the public.

- Support operation and management of existing roadway capacity. Some tools provide optimization capabilities, recommending the best design or control strategies to maximize the performance of a transportation facility.

- Monitor performance of existing transportation facilities. Analytical tools can also be used to evaluate and monitor performance. In the future, it is hoped that monitoring systems can be directly linked to analytical tools for a more direct and real-time analysis process.

Highway Capacity Software™ (HCS™) is a common traffic analysis tool that agencies and transportation professionals use (McTrans Center 2022). HCS is the software version of the *Highway Capacity Manual* (HCM) (TRB 2016). The HCM contains concepts, information, and procedures for computing the capacity and quality of service of various highway facilities and the effects of mass transit, pedestrians, and bicycles on the performance of these systems. HCS implements the procedures defined in the HCM to enable users to analyze various types of transportation infrastructure. With known traffic volumes and many other inputs, HCS can determine the current and projected level of service (LOS) and allows agencies to analyze various transportation data and explore possible improvements to their transportation networks. The following are key characteristics of the HCM:

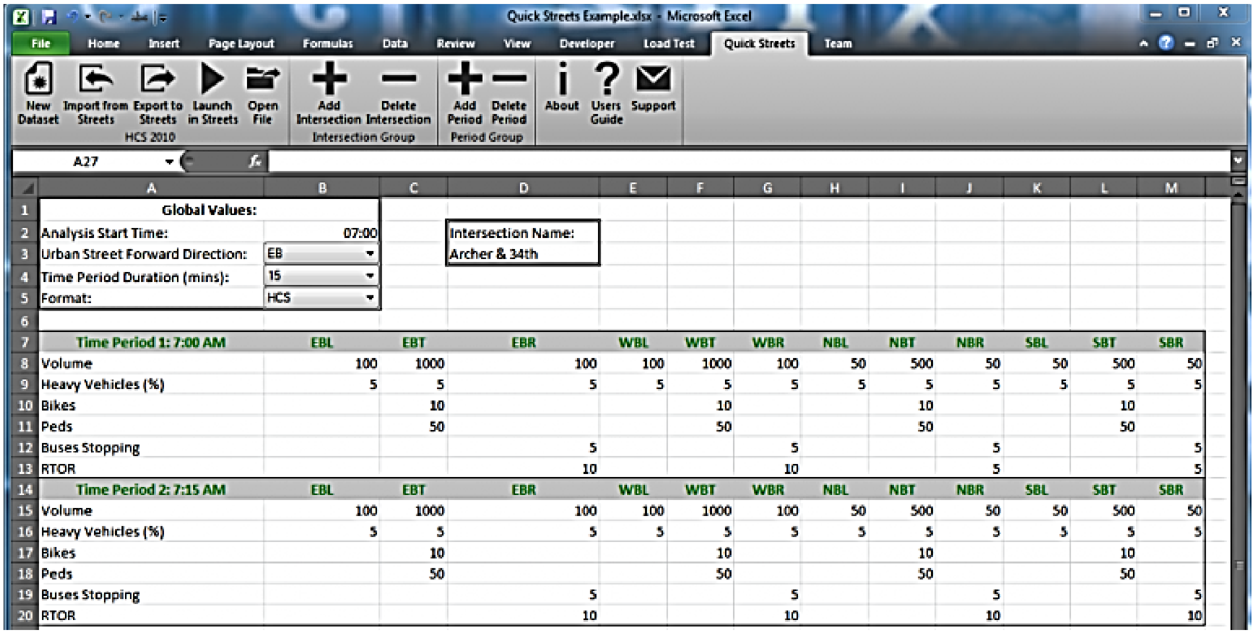
- Closed form—The practitioner inputs the data and parameters. After a sequence of analytical steps, the HCM procedures produce a single answer.

- Macroscopic—Inputs and outputs produce average performance during a 15-min or 1-h analysis period.

- Deterministic—Any given set of inputs yields the same answer every time.

- Static—They predict average operating conditions over a fixed period, and they do not deal with transitions in operations from one system state to another.

The tools in the HCM quickly predict capacity, density, speed, delay, and queuing on a variety of transportation facilities and are validated with field data, laboratory test beds, and small-scale experiments. Quick Streets (figure 7) is a spreadsheet add-in that converts traffic input data to an HCS Streets file (McTrans Center 2022). Users can import traffic count data from any source for the spreadsheet to use with HCS Streets. Quick Streets populates an HCS Streets file with multiple intersections, multiple periods, or both. It allows the user to save the input data to an HCS Streets file and launches the data directly, provided that HCS is installed on the user's computer.



© McTrans Center. Original spreadsheet: HCS Streets.

Figure 7. Screenshot. Quick Streets add-in interface (Miller et al. 2021).

Look-Up Tables

A look-up table is a DST that provides a table or matrix of conditions and responses to assist operators with consistent responses to events. While incident response plans may be offline tools, look-up tables integrated into a software program or routines coded into a software program will enable a real-time process for automating the selection of the appropriate plans. Look-up tables provide an online tool where operators enter a few values. The DST then uses algorithms embedded in a software program to calculate the desired output (e.g., plan, action) for a TMS operator to implement. The decision tree example shown in table 2 can be converted to an online DST, where an operator enters several variables (e.g., location, event type, and number of lanes blocked) into a single screen, and the duration is then calculated. The difference is that the decision tree asks one question at a time, but the look-up table asks several things simultaneously.

As an example, look-up tables are currently used in TMSs for traffic signal timing as part of an incident response plan. When an operator enters an incident's information into the TMS, certain basic information is collected through an event management screen. The DST uses the information provided by the operator, the current time of day, the congestion levels or LOS of an intersection, and the direction of a detour route to select a specific timing plan in response to the event. A look-up table can be thought of as a multivariable matrix coded into the TMS software. Table 4 shows the input variables the TMS's DST uses to select an existing traffic signal timing plan as part of a response plan. The intersection number is the signalized intersection that is part of the response plan. The time of day is based on local operations and typical rush hour times. The day of the week can be a weekday, weekend day, or specific day of the week. The current LOS is an indication of how much congestion the intersection is currently experiencing, based on traffic engineering principles. Lastly, the detour direction is the direction the traffic signal timing plan is trying to optimize for the detour. A look-up table provides the TMS with the output of a timing plan number for each combination of variables shown.

Table 4. Input variables within a look-up table.

Intersection Number	Time of Day	Day of Week	Current LOS	Detour Direction
A-1	Morning peak	Weekday	A, B, C	Northbound
A-2	Evening peak	Weekend day	D	Southbound
A-3	Off peak	—	E	Eastbound
A-4	—	—	F	Westbound

—No data.

Creating the look-up table would require creating multivariable data within the data subsystem used by the DST software subsystem to look up the signal timing plan number for a specific traffic signal when all other variables are known.

CHAPTER 3. INTEGRATING DECISION-SUPPORT TOOLS INTO TRAFFIC MANAGEMENT SYSTEMS

This chapter provides an overview of the subsystems used to assist in making decisions within TMSs and those systems with an operations center. As described in chapter 1, decision support enables better, faster, and more consistent decisionmaking. DSTs include all the different resources (e.g., look-up tables and analysis models) that can be used to improve decisions. The use of DSTs online or in the real-time management and operation of a TMS requires integration with the software and data subsystems.

The objectives of this chapter are to describe the following:

- Key functions of TMSs.
- Considerations for integrating DSTs into TMSs.
- Capability ranges for DSTs when integrated into the real-time operation of a TMS.

This chapter details the functions of DSTs, how they support decisionmaking and can be integrated for this purpose, and the types of data that are used and shared with various TMS subsystems. It seeks to increase readers' understanding of the capabilities of DSTs and their utility in managing and operating a TMS.

KEY TMS FUNCTIONS

Traffic operational strategies are functions and actions to improve the management and operation of roadway networks, optimize performance, and improve safety. Agency goals, policies, procedures, and performance metrics inform the deployment and use of operational strategies.

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

As technology continues to evolve, the functionality to collect and manage more complex forms of data has also evolved. This evolution of functionality shapes the way agencies implement operational strategies, as they can leverage more data to make informed decisions. As agencies upgrade their components and software, the timeframe for decisionmaking and responding to changing conditions has improved.

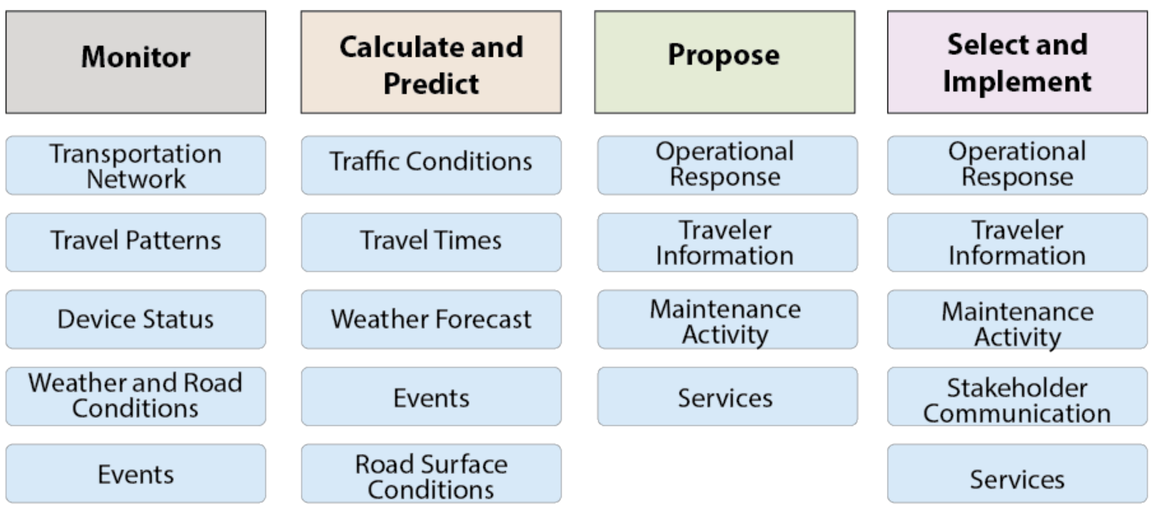
As discussed in the second section of chapter 1, the decisionmaking framework associated with traffic management involves four decision stages, which have the following functions:

- Monitor.
- Calculate and predict.
- Propose.
- Select and implement.

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

- Monitor roadway conditions.
- Collect weather information.
- Perform roadway maintenance during weather incidents.
- Analyze collected data.
- Disseminate traveler information.
- Deploy speed limit reductions or speed advisories.
- Use predictive decision-support software to assist operators in system adjustments and overrides.
- Provide traffic detection and surveillance.
- Manage incidents and special events.
- Manage freeway ramps.
- Manage preferential and priced lanes.
- Coordinate among agencies.
- Monitor and evaluate system performance.

Figure 8 breaks down these functions into subfunctions. The following three sections in this chapter discuss the functions in more detail.



Source: FHWA.

Figure 8. Diagram. Key functions of a TMS with DSTs (Miller et al. 2021).

Monitor

The monitor function includes many subfunctions focused on data and information review. During the monitoring process, DSTs monitor data and information available to TMSs to detect changes. When changes occur, DSTs move to the next function, calculate and predict. The following subsections outline types of data and information reviewed during the monitor function.

Transportation Network Data

Depending on the field devices used to collect data and the facilities or services being monitored, this subfunction may include monitoring a range of various types of data (e.g., speed, volume, occupancy, travel time, transit vehicle location, and transit service schedule adherence) stored on the data subsystem. New data sources—including connected vehicle (CV) data—will provide a tremendous amount of other data (e.g., hard braking, windshield wiper activation). CV data will provide TMSs with additional information on the conditions of the transportation network.

Travel Patterns

This subfunction includes monitoring vehicle trips throughout a network based on origins and destinations using data including transit routes, turning movements at intersections, and transportation flow patterns. Monitoring routes allows the system to calculate travel times, assess schedule adherence for transit vehicles, and use these data to determine where congestion is occurring.

Device Status

This subfunction includes monitoring the state and status of devices (e.g., dynamic message signs (DMSs) and traffic signals) and assets (e.g., transit buses, pumping stations, and air quality sensors).

Weather and Roadway Conditions

This subfunction includes monitoring travel conditions on roadways, occupancy levels on transit vehicles, and queues at intersections. Its process also looks at weather and environmental variables (e.g., moisture or water on roads, wind, precipitation, pavement temperature, and air quality).

Events

This subfunction includes monitoring incidents, construction, and special events within a transportation network (e.g., vehicle crashes, transit bus breakdowns, and construction projects).

Calculate and Predict

The calculate and predict function uses a variety of DSTs, which can include algorithms, rules engines, and models. (See chapter 5 for a more detailed discussion.) These DSTs are integrated into the software subsystem and can use data in the data subsystem to assess current conditions, identify when actions may be needed, and make predictions based on assessments of data from the monitor function. The DSTs used can be for a specific function or action or can be more advanced and perform multiple different calculations in support of the functions or actions they are designed to support. The following sections outline conditions that can be predicted during the calculate and predict function.

Traffic Conditions

Algorithms and models assess and report on current and predicted future travel conditions (e.g., LOS, congestion levels, and weather), with and without potential actions, on roadways being monitored. These calculations are usually based on historical information from similar times of day and accepted engineering formulas, and they have the potential to predict the timing and location of weather conditions and crashes (e.g., location, type, and severity) by using models.

Travel Times

Algorithms and software applications (e.g., traffic simulation models) integrated into a software subsystem predict travel times in the future with and without potential actions (i.e., the results of using a specific response compared to no action). Similar to predicting traffic, this prediction function estimates travel times based on current conditions or a future period. These predictions are usually based on historical information from similar times of day, weather conditions, and congestion levels.

Weather

Weather forecasting models (or services) predict current and future conditions for specific locations. The weather models use current and predicted weather conditions (e.g., wind, precipitation, and storm direction and speed) to determine conditions on a roadway on a link-by-link basis. This feature allows DSTs to consider the weather on a specific route.

Events

Algorithms and software applications on a software subsystem predict the probability of occurrences of unplanned events (e.g., crashes) and the likely impacts of events. This function typically uses historical crash data to predict probable potential locations for crashes. These predictions are based on current traffic and weather conditions, day of week, severity of any conditions, and time of day. Agencies can use this information to deploy response vehicles preemptively across networks. Additionally, this information can be used to select response plans for unplanned and planned events (e.g., incidents, construction, and special events).

Roadway Surface Conditions

Weather forecasting models (or services), road weather information system sensors, and historical data predict roadway surface conditions. Roadway maintenance providers use this information to predict weather and roadway conditions and optimize road surface treatments. Treatments can then be timed appropriately, and treatment locations and frequencies can be ranked based on where the effects of weather events are most severe.

Propose, Select, and Implement

The propose, select, and implement functions involve actions that an agency can take or implement based on information generated during the calculate and predict function—if an acceptance is needed prior to implementation. Some agencies are able to automate the select and implement function as their TMSs mature and confidence grows in their response calculations, which provide the basis for making these selections. However, the number of agencies using this functionality remains small. The automation of these functions can be based on the established policies, procedures, expertise, and experience of an agency's operations staff and on the capabilities of a TMS. By applying calibration techniques used in the transportation modeling industry, agencies can develop and calibrate their prediction models and algorithms. These models and algorithms need agencies to routinely monitor, evaluate, test, and make changes as more data are collected and TMSs are operated. The following sections outline primary subfunctions for the propose, select, and implement functions.

Operational Responses

Operational responses use predefined and dynamic response plans that suggest actions an agency can use to respond to changes in the transportation network. These response plans usually consist of changing the operation of devices, such as traffic signal timings, DMS messages, ramp metering rates, and lane control indicators. Responses also include deploying specific assets to the field, such as safety service patrols and temporary DMSs. This subfunction selects predefined response plans agencies have previously developed or use rules and algorithms to create a response plan based on its calculations.

Traveler Information

The traveler information subfunction disseminates information to the public about transportation network changes and recommended responses. Dissemination can include messages on DMSs, information within agency 511 systems, highway advisory radio messages, and various social media messages. This subfunction also provides special response plans for America's Missing: Broadcast Emergency Response (AMBER) Alerts, Silver Alerts, and other special events.

Maintenance Activities

The maintenance activity subfunction uses outputs from the weather and road surface condition subfunctions (in the calculate and predict function) to implement specific maintenance activities related to weather, such as snow removal, salt applications, and road closures. It also implements actions for other environmental incidents, such as alerts for poor air quality or high water levels. For some systems, this subfunction can also identify other required maintenance activities, such as preventative or emergency maintenance for devices, roads, and transit vehicles.

Services

The services subfunction uses output from the calculate and predict functions to request services from entities outside of a TMS. The services requested may include wrecker services, emergency services, and other services needed to fully respond to an event managed by a TMS.

Stakeholder Communication

The stakeholder communication subfunction informs stakeholders about TMS actions. Communication mechanisms include stakeholder requests for TMSs to perform actions as part of ICM programs.

DST INCORPORATION INTO TRAFFIC MANAGEMENT SYSTEMS

Objectives for incorporating DSTs into TMSs may include automating or supporting decisionmaking required by operators and actively managing and operating the surface transportation network. Any DST integrated into a TMS may require an interface, and there are generally certain procedures that must be followed for an operator or analyst to integrate and use a DST. The DST (and/or its software) may need to be integrated with a software subsystem, data subsystem, computing hardware, and DST-generated data users or decisions (data can be translated into appropriate formats, if needed). This integration process enables sharing and using the data generated by the tool. The following sections discuss issues to consider with these key interfaces.

Data Subsystem

The core functions of a data subsystem are to provide data processing and storage for the TMS and support access to the data by other subsystems and external users. The data subsystem uses application programming interfaces (APIs) to interface with other subsystems or components that extract, send, and enable the data to be transformed and loaded into the database in the TMS. An API specifies how software programs may interact, the data they exchange, and how the data are exchanged (i.e., format and type).

The data subsystem also receives data from external sources by using APIs or interfaces to receive the data, translate them into the appropriate formats, and save them. Once the data are received, the data subsystem uses tools to check and manage within the subsystem so that data use is efficient, timely, and easy to maintain. The data subsystem needs to have the following functionalities to support any DST integrated into the operation of a TMS:

- Retrieve data from all sources available to the TMS in a timely fashion, as they become available, including real-time data streams and data that are updated less frequently (or even manually).
- Catalog data received in an electronically accessible data catalog.
- Transform data received into a format suitable for storage, processing, and retrieval by users and other applications.
- Secure data so that they are only accessible according to the usage policy and authorization parameters of the agency.
- Manage user and application accounts, authentication, and authorization for accessing the data subsystem.
- Encrypt communications and data between the data subsystem and its users.
- Provide access to all data appropriate for the user making the request.
- Provide data to authenticated and authorized users in a timely fashion, including data in storage and real-time data streams.

- Sustain the level of availability and performance necessary to support the operations of the TMS.

- Produce and provide status and diagnostic information to support the operation, maintenance, and management of the data subsystem.

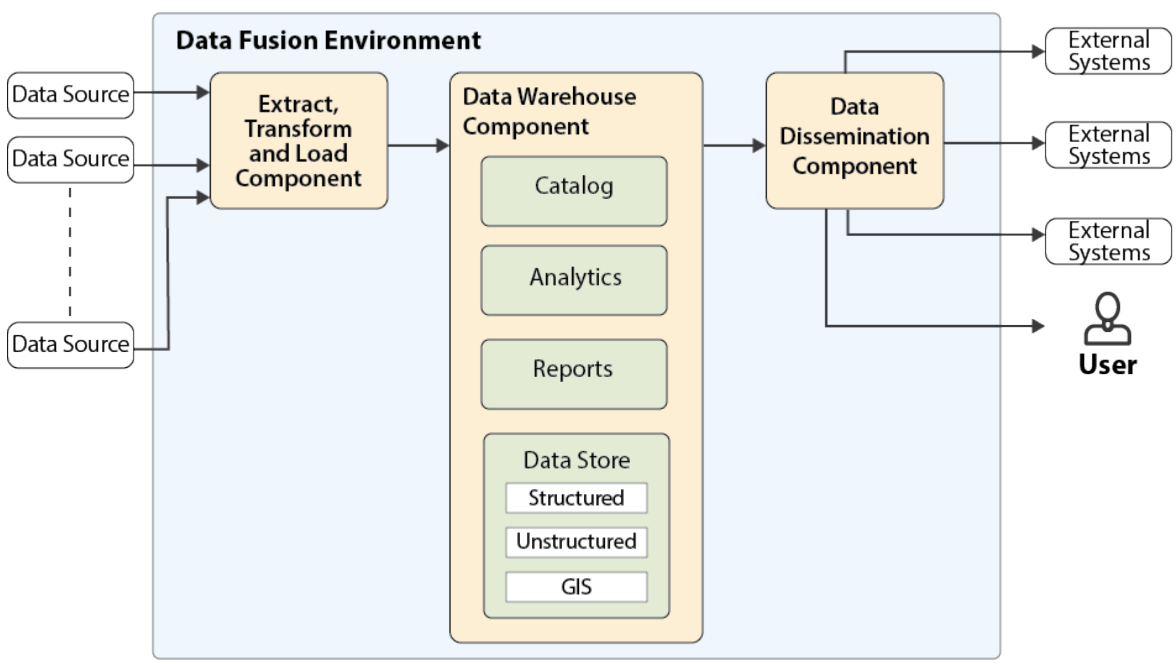
Interfaces With Software for DSTs

The TMS data subsystem uses APIs to integrate the data and functions of software programs installed on this subsystem or to share data with other subsystems. There are two types of APIs or interfaces typically developed and integrated into the software subsystem:

- Data providers (provide data to the TMS): The provider usually dictates the interfaces and the process, protocols, and requirements (e.g., formats) for receiving and using data from their system. The provider may furnish the associated API documentation (e.g., data dictionary, release notes, configuration guide, and user guide) to follow.

- Data subscribers (receive data from the TMS): The TMS typically dictates the data interfaces, and the subscribers develop their interfaces to meet the TMS requirements specified for the appropriate processes, protocols, and formats. The TMS provides the subscriber with an associated schema or data definition.

Figure 9 shows an example of a data subsystem that includes multiple databases with various sources generating and submitting data, which are extracted, transformed, and loaded into databases within the data subsystem.



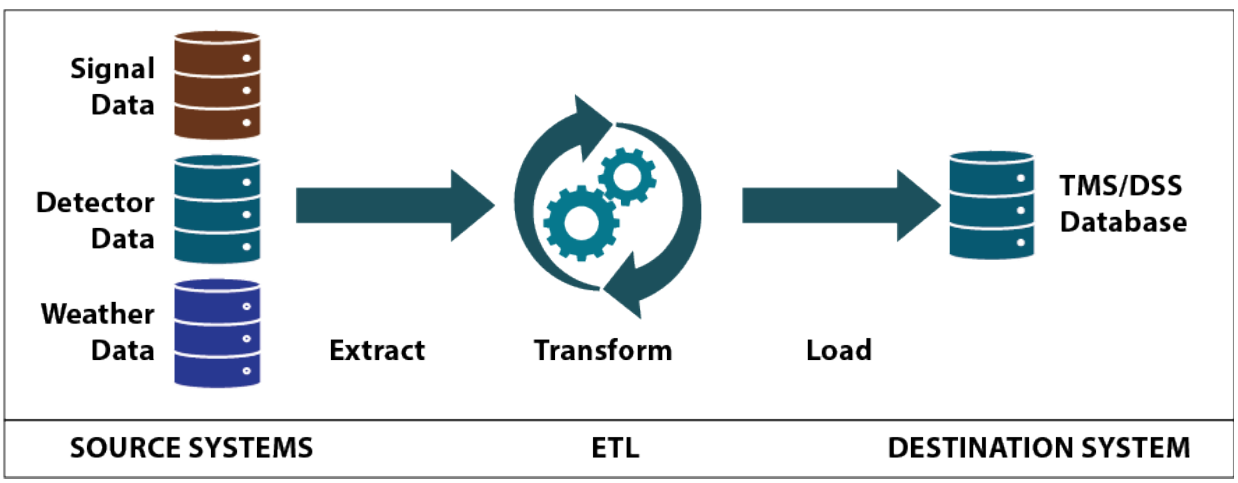
GIS = geographic information system.

Figure 9. Diagram. Sample data subsystem (Miller et al. 2021).

An API is developed for each data source, as each source will have data in different formats and will potentially use different protocols to send or receive data. Each API communicates with the data source, extracts the data, translates the data from the data source to the TMS system format, and then stores the data in the TMS database. For the TMS to provide data to other systems, an API interfaces with each TMS subsystem or other systems external to the TMS, where these systems may be subscribers and providers of data. For instance, the data subsystem may have a database specifically for storing traveler information that a statewide 511 system wants to use. The 511 system will then use the API to connect to the data subsystem and extract that information. Within the 511 system, an API will also be needed and will be integrated with its software to translate the data from the TMS database format to the format of the database the 511 system uses.

Figure 9 includes neither the use of the data nor the potential to control the field devices; rather, it is an example of the process within a TMS for carrying out functions supported by the software for a DST integrated into the software subsystem. The analytics and reporting functions shown are typically separate software that interface to the database to use and analyze the data for various reports and dashboards.

APIs are developed and installed between the DST and TMS subsystems or field devices to exchange data, issue commands, and integrate the operation of each system. Figure 10 illustrates the process to extract, transform, and load (ETL) data from external sources into a specific database on the data subsystem. The source systems provide APIs to developers who develop the tools, processes, and other information that use or incorporate the data.

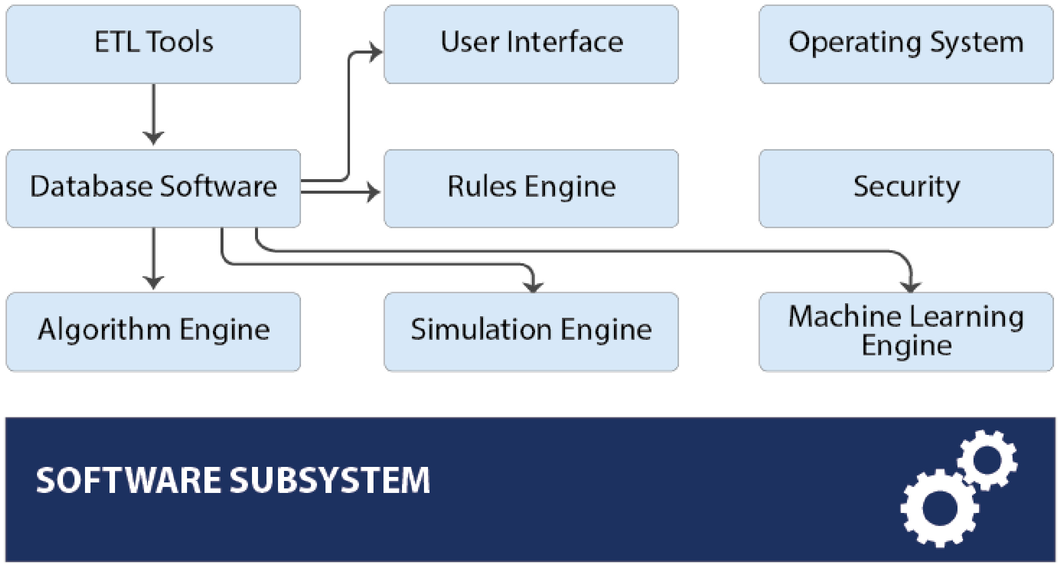


Source: FHWA.

Figure 10. Diagram. ETL process (Miller et al. 2021).

Software Subsystem

The software subsystem includes the programs that support the functions and services of the TMS. This subsystem will share some software products with the entire TMS and specific software programs installed for other subsystems or DSTs. The various engines are shown in figure 11.



Source: FHWA.

Figure 11. Diagram. Software subsystem and installed software (Miller et al. 2021).

Assorted software programs and APIs are integrated into this overall software subsystem to carry out all management and operating requirements of the system. A software subsystem can include multiple different software programs (e.g., commercial off-the-shelf software and proprietary), as shown in table 5.

Table 5. Software for different types of DSTs.

Software Products	Knowledge-Driven	Data-Driven	Model-Driven
Rules engine	Yes	Yes	Yes
Algorithm	Yes	Yes	Yes
Simulation software	No	Yes	Yes
Machine learning	Yes	Yes	Yes

These software products can be divided into two main categories: software products that will be part of any TMS and software products unique to DSTs.

Software Products Typically Used in TMSs

The primary types of software used in any TMS include the software needed to host the TMS on the computing hardware and some specialized functions, described as follows:

- ETL tools—Provide the functions for extracting data from the data interfaces, transforming the data into a specified format, then loading the data into a database to save for future use. Many ETL tools were originally developed to make it easier to save, access, and use data. ETL tools replace handwriting Structured Query Language code with drag-and-drop functionality to develop or make changes to a database when new data sources are introduced.

- Operating system software—Manages computer hardware, subsystems, and software programs installed on the software subsystem and provides common services to support managing, maintaining, and operating the software subsystem.

- Database software—Forms the database management system, which is a tool that makes it possible to organize data within a database. Several commercial off-the-shelf and open-source database software products are generally used in TMSs today.

- Security—Uses software that manages user profiles and access to the TMS. Security software is sometimes a part of the operating system or an agency's larger network (i.e., active directory). In other instances, a TMS will have its own security and user permissions. A DST may need separate dedicated security software to manage users and access to other software components.

- User interface (UI)—Provides users with a way to interact with the TMS and DST. UIs display information on the status of the transportation network, events, recommended responses, and the expected performance of the transportation network with and without the recommended response.

Software Products Unique to DSTs

Four types of software are typically used when integrating a DST or its associated software program. Table 5 shows the software that may be used in the three classifications of DSTs described in chapter 2. These software systems may have the ability to allow agencies to easily add or make changes when needed. The ability to easily make changes helps ensure the agency can continue to modify and evolve the capabilities of its system as the demands and needs of the system change. These four types of software are described in the following four sections.

Rules Engine

A rules engine is a software program or code integrated into or via an API to execute business rules used to make decisions in a DST. The rules might originate from external laws and regulations, agency policies, or other sources. Rules are configured and integrated into the rules engine software program to execute required functions or prepare information needed to support decisions. System developers or agencies can use several commercial products to develop a rules-based DST without having to completely develop custom code; these tools still need configuration and integration into agency systems to provide the desired functionality by operating agencies.

- A rules engine can be used when the following four conditions occur:
  - An agency has developed complex scenarios with simple rules.
  - An agency has not identified an algorithmic solution.
  - A TMS has endured ever-changing scenarios.
  - An agency has needed to make decisions quickly, usually based on partial data.

- A rules engine generally is not used when the following three conditions occur:
  - The project involves very few self-contained rules.
  - The business logic rarely changes.
  - The application demands rigid control of the execution flow.

Algorithms

Algorithms and software may use logical and mathematical formulas to calculate outputs (e.g., data, recommended actions) needed by a DST. The algorithms are usually based on specific formulas and may include engineering (e.g., traffic flow and environmental calculations), statistical (e.g., averages and means), and financial (e.g., cost and benefit) calculations. For example, HCS uses industry-recognized formulas and logic to process data and calculate results used for operations. Some agencies have integrated HCS into their TMSs for various traffic engineering analyses in realtime and nonrealtime (e.g., signal timing analysis). Using an API, the HCS receives data from a TMS requesting the HCS calculate a specific formula. Once the HCS calculates the result using an API, HCS provides the TMS with the result.

Simulation Software

Simulation software uses calibrated models to determine how a transportation network will perform based on various potential actions. Simulation can be used in realtime to determine effects on travel time, various environmental impacts, and person and vehicle throughput. Simulation tools integrated into a TMS as part of a DST can enhance an agency's ability to analyze strategies and perform complex data calculation in realtime. In certain cases, simulations can also offer predictive capabilities. Online modeling tools can be an effective way to predict future traffic conditions and thus are desirable—although not strictly required. Simulation software may be expensive to purchase, set up, and maintain; however, if used correctly, it can provide benefits. As confidence increases in the simulation software's results and agencies become more comfortable with its recommendations, a higher level of automation among TMS functions can be considered.

Machine Learning

Machine learning (ML) is based on the idea that data can be analyzed to identify patterns, and software can learn to make decisions based on these patterns with minimal human intervention.

ML software uses formulas that software developers and data scientists integrate into the software. The software uses the formulas to recognize patterns and learns how to optimize the ML software based on historical data and patterns. As more data become available, the quality and accuracy of the recommended or automated actions that use the formulas also improve. ML software may be challenging to set up and maintain due to the amount of data required to calibrate the learning algorithms. However, if calibrated correctly and monitored, it may provide benefits and lead to a higher level of automation among TMS functions.

Computing Hardware Subsystem

The computing hardware subsystem can vary depending on its purpose and location. A DST and its accompanying software program may be a part of a field device, traffic controller, TMS, or TMC. The computing hardware subsystem for a TMS is usually shared to provide economies of scale and reduce the overall cost. Most agencies use standard IT servers to host the software and database subsystems. The computing hardware includes servers with necessary processors and memory, network communication equipment (e.g., routers and switches) to enable data exchange, and data storage systems (e.g., storage area networks and hard drives), which are used for storing the software and data within the subsystem.

The capacity and performance requirements of the computing hardware are directly related to the functionality of the TMS, the processing power needed, and the amount of data involved. When considering computing hardware, agencies usually find they need to determine the requirements of the TMS and any specific DST, including processing and memory needs. This report does not offer information on how to select the appropriate computing hardware components; rather, agencies should use their IT department standards and sizing methodologies to select from existing options.

UIs Specific to a DST

A UI provides a visual means of interacting with a TMS using elements such as windows, icons, and menus. These elements are also used by most modern operating systems. Various UIs may need to be developed, either separately or by modifying the TMS to integrate the interface into it. The method of development depends on the function the DST is performing, how the software or algorithms are managed, and the tools used within the TMS.

For example, the Dallas ICM project consisted of three UIs, because three separate pieces of software were developed by three different companies. The primary interface was the operator UI, which was a modification to the existing TMS that allowed operators from all the agencies in the region to view its transportation data and manage events cooperatively through a recommended response plan. The TMS also had two administrative interfaces—one to manage the rules and algorithms for selecting response plans and another to manage the predictive model. However, ideally, a TMS will be modified to provide a single UI.

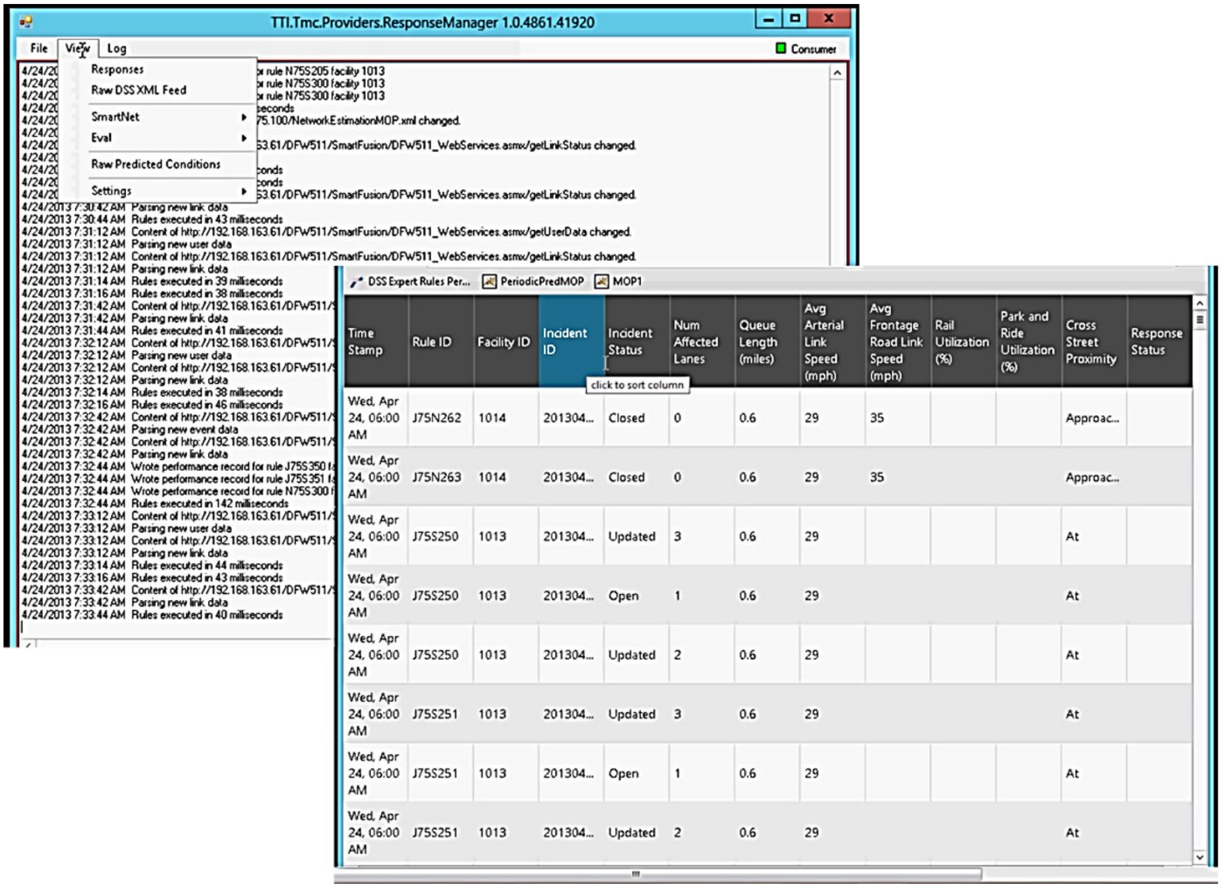
A graphical user interface (GUI), shown in figure 12, provides stakeholder agencies with a web-based information exchange tool. A GUI enables agencies to share information and manage incidents, construction, and special event information. A GUI is the presentation layer for the TMS. The Dallas ICM GUI enabled agency users to manage and monitor the status of their transportation networks, giving them a full event management capability and allowing them to make informed decisions about the management of their transportation infrastructure (FHWA 2015).

Figure 12. Screenshot. Dallas ICM project operator UI (Miller et al. 2021).

The main functionalities of a TMS's GUI software program are to do the following:

- Provide stakeholders with the ability to exchange data regarding incidents, construction, and special events in an interactive manner.
- Include an event management module that allows stakeholders and partner agencies to create incident or planned event trackers within the system and manage these events from detection to resolution.
- Provide the current status of devices and roadway and transit networks within the corridor on a map and through lists.
- Provide incident response plan information to corridor stakeholders.
- Monitor the status of recommended and implemented response plans from plan recommendation to incident resolution.

Figure 13 shows two rules engine administration interfaces for the Dallas ICM TMS. The administrator used these interfaces to view the current events and data received by the system (top left screenshot) and determine whether they match the rules within the rules engine (lower right screenshot).



© 2015 Dallas Area Rapid Transit.

Figure 13. Screenshot. Dallas ICM project business rules component UI (Miller et al. 2021).

The data input screen provides a time-stamped list of the event data received by the rules engine, the evaluation performed by the engine, and the actions the rules engine recommended. The rules evaluation screen shows a list of the active events within the TMS and which rules within the rules engine can be applied. This list shows the location of the event (Rule ID translated from the actual roadway link), number of lanes affected (percentage of lanes affected based on the total number of lanes), queue length (miles of backup from incident location), average speed on the roadway and potential diversion routes, transit and park and ride utilization (percentage full), and response status (if the event and rules were met and a recommendation was made). The DST administrator uses the information provided in these interfaces to troubleshoot errors and analyze why the DST selected a response to ensure the DST is operating correctly. The Dallas-area agencies used this information at their monthly operations meetings to decide if changes to the rules were needed and provide metrics on the use of the DST (e.g., number of events where it was used) (FHWA 2015).

The Dallas ICM TMS also used simulation software to predict the performance of the recommended response plan from the rules engine versus a do-nothing response. Figure 14 shows the interface for the simulation software to assess two such scenarios. Once the simulation software modeled the do-nothing and recommended responses, it provided a performance measure for both the recommended response plan and the do-nothing response option. If the recommended response plan improved the average travel time through the corridor for an individual vehicle by more than 2 percent, the response plan was recommended; otherwise, a do-nothing response was recommended.

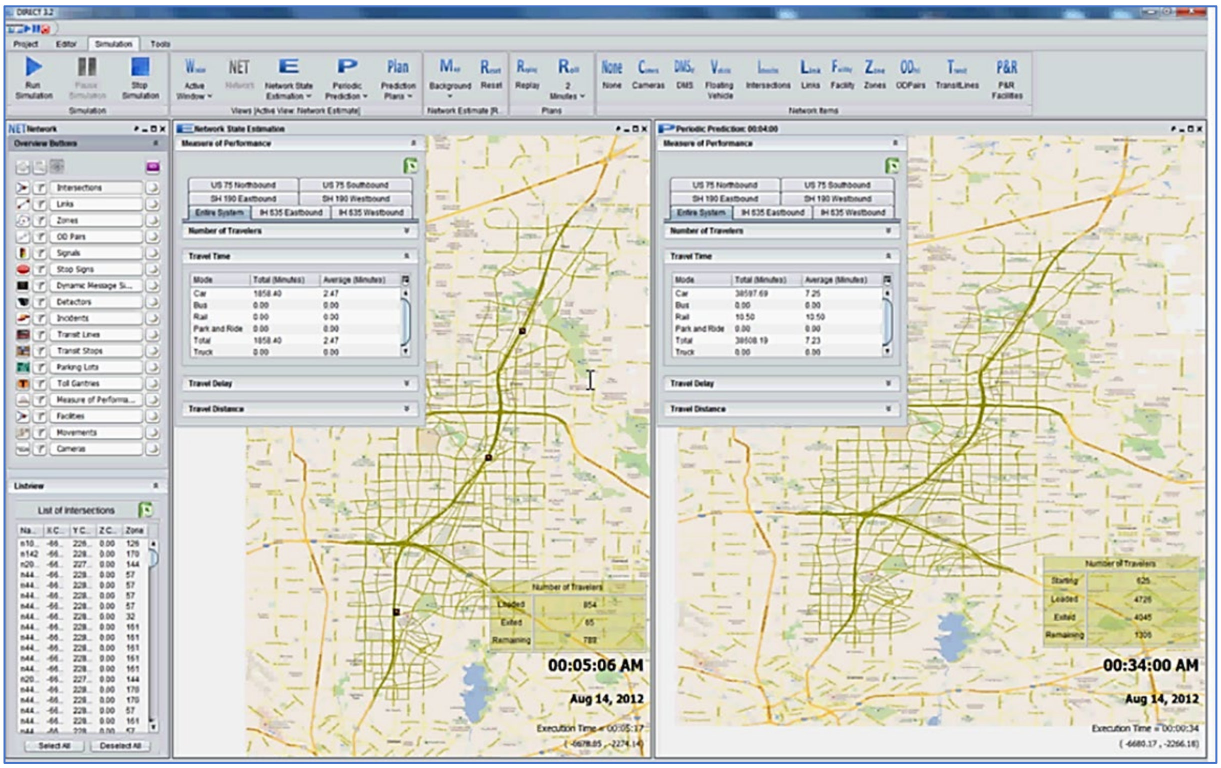


Figure 14. Screenshot. Dallas ICM project prediction component UI (Miller et al. 2021).

Logical Architecture of a TMS

Fully integrating a DST into a TMS provides a single software program to support all the functions of the tool. An advantage of integrating a DST into the software subsystem of the TMS is that a smaller computing hardware footprint can be used, maintained, and managed. Upgrading and changing the software program or API for a DST may only be needed in one location, depending on how the TMS is structured or designed. If a DST is not located in the software subsystem, any upgrade may need revisions to the software. Additionally, both the APIs and the TMS's UI may need to be upgraded as well.

One example of a fully integrated system is the Maryland CHART TMS. The goal of the CHART system is to manage freeway and arterial traffic flows more efficiently and safely. When freeways and other primary routes are unexpectedly congested, the TMS recommends response plans based on business rules. These response plans include changes in DMS messages, detour routes, and traffic signal timing plans. Arterial signal systems provide remote and adaptive traffic signal control and coordinated signal timing. Traffic signal technicians and

CHART system operators can better balance demand and capacity by adjusting traffic signal timing remotely through the TMS. An advantage of this system is that operators of different experience levels are likely to respond to incidents in a consistent manner—a new operator can respond with the same response plan as an operator who has years of experience. By integrating the DST with the CHART TMS, the Maryland State Highway Administration can reduce the computing hardware needed, only employ a single systems developer, and more easily make system updates to the TMS (Chart.maryland.gov n.d.; FHWA 2015).

An example of a fully integrated software subsystem is the Australian VicRoads TMS (figure 15). The Australian VicRoads TMS implements a feature called dynamic plan selection. Depending on the density of traffic and the dominant direction of traffic (e.g., inbound, outbound, or bidirectional) on a road, nearby signalized intersections are operated using several predefined traffic plans. A user sets up the signal timing and picks the traffic density levels and direction that apply. The system then automatically selects the appropriate signal timing. When a time-based traffic plan schedule is inappropriate due to varying traffic levels, the system automatically adapts the signal timing plan. The Australian VicRoads TMS uses many of the same functions as the CHART system, but it uses a real-time model to calculate congestion, travel times, and other measures used to manage and operate the transportation network (FHWA 2015).

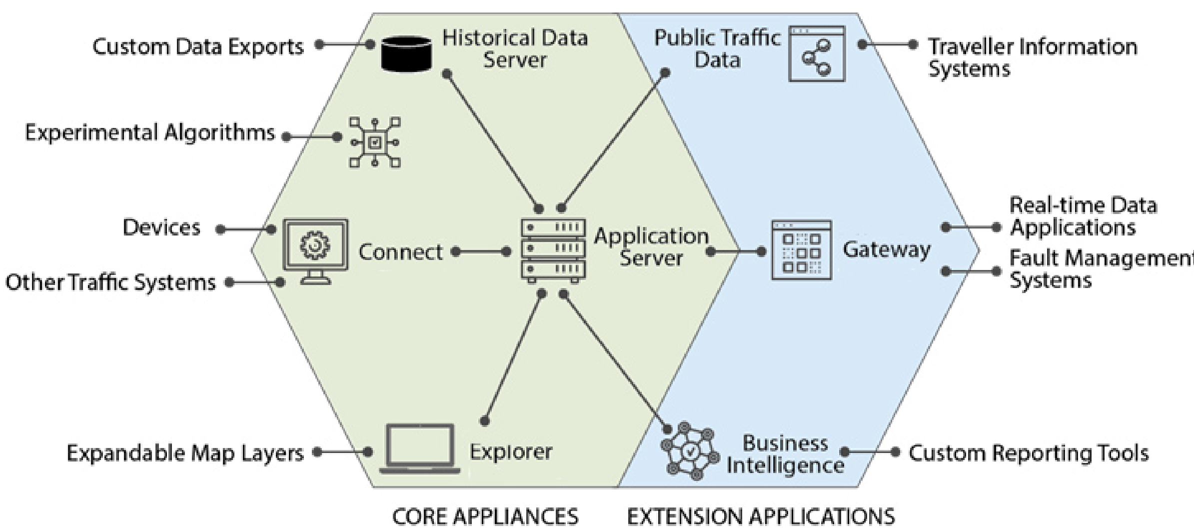


Figure 15. Diagram. VicRoads TMS decision-support subsystems architecture (Myers 2018).

The Australian VicRoads is fully integrated and provides a shared data subsystem, computing hardware, and UI. The software is integrated into the TMS so that VicRoads uses a single fully integrated TMS. Similar to the CHART system, an advantage of the Australian VicRoads is the reduced costs for the computing hardware, data subsystem, and ongoing operations and maintenance of the TMS. The Australian VicRoads software provides each of the four functions discussed earlier in this chapter, as follows (FHWA 2015):

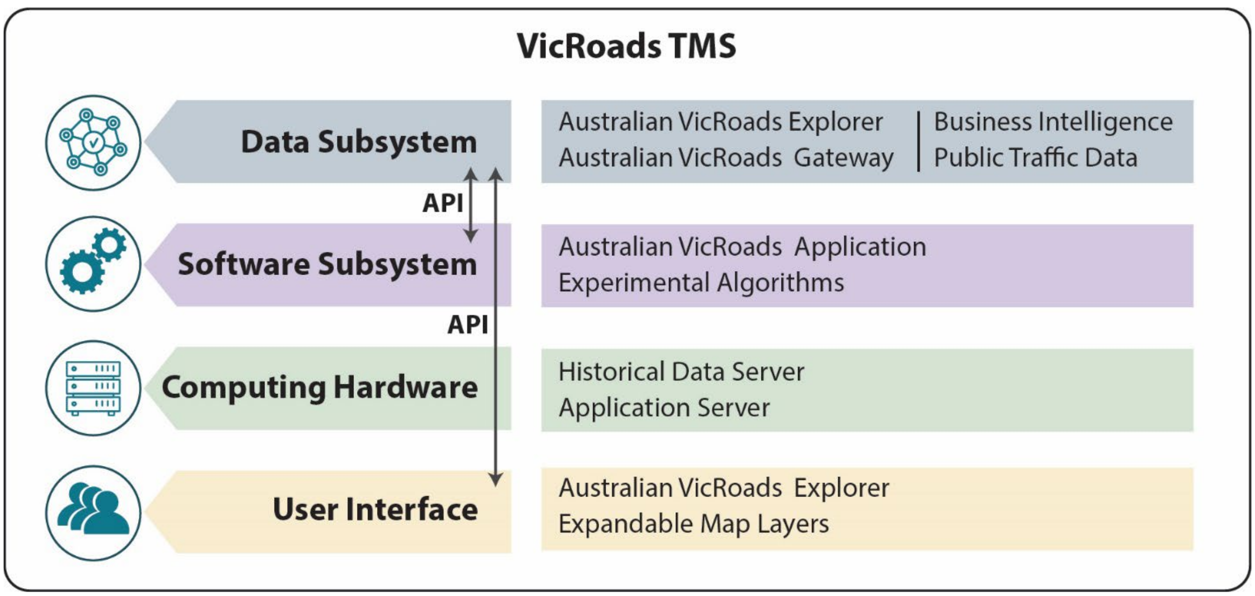
- Monitor: The Australian VicRoads TMS collects and processes data from various systems, including devices and other traffic systems (left side of figure 15). It analyzes this information to determine when the data have changed and compares them to the data in the historical data server.

- Calculate and predict: The Australian VicRoads DST uses traffic signal algorithms and models to make traffic signal timing calculations and recommendations.

- Propose: The Australian VicRoads DST provides recommendations to the TMS operator to improve the performance of the transportation network based on the output of the traffic signal timing plans that are selected or created within the calculate and predict function.

- Select and implement: The Australian VicRoads TMS automatically changes the signal timing plans in the affected traffic signal controllers, deploys messages on DMSs, and provides traveler information through various media when the TMS operator approves proposed actions.

The architecture shown in figure 15 is mapped directly to the Australian VicRoads subsystems, as shown in figure 16.



Source: FHWA.

Figure 16. Diagram. VicRoads TMS mapped to the four key subsystems of TMCs (Miller et al. 2021).

The data subsystem includes APIs to receive data from external systems and field devices and provides data to those systems through the Gateway, business intelligence, and public traffic data components shown in figure 15. The software subsystem consists of the application and the experimental algorithms. The application comprises the TMS capabilities, while the experimental algorithms provide additional decision-support software functions. The computing hardware consists of the application server and the data server. The data server provides some of the computing hardware for the data, and the application server provides the computing hardware for the TMS. The UI provides a map-based interface for the operators to monitor, control, and manage traffic on the streets and highways. The subsystem UI is called Explorer.

CHAPTER 4. TRAFFIC MANAGEMENT SYSTEM DECISION-SUPPORT NEEDS

This chapter describes the process of planning for and integrating DSTs into a TMS. It examines the needs, requirements, benefits, and issues to consider when integrating a DST into a TMS and its TMC.

The objectives of this chapter are as follows:

- To describe the issues agencies should consider before making an investment in a DST.
- To frame the needs for decisionmaking in the context of overall TMS system planning.
- To describe the strategies that can be used to assess the decision-support needs of a TMS.
- To present a process for evaluating and developing needs for DSTs.

This chapter introduces the issues an agency might consider as it evaluates its TMS capabilities, plans to improve the system, and considers its decisionmaking needs. It also identifies institutional issues to consider in these processes and in making decisions involving TMSs. After reading this chapter, the reader should better understand the needs and implications of integrating a DST into a TMS.

DST SELECTION AND USE: ISSUES TO CONSIDER BEFOREHAND

As stated in the *Systems Engineering Guidebook for Intelligent Transportation Systems 3.0*:

> Needs assessment is an activity accomplished early in system development to ensure that the system meets the most important needs of the project's stakeholders. The goal is to ensure that their needs are well understood before starting development. In many cases, there will be more needs than can be met, even conflicting needs (California Department of Transportation and FHWA 2009, 39).

When considering a DST, agency practitioners can judge whether they are trying to solve issues the agency's existing TMS does not address. The following questions should be considered prior to pursuing a DST:

- What needs or issues does the agency seek to solve?
- What constraints does the agency face in implementing a solution?
- What decisionmaking process is presently in place?
- What information and performance data are currently considered and can be used as starting points for framing other alternatives?

An agency may want to assess situations where decision support can possibly be beneficial or steps in the existing process that have bottlenecks or potential for human error. It may identify and assess how decisions are currently made and evaluated and the information and tools used to support decisionmaking. These steps can lead an agency to identify where in its decisionmaking process support tools, including a DST, may potentially assist users in their task flows.

UNDERSTANDING NEEDS IN THE CONTEXT OF OVERALL SYSTEM PLANNING

The processes for determining needs; assessing feasibility; and planning, designing, and implementing a DST may seem complex. However, following the systems engineering process and answering questions at each step may be an option for designing, pursuing or procuring, and implementing a DST. Systems engineering is an organized approach to developing and implementing a system. The International Council on Systems Engineering (INCOSE) defines systems engineering as follows:

> [Systems engineering is] an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem (INCOSE 2011).

It is valuable to use the systems engineering approach in designing ITS infrastructure so that the technology effectively supports the management and operation of the transportation system. In addition, applying the systems engineering approach is consistent with 23 Code of Federal Regulation (CFR) Section (§) 940.11(a), which states that all "ITS projects funded with highway trust funds shall be based on a systems engineering analysis" (National Archives eCFR 2022).

Assessing Traffic System Needs

A project team should consider assessing needs as a part of the overall planning, design, and implementation process for a DST. The key steps are as follows:

- Assess the current capabilities and performance: This assessment usually begins with gathering information about the overall landscape of the traffic system being managed. Identify existing capabilities, available data sources, and desires for enhanced capabilities. Gather input from stakeholders, who can often be identified by examining complaints or concerns about certain decision points that indicate problems.

- Identify the user needs, evaluate them, and analyze gaps: Build on information gathered in the first step to conduct a more detailed stakeholder needs assessment and gap analysis. Identify shortcomings and elicit stakeholders' needs, desires, and constraints. Needs assessments can help the project team and agency set aside preconceived notions of what the DST may accomplish.

- Develop a concept of operations (ConOps): The ConOps frames the overall system, including specifying the problems to be addressed by the DST on the basis of user needs. The ConOps identifies the stakeholders, elements, and capabilities of the planned DST. It may also establish relationships among the stakeholders and system elements, including the flow of information and processes to be performed.

The project team should consider the following high-level issues in determining the appropriateness of a DST:

- A DST is often well-suited to environments requiring structured and quick decisionmaking, particularly multitiered decisionmaking across a range of transportation modes and agencies.
- A DST offers a mechanism for managing, harnessing, and optimizing the power of information as ever-growing volumes and varieties of data with increasing complexity become available to transportation practitioners.
- A DST potentially facilitates fast, structured, objective decisionmaking that builds on the experience of experts and promotes collaboration across multiple agencies, transportation modes, and stakeholder groups.
- A DST possibly lessens the risk of unintended operator bias in actions and decisionmaking because it relies on empirical data and structured rulemaking.
- A DST potentially assists with predicting adverse transportation conditions and identifying corresponding mitigation strategies if it is suitably designed and implemented.

Once a project team determines a DST may be an option to meet its needs, the team can conduct a more in-depth evaluation of circumstances and conditions, examining the following issues:

- At what level of implementation will the DST function?
    - Implementation levels may correspond to offline strategic uses for long-term decisionmaking. Historically, DSSs that might not have included data from a TMS (e.g., asset management and traffic analysis) were used for this purpose.
    - A TMS, device, or TMS operator may make online, real-time traffic management decisions that can be used as an integrated tool within the TMS.
- What roles and responsibilities might system users undertake, including agency personnel (operators, managers, etc.) and those at partner or stakeholder organizations?
- What modality will present information to operators and other users? Will information be presented using visual displays, through alerts, or by other means?
- What timeline will decisionmaking follow? What time demands will system users have? How much time is available to implement recommended actions? Are there gaps between the time it currently takes to make decisions and the timeframe when those decisions are actually needed?
- What types of data, information, and requirements will the DST need to achieve the desired functions and performance? How detailed will the recommended actions communicated to users need to be?

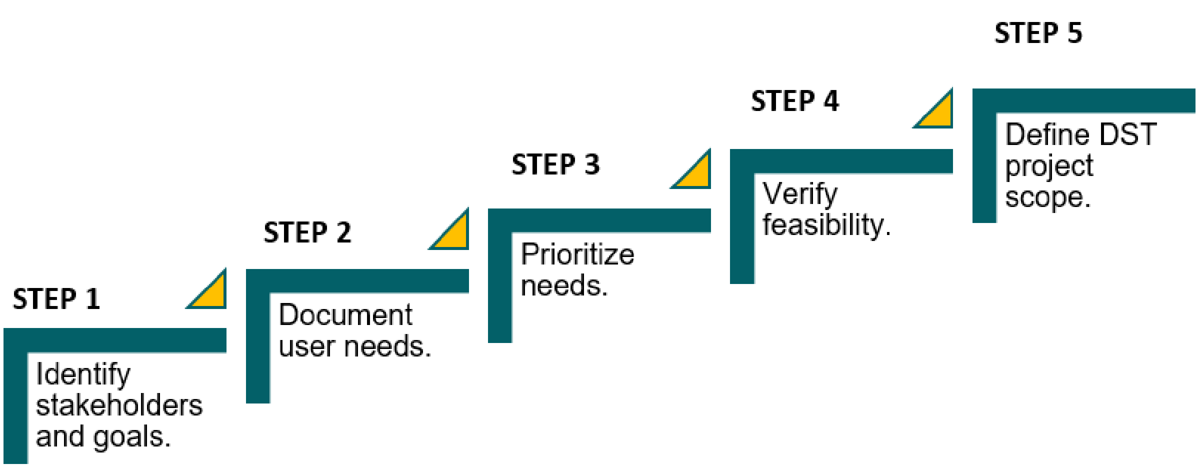
- What is the expected benefit of the selected DST, given the data required and improvements in performance, versus other types of DSTs that can be used?
- What is the return on investment for the expense of development, implementation, management, and use of different types of data? Is the DST worth the added expense?

STEPS TO IDENTIFY NEEDS FOR A DST

The purpose of the needs-gathering process is to move a project from the phase of considering a DST as a concept to the phase of designing a DST. The goal is to create a clear enough vision of the project to support the system design and subsequent verification.

Understanding stakeholder needs is key; without a clear understanding of stakeholder needs, a DST may drift and lose value to the organization. Needs gathering for a DST can be complicated by the fact that the project often introduces changes into how operators perform tasks or functions. It is important that the needs-gathering process asks people what they need to do their jobs in the future rather than what they need to do their jobs today.

Gathering needs and requirements is a structured, but not rigid, process. This distinction can be important because stakeholders will often learn about DSTs as the process unfolds and may want to revise their needs statements as they learn more about what DSTs can do for them. It is helpful for stakeholders to be open to this kind of iterative process to develop or refine DST needs and requirements. Figure 17 shows the five steps in the needs assessment process for a DST.



Source: FHWA.

Figure 17. Diagram. Needs gathering for a DST.

Step 1—Identify Stakeholders and DST Goals

Clearly state what the project hopes to accomplish and identify all stakeholders who may be affected by or use a DST. Ensure the list of stakeholders is comprehensive and looks beyond the end users of the new system. Stakeholders are not limited to system users. The list can include anyone with a stake in the system from an institutional, operational, or technical perspective.

Step 2—Elicit and Document User and System Needs

Engage with all stakeholders to learn about and document what they need to accomplish project goals. This process has multiple stages, which may include workshops, interviews, and data analysis. Project sponsors may need to educate stakeholders about DSTs, as many of them may not understand the potential.

Step 3—Reconcile, Validate, and Prioritize Needs

The input from stakeholders may have conflicts and gaps. Consolidate the input, resolve any conflicts, and fill in any gaps. Present a unified vision of all the DST needs back to the stakeholders. Confirm the result holds value for everyone. Prioritize needs, as the project may not have the resources to address them all.

Step 4—Verify System Is Feasible and Necessary

At this point, a clear, coherent picture emerges of what needs the DST will and will not address. Confirm with stakeholders the resulting vision is feasible and necessary.

Step 5—Define Project Scope

Budget and time constraints may make it infeasible to build the entire DST at once. Review the complete requirements and partition them into subprojects that can be completed as time and resources allow if necessary.

NEEDS ASSESSMENT STRATEGIES

Once needs gathering is completed, a needs assessment is appropriate to pursue. A needs assessment is a systematic process for understanding and evaluating underlying gaps between desired and actual conditions. It can be used to plan for evaluating the options to change the system or process and to improve current processes and activities. This section discusses some generic approaches to performing a needs assessment. While it is beyond the scope of this chapter to provide complete instructions for performing a needs assessment, examples and additional information are provided in the following sections. For instance, the National Oceanic and Atmospheric Administration (NOAA) uses the following 12-step needs assessment process (NOAA 2018):

1. Confirm the issue and audiences.
2. Establish the planning team.
3. Establish the goals and objectives.
4. Characterize the audience.
5. Conduct an information and literature search.
6. Select the data-collection methods.
7. Determine the sampling scheme.
8. Design and pilot the collection instrument.

9. Gather and report the data.
10. Analyze the data.
11. Manage the data.
12. Synthesize the data and create a report.

The following two sections summarize the generalized techniques for identifying and understanding needs—strengths, weaknesses, opportunities, threat analysis, and gap analysis. For information about needs assessment approaches and models, see *Needs Assessment: An Overview* (Altschuld 2010).

Determining the Need for a DST

The five steps identified in the previous section can be tailored for gathering and assessing decisionmaking needs among transportation system management and operations staff and agency executives. A needs assessment for a DST can be adjusted to use different methodologies and focus on specific areas. The following five processes can be used for eliciting needs for decision support:

- Structured interviews—Uses questionnaires and interviews with operators and agencies to document current problems and issues the DST may help solve.

- Decision analysis—Reviews operator actions and TMS decisions from previous incidents and events.

- Data analysis—Analyzes data from the TMS to identify issues, bottlenecks, and missing functionality that can be improved through the DST.

- Technical analysis—Reviews the computing hardware and software to identify issues that can be reduced or eliminated with updates to the system.

- Decision-support orientation—Provides a list of expectations from project stakeholders and ensures commitment of resources.

Additional information and examples of DST needs assessments can be found in Tavasszy, Smeenk, and Ruijgrok's (1998) journal article titled "A DSS for Modelling Logistic Chains in Freight Transportation." Additionally, Robinson et al (2017) discussed this topic in their report titled *Elements of Business Rules and Decision Support Systems Within Integrated Corridor Management: Understanding the Intersection of These Three Components*.

Identifying Gaps and Opportunities To Improve Decisionmaking

A gap analysis assesses existing systems and processes. Additionally, it identifies needs that are not currently being met by the tools and processes that are already in use to assist with making decisions within a TMS. A gap analysis is a process for comparing actual performance with desired or potential performance. A gap analysis is a process that involves many issues and considerations; therefore, this report provides only a summary and then suggests additional sources for further reading. Following is a high-level overview of the process for identifying gaps, especially for DSTs:

- Identify current processes used for making key decisions and managing software, APIs, and DSTs.
- Identify current outcomes impacted by these domains.
- Compare the current outcomes to the desired outcomes (i.e., how might decisions and DSTs operate in an ideal environment?).
- Document each gap specifically and in detail.
- Identify the process for closing each gap (i.e., current situation to desired outcome).
- Focus resources on eliminating the gap (e.g., restructuring or changing processes involved in decisions or implementing DST improvements).

Table 6 through table 10 provide a summary of possible questions and issues to consider in support of assessing the needs for a DST.

Table 6. Agency-related questions and considerations for determining decision-support needs.

Question	Area of Consideration	Consideration
How is the agency currently managing decisionmaking?	Big picture and overall motivations	• Document current decisionmaking process. • Specify what works well and what is deficient. • Identify gaps between current decisionmaking processes and what is needed.
What issues is the agency trying to solve?	Big picture and overall motivations	• Determine clear performance goals and priorities. • Devote sufficient time and effort to fully defining the problem before considering solutions.
What overall constraints does the agency face?	Big picture and overall motivations	• Be mindful of trade-offs, not only in DST design but also in agency goals, when diverting resources to DST implementation. • Look for both obvious and subtle boundaries in the decisionmaking process, making certain that identified decisionmaking is appropriate (e.g., TMS-level); also, distinguish between operator and manager decisions. • Identify the range of situations and accessible data.
Who are the users and at what level will they operate the DST?	Users and expertise	• Consider user backgrounds and changing workforce skills. • Consider user reactions, including acceptance and feedback.
Who will administer the DST?	Command and control	• Have clearly designated roles been defined? • What is the skill base and experience of the staff administering the DST? • How is the DST going to be administered, monitored, and updated?
Will there be a direct line of command? Will responsibility be given to a sole office, or will there be joint responsibility?	Command and control	• Clearly outline responsibility across various situations (if joint responsibility). • Clearly outline priority across various situations.

Table 7. DST-related questions and considerations for determining decision-support needs.

Question	Area of Consideration	Consideration
What are the lifecycle expectations of the DST?	Lifecycle	• Consider all elements of the project lifecycle, including the development process. • Consider not only immediate integration issues, but also the simplicity of integrating with newer subsystems and components in the future.
Will the DST have the ability to be updated modularly, or will a new system have to be installed each time?	Updating and maintenance	Evaluate this question in coordination with the lifecycle expectations.
How much skill will be needed to update it, and who will do the updating?	Updating and maintenance	• Consider making minor changes in-house so the system can be adaptable to constantly changing demands. • Develop maintenance and updating plans early on.
How will the system be maintained, and will resources be allocated for maintenance?	Updating and maintenance	The cost of maintenance and updating can often get overlooked (to the detriment of long-term viability of the DST).
Who will pay for the DST, and how will it be funded?	Funding	Investigate nontraditional avenues such as public-private partnerships; this aspect will tie into administration and responsibility.
What DST solutions already exist?	Existing solutions and subsystems	Do not limit the search to transportation; also look at DSTs in other fields.
Are there subsystem considerations in deciding on a new DST?	Existing solutions and subsystems	The best DST still has to work well in the environment it is being integrated into.
What are the differences between open source and commercial off-the-shelf?	Existing solutions and subsystems	• Consider a combination, with some proprietary components and some open-source add-ons or vice versa. • Assess any limitations on allowable functionality, the sharing of data among partners, etc. carefully when proprietary components will be in the system.

Table 8. Existing infrastructure, interface, and integration questions and considerations for determining decision-support needs.

Question	Area of Consideration	Consideration
Can an older DST be modified and borrowed from to meet the current needs?	Existing solutions and subsystems	Borrow lessons and steps from earlier uses of a DST even if the entire system cannot address current needs.
What is the maturity of the system infrastructure that will support the implementation of the DST?	Existing infrastructure	Even if the design process for the DST coordinates with infrastructure early on, it is imperative to determine its boundaries; it is easier to change a developing DST than to change a well-established system already in place.
What systems are in place the DST can build from?	Existing infrastructure	Check for existing components that can be reused in the DST or data that are already useful to a DST as they are.
What will be the constraints on interfacing the TMS to the DST so that the two can work together seamlessly?	Interface and integration	• Clearly map out potential barriers to interfacing. • Keep in mind the importance of user acceptance and usability in the DST interface. (The DST may provide accurate recommendations, but they will not matter if the operator does not understand them.)
Can the DST and TMS share components, and is the DST partially integrated into the TMS?	Interface and integration	Investigate the amount of sharing that will occur between the DST and the overall TMS, which can be both advantageous and problematic.
What are the issues and considerations to consider for a completely integrated DST and TMS combination?	Interface and integration	Weigh the benefits and costs of completely integrating the DST and TMS.
What are the considerations for choosing a distributed DST that combines interfacing with the TMS and being integrated?	Interface and integration	Outline the pros and cons of a distributed DST and determine agency needs.
How will information exchanges occur, especially between different agency systems?	Interface and integration	Finding clear ways to communicate across legacy systems is challenging but try to minimize the workload needs for this task.

Table 9. Questions and considerations related to organizational and stakeholder support for determining decision-support needs.

Question	Area of Consideration	Consideration
How can the impact and success of a DST be evaluated and assessed?	Evaluation and performance	• Evaluate the performance of the DST in comparison to similar systems or to no system at all (all-human decisionmaking). • Expect that performance will become increasingly important as DSTs become more capable of iteratively updating and adapting due to real-time feedback. Performance assessment is often overlooked in DST deployment (even outside of transportation).
How can organizational buy-in and support (especially at the most senior levels) be secured?	Business case for a DST	Develop the case for direct benefits in performance and the cost for senior management.
What is the business case for implementing a DST?	Business case for a DST	Look beyond just economic benefits; consider overall efficiency and stakeholder satisfaction.
Are stakeholders aware of the need for a DST, and are they involved in the process early on?	Business case for a DST	• Hold discussions with stakeholders from the beginning to understand their concerns, fears, and misconceptions about what DSTs can and cannot do; stakeholders and users are often omitted in early design planning (only to be brought in when things go wrong). • Present business cases to stakeholders so that they are aware of potential benefits. • Engage stakeholders in the process early in the planning and encourage their ongoing involvement throughout DST development and implementation; secure stakeholder buy-in.
What are some strategies for engaging stakeholders and incorporating their needs and insights into the DST development and planning process?	Business case for a DST	Map out stakeholder needs and the goals and benefits they seek from using a DST (even if it is not what was originally planned) based on the discussions with them.

Table 10. Implementation-related questions and considerations for determining decision-support needs.

Question	Area of Consideration	Consideration
What operational or procedural challenges can impact successful implementation of the DST?	Business case for a DST	• Work with leadership and stakeholders to identify both internal and external sources of resistance (and potential strategies to lessen resistance). • Look for ways to fit DST operations and recommendations within cross-agency realities, as DSTs often provide recommendations in a political/procedural vacuum (e.g., ICM). • Define objectives to consider the context of the network, traffic demand, network configuration, user/mode mixture, land use, and time of day; based on the context, the DST can be implemented to identify the most appropriate objective and performance measure.
Programmatic considerations	Business case for a DST	Ensure the planned DST will be capable of responding to the range of operational objectives appropriate for the subject network.
What programmatic challenges may impede DST implementation and success?	Business case for a DST	Identify areas where overall program processes may run counter to the idealized DST implementation and find room for compromise (while focusing on the long-term goals).
What are the workforce challenges to the design and implementation of a DST?	Business case for a DST	Tie the workforce changes and challenges back to the user assessment noted earlier, because it is important that the user workforce buys into the system if it is to succeed.
What are the potential system procurement approaches and avenues?	Business case for a DST	• Tie this question to the earlier funding sources sections and coordinate. • Choose contract mechanisms and approaches likely to accelerate system planning and development, optimize innovation, and minimize risk to the procuring entity.

DEVELOPING AND USING SYSTEM REQUIREMENTS FOR DST AND TMS ASSESSMENTS

Requirements are the foundation for building TMSs or ITSs. They determine what the system does and drive system development. Requirements are used to determine if the project team had built the system correctly. The requirements development process identifies the activities for producing a set of complete and verifiable requirements. This process is central to defining the key functions and performance requirements of the system.

The requirements development process is also important for defining and describing functions and requirements to a sufficient level of detail such that a TMS or system can be designed, procured, and implemented. A system and subsystems requirements document organizes information about the system, including overall system functionality, internal and external interfaces, constraints, performance, reliability, maintainability, availability, safety, and security. A system requirements specification can provide stakeholders with an opportunity to verify that aspects of the system have been adequately captured and the project is ready for software and hardware development and implementation (i.e., build and test).

ADDITIONAL RESOURCES

The following resources can assist with developing and understanding system requirements:

- California Department of Transportation and FHWA's (2009) *Systems Engineering Guidebook for Intelligent Transportation Systems 3.0* provides an overview of system requirements development and a template for documenting requirements. It also provides recommendations on defining needs and using them to develop requirements.

- International Organization for Standardization's (ISO) (2011) *Guidance for the Development of the Set of Requirements, System Requirements Specification (SyRS)* is a standard that can be used to develop the system requirements specifications.

- Florida Department of Transportation's (FDOT) (2005) *Statewide Systems Engineering Management Plan for Intelligent Transportation Systems* explains requirements development and provides a template for documenting system and subsystem requirements.

In the initial stages of requirements development, stakeholders make decisions by consensus to initiate and finalize the system needs, which are used to develop requirements. The requirements development process may be difficult, especially with many stakeholders. One way to begin is to create questions about the proposed DST requirements and then answer the questions with the consensus of the stakeholders. The requirements development step enables agencies to communicate what the system can do to meet the needs stakeholders have identified.

An agency can also establish environmental and nonfunctional requirements that define under what conditions the system may 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, and testing programs and procedures.

Following is a list of possible questions about DST requirements to start from; these questions may need to be revisited multiple times during the requirements development process:

- What operational decisions and tasks can ideally be performed more rapidly and with greater consistency?

- What operational decisions and tasks may heavily rely on the individual operator's experience and knowledge?
- What operational decisions and tasks may be so complicated or cumbersome that they are overly burdensome to some operators?
- What operational tasks should be prioritized for improvement?
- What constraints will exist for the DST (e.g., IT requirements, existing systems to be used, data interfaces)?
- What methods will be used to measure the DST's actual operational performance against its expected performance (e.g., providing responses in a specific amount of time, providing the correct responses)?
- What outcomes are desired?
- What performance measures will be used to measure success?
- What requirements can be derived from those measures?

These questions may need to be answered for each identified function rather than answered only once for the entire system.

Types of Requirements for DSTs

Requirements development is an iterative process. Developing requirements for a DST begins by analyzing needs to develop high-level requirements to meet those needs, decomposing the high-level requirements into system requirements, and then further decomposing down to several levels of software requirements. The requirements document answers the following questions:

- What is the software intended to do? What functions can it perform?
- How does the software interact with people, the system's hardware, other hardware, and other software? What interfaces does it need?
- What information and data does the system need? What data can the system store, use, and provide?
- What speed, availability, response time, and recovery time do various software functions require? What is the expected performance?
- What, if any, standards are in effect? What implementation language, policies, resource limits, and operation environments are necessary? What are the design constraints?

These questions can be answered by classifying requirements into the following five types:

- F = functional.
- I = interface (interface between the TMS and external systems).
- D = data (internally store, send, and receive data within the TMS).
- C = constraint.
- P = performance.

In software engineering, many other requirement types are used depending on a software team's methodology and expertise. However, these five types of requirements are sufficient for most TMSs, DSTs, and projects looking to explore DSTs.

For example, the FDOT District 5 ICM project had more than 20 needs related to the TMS and DST, two of which are provided in table 11. After several project briefings, questionnaires, and stakeholder interviews, FDOT developed a set of user needs. After reviewing and discussing the user needs at a workshop, stakeholders reached a consensus on which needs were truly necessary (FDOT 2022).

Table 11. Example decision-support subsystem needs.

No.	Need	Need Description
9	Need to store pre-agreed incident response plans	Corridor agencies need a means to collect and store pre-agreed response plans to allow corridor agencies to understand collective roles and responsibilities, communicate effectively, and improve response times in reacting to events within the corridor.
16	Need to assess the impact of an enacted response plan on the transportation network	During the response to an event in the corridor, agencies need to be able to determine if the preplanned response is effective and if the response is having the intended effect. This process includes verifying what conditions exist after implementing the response. If the operators of the systems determine their response is not effective, they may be able to change components within their response plans or implement a new response plan.

In table 11, user need number nine is not a direct DST user need, but it identifies some of the functionality the system can have to support the DST functionality. The system requirements may include the need to store the pre-agreed incident response plans used by the DST to inform stakeholders about which response plan to enact or follow. This need implies several functions the system must provide to support the operation of the TMS—for example, response plans must be stored, accessed by users, and understood before the rules engine can be involved in selecting the appropriate response. Another example is an administrative function to enable staff to add, modify, and delete plans.

Stakeholders for the FDOT ICM project wanted functionality that evaluated the impact a proposed response plan had on the transportation network; specifically, they wanted the calculate and predict and propose functions. The DST they envisioned provided a real-time integrated model that could predict the impact of the various proposed response plans within a few minutes (FDOT 2022). User need number 16 in table 11 identifies this need and provides additional requirements in the need description. Needs are not solution-specific; thus, although it could be argued that a specific technology will be used to assess the impact of an enacted response plan on the transportation network, many technologies may potentially meet this need.

When developing requirements for software-based systems, a well-written requirements document will:

- Establish the basis for an agreement between agencies and suppliers on what TMS and DST products will do.
- Reduce the development effort.
- Provide a basis for estimating costs and schedules.
- Provide a baseline for validation and verification.
- Become a basis for later enhancements (especially if an agency does not have the funds to do the entire project at once).

As described in the Institute of Electrical and Electronics Engineers (IEEE) (1998) standard IEEE 830-1998 *IEEE Recommended Practice for Software Requirements Specifications*, agencies should consider several basic categories when developing software requirements documents. These categories include type of requirement, expected verification method, and importance of requirement.

How Requirements May Vary Within a System

The relationships among requirements can be well-defined to show how the requirements form a complete system. Each requirement can be uniquely identified (i.e., have a specific number or name). This identification can reflect the linkages and relationships between requirements. Agencies can show this hierarchy in many ways, but the hierarchy agencies select should trace back to the need statements developed during the planning process. As an example, the FDOT District 5 Regional ICM System (R–ICMS) requirements used a numbering scheme to indicate the following hierarchy (FDOT 2022):

- Level 0—High-level system requirements = 1.
- Level 1—TMS software system level = 1.X.
- Level 2—TMS software subsystems = 1.X.Y.
- Level 3—TMS software subsystem components = 1.X.Y.Z.
- Level 4—Functions and data elements within a component = 1.X.Y.Z-A.

Once needs have been converted to high-level business requirements (level 0 requirements), those requirements are decomposed to system-level requirements (level 1 requirements).

Agencies should consider how these organizing requirements are accomplished and documented so that developers will optimally understand the requirement structure.

For example, the first step in the requirements development process in the FDOT project was to translate the needs and develop system-level business requirements. The next step was to decompose the requirements to software system-level requirements, which were numbered based on the level within the system. The requirements covered several types, including functional, performance, interface, data, and hardware requirements. These requirements also covered nonfunctional and enabling requirements and constraints (FDOT 2022). For the requirements in table 12, the requirement identifier provides the level within the system for the requirement.

Table 12. Example system-level requirements for an ICM system.

Requirement No.	Requirement Description	Type	Need	Verification	Critical	System
1.9	The ICM system will store pre-agreed incident response plans.	D	9	Demonstrate	H	DSS
1.16	The ICM system will evaluate the impact of enacted response plans on the transportation network.	F	16	Demonstrate	H	DSS

H = high.

The software system-level requirements are further decomposed to subsystem-level requirements, as shown in table 13. The system column of the table indicates which subsystem the requirement refers to—in this case, the DST—and the method for testing is shown in the verification column to indicate the method to verify that the requirement is met during the testing phase.

Table 13. Example subsystem requirements.

Requirement No.	Requirement Text	Type	Parent Requirement	System	Verification
1.9.1	The DST will store pre-agreed incident response plans as defined in the data dictionary.	F	1.9	DST	Demonstrate
1.9.2	The DST will provide the ICM manager the capability to add pre-agreed incident response plans for a specified incident.	F	1.9	DST	Demonstrate
1.9.3	The DST will provide the ICM manager the capability to query pre-agreed incident response plans.	F	1.9	DST	Demonstrate
1.9.4	The DST will provide the ICM manager the capability to edit pre-agreed incident response plans for a specified incident.	F	1.9	DST	Demonstrate
1.9.5	The DST will provide the ICM manager the capability to delete pre-agreed incident response plans for specified events.	F	1.9	DST	Demonstrate

In table 14, the expert rules engine (ERE) shows how DST requirement 1.9.1 (table 13) is further decomposed into requirements for the ERE component.

Table 14. Example ERE requirements.

Requirement No.	Requirement Text	Type	Parent Requirement	System	Verification
1.9.1.1	The ERE will store pre-agreed response plans in a network-accessible location.	F	1.9.1	ERE	Demonstrate
1.9.1.2	The ERE will provide the prediction engine with pre-agreed response plans.	F	1.9.1	ERE	Demonstrate
1.9.1.3	The ERE will provide the evaluation engine with pre-agreed response plans.	F	1.9.1	ERE	Demonstrate

This process shows the importance of iteration—moving from needs to increasingly detailed requirements and repeatedly consulting with stakeholders and the technical team at every stage.

Determining How to Verify and Validate a Requirement

Each requirement can indicate how the agency expects the requirement to be verified and validated. Software verification and validation performed after the DST has been completed will help an agency determine whether the software requirements have been implemented correctly and if the requirements meet the needs as intended.

The following types of verification and validation are typically seen in requirements documents for TMSs:

- Analyze: Use established technical or mathematical models or simulations, algorithms, and other scientific principles and procedures to provide evidence the item meets its stated requirements.
- Inspect: Use one or more of the five senses to observe and simple physical manipulation and mechanical and electrical gauging and measurement to verify the item conforms to its specified requirements.
- Demonstrate: Operate an item to provide evidence it accomplishes functions under specific scenarios.
- Test: Apply scientific principles and procedures to determine the properties or functional capabilities of items.

Priority or Importance of Requirements

Agencies can identify the priority or importance of each requirement through the consensus-building process. A scale, such as 1–10 or a simpler scheme, can identify the priority of each requirement.

In the majority of TMS and DST projects reviewed, a simpler scheme is used in the requirements document, typically as follows:

- H = high.
- M = medium.
- L = low.

Finalizing Requirements and Beginning the Design Phase

There are many ways to develop a requirements document for the design and implementation of a DST; the examples in the previous sections are one approach. Well-written, well-defined, and properly organized requirements should consider the specific needs that were identified during the planning phase. A DST requirements document has two primary audiences—the agency and the technical implementers of the DST—and details an agreement between them.

TRACING REQUIREMENTS

Tracing requirements throughout the system lifecycle provides visibility into the activities that have been completed for each requirement. A requirements traceability matrix (RTM) is a tool that agencies can use to trace requirements through each project phase. Project teams may use an RTM to track requirements against the deliverables of each project phase. Many tools on the market support performing requirements tracing during each project phase. Requirements may be traced during the design phase to ensure that all requirements are accounted for and allocated to each component of the overall TMS and DST design.

For the verification and validation phase, requirements traceability is used to show that each test performed by the project team is allocated to the various test procedures for verification and validation of the DST and TMS. As stated by the Project Management Institute:

> Testing plans can be developed considering how to prove the solution features and functions, taking into consideration the way that the customer can perceive the test, and the way the test will be documented. The RTM will be of help in the testing plan development. The main objective of the test is to show the customer how the solution resolves each of all the requirements on the left RTM column. Information on the design and building RTM columns will help identify what features and functions can be tested, and you can use this information to define specific testing data and procedures (Marone 2000).

Table 15 provides an example of an RTM that shows user need information, requirements, documentation references, verification testing, and comments and approval. The contents of an RTM will assist agencies and developers with monitoring and managing the various needs and requirements for a DST.

Table 15. Example RTM.

User Need ID	User Need Summary	Detailed Req. ID	Detailed Req. Summary	Doc. Sec.	DR Source Doc.	Ver. Test Case ID	Compliance: Yes, No, Partial, or N/A	Notes, Comments, Date	Reviewer Initial
UN009	Continuous electrical power and communications	DR001	Install power service assembly	639-3	FDOT standard specs	TC015	Yes	APL products used	HAS
UN019	Performance measures and system validation	DR002	Send traffic MOEs to RTMC master server and save for MOE report	Testing	RFP	TC007	Partial	APL products used	HAS

APL = approved product list; doc = document; DR = detailed requirement; ID = identifier; MOE = measure of effectiveness; N/A = not applicable; RTMC = regional TMC; RFP = request for proposal; req. = requirement; sec = section; specs = specifications; ver. = verification.

CHAPTER 5. ASSESSING CURRENT AND FUTURE DECISION-SUPPORT TOOLS

Chapters 2 and 3 provided background information on DSTs and how they fit into an agency's TMS, and chapter 4 discussed identifying the needs for DSTs for a TMS. Chapter 5 focuses on assessing an agency's capabilities and existing DSTs (e.g., processes, procedures, business rules, noncomputer-based tools, datasets, and current DSTs). This assessment may support identifying potential DSTs to improve how agencies manage and operate their systems or capabilities of their TMSs. Identifying potential DSTs to consider using provides the basis for a new DST to be considered. Agencies decide how and when to reuse existing DSTs, what modifications may be needed, if a new DST is needed, whether a new DST should be developed or procured, and when and how to retire existing DSTs.

The objectives of this chapter are to understand the following:

- How to use existing DSTs during DST design and development.
- How to accommodate the need to adapt business processes once a DST is deployed.
- How to determine when existing DSTs may no longer meet an agency's needs.

After reading this chapter, the reader should better understand the processes to assess the current decisionmaking tools and determine when a DST may be needed. Additionally, the reader should have a better understanding of how to assess their current and future DST needs and identify if their current or planned DSTs are feasible and meet those needs.

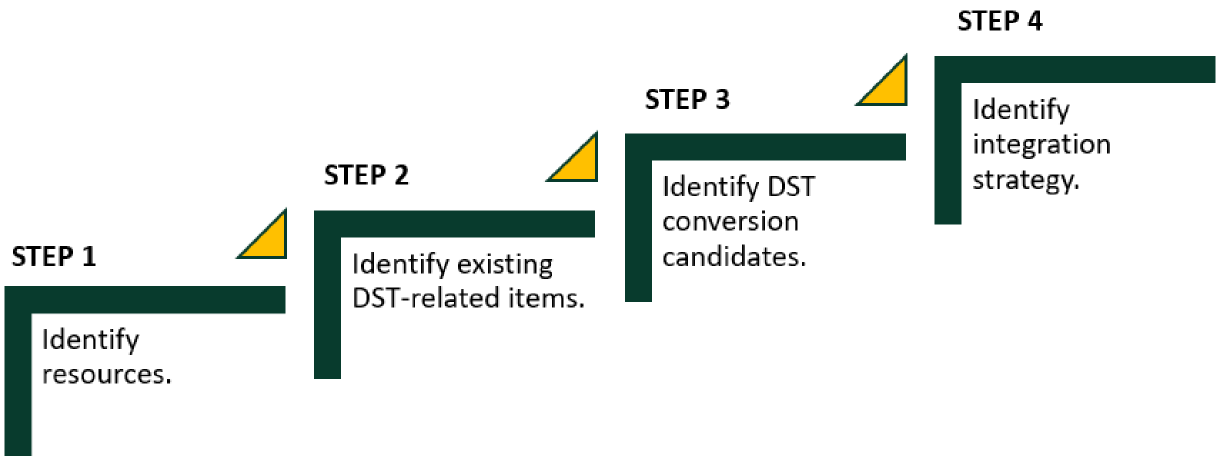
KEY ISSUES TO CONSIDER

When evaluating if existing DSTs can be reused or modified, an agency should review the following key issues to determine if current or future DSTs are necessary:

- What existing operational tools and processes can a new DST replicate?
- What existing business processes can a new DST accommodate?
- When should existing business processes be modified for use in a new DST?
- How can the knowledge necessary to support the DST be captured and expressed?
- How is the current DST being maintained?
- What sources of knowledge contribute to current decisionmaking?
- What new sources of knowledge can potentially contribute to decisionmaking using the DST?
- What, if any, existing tools support manual decisionmaking and are structurally similar to the planned approach for the DST?

STEPS TO IDENTIFY EXISTING DECISION-SUPPORT RESOURCES

Agencies must understand the purpose of assessing the current resources, processes, procedures, and tools they use in making decisions within their TMS to define the future capabilities and tools they will need from a new DST. This assessment includes current and future resource needs for the design, development, deployment, and ongoing operations and maintenance of the DST and TMS, as shown in figure 18.



Source: FHWA.

Figure 18. Diagram. Steps to identify existing DST resources.

Step 1—Identify Resources

The first step is to identify organizational resources to assist in evaluating existing DST development and future DST design, development, deployment, and maintenance. Adopting DSTs as part of a TMS program may require the specific skills and capabilities of in-house or contracted resources. Agencies will need to determine what departments and staff will be involved in planning and executing DST initiatives.

Step 2—Identify Existing DST-Related Items

The second step is to identify processes, procedures, and tools used in operating a TMS. Agencies should perform an analysis to determine which of these items can be reused and which may need to be converted to an online DST that will meet the identified needs and requirements.

Step 3—Identify DST Conversion Candidates

The third step is to identify the processes, procedures, and tools that must be implemented with an online DST. If some reusable components need to be customized, the agency can evaluate and document as additional criteria what products and components have customization possibilities and the complexity that would be involved with any possible customizations.

Step 4—Identify Integration Strategies

The fourth step is to identify a strategy for integrating a new DST into the TMS. It is important to understand the capabilities and interfaces available from the current TMS to develop a strategy for integrating the DST with the TMS. Various strategies exist for integrating a DST with a TMS, as discussed in chapter 6. These strategies include creating a stand-alone DST and developing or procuring a new TMS with a fully integrated DST.

ORGANIZATIONAL RESOURCES

To maximize the investment in a DST, agencies should rely on operational and technical experts, who may also support the DST's development lifecycle from planning to operations.

Project Champions

A project champion's role is to advocate for and support the DST project to help ensure its success. The project champion will educate stakeholders on the needs and benefits of the DST. The project champion will be the liaison with the project sponsor, project team, and senior management to ensure the appropriate resources are provided to support the project and to help solve issues and mitigate concerns that arise.

Qualities of a project champion may include the following:

- Respected by the agency and its leadership.
- Adept at understanding and navigating institutional and operational politics.
- Able to adapt conversations, have difficult conversations with ease, and avoid and resolve conflict.
- Functions with strong organizational skills and able to select the right personnel and keep them motivated and on track.
- Proficient at empathy and an understanding of how others will interpret words and behavior.
- Possesses extensive experience and understanding to mitigate issues.

The project champion may own the following key responsibilities to ensure the project happens and is successful:

- Defines the strategic objectives for the project and works to make sure everyone in the organization is aligned.
- Oversees the definitions of project needs, features, and requirements.
- Ensures the design and implementation fulfill agency needs and requirements.

- Helps select the subject matter and define agency practices.
- Identifies and eliminates risks and obstacles to ensure project viability.
- Works with management to make resources available for the project and for postimplementation operations and maintenance.

Subject Matter Experts

DSTs are complex tools that will support key operational elements of a TMS. It is important to identify subject matter experts (SMEs) who have specific expertise in the operational procedures and processes the DSTs will support. SMEs will exemplify the best traits for the operational activities and strategies employed by the agency, including practices for detecting and managing congestion; practices for detecting, assessing, and responding to events; familiarity with all data sources and systems integrated into the TMS; and understanding the capabilities and shortcomings of the TMS.

Qualities of an SME may include the following:

- Someone who is a recognized domain expert and consistently performs at the highest level among their peers.
- Someone who is an effective communicator and can easily explain agency operational procedures and policies and describe operations practices.
- Someone who is a willing and excited participant in the project.
- Someone who is able to devote the time and effort to make the project successful.

Readiness for DSTs in TMS Operations

In addition to identifying and prioritizing organizational resources, agencies should consider the following activities in advance of DST implementation:

- Operational concept: Deploying DSTs may cause changes to the agency's traffic management operational procedures and workflows, including how the TMS functions and the roles and responsibilities of personnel. Developing an operational concept is useful for identifying changes in processes and workflows, defining how the agency may inform and educate personnel, and describing plans to enforce these new processes.
- Data inventory: Accessing agency data will likely be a DST need. This data will include data stored in agency warehouses and data streaming from agency systems (e.g., TMSs) or data partners (e.g., probe data providers). A data inventory should be performed to enumerate the available data sources, identify the access to these data sources, and define any data integration issues that must be addressed as part of the project.
- TMS integration plan: Affirming the level of effort needed to integrate the DSTs into the TMS is accomplished by the agency asking, prior to development: "Does the TMS have

standard interfaces and APIs, or will custom integration be necessary? Are the resources available to support the integration project?"

- Benefits and benchmarks: Evaluating the success of the project and the recognized benefits to the agency should be accomplished by identifying performance metrics and benchmarks.

EXISTING PROCESSES, PROCEDURES, AND TOOLS ALREADY AVAILABLE IN THE TMS

Many agencies already have existing offline and online tools that are used in their decisionmaking processes within the TMS. Understanding these existing processes, procedures, and tools can be helpful in deciding which of them can be converted to an online DST and integrated with the TMS. Specifically, the following should be evaluated for future usefulness:

- Existing operational tools and processes: DSTs encompass the universe of decision support, including online computer-based tools and offline noncomputer-based tools. Agencies can reuse many of these tools or use them as the basis for the development and procurement of a new DST.

- Business processes and standard operating procedures: Many written materials usually exist within organizations that define operational processes and procedures for TMSs. Written materials may include standard operating procedures; manuals for incident management; and planned event, work zone, and incident response plans.

PLANNING CONSIDERATIONS FOR SPECIFIC DST TYPES

Three primary types of DSTs are typically most useful for supporting traffic management: knowledge-driven DSTs, data-driven DSTs, and model-driven DSTs. In addition to general planning issues that apply equally across all types of DSTs, each specific type of DSTs has its own planning considerations.

Knowledge-Driven DSTs

Knowledge-driven DSTs apply operational practices by emulating human reasoning. Planning for knowledge-driven DSTs needs additional considerations related to creating and validating the knowledge base.

Identifying the Source of Expertise

Agency practices and standard operating procedures will form the baseline for the expertise to be incorporated into knowledge-driven DSTs. When considering the source of expertise there are three items to explore:

- Written materials: Agencies typically produce standard operating procedures; manuals for incident management; and planned event, work zone, and incident response plans that define operational processes and procedures for traffic management. The project team must have access to the most up-to-date versions of the written materials.

- SMEs: Personnel who are SMEs often contribute to the composition of written materials and are experts in understanding how these practices and operational procedures are applied in real-time traffic management. SMEs may also be adept at using a TMS to execute these operational procedures.

- Approval authority: Each project generally addresses and resolves the issue of who will make the final decision on what knowledge is to be represented in the DST when there are multiple SMEs and written sources. The project must agree on the person who is to verify and validate the DST and issue final approval that it accurately replicates agency operating procedures. There are roles and responsibilities to clarify for each project. The project sponsors and the project champion may identify and assign a final arbiter to make final decisions. The final arbiter can be a senior member of the team who is an acknowledged expert respected by the team.

Knowledge-Driven DSTs as Compulsory or Advisory

When integrating knowledge-driven DSTs into TMSs, it is important to determine how the outputs may be used by operations personnel. Following are two common ways it may be used:

- Compulsory: In some instances, an agency may want personnel to use the outputs from the knowledge-driven DSTs without making changes.

- Advisory: In other cases, an agency may want to use the knowledge-driven DSTs to provide a recommended course of action but offer personnel the flexibility to modify or override the outputs.

Decisions about making the DSTs compulsory or advisory may vary based on capabilities of individual personnel (e.g., a team may decide to make the tool compulsory for novice staff but advisory for experienced staff) or on the problem being solved.

Data-Driven DSTs

Unlike knowledge-driven DSTs that are inherently constructed around agency policies, data-driven DSTs use advanced mathematical models to identify data patterns. Data-driven DSTs generate decisions and predictions, but it is difficult to explain how or why decisions are reached. Planning to use a data-driven DST involves a different mindset than planning for knowledge-driven DSTs.

Data-driven DSTs typically use data from databases that are designed to be queried, which enables processing and analysis of data to develop insights that support decisionmaking. Statistical analysis software is one of the most common types of data-driven DSTs. More recent systems use ML algorithms to learn from historical data to identify patterns and make predictions based on current data. The effectiveness of a data-driven DST depends on the quality of the data gathered and the effectiveness of the analysis and interpretation by the decisionmaker.

Data Inputs: Training and Testing

Understanding the problem to be solved is the first step in determining if a data-driven DST is an option. For instance, an agency may want to predict when current conditions on the roadway indicate that an incident is likely to occur. A data-driven DST can be used to compare historical data against current conditions and make a statistical determination that the current data show an incident is likely to occur at a specific location.

This example indicates the data used to develop and train the data-driven DST is a key factor for success. In the planning phase, an agency may review and evaluate the historical dataset for the problem it is building the data-driven DST to address. If the historical data show incident conditions, such as time of day, weather, levels of congestion, and average speed, these measures can be used to train a multivariable statistical algorithm used within the data-driven DST. If an agency's incident data are unavailable or lack the granularity, completeness, and quality needed to train the data-driven DST, other sources of data, such as research institutions, third-party data providers, and other State agencies, may need to be considered.

Model-Driven DSTs

Model-driven DSTs use mathematical models that express the theoretical relationships among data elements or key variables of interest to conduct an analysis. These tools can be used (either online or offline) to simulate the behavior of a transportation system (or parts of the system) using different values for certain parameters. Model-driven DSTs use different types of analysis tools (e.g., statistical software and traffic analysis software) to assess the available data, evaluate them, and report on conditions. Simulation models, in which a transportation network is modeled to replicate historical conditions, are a major subset of a model-driven DST. Traffic analysis tools that use data captured by a TMS can be used offline or online to assess how the transportation network will perform based on various potential actions. Model-driven DSTs can be used in realtime as part of a TMS to predict the possible outcomes of actions a TMS is considering implementing. This use allows agencies to assess the impacts on key metrics like travel time, environmental impacts, and person and vehicle throughput.

Data Inputs: Training and Testing

Understanding the problem to be solved is the first step in determining if a model-driven DST is an option. For instance, an agency may want to model various responses to events within the TMS to determine the best response to a particular event.

A simulation model is a type of model-driven DST that can be developed and used by the TMS to evaluate the current transportation network and whether a particular response can be implemented. Algorithms and software applications (e.g., traffic simulation models) are integrated into the software subsystem to predict travel times in the future with and without potential actions (i.e., the results of using a specific response compared to taking no action). Similar to predicting traffic, this prediction function estimates travel times based on current conditions or a future period. These predictions are usually based on historical information from data collected at similar times of day and during similar weather conditions and congestion levels.

A typical approach used in the development of a model-driven DST is to create a mathematical model or use simulation tools to replicate the decisions an operator makes in various scenarios. This approach relies on an understanding of TMS operations, the data needed to create the model, and real-world scenarios to validate that the model is calibrated. A simulation model uses a representation of the transportation network (e.g., roads, intersections), the devices that control that network (e.g., traffic signals, ramp meters), and the vehicles traveling on the network (e.g., origin/destination, volumes at various times of day). The model then attempts to replicate how the transportation network operates and is used to evaluate the impact of different operational decisions on the transportation network.

Agencies considering a model-driven DST can leverage existing planning demand models as a basis for building a simulation model. Model-driven DSTs need to replicate the transportation network at a resolution to simulate various control strategies. Agencies can use *Traffic Analysis Toolbox Volume XIII: Integrated Corridor Management Analysis, Modeling, and Simulation* to better understand the requirements and data needs of a simulation model used within a model-driven DST (Alexiadis, Salman, and Armstrong 2012).

DST ASSESSMENT EXAMPLE

To manage congestion on the I–4 corridor, FDOT wanted to develop a DST and TMS to support the future development and operation of the surface transportation system. FDOT hired a consultant to lead the assessment and strategy for developing the DST and its integration with their TMS (FDOT 2022).

The first steps in the project were for FDOT to develop the user needs and initial requirements as part of the ConOps for the TMS. The DST that was developed was focused on coordinating the actions and traffic operations of regional agencies responding to events on the I–4 corridor. It was expected to consider various response plans based on rules the operations experts in the region developed. The TMS was used to integrate and facilitate the sharing of information between the freeway TMS and the arterial TMS, so that traffic signal timing plans could be implemented for detour routes identified as part of response plans developed for incidents.

The FDOT consultant met with each stakeholder agency to assess the feasibility of integrating a DST into the operation of the TMS. The goals of this assessment included the following:

- Integrate multiple separate systems from partners (including the counties of Orange, Seminole, Osceola, Brevard, Volusia, Flagler, Lake, Marion, and Sumter and cities within these counties not under county control) to unify responses and optimize system performance.
- Develop signal timing to support system needs by partnering with an active arterial management contractor.
- Evaluate alternative means for effective control of traffic signal systems; determine the impact of alternatives (e.g., legal, political, societal, and cost).

After completing this assessment, a comprehensive alternative analysis was performed for FDOT and its stakeholders to select a strategy for integrating the DST with the TMS. The alternative analysis that was conducted included inviting vendors to demonstrate their products for various components of the software subsystem of the DST and TMS. The alternative analysis process involved developing high-level concepts that had been planned for the DST and TMS. The following process ensured that alternatives were evaluated and reviewed, with the best approach and solution being selected:

- The first step in the alternative analysis was to complete a high-level system concept (logical architecture). The project team reviewed the existing TMS architecture to ensure understanding and to identify necessary updates to the TMS.

- The next step was to analyze alternatives for the products and identify key product components and interfaces that traced to the key requirements of stakeholders.

- The next step was to identify software products, customizable software products, and/or DST components available to meet the requirements of the DST and TMS. Vendors were asked to demonstrate that their products could meet the requirements and needs. Based on the product demonstrations and research conducted during the state-of-the practice document and ConOps, the team identified software products available to meet the needs of the stakeholders. Some products that were identified needed some level of customization, and an analysis of the relative cost to develop a new DST was considered.

- The final step was to develop criteria for evaluating options for build/buy/reuse product components, subsystem solutions, and integration needs. The team developed a scoring matrix and selected alternatives based on their scoring. The scoring methodology for this alternative analysis was based on rating the primary functions of the desired system and scoring functions based on the alternatives. The scores were multiplied by a relative priority (1 = low, 2 = medium, and 3 = high) and added to give the total functional score for each alternative.

A score percentage was calculated by dividing the functional score by the total possible score. Next, based on the assumptions and similar system analysis, an approximate deployment cost and 10-yr operations and maintenance cost was calculated, as shown in figure 19.

$$\sum Costs = \sum Costs_{Deployment} + \sum Costs_{10-year\ O\&M}$$

Figure 19. Equation. Total system cost over a 10-yr period.

Where: O&M = Operations and Maintenance

As shown in figure 20, the relative benefit/cost ratio was calculated by multiplying the score percentage by the average benefit-cost found in similar systems (15:1).

$$Benefits:Costs_{relative} = \left(\frac{Total\ Functional\ Score}{Total\ Possible\ Score}\right) \times \left(\frac{Benefits}{Costs}\right)$$

Figure 20. Equation. Relative benefits to cost ratio.

Finally, the alternatives were compared by calculating an estimated benefits score for each alternative, shown in figure 21.

$$Benefits_{est} = Benefits:Cost_{relative} \times \sum Costs$$

Figure 21. Equation. Estimated benefits.

From this alternative analysis, FDOT identified several feasible alternatives based on available time and budget, selected several potential DSTs that were further evaluated, and eventually developed a request for proposal (RFP) for a vendor to develop the DST.

ISSUES TO REVIEW FOR DST AND EXISTING RESOURCE EVALUATIONS

Agencies should assess current and future DSTs, processes and procedures used in decisionmaking, and strategies for integrating new DSTs with a TMS. After this assessment, agencies can double-check that they have collected all information needed prior to selecting a DST using the following questions:

- Has the agency identified the resources needed to evaluate current DSTs? Resources may include the people, processes, and tools needed to perform the evaluation.
- Has the agency reviewed existing decision processes, procedures, and tools?
- Has the agency identified the capabilities a new DST should provide?
- Has the agency developed a strategy to integrate the DST with the TMS?

CHAPTER 6. SELECTING A DST FOR A TMS

This chapter discusses the process of selecting a DST, which includes considering the agency's needs and requirements, the existing processes and tools and its users, the institutional capabilities, and the integration of the DST into a TMS. It describes a process for evaluating current DSTs and comparing them against the needs and requirements identified in previous chapters. Additionally, it discusses an analysis of build versus buy versus reuse and some lessons learned.

The objectives of this chapter are as follows:

- To develop an understanding of how to evaluate existing DSTs before making decisions about the planning, procurement, or design phase of a project.

- To develop an understanding of general strategies for using DSTs to improve the management and operation of a TMS.

- To identify the issues for consideration during the selection of a DST, including evaluating an existing DST or creating a new DST either through development or procurement.

After reading this chapter, the reader should better understand the processes for selecting a DST to be used with a TMS and preparing for projects to support procurement of a new DST.

KEY ISSUES TO CONSIDER

When selecting a DST, agencies should consider the following key issues prior to deciding if the development or implementation of a DST is needed:

- What are the trade-offs between build, buy, and reuse? Has the agency analyzed and documented those options in a build/buy/reuse trade-off study?

- What are the options for custom development of a DST? Can the agency use existing contracts, or does the agency have staff who can develop a DST or configure an existing DST to meet the needs?

- How does the agency value the reliability of an off-the-shelf product versus the flexibility of a custom product if pursuing a stand-alone DST?

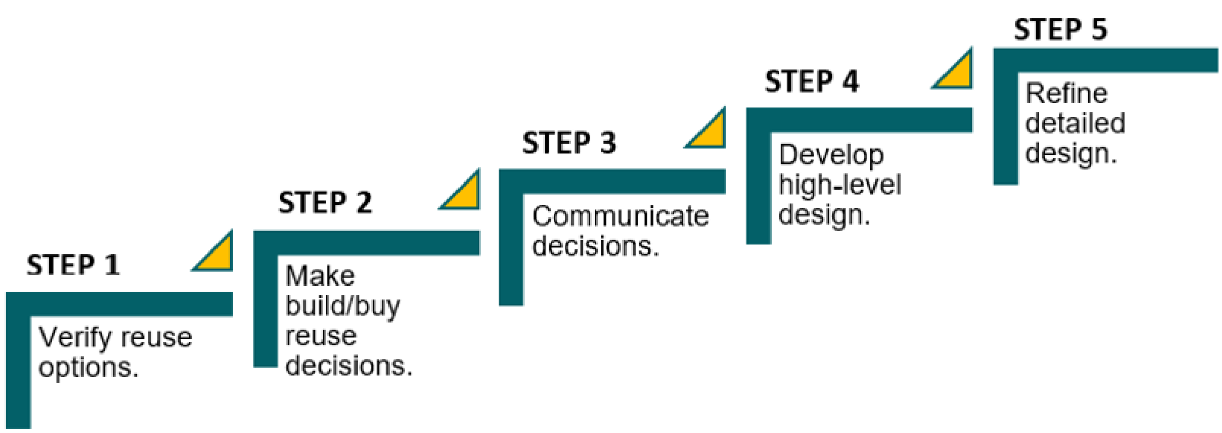
- How would a current practice or trade study help the agency to better understand available DST products? Is this type of study needed? How closely do agency requirements match existing off-the-shelf products?

STEPS FOR SELECTING AND DESIGNING A DST

As with many software systems, agencies can consider options to build, buy, or reuse their DSTs. There may be multiple commercially available software packages or services and/or customizable open-source or commercial products that might meet an agency's needs and requirements. Agencies should evaluate these products and services and document the potential positives and negatives of the various DSTs. If none of the commercially available products or services or internal reusable DSTs are suitable, agencies should consider building a new DST. A build/buy/reuse analysis may include the following steps:

- Determine costs, timeline, and overall resources required to build a custom DST.
- Determine long-term maintenance costs of a custom DST (license, maintenance agreements, etc.).
- Analyze trade-off between build, buy, and reuse options and document options in a build/buy/reuse trade-off study.
- Obtain feedback from technical (e.g., IT department, developers on staff), procurement, and management teams regarding the analysis of build/buy/reuse options and criteria.
- Create documentation of build/buy/reuse decision recommendation and rationale once a decision is made and communicate the decision.

This analysis is described further in the following section and shown in figure 22.



Source: FHWA.

Figure 22. Diagram. Steps to define the design of a DST.

Step 1—Verify Reuse Options

As discussed in chapter 5, agencies may want to perform an analysis to identify existing DSTs and software components that may be reused to meet the agency's needs. The agency may already have licenses or services available that can be reused or customized.

If some of the reusable components need customization, agencies can evaluate, as additional criteria, the products and/or components with customization possibilities and the complexity that would be involved with carrying out any customizations.

Step 2—Make Build/Buy/Reuse Decisions

Next, agencies may want to identify build/buy/reuse decisions for each physical component and present recommendations to the appropriate procurement, management, and technical teams. Based on team feedback and approval, agencies should document the recommended product component. The build decision can include hiring a contractor or developing the tool using agency resources. The integration strategies described in this chapter will constrain the options for procurement discussed in chapter 7. Table 16 shows where integration strategies are applicable based on procurement options.

Table 16. Integration strategies and procurement options.

Strategy	Reuse	Build	Buy	Comments
Configure TMS	Y	N	N	This strategy will almost always correspond to a reuse decision. The agency is configuring the existing TMS using native DST capabilities.
Customize TMS	N	Y	Y	This strategy is most often associated with a build decision. The agency is getting local customizations for the TMS. It is important that the resources performing the customization have an excellent grasp of the TMS. This model may also include a buy model because a new module or package may have to be purchased for the TMS.
UI integration with stand-alone DST	N	Y	Y	This strategy may be both build and buy. The stand-alone DST may be an existing product that is purchased or may be custom built. In either case, the integration work with the TMS may be major and may need buying services.
Data integration with stand-alone DST	Y	Y	Y	A stand-alone DST may be bought or built. The integration work may not be as significant and can conceivably be managed by local resources.
Operational integration	N	Y	Y	There is no technical integration, and the stand-alone DST may be bought or built.

Y = applicable; N = not applicable.

Step 3—Communicate Build/Buy/Reuse Recommendation

In this step, the agency captures and communicates the recommendation to build, buy, or reuse the DST to the procurement, management, and technical teams. The agency may develop a make-buy document to capture the strategy for meeting the needs and requirements previously developed either by creating a new DST or procuring a DST.

Step 4—High-Level Design of a New DST

In this step, the agency designs a new DST using the offline tools, processes, and procedures identified in the review process. The agency develops the high-level design and specification of the new DST.

Step 5—Detailed Design for the Integration of the DST With a TMS

In this stage of designing a DST, the agency refines and finalizes the design document, thus giving software programmers and vendors the information they need to begin writing code or configuring their DST product.

IDENTIFY EXISTING DECISION-SUPPORT TOOLS

Determining what DST or DST components to acquire is often referred to as a make-or-buy analysis. This analysis is based on the needs of the project and begins early in the project during the first iteration of the design. It continues during the design process and is completed with the decision to build, buy, or reuse a DST.

Verify Reuse Options

Agencies should perform an analysis to identify existing DSTs that may be reused or that may be customized to suit the current stakeholder needs. If some of the reusable components need customization, the agency can evaluate as additional criteria the products and/or components with customization possibilities.

Build Option

If multiple DSTs, customizable DST products, and/or components are available, agencies should evaluate the commercially available DSTs and the vendor and document potential positives and negatives of the various DSTs. If none of the commercially available DSTs or internal reusable products and/or components with customization possibilities meet the agency's needs and requirements, the agency can consider the build option. The build option includes several steps, as follows:

- Determine costs, timeline, and overall resources required to build a custom DST.
- Analyze trade-off between build, buy, and reuse options and document options in a build/buy/reuse trade-off study.
- Obtain stakeholder feedback on the analysis of build/buy/reuse options and criteria.
- Create documentation of build/buy/reuse decision recommendation and rationale once a decision is made and communicate the decision to the stakeholders.

As technology evolves, so does the rationale for choosing to develop or purchase a DST. While complex development efforts may favor purchasing an off-the-shelf DST, advances in productivity and tools may provide an opposing rationale. Off-the-shelf products may have incomplete or inaccurate documentation and may or may not be supported in the future.

Once the decision is made to purchase an off-the-shelf DST, the requirements are used to establish a bid document for purchasing the DST. At times, off-the-shelf refers to an existing item that may not be readily available in the marketplace.

HIGH-LEVEL DESIGN

The design phase begins the transition from user needs and requirements to the design so that developers can begin the development process. At the conclusion of the design phase, a clear picture emerges of the architecture, data elements, interfaces, electronic messages and protocol, UI specifications, software changes, API specifications, and user interactions.

The deliverables for this phase of design may include the following:

- Architecture—Shows the logical systems and interfaces that are needed, and what standards will be used for the interfaces.
- Preliminary UI—Shows some preliminary descriptions and pictures of the potential UI.

Data Subsystem Design

As discussed in chapter 3, the data subsystem primarily consists of the data and the interfaces or APIs that extract data from other systems and devices to enable the data to be transformed and loaded into the TMS database. Agencies should identify the data subsystem early in the process because the availability of certain data may constrain the types of analytics or process automation that are possible within the system. When designing a DST, agencies and developers may ask the following key questions:

- Does the DST need to provide data for decision support? If so, what data needs to be provided?
- Do the data currently exist in the systems? If not, is there a way to get the missing data?
- Are these sources for new data elements already integrated into the TMS data subsystem, or will they need to be integrated with the TMS and the new data elements also added to the data subsystem?
- Do the new sources of data have defined APIs that can be used to integrate these new sources into the TMS and/or data subsystem?
- Do the current data provide the requirements needed (e.g., 10-s intervals instead of 60-s intervals, area of coverage, accuracy)?
- Is the quality of the available data sufficient to support decisionmaking?
- Is the coverage area of the data sufficient to support decisionmaking?

The data subsystem can store data the DST needs to operate and facilitate data exchange with other systems. The data subsystem also needs to provide the administrative and maintenance interfaces necessary to manage data access and monitor the system. The following sections discuss what the design of the data subsystem can address.

Data Types

Within the transportation domain, common measurements and observations are used by many different agencies. Agencies often find it useful to understand the range of common data elements the system needs in order to scope the requirements and effort. Examples of data types include traffic data (e.g., volume, density, and speed) and incident data (e.g., duration and severity). For data to be effective in a DST, they are stored using common formats and interpretations. If they are not stored using common formats and interpretations, the data subsystem and DST may need reformatting, or data may have to be transformed as they are collected from various sources before they can be used by the data subsystem or DST.

Data Formats

Once the necessary data types are well understood, system developers consider which, if any, data format standards to use. Examples of data format standards include the *Traffic Management Data Dictionary* (Institute of Transportation Engineers 2020) and *IEEE 1512* (IEEE 2006). These decisions may impact the storage approach but may be particularly important in establishing the data import and export requirements.

Data Validation and Cleaning

Different data sources may have different formats, data quality, or other attributes. Platform designers can consider what data conditions are valid (i.e., which values may or may not be missing), what data ranges are acceptable, and what the system does in response to invalid data.

Storage Approach

When data are accumulated, they can be stored in raw form as collected, aggregated, or otherwise restructured. The use cases for accessing data as they age will determine the best long-term storage formats. Aggregating data can reduce storage space and speed up some operations, but the system may lose the capability for some fine-grained analysis. Designers may decide to store raw data for a certain period of time and then aggregate the data for longer-term storage.

Archival Requirements

Once data access and storage are determined, designers can decide how long data will need to be retained and in what formats if multiple storage approaches are being used.

Data Volume

Agencies should consider the size of the data elements, frequency of exchanges, and desired retention periods to ensure the network and communication infrastructure support regional DST needs. Communication capacity considerations can consider short-term burst rates for data flow, and storage capacity is based on long-term data flow rates.

Data Management Plan

The data subsystem needs routine and preventive maintenance and management, including processes for server hygiene and data migration and retention. Data management plans discuss the plans for managing data; they typically describe how data will be collected, managed, integrated, and disseminated before and during the operation of a DST. This data management includes real-time and archived data that are inputs to and outputs from systems managed by the TMS.

For example, the data management plan for the New York City Connected Vehicle Pilot Demonstration program includes the following structure (Van Duren, Rausch, and Benevelli 2017):

- Chapter 2 provides an overview of the New York City Connected Vehicle Pilot Demonstration.
- Chapter 3 provides the data management approach, consisting of:
  - Data sharing and reuse.
  - Data privacy and intellectual property issues and risks.
  - Data privacy and security controls.
  - Quality control.
  - Data preservation and archiving.
- Chapter 4 provides the New York City data plan, consisting of:
  - Full description of data types, sources, and destinations.
  - Data quantity and data collection constraints.
  - Detailed description of data collection, processing, and storage processes.
  - Description of how data are documented and organized, including metadata.
- The appendix contains a list of each log file emanating from aftermarket safety devices and roadside units, including the log file's structure, contents, and format.

DST Type Selection

Once the designers have completed the high-level design of the data subsystem or database and have identified related fundamental constraints, the next step is to make a final decision on the type of DST that will meet the needs and requirements of the TMS.

Availability of certain data types will influence the design and selection of the DST. If data are unavailable or are not available at the level of detail needed, the DST selection can take that into consideration. For example, many TMS data subsystems provide roadway link data that are averaged over a period of time and across the lanes. If the DST needs to use individual lane data, changes to the TMS may also be needed.

At this stage, system designers make a final decision on the type of DST to be deployed. The three different types of engines were summarized in chapter 3 and are described in more detail in the next three sections of this chapter.

Knowledge-Driven DSTs

Knowledge-driven DSTs provide specialized problem-solving expertise based on the processing of stored facts, rules, and procedures or similar forms of knowledge. They attempt to emulate human reasoning but with more consistent results. Expert systems are the best-known type of knowledge-driven DSTs and use databases of knowledge generated by previous expert users, along with a system's business rules, to emulate the decisionmaking capabilities of an expert user of the system. Based on this knowledge base, knowledge-driven DSTs recommend actions to traffic operators. Knowledge-driven DSTs are different from table-based tools (e.g., decision tables, as described in chapter 1) in the way knowledge is extracted, processed, and presented. The knowledge-driven DST attempts to emulate human reasoning, while the table-based tool responds to all events in a predefined manner.

Data-Driven DSTs

Data-driven DSTs use data to aid in the decisionmaking process. They typically use data from databases that are designed to be queried, which enables processing and analysis of data to develop insights that support decisionmaking. Statistical analysis software is one of the most common types of data-driven DSTs. The effectiveness of a data-driven DST depends on the quality of the data gathered and the effectiveness of the analysis and interpretation by the decisionmaker. With many of the data analysis tools in use by the industry, transportation agencies can customize dashboards to display the data they want to see and run custom reports. Ongoing advances in how data can be accessed, analyzed, and visualized are allowing more and more agency staff without a technology background to work with analytical tools, analyze data, and make informed decisions.

Model-Driven DSTs

Model-driven DSTs use mathematical models and simulation tools that express the theoretical relationships among data elements or key variables of interest for an analysis being conducted. These tools can be used (either online or offline) to simulate the behavior of a transportation system (or parts of the system) using different values for certain parameters. Model-driven DSTs use different types of analysis tools (e.g., statistical software and traffic analysis software) to assess the available data, evaluate the data, and report on conditions. Traffic analysis tools that use data captured by a TMS can be used offline or online to assess how the transportation network will perform based on various potential actions. Model-driven DSTs can be used in realtime as a part of the TMS to predict the possible outcomes of actions a TMS is considering implementing, thereby allowing agencies to assess the impacts on key metrics such as travel time, environmental impacts, and person and vehicle throughput.

Integration Strategy

Agencies can use several potential integration strategies when selecting a DST and designing how it will be integrated with a TMS. These strategies include the following:

- Configuring a TMS.
- Customizing a TMS.
- Integrating a UI with a stand-alone DST.
- Integrating data with a stand-alone DST.
- Integrating operations.

Workflow Design

The use cases identified in the ConOps and the scenarios within those use cases can be articulated into clear workflows for the system operators. These workflows clearly delineate between automated tasks the DST performs and the manual tasks operators perform. It may be useful to express workflows with flowcharts or other design visualization tools, as these visually oriented tools help make workflows accessible to nontechnical audiences. Workflows are validated with operational staff and against real-life examples of the problems the DST is expected to address.

UI Design

To the degree possible, the DST maintains UI conventions and approaches that are familiar to the operators. Having a similar look and feel between the TMS and DST can simplify the rollout process and increase user satisfaction with the new system. It may be more challenging if the DST is an entirely different system from the TMS than it would be if the DST were a new module within an existing TMS. UI designers have access to systems that operators currently use so that the designers can understand user expectations and preferences.

The design process includes a phase to develop wireframes. Wireframes are layouts of user screens that identify major elements of the interface but do not specify the details of the interface's look and feel. Wireframes are the transition point from workflows to visual design. Operators and other stakeholders can use wireframes to confirm that workflows are correct and effectively presented.

Response Design

It is important that the technical implementation of the response generation process does not inadvertently diverge from the operational goals set forth in the ConOps. This divergence can occur when an aspect of a response may be lost in translation when going from ConOps to technical implementation.

Designing the encoding of response rules and algorithms is an iterative process involving both technical and operational staff. In the case of a rules engine, this ongoing fine-tuning will mean having technical staff convert response rules described in the ConOps into formal business rules usable by the system. Technical and operational staff can work together to confirm the formal business rule definitions match the intent of the ConOps. Technical and operational staff walking through real-life examples together can be an effective approach to validation.

Computing Hardware Design

The requirements and design for computing hardware that supports a DST follow the IT standards and requirements of the TMS. If a legacy TMS exists, agencies can evaluate whether the current computing hardware will support the added DST requirements and software or if additional computing capabilities or a new platform will be needed. Agencies and developers can ask the following key questions when developing requirements and design for a DST's hardware platform:

- Does the DST need to be hosted within the agency's TMS software platform or subsystem? (Is it a requirement?)
- Does the current hosting environment have the available resources (e.g., processing, memory, and hard disk space) needed to support DST requirements?
- Can additional capabilities or resources be appended to the existing hardware platform?
- Does the current hardware platform need to be replaced?
- Can changes be made to the hardware platform, given the software being used for the TMS?

The Dallas ICM DST is a multiagency platform that could not be hosted on the existing computing hardware of the agencies. The existing TMSs of Dallas Area Rapid Transit and Texas Department of Transportation (TxDOT) are fully using their computing hardware; therefore, new computing hardware specifically for the ICM system and associated DST was designed and deployed (FHWA 2015). FDOT District 5 TMS uses a large set of computing hardware for its TMS, and it had designed future expansion into its original computing hardware. After evaluating the data, processing, storage, and memory requirements of the new DST, FDOT and the software development vendor determined the existing TMS hardware platform or subsystem could support the additional software needed for the DST .

DETAILED DESIGN

In this stage of designing a DST, the design document is refined and finalized so that software programmers have the information they need to begin writing code.[1] A common challenge in DST development is that, when a rule is formalized into something that can be incorporated into an algorithm or software program, the original intent of the rule can be lost. To address this challenge, operations staff can work vigilantly with technical staff to ensure the formal definition returns the correct results.

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[1]This design and development approach assumes a waterfall software development method. As discussed in chapter 7, other software development methods (i.e., agile) may change the level of detail in this stage of the design.

The deliverables for this phase of design usually include:

- Data interface specifications—Describe each data interface, the relevant standards that will be used how the data will be exchanged (i.e., format and frequency), and the content of the data. An interface control document is usually created by the software developer to document the data interface. It is used to create the API to facilitate the exchange of data between each system and subsystem within the TMS.
- Detailed UI—Provides visual representations and a more detailed description of the UI.
- Detailed rules/algorithm/analysis specifications—Describe the rules the DST will use, ranges of expected values for each rule, and formulas or algorithms the DST will use to calculate various measures.
- Detailed functional descriptions for each component—Describe each component of the DST, how each component will interface with other components, the data each component needs from other systems, and the functionality each component provides referenced to the requirements developed during the planning phase.
- Design review at 90 percent completion—Involves a meeting between the design team and project stakeholders to review the almost-completed system design; this meeting usually occurs when 90 percent of the design is complete.

Using the concepts and preliminary design developed in the high-level design phase, the detailed design phase makes the technical decision on what will be developed, provides more detail, and documents the complete specification for each DST component. Questions provided in the high-level design sections for the various components can be revisited by the designer and further detail developed. The type of DST being developed is finalized at this point. While the high-level design provides a logical and physical architecture at a conceptual level, the detailed design includes the following:

- Functional logic of each DST component: The logic, algorithms, and processes for each component are finalized and documented so that a software developer can configure or develop the software components of the DST.
- Database tables finalized: The data subsystem design is finalized and documented to include the type and size of all data elements and a data catalog that identifies all data within the data subsystem.
- Complete detail of the interfaces: The APIs and associated interface control documents are developed and finalized to allow developers to integrate the various TMS software subsystems with the DST.

The detailed design phase provides a complete design that software developers and system integrators can use to develop the DST and integrate it into the TMS.

EXAMPLE OF SELECTING A DST

As part of the ICM program, the U.S. Department of Transportation (USDOT) has released several versions of the *Implementation Guide and Lessons Learned* (Christie et al. 2015). One example seen in this text is the Dallas Pioneer Site, which included in its system documentation an ICM system context diagram that helped show the ICM system interfaces with existing transportation-related systems. This display allowed system developers to use the context diagram to help explain the system environment and its constraints to project stakeholders.

As part of the detailed design activities and documentation, the Dallas team included a process for making the build, buy, and reuse decisions.

This process involved investigating and documenting, through a formal process, the options and related rationale for developing or acquiring the necessary capabilities, as follows (Christie et al. 2015):

- Make build/buy/reuse analysis.
- Verify reuse options.
- Develop and analyze design alternatives.
- Make build/buy/reuse decisions.
- Communicate build/buy/reuse recommendation.
- Create bill of materials.

Having a process helps to ensure that the best decisions are made and stakeholders have the confidence to move forward with the project.

ISSUES TO REVIEW: THE OPTIONS FOR SELECTING A DST

After assessing potential DSTs, verifying build/buy/reuse options, and developing a high-level DST design, readers can double check they have collected all information needed to select a DST and begin procuring or implementing their DST and TMS. This review for the assessment may include the following questions:

- Did the agency analyze the trade-off options between build, buy, and reuse and document options in a build/buy/reuse trade-off study?
- Did the agency make a build/buy/reuse decision?
- Has the agency identified existing contracts that can be used for DST development?
- Do agency requirements closely match existing off-the-shelf products?
- Has the agency decided on the DST that will be procured?
- Has the agency decided on the integration strategy for the DST with the TMS?

CHAPTER 7. PROCURING AND IMPLEMENTING DECISION-SUPPORT TOOLS

The purpose of this chapter is to introduce the considerations when agencies procure or develop a DST. It builds off the analysis and design considerations introduced in the previous chapter, the build/buy/reuse analysis, and high-level design.

The objectives of this chapter are to understand the following:

- Steps for procuring a DST.
- Options for procuring a DST and how they may influence product selection.
- Potential issues with procuring a DST.
- Steps for implementing a procured DST.

After reading this chapter, the reader should better understand which procurement options may be applicable or suited to their goals for the types of DSTs they are contemplating. Information is also provided about issues to consider when reviewing the agency's policies, procedures, and options for procuring different types of DSTs.

KEY ISSUES TO CONSIDER

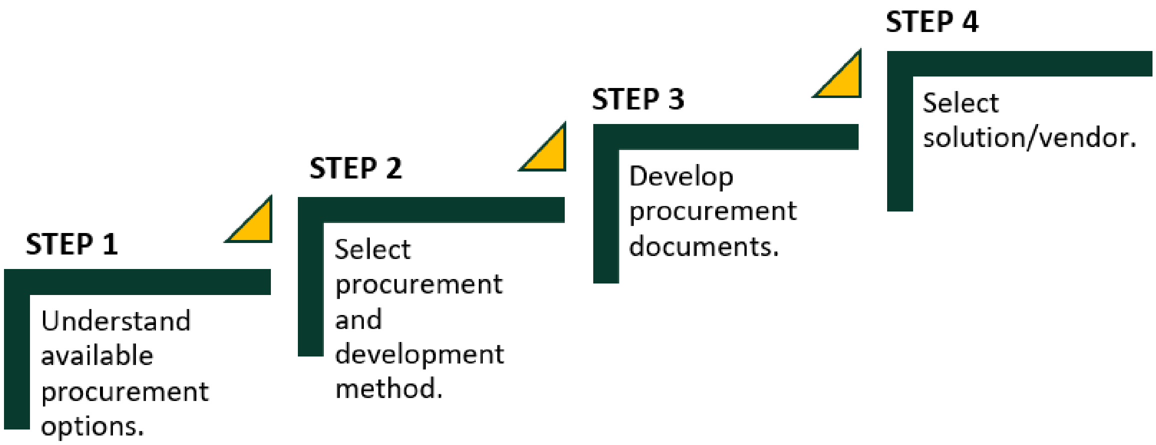
An agency may have several procurement options when planning the procurement of a DST into a TMS. These options may be based on policies at the agency or governmental entity (city, county, State). Agencies should consider the following key questions when planning to procure a DST for a TMS:

- What institutional policies or preferences may influence the choice of procurement models?
- What specific technology policies should the agency follow (e.g., cloud-hosted solution or hosted on-premises)?
- What intellectual property requirements are there for the DST (e.g., own, license, etc.)?
- What funding mechanisms for recurring costs are associated with hosting and ongoing operations and maintenance, if any?
- What preferred procurement method (e.g., low bid, best value, qualifications-based negotiation) do the needs and requirements previously identified indicate, if any?

STEPS TO PROCURING AND IMPLEMENTING A DST

Once a DST has been designed to a level that it can be developed or procured, a procurement process may be needed. A standard procurement process for software is commonly used when procuring a DST or procuring the development of a DST.

The procurement process includes understanding the options to procure the DST, developing procurement documents, and evaluating and selecting a vendor for the DST. This process may use multiple procurements for different components of the TMS, which might include the computing hardware subsystem, software subsystem, and data subsystem needed to procure a full DST solution. Figure 23 provides a high-level process for procuring a DST.



Source: FHWA.

Figure 23. Diagram. Steps to procure a DST.

Step 1—Understand Available Procurement Options

Based on the funding sources for a DST project, an agency may need to follow various rules and regulations. Many DSTs are software procurements, which may need oversight by a State's IT department.

Step 2—Select Appropriate Procurement and Development Method

Once an agency understands the rules and regulations dictated by the agency's policies, the agency will decide the actual method for procuring a DST. Contacting other agencies that have procured similar systems may help the agency understand lessons learned and potential issues in procuring the DST.

Step 3—Develop Procurement Documents

Procurement documents for the development of a DST or DST service will provide the contracting mechanism for vendors to bid on the development of a DST or provide a service that meets the requirements identified in the previous chapters.

Step 4—Evaluate Proposals and Select a Vendor or Developer

After the agency receives proposals from vendors/developers, the agency can evaluate and select the vendor/developer based on the agency's rules and criteria. Typically, these procurements use low-bid, best value, or a qualifications-based selection leading to negotiations and DST procurement.

PROCUREMENT OPTIONS

While the solution architecture describes the functional integration of TMS and DST components, the system architecture describes the technical hosting and integration plans and is heavily influenced by the nonfunctional requirements. Once the decision on build/buy/reuse has been made and agreed to by stakeholders, the physical system architecture can be completed. The system architecture will depend on the agency's IT requirements and the technical architecture for the DST solution. In the past, with agencies favoring systems hosted on-premises, the legacy TMS, along with a DST, were both in the same location and perhaps even used the same computing platform.

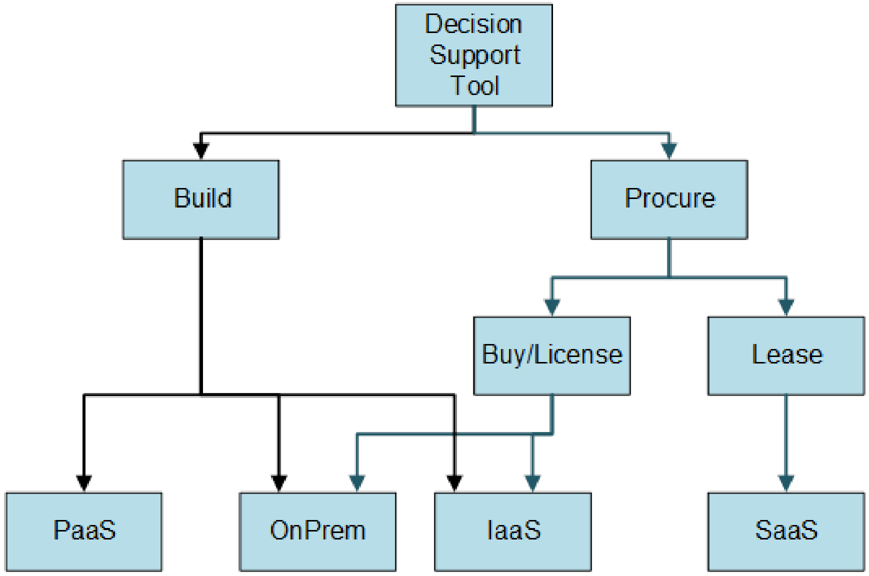
As agencies have moved to open, modular TMS architectures and acceptance of remote hosting options has grown, more options have come into play for designing system architectures. What matters in the end is whether both the TMS and the DST(s) are built around standards-based APIs and whether there is a strong communication link between where the TMS and DST(s) are hosted. This issue is directly relevant to procurement because some modern products may only be offered as cloud-based services. The agency will need to understand the options for cloud-based services and how they conform with agency policies and conventions.

Hardware Subsystem Options

The requirements and design for a hardware subsystem to support a DST can follow IT standards and requirements of the TMS. If a legacy TMS exists, agencies can evaluate whether the current hardware subsystem will support the added DST requirements and software subsystem or if additional computing capabilities or a new hardware subsystem will be needed. When developing the requirements and design for the hardware subsystem of a DST, agencies and developers should ask the following key questions:

- Do DSTs require on-premise installation within the current hardware subsystem within the agency's TMS?
- Does the current hardware subsystem have the available resources (e.g., processing, memory, and hard disk space) to support DST requirements?
- Can additional capabilities or resources be appended to the existing hardware subsystem?
- Is the hardware subsystem scalable to allow for additional processing and storage for future growth?
- Does the current hardware subsystem need to be replaced?
- Can changes be made to the hardware subsystem, given the software subsystem being used for the TMS?

As shown in figure 24, there are several options for the hardware subsystem of the next-generation TMS.



Source: FHWA.
OnPrem = on premises.

Figure 24. Diagram. Hardware models for the build scenario versus the procure scenario.

DST solutions for the hardware subsystem of the next-generation TMSs are available as follows (California Department of Transportation and FHWA 2009):

- On-premise deployment offers users the ability to install, manage, and maintain every aspect of a system deployment. Typical on-premise deployments involve up-front costs (hardware, software licensing, etc.) but allow for greater control of the system.
- Infrastructure-as-a-service (IaaS) deployment provides scalability and minimizes responsibility for the DOT. Users are responsible for managing applications, data, runtime, middleware, and operating system. Instead of having to purchase hardware outright, users can purchase IaaS based on consumption (e.g., database reads/writes or computing cycles), similar to electricity or other utility billing.
- Platform-as-a-service (PaaS) deployment allows users to develop, test, and deploy applications quickly and efficiently. With PaaS, users are only responsible for data and application tiers. Similar to IaaS, users can purchase PaaS on a subscription basis and pay only for what they use.
- Software-as-a-service (SaaS) deployment uses the web to deliver applications. Most SaaS applications can be accessed directly from a web browser on the client side. This model is entirely maintained by the vendor. Like the other service models, users typically purchase a subscription to access the application.

On-premise and IaaS are the most common approaches to hosting agency-developed and vendor-provided solutions. PaaS may be a good option for agencies that build their own solution and want to leverage the tools that many cloud providers offer. SaaS applies exclusively to leasing services from a vendor on a per-seat or per-agency basis.

PREPROCUREMENT CHECKLIST

Once a DST has been designed to a level that it can be developed or procured, a procurement process may be needed. When procuring a DST or procuring the development of a DST, available procurement processes should be reviewed. This review may include the following questions:

- Has the agency considered how the preferred integration strategy influences procurement options?
- Has the agency considered how institutional preferences influence procurement options?
- Has the agency examined existing vehicles that can be used to procure integration services?
- Has the agency completed and documented the build/buy/reuse analysis?
- Has the agency identified all agency policies that may impact options for procuring the DST (i.e., cloud-based products)?
- Has the agency examined the trade-offs for different options for hosting the DST?

POTENTIAL ISSUES

Depending on the scope of a DST procurement, the agency may face the following potential issues:

- Interfaces to external systems and a mechanism to modify or develop that interface may be needed. Existing TMS software may or may not have a well-defined API for the integration of tools and other software. A contract with the TMS software developer or an external system may be needed to integrate those systems with the DST.
- Multivendor developments can lead to issues when integrating technologies into an overall system. An overall systems integrator can be used to manage all the various systems and ensure that TMS and DST integration is successful.
- Some DST technologies are new to agencies and may need more effort than planned to ensure the DST meets the needs and requirements. A systems manager and independent verification and validation process should be considered, especially if the agency does not have the technical expertise to oversee the vendor.

EXAMPLE OF PROCURING A DST

The FDOT District 5 R–ICMS project had several options to procure its R-ICMS software. One of the options included a DST to select and coordinate multiagency, multimodal response plans to incidents on the I–4 corridor. FDOT allowed several mechanisms for procuring software and services, including a professional services RFP, an invitation to bid (ITB), and an invitation to negotiate (ITN) (FDOT 2022).

The RFP process is typically used for contracting professional engineering services from prequalified companies, the ITN process is typically used for buying commercial products, and the ITB process is typically used for buying systems and technologies. For this procurement, FDOT chose the ITB process using a two-stage procurement. The first stage was a qualification phase, where potential teams provided their qualifications in the development of the R–ICMS software. From the first stage, FDOT selected two companies to provide a technical proposal and price proposal for development of the R–ICMS software. The respondents provided two approaches: a works for hire and the license of a commercial product. The works-for-hire approach meant that FDOT would own the software and the vendor would not have rights to reuse it without permission from FDOT. The license of a commercial product approach meant that FDOT would have a license to use the software but would not be able to reuse or make modifications to the software in the future without contracting with the vendor.

Because FDOT wanted to potentially reuse the software in other parts of the State, and even license the software to other agencies in the United States, FDOT selected the works-for-hire approach. Additionally, since the project was a software procurement, FDOT had to follow the State's Office of Technology and Information Services process for Enterprise Application Services for the design, development, and implementation of the DST.

FDOT also decided that its on-premise hardware subsystem located at its TMC would host all software developed for the DST, which required staff to deploy and configure the hardware where the vendor would install the software.

Understanding the process and procedures that needed to be followed for procuring the DST allowed FDOT staff to contract, design, develop, and deploy the DST to meet the needs and requirements it had identified before procuring it.

ADDITIONAL RESOURCES

As stated in *Federal-Aid ITS Procurement Regulations and Contracting Options*:

> State and local agencies planning to procure intelligent transportation systems (ITS) projects with Federal highway funds face unique challenges. They choose appropriate contracting techniques that optimize project quality and cost while meeting applicable Federal, State, and local procurement regulations. These challenges are especially paramount when procuring ITS projects that involve advanced technologies and require specialized skills and knowledge. Even deployments of simple ITS system expansions have become complex undertakings to ensure consistency with the National ITS Architecture and evolving standards. Typically, the requirements of these ITS projects

cannot easily be specified at the outset of the project—resulting in the difficulty of establishing realistic low bids and ensuring end-product quality (Gord 1997).

The Federal-aid procurement regulations, as set forth in 23 CFR §172, 23 CFR §635, 23 CFR §655, and 49 CFR §18, define the requirements that State and local agencies adhere to when procuring projects with Federal-aid highway funds. These procurement regulations identify possible contracting options available for designing and constructing projects, including such contracts as engineering and design-related services, construction, and nonengineering or nonarchitecture. The regulations also require competitive contract award procedures for any project financed by Federal highway funds (23 U.S. Code (USC) § 101(a)). Use of a qualified on-call consultant may be acceptable if the list of on-call consultants resulted from a competitive, qualifications-based process (National Archives eCFR 2022; National Archives eCFR 2023; GovRegs 2023).

The process of developing a DST includes considering the development methodology an agency and vendor uses in the development and implementation of the DST. Traditionally, Federally funded projects have used a systems engineering approach that employs a waterfall methodology. More recently, system development projects have used agile development.

The following resources provide background on these methodologies:

- FHWA's (n.d.) "Welcome to the Systems Engineering Guidebook for ITS Web Site"
- Staples et al.'s (2017) *Applying Scrum Methods to ITS Projects*
- Scrum Alliance's® (n.d.) "What Is Scrum?"
- Marbach's (2016) "Introduction to Agile Practices"
- Agile Alliance's (n.d.) "Agile 101"
- DeWeese's (1994) *MIL-STD-498 Software Development and Documentation*

CHECKLIST: ISSUES TO REVIEW WHEN PROCURING A DST

After planning the procurement of a DST, deciding which procurement options may be applicable and/or suited to the agency's goals, and contemplating the types of DSTs, an agency should review the following issues prior to initiating procurement:

- Have all options for DST procurement been investigated?
- Have specific technology policies (e.g.., cloud-hosted solutions) been documented?
- Do intellectual property requirements (i.e., own, license, SaaS, etc.) determine the type of procurement?
- Does the agency have hardware subsystem requirements (on-premises, cloud) the vendor must follow?
- Does the agency have funding mechanisms for recurring costs associated with hosting and ongoing operations and maintenance?
- Has the agency selected a procurement method based on policies and requirements?

CHAPTER 8. INITIATING THE USE OF DECISION-SUPPORT TOOLS

This chapter provides agencies with an overview of the steps following the development or procurement of a DST to prepare for operations. It discusses DST verification and validation to help ensure the DST meets the needs and requirements the agency previously developed. Additionally, it enumerates deploying the DST software onto the computing hardware platform and ensuring all data and interfaces are complete and integrated so that the TMS is ready for operations.

Verification of a DST determines that the DST was developed correctly and meets requirements. Validation of a DST focuses on ensuring the correct type of DST was developed to meet the needs of the agency.

The objectives of this chapter are as follows:

- To understand the implementation and initiation process for DSTs.
- To discuss the verification and validation of DSTs.
- To discuss activities to consider when transitioning from testing to day-to-day use of a DST.

This chapter introduces the processes of implementing and initiating the use of a DST and describes the following stages of the systems engineering process:

- Systems verification.
- Systems validation.
- Operations and maintenance transition.

After reading this chapter, the reader should better understand the steps in DST verification and validation and the steps to transition to operations.

KEY ISSUES TO CONSIDER

An agency should consider the following key questions when preparing to operate a DST:

- Has the agency developed the test plans? Do all the staff members who will be involved understand the plans?

- Are all tests traceable to all the requirements?

- Are ongoing activities needed to train operators to use the DSTs efficiently and effectively? If so, what are these activities?

- Has the agency developed plans for potential issues during deployment? Does the agency have back-out plans if the deployment must be halted?

- Has the agency documented the testing (unit, integration, and acceptance) results?

- Has the agency completed a test readiness review?
- Has the agency performed a systems acceptance test to verify all requirements have been met and demonstrated?

STEPS TO PREPARE FOR OPERATING A DST

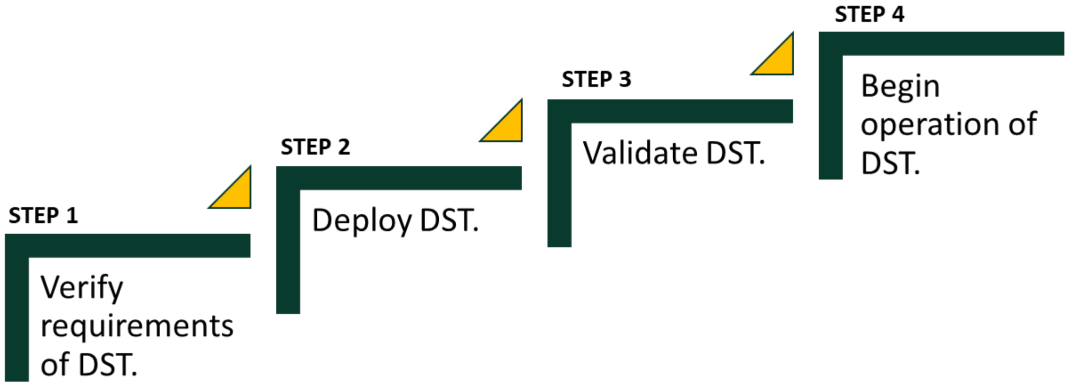
A testing process is needed to verify and validate a DST has been developed correctly and operates to meet the requirements and needs the agency previously identified. This process, shown in figure 25, is described in the following paragraphs.

As stated in *ISO/IEC* [International Electrotechnical Commission] *15288:2008*, the verification process confirms the specified design requirements are fulfilled by the system. The verification process provides the information necessary to affect remedial actions that correct nonconformances in the realized system or the processes that act on it (ISO 2008).

Once the verification process has been completed, the agency can transition to operations. The purpose of the transition process is to establish a capability to provide services specified by stakeholder requirements in the operational environment. The transition process installs a verified system (DST and TMS) together with relevant enabling systems (e.g., operating system, support system, operator training system). The transition process is used at each level in the TMS structure and in each stage to complete the criteria established for exiting the stage.

The validation process provides objective evidence that the services provided by a system when it is in use comply with stakeholder requirements, achieving the DST's intended use in the DST's intended operational environment. The validation process performs a comparative assessment and confirms that stakeholder requirements are correctly defined. Where variances are identified, they are recorded and help with corrective actions. The stakeholders ratify system validation.

Ultimately, the transition process transfers custody of the DST and TMS and responsibility for system support from one organizational entity to another. This transition includes transfer of custody from the development team to the organizations that will be operating and supporting the system. After the transition process has successfully concluded, the operation and maintenance phase of the DST typically begins.



Source: FHWA.

Figure 25. Diagram. Steps to prepare for operation of a DST.

Step 1—Verification of Requirements

Verification is an ongoing process that tests each subsystem as the subsystems are assembled and integrated to ensure subsystem performance meets design requirements. Verification is repeated at each level of integration until the entire system is assembled, at which point the entire system's performance may be verified a final time. Each time verification testing has been completed, the tests, results, and corrective actions are documented. Verification is typically conducted using an installation of the system dedicated to development or quality assurance (i.e., not under real-world conditions).

Step 2—Deployment of System

Deployment and validation are the process of installing the system in the field, confirming that the system functions in its intended environment (i.e., performs according to system requirements), and confirming the system meets the needs of the intended users. This process can be a challenge for any TMS. The simplest approach may be to switch operations over to the new system, but this switch also has the potential to disrupt operations. This situation can be particularly challenging with DSTs because the situations necessary for DST validation (congestion and incidents) are the situations where the most important factor is to not disrupt operations. It is ideal to run the new and old systems parallel to each other for a period of time. This dual use of systems allows for uninterrupted operations and enables observing the behavior of the new system under field conditions.

Step 3—System Validation

The validation process is invoked during the stakeholder requirements definition process. Validation confirms that the requirements properly reflect stakeholder needs and establishes validation criteria (i.e., that the right system has been built). The validation process is also invoked during the transition to operations to handle acceptance activities.

The validation process includes the following activities:

- Plan the validation: Develop a validation strategy—a plan for validating the system and ensuring the system meets the operational needs of the TMS operations staff.

- Perform the validation:

    - Develop validation procedures that demonstrate the system is fit for its purpose and satisfies stakeholder requirements.

    - Ensure staff readiness to conduct the validation.

    - Support in-process validation activities throughout system development.

    - Conduct validation to demonstrate conformance to stakeholder requirements.

    - Analyze detected anomalies for corrective actions, detect trends in failures to find threats to the system, and detect evidence of design errors.

    - Recommend corrective actions and obtain stakeholder acceptance of validation results.

    - Document validation results and enter data into the requirements tracking database.

Step 4—Transition to Operations

As stated in *ISO/IEC 15288:2008*, the operational transition process establishes a capability to provide services specified by stakeholder requirements in the operational environment (ISO 2008). The operational transition process installs a verified system together with relevant enabling systems (e.g., operating system, support system, operator training system). This process is used at each level in the system structure and in each stage to complete the criteria established for exiting the stage. It includes preparing applicable storage, handling, and shipping of the systems.

Ultimately, the transition process transfers custody of the system and responsibility for system support from one organizational entity to another. This transition includes transferring custody from the development team to the organizations that will be operating and supporting the system. After the transition process has successfully concluded, the utilization stage of the system of interest typically begins.

The transition process includes the following activities:

- Plan the transition:

    - Prepare a transition strategy, including operator training, logistics support, delivery strategy, and problem rectification/resolution strategy.

    - Develop the installation procedures.

- Perform the transition:
    - Prepare the installation site and install the system according to established procedure.
    - Train the system users in its proper use and ensure they have the knowledge and skills necessary to perform operations and maintenance activities. This process includes a complete review and handoff of operator and maintenance manuals, as applicable.
    - Receive a final confirmation that the system, as operated and maintained by the intended users, meets their needs. This process typically ends with a formal written acknowledgement that the system has been properly installed and verified, all issues and action items have been resolved, and all agreements pertaining to development and delivery of a fully supportable system have been fully satisfied or adjudicated.
    - Document any postimplementation problems that may lead to corrective actions or changes to requirements.

VERIFICATION

Some aspects of verification can be particularly challenging for DSTs. Because DST behavior often depends on a complex combination of inputs from multiple data sources, it can be difficult to recreate large, varied input streams to be useful for repeatable testing and verification.

Some approaches for verification include the following:

- Randomized inputs: Testing tools can be created to provide random numbers that approximate data sources (e.g., traffic detector readings). These tests can be made repeatable by reusing the same random number seed. This process can be a simple way to produce data that can be input to the DST for testing. The drawback is that the data may not match realistic inputs when viewed from a system perspective. A key aspect of a successful DST is that it responds correctly to conditions over a large area or time interval, and it is difficult to get a coherent dataset over widely ranging values of time and space using randomized inputs.

- Record and playback: Testing tools can be built to record live data inputs and play them back for testing purposes. This process can be a simple way to collect data that are realistic and coherent over time and space. A limitation of this approach is that it may be challenging to collect data reflecting extreme circumstances.

- Traffic simulation: A realistic traffic simulation can be created to derive inputs such as traffic volumes and speeds. This process can be used to create realistic testing scenarios, and simulation parameters can be varied to create extreme conditions. However, it may be expensive and time-consuming to build and calibrate a model if one does not already exist.

Deliverables for this phase may include the following:

- Test plans provide the step-by-step script an agency can follow to verify that the system developed meets the requirements determined during the planning and design phases.
- Test readiness reviews involve meetings between the development team and stakeholders to review the results of internal testing and ensure the system is ready for system acceptance testing by the agency.
- System acceptance testing verifies the completed system to ensure it meets all requirements and performs as expected, and the agency accepts the completed system and is ready to deploy it and begin operations.
- The agency develops documentation of each previous deliverable:
  - A test plan is created during the design phase and reviewed again prior to verification.
  - A test readiness review is drafted, including all preliminary testing that has been completed, the test results, and any known defects.
  - A final test report is created after system acceptance testing has been completed. This report shows the test results, any corrective actions, and the acceptance of the DST.

Verification of Knowledge-Driven DSTs

A knowledge-driven DST may be tested to verify the requirements and ensure that the logic within the DST functions as expected. The most typical knowledge-driven DST uses business rules within a rules engine. Testing a rules engine consists of developing random inputs for the key variables of the rules engine to verify the correct recommendation is provided. Using randomized inputs can generate a wide range of test cases easily. It is important that all tests are repeatable; the test inputs are stored to enable the tests to be rerun. In addition to randomized inputs, SMEs work with the technical team to ensure that input combinations common in the real world are represented in the test cases.

As an example, a typical incident response rules engine uses the current conditions of the network, the time of day, day of week, incident location, and incident severity to determine a recommended response plan. The response plan might include DMS messages, detour routes, and signal timing plans for an agency to implement. Testing the logic of the DST is needed to ensure the logic is developed correctly.

Verification of Data-Driven DSTs

A data-driven DST may be tested to verify the requirements and ensure that the algorithms within the DST function as expected. The two typical data-driven DSTs are predictive analytics algorithms and ML algorithms. Predictive analytics algorithms may be tested to ensure the output is reasonable and provides expected results. ML systems may compare the actual output of the engine to the expected output.

Testing predictive analytics models is different from testing most other types of software. While agencies need to test the model's performance, the testing also needs to demonstrate how well the model performs on data. An algorithm's accuracy depends on the model itself, which is developed from historical data, and the data that feeds the model. The training data need to be relevant to the problem the algorithm is trying to solve. A good predictive analytics algorithm performs well on different sets of data without favoring one set over another. However, insufficient testing can leave unresolved bias and variance in a model, which reduces the model's overall value.

Testing ML engines qualitatively is different from testing any other type of software. In most testing situations, agencies may seek to ensure the actual output matches the expected one. With ML engines, looking for exactly the right output is exactly the wrong approach. Typically, agencies will be unable to calculate the right output without writing the software twice.

The key to testing an ML engine is to understand both the requirements for the production results and the limitations of the algorithms. The requirements need to translate into objective measurements—ideally, the standard deviation of the mean result, assuming that the mean result is closely related to the actual result found in the training data. Using objective measures instead of qualitative testing methods allow agencies to assess the results of an ML engine from a statistical standpoint, rather than from a yes-no standpoint.

Agencies may not expect an exact right answer all of the time, or even most of the time. How agencies test and evaluate may entirely depend on the goals of the system (Heusser and Varhol 2017).

Verification of Model-Driven DSTs

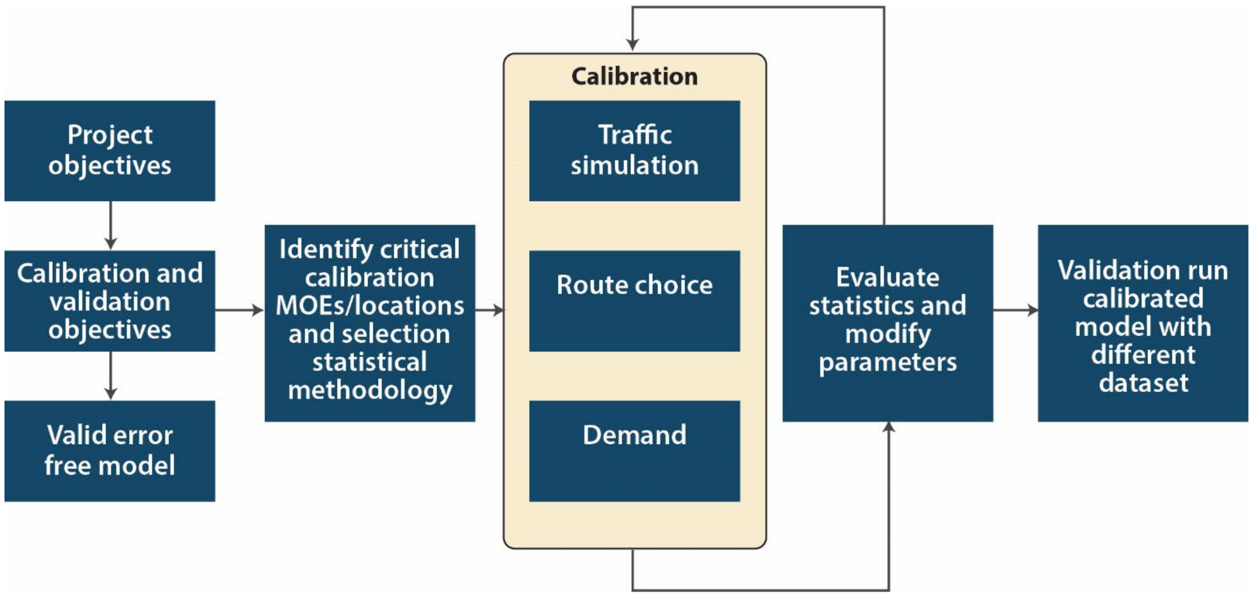
Verification of a model-driven DST begins with overseeing the calibration of the model and ensuring a proper calibration is performed. The following list summarizes the process for calibrating a model:

- Establish calibration objectives and review project objectives to ensure the calibration task directly supports the project objective.
- Identify the performance measures and key locations against which the models will be calibrated.
- Determine the statistical methodology to be used to compare modeled results to the field data.
- Determine the strategy for model calibration and identify parameters within the dynamic traffic assignment (DTA) models that are the focus of adjustments.
- Assemble the field data that has previously been collected for comparison to model outputs.

- Conduct model calibration runs following the strategy and conduct statistical checks. When statistical analysis falls within acceptable ranges, the model is considered calibrated.

- Test the calibrated model or compare it with a dataset not used for calibration. If the model replicates the different datasets, the calibration parameters and model are considered validated.

Figure 26 depicts a general process applicable to calibrating a DTA model.



Source: FHWA.

Figure 26. Diagram. Model calibration process (Sloboden et al. 2012).

After a model has been calibrated, the verification process may test the model using multiple scenarios and objectives and an expected level of accuracy for each test. As discussed in *Dynamic Traffic Assignment: A Primer*, a model can be tested with alternative scenarios and evaluated relative to the base model. Alternative scenarios can be developed to reflect the effect of various possible demand and network scenarios in the future (Chiu et al. 2011).

SYSTEM DEPLOYMENT AND VALIDATION

Deployment and validation are the process of installing the system, confirming the system functions in its intended environment (i.e., performs according to system requirements), and confirming the system meets the needs of the intended users. It is helpful to run the new and old systems in parallel for a period of time, which is known as a soft launch. This parallel operation can last from a few days to a few months, depending on the technological risk of the new system. For instance, if a DST is added to an existing TMS and the stakeholders want to use it for a period of time to ensure it operates as expected, a longer soft launch of the DST may be warranted.

The deliverables for this phase may include the following:

- A validation report documenting any issues or nonconformances to ensure that all requirements and use cases are validated.
- A change request identifying, through the verification and validation process, additional requirements or desired changes that need to be requested from the DST developer.

The agency approves system acceptance once validation has been completed, and then the DST will be ready for operation.

VERIFICATION AND VALIDATION OF A DST

Example of a Regional DST for ICM

FDOT's R-ICMS includes several subsystems that assist regional agencies with multimodal, multiagency responses to incidents within the I–4 corridor. The R-ICMS DST consists of two DSTs, as follows (FDOT 2022):

- ERE—A knowledge-driven DST that contains the logic to make determinations based on predefined rules. This DST includes monitoring current conditions to determine when a response plan needs to be implemented, modified, or deactivated.
- Prediction engine—A model-driven DST that consists of a real-time mesoscopic model that calculates the predicted conditions of the transportation network and determines changes to signal timing plans, detour route selection, and expected conditions 30 min into the future with and without a response plan.

To develop and test the prediction engine, a model calibration and validation process was performed by the development team. The prediction model was calibrated to a level of accuracy to support the potential R-ICMS scenario analysis. However, recognizing that a model will never be perfect, the development team identified a level of error tolerance after studying the variability of field data in the real world and the stochasticity of the DTA model.

The following calibration performance metrics and target acceptance values for different performance metrics are used by a development team:

- Screenline volumes: Natural or artificial divisions of the study area are reflected into sectors and intercept all traffic traveling between these sectors of the model. The targeted calibration threshold of the screenlines is to have the mean modeled screenline volumes within 5 percent of the mean observed screenline volumes.
- Link volumes: All locations with observed traffic counts are assessed by comparing the modeled counts against the observed counts at the hourly level for each link. Methods to examine the counts can include scatterplots, root mean square error (RMSE) percent, and Geoffrey E. Havers (GEH) statistics. Both the *R*-squared value of that regression line and the slope of the regression line are examined. First, the *R*-squared value is targeted to be 0.90 or higher, and the slope of the regression line is targeted to be between 0.95 and

1.05. Second, the RMSE percent is calculated for different road classes (e.g., freeways, ramps, major arterials, and other roadways). While the RSME percent value is expected to be higher for the lower class roadways, the target is to have an RMSE percent value of less than 10 percent for all freeway counts. Finally, GEH statistics are computed for selected key roadways in the mesoscopic model study area. Given the importance of the I–4 corridor to the mesoscopic model, count locations along I–4 are tracked and reported by computing a GEH statistic for each link for each hour of the simulation. The target is to have 85 percent or more of GEH statistics with a value of seven or higher for these key roadway counts.

- Corridor travel times: Travel time data are compared for the directional freeway corridors as well as selected arterial corridors. The arterial corridors selected for travel time validations are major arterials in the system or significant routes along key diversion routes within the defined response plans. These variation envelopes are used to assess the fit of the modeled travel times. The modeled travel time reflects the average modeled condition. The first validation target is to have 95 percent of all modeled travel times fall within the 2-sigma band. This target ensures that the modeled travel times are not producing significant outliers when compared to the range of typical weekday travel times. The second validation target is to have two-thirds of the modeled travel times within the 1-sigma band. This target helps ensure the modeled travel times are generally similar to the typical travel times seen on typical days.

CHECKLIST FOR PREPARING FOR OPERATIONS

After the agency procures the DST or the selected vendor has provided or developed the DST, the agency verifies and validates that the DST meets the requirements. Prior to accepting the DST to begin operations, agencies ask the following questions to demonstrate the DST is ready for operations:

- Has the agency developed and understood the test plans?
- Are all tests traceable to all the requirements, and is an RTM provided?
- Does the deployment plan include criteria for back-out plans for potential issues during deployment?
- Has the agency documented testing (unit, integration, and acceptance) results?
- Has the agency performed a systems acceptance test to verify all requirements have been met, demonstrated, and documented? Has the agency documented formal stakeholder acceptance?

CHAPTER 9. MONITORING, EVALUATING, AND USING A DST

Once the DST is operational, the agency can validate and calibrate the operation of the DST. The agency can continually monitor and evaluate the DST to ensure it is meeting the ongoing needs and requirements of the TMS and the performance metrics the agency has established. The purpose of this chapter is to present effective practices and recommendations for monitoring, validating, and calibrating the DST.

The objectives of this chapter are as follows:

- To provide an overview of the operations activities to consider for monitoring, evaluating, and adjusting a DST.
- To identify typical performance measures for each type of DST.
- To discuss the data requirements for performance measures that have been identified.

After reading this chapter, the reader should better understand the measurement and monitoring of DSTs to ensure they are operating as expected and continue to meet the agency's needs. Agencies should better understand how to identify and select key performance indicators (KPIs) to assist in the ongoing monitoring and evaluation of a DST.

KEY ISSUES TO CONSIDER

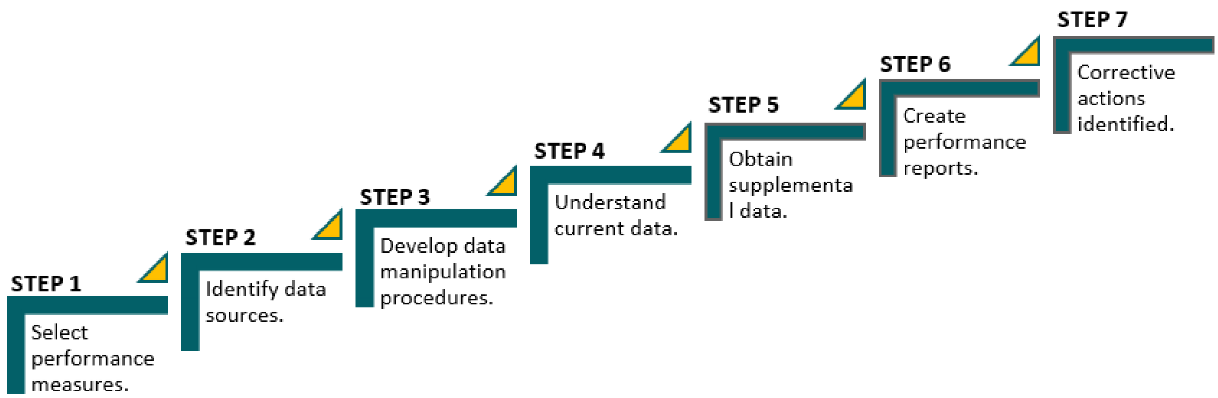
When monitoring an operational DST, agencies should consider the following key questions:

- Has the agency identified key performance criteria for the DST? Which performance measures and KPIs does the agency use?
- Has the agency identified the data needed to calculate the performance measures and KPIs?
- Does the agency want to review performance measures on a weekly, monthly, or annual basis? How many times a year will the reviews occur?
- Has the agency decided on thresholds for each performance measure and KPI that indicate corrective actions are needed?

STEPS FOR MONITORING, EVALUATING, AND ADJUSTING A DST

As discussed in *Guide to Effective Freeway Performance Measurement*, developing a performance measurement program to evaluate the effectiveness of a TMS and DST(s) begins with identifying the data available to perform the evaluation (Margiotta et al. 2007). Figure 27 illustrates this principle.

During design and development of a DST, an agency can consider the purpose of the DSTs and how to measure whether the DST is performing correctly. This assessment will allow vendors to configure or develop the DST to ensure the data needed for the performance measures are available. Depending on the contract method, a vendor should report KPIs and performance measures for the DST on a routine basis. Some agencies have used service-level agreements to incentivize the performance of the TMS and DST vendor. A service-level agreement defines the LOS an agency can expect from a vendor, the KPIs by which the DST is measured, and the remedies or penalties when agreed-upon KPIs are not achieved.



Source: FHWA.

Figure 27. Diagram. Evaluating DST performance.

The following seven sections discuss the steps for developing performance measures to evaluate the performance of a DST as part of a TMS.

Step 1—Select Performance Measures and KPIs

Based on the DST the agency has selected, the agency can identify performance measures and KPIs associated with the DST's operation to address the four characteristics used to evaluate TMSs and DSTs: effectiveness, efficiency, use, and satisfaction. For instance, the availability of the DST is a common performance measure that agencies use. The actual measure is related to how important the DST is to the agency's operation. An agency decides how long a DST can be nonoperational and still meet its needs. For instance, a 99.999-percent availability means the system can only be nonoperational for a period of 6 min per year. A 95-percent availability would allow 3.65 d of downtime per year (or about 36 h per month). When measuring availability, agencies should consider both software and hardware in the overall calculation.

Step 2—Obtain Existing Data

Since most available performance data are collected for purposes other than reporting performance, obtaining data from existing TMSs and traveler information systems is often more difficult than logic would indicate. Budgets for developing and deploying TMSs and traveler information systems may often be smaller than needed. A common cost-reduction strategy is to remove or curtail the data-archiving function needed to store and efficiently retrieve data collected as part of a TMS. Consequently, creating a performance monitoring system often starts with constructing the software needed to efficiently store and retrieve data already collected by an existing TMS. Steps 3–5 may or may not be needed, depending on the TMS, the DST, and the data needs.

Step 3—Develop Data Manipulation Procedures

Data manipulation allows agencies to perform actions on raw data to organize and store the data the TMS and DST need more efficiently. Data scientists and database developers use tools and data manipulation languages for adding, deleting, and modifying data in a database.

Once obtained from the data subsystem, the data collected from the TMS can be manipulated in the database and used as follows:

- As a direct measure of performance (e.g., vehicle volumes, vehicle speeds).
- In combination with other data from other devices in the field to compute a new performance statistic (e.g., travel times computed from toll tag readers at different locations).
- For mathematical transformation into a different performance measure (e.g., point speeds at consecutive locations can be used to estimate travel times along a corridor).
- In combination with other directly measured data to produce more complex performance measures (e.g., vehicle volume and speed data can be used to compute vehicle hours of travel or vehicle hours of delay).
- As input into various transportation modeling systems to estimate a wide variety of statistics that cannot be measured by the available sensor equipment (e.g., volume data used to feed a simulation model can produce estimates of pollution emissions).

Step 4—Understand Available Data

Once the agency has identified all available data, the next step is to understand exactly how well those data represent the performance of the DST they are collected from and how limitations in the data affect their use as performance measures. The "Additional Resources" section at the end of this chapter identifies resources agencies can use to further identify the data requirements of the performance measures.

Understanding strengths, weaknesses, and holes in the available data helps determine what supplemental data need to be collected specifically for performance monitoring. The agency also defines the need for many of the data manipulation steps necessary and many of the assumptions that are made to convert the available data into performance statistics.

Step 5—Collect Supplemental Data

Once the agency understands the available data, the agency can define the supplemental data collection needed to complete the datasets for the desired performance monitoring system.

Supplemental data will be used as follows:

- To fill in gaps in available data, which for a DST may be historical data available from other agencies.
- To provide information that helps eliminate biases in the previously collected data.

Step 6—Create Performance Measures and Develop Reports

The agency can develop performance reports using the performance measures and measures of effectiveness selected in step 1 and the data collected during steps 2–5. These reports can show how the DST is performing based on the effectiveness, efficiency, use, and satisfaction recommended to evaluate the performance of a DST. The performance reports can be provided to meet the operational needs of the agency and the importance of the DST. Reports may be run daily to indicate any current operational issues, weekly or monthly to show trends, and annually to provide longer-term performance measures.

Step 7—Develop Corrective Actions

If a DST or TMS is not performing as desired (or expected), corrective actions may be needed. Actions may include modifying processes and procedures used by TMS operators, changing DST parameters and configurations, expanding DST capabilities, and implementing needed DST changes. TMS and DST maintenance involves ongoing monitoring, evaluation, and calibration of the performance of the system. See chapter 10 for further discussion on maintaining a DST.

SELECTING APPROPRIATE PERFORMANCE MEASURES

All DSTs will have basic performance measures that agencies may consider using to ensure the DST is meeting the needs of TMS operators. Procurement of a DST can include specific performance measure requirements the selected vendor must meet. Performance measures may be considered that measure how well the DST is operating, if the DST recommendations are implemented by operators, and the operator's perception of the DST.

These types of performance measures may include the following:

- How quickly the DST provides a recommendation.
- How varying conditions and data loads (e.g., minor versus major incidents) impact TMS and DST performance (i.e., how quickly a decision can be calculated based on the load on the computing platform and data platform).
- What percentage of the time a TMS operator implements responses recommended by the DST.
- How TMS operators and TMS management perceive the quality of the DST responses.

The discussion for each type of DST is not meant to be exhaustive. While these common performance measures may be considered on the basis of the type of DST used by a TMS, additional specific DST performance measures can also be considered.

Knowledge-Driven DSTs

As previously discussed, knowledge-driven DSTs provide specialized problem-solving expertise based on the processing of stored facts, rules, procedures, and similar forms of knowledge. They attempt to emulate human reasoning but with more consistent results. Expert systems or rules-based systems are the best-known type. These systems use databases of knowledge generated by previous expert users along with a system's business rules to emulate the decisionmaking capabilities of an expert user of the system.

For the purpose of monitoring, evaluating, and adjusting a knowledge-driven DST, performance is mostly related to the speed of making a recommendation based on the rules and knowledge base. For example, a TMS may have a rules engine and business rules that calculate the message for an incident verified within the TMS. When an operator verifies the incident, the DST recommends displaying specific messages on DMSs prior to the incident. The performance of the knowledge-driven DST in this situation should include the speed of the response.

Efficiency Performance Measures

Efficiency performance measures indicate the results achieved by the DST and the response strategies the DST uses to provide an operator with the best decision using the fewest resources.

Performance measures to evaluate DST efficiency can include the following:

- Capacity indicator: The ratio between the number of recommendations the DST provided and the time it took to make them.
- Quality indicator: The ratio of correct response recommendations to total number of response recommendations.
- Productivity indicator: The amount of time a DST takes to make a recommendation compared to the time it would take a human operator to decide.

Effectiveness Performance Measures

Effectiveness performance measures indicate the results achieved by the DST in providing timely and accurate decisionmaking.

Performance measures to evaluate the effectiveness of the DST can include the following:

- Speed of response generation: An indicator of how quickly from when an event occurred to when a recommendation was generated once minimum thresholds were met.

- Accuracy of the response recommendation: An indicator of the correctness of the recommendation in the context of the rules and operating procedures a TMS uses for responding to events.

Data Requirements To Support Performance Measures

Performance measures for knowledge-driven DSTs use the DST's and TMS's logs of data associated with the incident management timeline, as follows:

- When an incident has occurred (date, time usually from the 911 system).
- When an incident is detected (date, time usually from the TMS).
- When a response is requested (date, time usually from the DST).
- When a response is enacted (date, time usually from the DST).
- When an incident is cleared (date, time usually from the TMS).
- When the network returns to normal (date, time usually from the TMS).

Table 17 provides example data for an incident and its source. It is important to use a common clock to ensure different systems are using the same time for measurements.

Table 17. Example incident management timeline.

Event	Date	Time (a.m.)	Source
Incident reported	August 1, 2020	08:23	CAD 911
Incident detected	August 1, 2020	08:25	TMS
Incident verified	August 1, 2020	08:35	TMS
Response requested	August 1, 2020	08:36	TMS
Response recommended	August 1, 2020	08:44	DST
Response enacted	August 1, 2020	08:55	DST
Incident cleared	August 1, 2020	09:30	TMS
Return to normal	August 1, 2020	09:45	TMS

CAD = computer-aided dispatch.

From the data provided in table 17, several performance measures can be created:

- TMS incident verification time: 12 min (incident verified—incident reported).
- DST response plan enacting time: 19 min (response enacted—response requested).
- Incident clearance time: 1 h, 7 min (incident cleared—incident reported).

Agency operators can use these values to identify potential corrective actions and improvements in the systems, processes, and tools the agency uses as part of its TMS.

Data-Driven DSTs

Data-driven DSTs typically use data from databases that are designed to be queried, which enables processing and analysis of data to develop insights that support decisionmaking. Statistical analysis software is one of the most common types of DSTs. More recent systems use ML algorithms to learn from historical data to identify patterns and make predictions based on current data. The effectiveness of a data-driven DST depends on the quality of the data gathered and the effectiveness of the analysis and interpretation by the decisionmaker. Two basic types of data-driven DSTs measure performance in different manners, as discussed in the following two sections.

Statistical Model Data-Driven DST

Statistical models use mathematical formulas and historical data to predict future conditions. Some of the more common types of statistical models used for data-driven DSTs are linear regression, logistic regression, time series, decision trees, neural networks, support vector machines, and Naïve Bayes classifiers (Mitchell 2017). Each model works best for specific types of data and desired output. A statistical model data-driven DST's performance measure is related to how well it predicts and recommends a response to an event within a TMS.

ML Data-Driven DST

The challenge for ML data-driven DSTs is that they need different measures, depending on the purpose of the DST. ML data-driven DSTs can self-learn as new data are received, so measuring their performance can be a challenge. However, systems and data used by the ML data-driven DST need to be measured and monitored to detect issues at the right time. This monitoring includes monitoring the data input into the DST and measuring the performance metrics for detecting strange model behavior, which ensures the DST does not provide unexpected results. For example, ensuring the data input into the DST is accurate and timely can be monitored and measured. The availability and response time of the DST can be measured to ensure the DST is operating as expected in a timely manner.

Performance Measures for Data-Driven DSTs

Which performance measures are used influences how the performance of a data-driven DST is measured. However, performance measures can also be deceiving. If agencies do not choose performance measures that correctly measure how accurately the DST is predicting, they may falsely conclude a DST is a robust prediction engine. All problems that data-driven DSTs can solve fall into two categories: classification problems and regression problems.

A classification performance measure indicates what category something falls into. The following performance measures can be used to evaluate a classification of the DST:

- The classification accuracy is the ratio of correct predictions to the total number of predictions made. For instance, a DST might predict when an incident is likely to occur. The correct prediction can be measured if the incident does occur. However, this may also be challenging, because part of the DST's functionality is to recommend an action to mitigate the predicted incident. To measure accuracy, an agency may need to choose not to respond to the prediction to ensure the DST is accurate.

- A confusion matrix provides a matrix as output and describes the complete performance of the model. This description includes four key terms:
  - True positives: the times the DST provided correct predictions and recommended actions.
  - True negatives: the times the DST provided correct predictions and recommended no actions.
  - False positives: the times the DST provided incorrect predictions.
  - False negatives: the times the DST provided incorrect actions.

A regression performance measure is about predicting a quantity. The following performance measures can be used to evaluate a DST's regression values:

- *R*-squared indicates how well the variation of a measure is explained by the other variables included in the DST prediction. *R*-squared does not take into consideration any biases that might be present in the data. Therefore, a good data-driven DST might have a low *R*-squared value, or a data-driven DST that does not fit the data might have a high *R*-squared value.
- Average error is the numerical difference between the predicted value and the actual value.
- Median error is the average of all differences between the predicted and the actual values.
- Average absolute error is similar to average error but is calculated by using the absolute value of the difference to balance out the outliers in the data.

Choosing the correct granularity of the data being used for the regression analysis is important to ensure the precision of the analysis. For instance, an agency may have micro-second traffic signal data used to determine the effectiveness of changing a signal timing plan. However, condensing the data into a longer time frame (1 s, 10 s, etc.) may be quicker, require less work to perform the analysis, and yield just as useful results.

Data Requirements To Support Performance Measures

Performance measures for data-driven DSTs use data to calculate when the predictions and actions are correct versus when they are incorrect and the associated data types. This task may require an assessment by operations experts to compare the DST's recommendation to the experience and expertise of the senior operations personnel in the agency.

Model-Driven DSTs

Model-driven DSTs use mathematical models that express the theoretical relationships among data elements or key variables of interest for an analysis being conducted. These tools can be used (either online or offline) to simulate the behavior of a transportation system (or parts of the system) using different values for certain parameters. Model-driven DSTs use different types of analysis tools (e.g., statistical software and traffic analysis software) to assess the available data, evaluate the data, and report on conditions.

Performance Measures for Model-Driven DSTs

Performance measures for model-driven DSTs use data to calculate when the predictions and actions are correct versus when they are incorrect and the associated data types to include all traffic data associated with the output of the model (i.e., volume data—both predicted and actual). The most common performance measure is volume accuracy (GEH statistic): For traffic simulation models, the model will predict traffic volumes on the transportation network, which is compared against the actual volumes from field equipment connected to the TMS. The volume accuracy will be defined by 95 percent of available count locations using the formula in figure 28.

$$GEH = \sqrt{\frac{(E-V)^2}{(E+V)/2}}$$

Figure 28. Equation. GEH statistic.

Where: E = model-estimated volume.

V = field count or volumes from the TMS.

The GEH formula is useful in the following situations:

- Comparing the traffic volumes obtained from a travel demand forecasting model with real-world traffic volumes.
- Adjusting the traffic volume data collected at different times to create a mathematically consistent dataset that can be used as input for travel demand forecasting models or traffic simulation models, as discussed in NCHRP Report 765 (Horowitz et al. 2014).

Data Requirements To Support Performance Measures

Performance measures for model-driven DSTs use data to compare the simulated network and the actual network to determine if the model-driven DST needs recalibration.

DST Performance Measure Checklist

Following is a performance measure checklist with useful questions to ask:

- Has the agency selected the performance measures for the TMS and DST?
- Has the agency identified existing data for calculating the performance measures?
- Has the agency developed a process for manipulating existing data sources, if needed?
- Has the agency decided on the data collection process and defined the storage requirements?
- Has the agency decided on the algorithms and formulas for calculations of the selected performance measures?
- Has the agency decided the reporting format and frequency for each performance measure?

OBTAINING THE DATA NEEDED FOR MEASURING PERFORMANCE

During the design and development phases of a DST project, an agency identifies the performance measures that will be used to monitor a DST during operations. Next, the agency identifies the data requirements for those measures. Requirements for the TMS, the DST, and external systems are developed to ensure that all data, with the correct granularity, is available once the DST becomes operational.

If the current TMS and external systems do not have the data or the granularity needed, agencies may decide to modify those systems to make the data available. Additionally, other sources of the data may be investigated. For example, the Dallas ICM DSS needed traffic volume and speeds by lane for the US 75 freeway. However, the regional center-to-center system only provided aggregated speed and volume data across all lanes. To receive the more granular data, an interface to the TxDOT TMS software was integrated, which did provide the volume and speed data per lane (FHWA 2015).

PERFORMANCE REPORTING

The performance of a TMS, DST, and the transportation network can be assessed using three levels of performance. The three levels of performance reports used in operations include the following:

- Real-time dashboards and reports: Operators use these reports and dashboards to view and analyze real-time systems, check whether the DST and TMS are working properly, and provide a list of current active decisions being managed.
- KPIs and deviations from historical norms: TMS managers and supervisors use these reports and dashboards to identify if the TMS, DST, or transportation network is operating outside of historical norms. For instance, if a freeway is operating at an average

speed of 25 mph during the morning rush, the DST can analyze this data and inform users that a 40-mph speed is normal and further investigation may be needed. These reports and dashboards can provide real-time KPIs on how quickly a DST moves from event notification to decision recommendation versus the average time this determination has been made in the past using a legacy system or staff. This measurement will indicate whether the DST is operating less efficiently or having issues that maintenance personnel may need to investigate.

- High-level summary data and KPIs: Managers and agency executives use these dashboards to view summary data from the TMS and DST. These data might include current average speed of the network (versus historical) and current number of active events.

Similar to the requirements for the data needed for performance measures, the performance reporting and dashboards are identified during the design phase to ensure the correct data and format will be available once the DST is developed.

CORRECTIVE ACTIONS

By using performance measures and KPIs, agencies can identify TMS or DST systems, procedures, and field equipment that may need corrective action. Through the proactive use of the data and KPIs, agencies can quickly identify when a DST may not be operating as expected. The DST may need routine maintenance or recalibration (i.e., retraining and calibration of a model-driven DST). The performance measures and KPIs can also provide trends over time to show a degradation of the performance of systems and equipment that may need maintenance, enhancement, replacement, or retirement.

ADDITIONAL RESOURCES

The following additional resources can assist agencies in developing performance measures and evaluation processes for DSTs:

- Park's (2005) *Transportation Management System Performance Monitoring, Evaluation, and Reporting—A Technical Handbook*.

- National Academies of Sciences, Engineering, and Medicine's (2022) *Evaluating Alternative Operational Strategies To Improve Travel Time Reliability*.

- Margiotta et al.'s (2007) "Guide to Effective Freeway Performance Measurement: Final Report and Guidebook."

- Dowling's (2007) *Traffic Analysis Toolbox Volume VI: Definition, Interpretation, and Calculation of Traffic Analysis Tools MOEs*.

- Breck et al.'s (2017) *The ML Test Score: A Rubric for ML Production Readiness and Technical Debt Reduction*.

- Amershi et al.'s (2019) "Software Engineering for Machine Learning: A Case Study."

EXAMPLE OF MONITORING AND EVALUATING A DST

For the ICM program, the USDOT evaluation team developed an evaluation plan for the DSTs for both the Dallas and San Diego ICM projects. These evaluations considered several key performance and accuracy measures, as follows:

- The quality of responses generated by the DSTs.
- The accuracy of the simulation software's predictions as to transportation system conditions 30 min or more into the future.
- The speed of response plan generation.
- The impact of varying conditions and data loads (e.g., minor versus major incidents) on TMS and DST performance (i.e., how quickly a decision can be calculated based on the load on the computing platform and data platform).

The evaluation of the DST considered different measures of effectiveness to be analyzed, including the following:

- Percentage of times a TMS operator implements responses recommended by the DST.
- Percentage of times a TMS operator alters the recommended responses (without dismissing them completely).
- Average time for the DST to deliver an actionable response plan.
- Average time for the DST to deliver predictions of response plan effectiveness.
- Average number of response plans generated per hour during event.

In addition, the following qualitative measures of effectiveness were selected and used as a basis for the evaluation:

- Responses consistent with operator's experience and perceptions (per the TMS operators).
- Perceived quality of responses, including improvements relative to any comparable preICM approaches (per the TMS operators).

For the evaluation, the data collected were through a mixture of interviews and directly from the TMS data subsystem by the evaluator. The performance measures were developed offline after the project was completed. Through APIs provided by the Dallas ICM TMS, the evaluator connected to the data subsystem and routinely downloaded all data into their own data platform, which was used for the evaluation.

CHECKLIST: MONITORING, EVALUATING, AND ADJUSTING A DST

After the agency has begun DST operations and wants to ensure the DST is performing as expected, the agency can begin DST measurement and monitoring. The following questions can assist agencies in ensuring they are prepared to monitor, evaluate, and adjust the operation of a DST:

- Has the agency identified the key performance criteria for the DST?
- Has the agency identified which performance measures and KPIs will be used?
- Has the agency identified what data are needed to calculate the performance measures and KPIs?
- Has the agency identified any additional data needed to calculate the performance measures and KPIs that must be created or developed?
- Is the agency planning to review performance measures weekly, monthly, or annually?
- Has the agency decided the threshold for each performance measure and chosen KPIs to indicate when corrective actions will be needed?

CHAPTER 10. USING AND MAINTAINING DECISION-SUPPORT TOOLS

The purpose of this chapter is to provide agencies with an overview of the ongoing operations, monitoring, and maintenance of a DST once it is operational. This chapter discusses the routine maintenance activities for each type of DST technology and focuses on DST maintenance to ensure it is operating, and continues to operate, as expected.

The objectives of this chapter are to provide the following:

- An overview of the maintenance activities to consider for a DST.
- An overview of the types of maintenance to consider for a DST.
- A framework for monitoring the operation of a DST and deciding when maintenance is needed.

After reading this chapter, the reader should better understand when DST maintenance is needed, the activities used to tune the DST, and how to identify when enhancements or the replacement of a DST may be needed.

KEY ISSUES TO CONSIDER

Agencies should consider the following key questions when preparing for and maintaining a DST:

- What key processes are involved in maintaining a DST?
- What activities are needed for the routine maintenance of a DST?
- Does the agency have monitoring tools in place to ensure the DST is operating correctly?
- Does the agency have a process for reporting DST issues?
- Does the agency have a process for managing changes?
- Does the agency have a process for managing enhancements and new releases?
- Does the agency have a plan to train operators when changes are made to the DST?

MAINTENANCE PROCESSES

Many agencies may already have maintenance processes for their IT systems. The maintenance processes for TMSs and DSTs may be similar. Agencies perform TMS and DST maintenance for reasons including the following:

- To correct failures in the TMS and DST.
- To interface with new systems.
- To enhance the TMS or DST.
- To migrate to a new TMS or DST.
- To retire a TMS or DST.
- To upgrade the TMS subsystems (computer hosting platforms and data platforms).

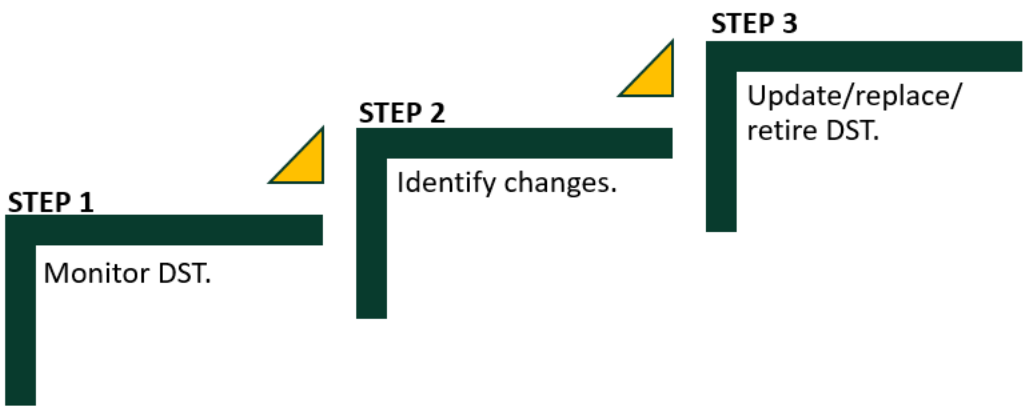
Two of the most common types of DST maintenance are as follows:

- Corrective maintenance: This category includes modifying and updating the TMS subsystems and DSTs to correct or fix problems and failures that are either discovered by operators or identified through performance reports.

- Preventive maintenance: This category includes modifying and updating the TMS to prevent future problems with the subsystems. Preventive maintenance aims to prevent problems that might not cause issues in the moment but may cause issues in the future. This type of work may include archiving old data within the data subsystem to free up resources and space on the computer-hosting platform.

STEPS FOR MAINTAINING A DST

The purpose of the operations and maintenance phase is to use the system to deliver its services. TMS personnel operate the system, monitor the system and services, and measure the system performance. To sustain the DST, monitoring tools may identify and analyze operational problems in relation to vendor contracts, stakeholder requirements, and organizational needs and constraints, as shown in figure 29.



Source: FHWA.

Figure 29. Diagram. Maintaining a DST.

The following three sections describe the steps for the ongoing maintenance and monitoring of a DST.

Step 1—Monitor and Maintain the DST

Monitoring a DST is similar to monitoring any software application. Using monitoring tools, a DST may be monitored for operational and performance conditions. Operational monitoring is used to ensure the DST is working. The resources from the computer hosting platform and software subsystem are monitored to ensure the DST has the needed resources, including computer memory, disk space, and connectivity between the DST and other software.

Performance monitoring is used to ensure the DST is performing as expected with tracking and reporting on performance issues. Performance monitoring for a DST may be based on the type of DST and its key performance measures. Performance monitoring includes performance indicators, such as the average response time for a DST to provide a recommendation. Data from both operational and performance monitoring may be recorded for calculation of longer-term performance measures, which can be used to identify when DST changes may be needed.

Step 2—Identify When Changes Are Needed

The DST and its related subsystems may need changes when the performance has degraded, new functionality is necessary, or new business processes are identified. A DST may need its hardware, software, logic, or underlying data updated when it no longer performs as expected, when new information and data become available, or when changes are made to one of the components. Updates are also needed when the computing hardware platform, DST (e.g., software and algorithms), or TMS has reached the end of its life or when upgrades are made to one component. Changes to a DST may be needed when expectations, policies, and technologies evolve. Additionally, agencies may identify unintended and undesirable effects when monitoring the DST due to the DST's actuating process or its recommendation of inappropriate, unacceptable, or outdated actions, which means changes to the DST are needed.

Step 3—Update and Replace the DST

Once the agency has identified changes to the DST, the agency can follow a defined change management and configuration management process to make changes to the TMS and DST subsystems.

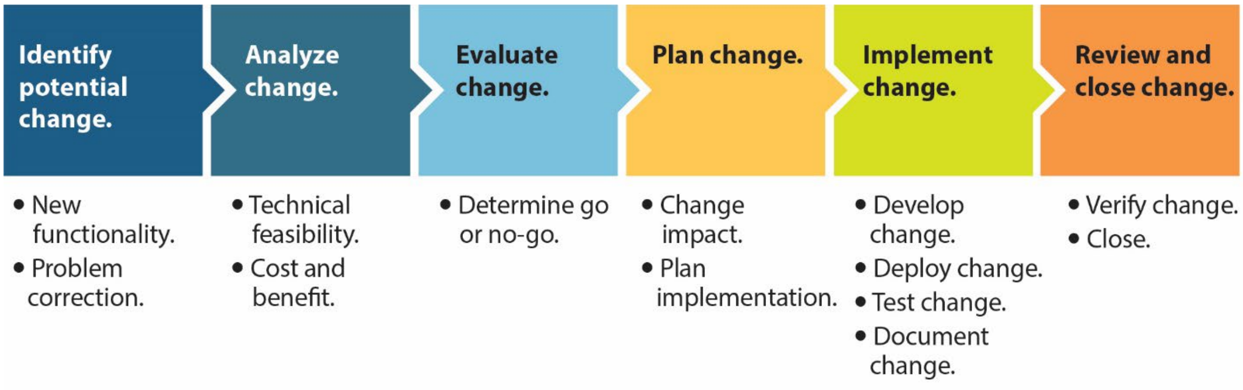
KEY MAINTENANCE CONCEPTS

A TMS and its DST(s) may need hardware, software, logic, or underlying data updated when performance is not as expected, when new information is available, or when changes have been made to one of the components. Agencies will likely need to evaluate and plan for potential changes to DSTs any time changes occur in a TMS. Enhancements to DSTs or APIs can be done simultaneously with TMS changes or after they have been made, depending on how complex the changes are. If there are numerous changes, agencies might want to consider modifying one subsystem at a time so that errors are more easily detected and analyzed if they occur.

Managing and Improving DST Operation

A DST provides key information and decisionmaking support to assist transportation agencies in understanding the increasing volume of incoming data and choosing from a complex array of alternative actions. To consider changes to a DST, an agency can follow a change management process similar to the one seen in figure 30. The first step is to identify a potential change to the DST based on monitoring and agency needs. Potential changes may include new functionality or fixing an identified problem.

Before implementation, an agency may want to evaluate any change to any software system to determine its potential impact on the overall TMS, cost, and benefits. Once this information is known, an agency can decide whether the change can be made or not.



Source: FHWA.

Figure 30. Diagram. Change management process.

Once the agency decides to proceed with a change, the agency can develop a plan for the change. This plan may include the updating process for the various subsystems, the installation procedures, and back-out procedures if the change does not go as planned. Once the change has been deployed, the TMS can be fully tested to ensure the change is performing as expected and has not created unforeseen impacts. Lastly, the configuration changes are documented and verified. Following these procedures, normal operation can continue.

Assessment Approaches and Evaluation Methods

How an agency assesses DST performance depends on the type of DST and the data available from the TMS, the outputs of the DST (its functions and types of decisions), and data from various field devices. From a computer system point of view, many tools and processes are available to ensure the hardware, network, and software are operating correctly. From an operational perspective, agencies can monitor the following TMS and DST system elements to evaluate whether a DST is operating correctly:

- The availability and accuracy of data, information, and content as decision inputs.
- Any decision-process bottlenecks and traffic (i.e., whether decision calculations are taking too long due to a resource constraint within the system).

As discussed in chapter 9, performance measures can be established through assessing effectiveness, efficiency, use, and satisfaction. The following example measures address these items:

- Correctness and precision of DST response recommendations: Is the recommendation accurate?
- Problems resolved after DST response recommendations (percentage): Is network performance improved?
- Speed of decisionmaking: Does a DST take too long to recommend a response?

- Timeliness and efficiency of operator process: How long does it take a TMS operator to accept, reject, or modify a response recommendation?
- Productivity of DST: How many response recommendations are calculated for a given event?
- Operator confidence in DST predictions and response recommendations: Does the operator trust the system? (This assessment is a qualitative measure).

Computing Hardware Updates

Computing hardware or subsystem updates usually occur when the current hosting servers are near or at end-of-life. Due to growth, budget cuts, or rack limitations, servers deployed for one purpose often begin fulfilling additional services and responsibilities; therefore, it is important to periodically audit systems. Reviewing a server's resource load helps ensure the organization optimizes performance and prevents downtime. Server upgrades always need planning.

Data Updates

Changes in the transportation network can occur frequently, depending on where the data originate (e.g., third-party data, detectors, and other TMSs). For the majority of TMSs, two types of data changes may occur: static and dynamic. Static data (e.g., roadway network and device location) do not change often; dynamic data (e.g., speed, volume, and occupancy) are constantly changing. The accuracy of the static data used by a TMS can impact DST operation. Agencies may implement a defined update period to ensure changes can be made to all systems affected by data changes. Quarterly updates to the static data may be appropriate for traveler information systems, TMSs, and ICM programs.

New sources and types of data may become available as a TMS matures (e.g., additional field detectors, third-party data, CV data). When these sources become available, an analysis should be done to determine if these data will improve DST accuracy and reliability. Just because a new data source is available does not necessarily mean it should be integrated into the TMS and used by its DST(s).

Software Updates

Knowledge-Driven DSTs

Knowledge-driven DSTs may need updates when the business process or operating process has changed. Business rules management systems are the most common type of knowledge-driven DSTs and use an expert's experience and knowledge to develop a set of rules. When the operating procedures for a TMS change due to experience, policy, or new technology, the knowledge-driven DST may need to be updated.

Updates to a knowledge-driven DST should occur if the current DST is not performing as expected or if new operating policies and procedures are implemented. For example, if a TMS adds CV infrastructure to its system, a business rule to post a CV message on a series of roadside units may be added to the rules engine logic for specific situations. If new or additional response plans have been developed due to changes in the transportation network because of temporary construction or longer-term construction, then changes to the DST may be needed.

Performance issues may be another reason for an update. For example, if a DST is taking longer than expected to make a recommendation, a change to the DST may be needed. Replacing a knowledge-driven DST to acquire new technology with additional functionality or features that the current DST lacks is the change most likely to be needed.

Data-Driven DSTs

Data analytics models and ML models are two types of data-driven DSTs. The effectiveness of a data-driven DST depends on the quality of the data gathered and used to train/calibrate the data-driven DST and the analysis and interpretation by the decisionmaker using the model.

Both types of data-driven DSTs may need updating when new training data have become available, and the current DST is not providing the expected results because of changes in the data. Two types of retraining or calibration can occur for ML engines: manual retraining and continuous learning.

Manual retraining maintains the data-driven DST with fresh data to train and deploy the DST using the same process used to develop the ML engine. Continuous learning, the process to support a data-driven DST, keeps it up-to-date using an automated system to continuously evaluate and retrain the ML engine. Continuous learning may include the following aspects:

- Saving the new training data as they are received. For example, if updated travel patterns and incident data are being received, saving that information to a database.
- Testing the data accuracy against the ML engine when enough new data have been received.
- Using the new data if the accuracy of the ML engine degrades over time, or a combination of the new data and old training data, to build and deploy a new ML engine.

The benefit to a continuous learning system is that it can be completely automated. Since data-driven DSTs can be recalibrated or retrained, replacing them need only occur if there is new technology, if a new vendor is selected, or if a new type of DST is being implemented. A release management plan should be developed to deploy and test the new DST and retire the old DST, similar to other software system replacements.

Model-Driven DSTs

Model-driven DSTs use mathematical models that express the theoretical relationships among data elements or key variables of interest for an analysis being conducted. The most common type of model-driven DST is a simulation model. Similar to planning models, a model-driven DST needs to be updated when travel demand and travel patterns change, when the transportation network changes, or when the commercial modeling product changes.

Updating a model-driven DST is done for three components of the simulation model: updating the transportation network model, updating the transportation data, and updating the software product. When new roads are constructed or modifications are made to the physical transportation network, the DST may be updated to reflect these changes. This updating may include changes to a signalized traffic intersection that include a new lane configuration, a new road being built, or changes to an existing road that include new lane configurations.

Since simulation models use historical and real-time data to simulate the transportation network, recalibrating the model may be necessary when data changes for travel patterns and travel demand.

Lastly, if a vendor updates the software product the model-driven DST uses, a change management process can be followed for testing the updated product to determine whether the model is still valid or if it needs to be recalibrated. Like a data-driven DST, a model-driven DST can be recalibrated or retrained—replacement is needed if there is new technology, a new vendor is selected, or a new type of DST is being implemented.

FRAMEWORK FOR DETERMINING WHEN MAINTENANCE IS NEEDED

When changes occur in the TMS, agencies may evaluate and plan for potential changes to the DSTs. Depending on the complexity of the change, the enhancements to the DSTs or APIs can be done simultaneously or after the TMS changes have been made. If there are numerous changes, agencies may want to consider doing one subsystem at a time; this way, errors can be more easily determined if they occur.

All TMS and DST changes should follow a change management process, with defined back-out procedures in case the changes fail or do not deliver the expected result. According to the Information Technology Infrastructure Library process framework, the goal of change management is to control risk and minimize disruption to associated IT services and business operations (Change Management Institute 2015).

Computing Hardware Updates

Computing hardware or subsystem updates usually occur when the current hosting servers are near or at end-of-life. Reviewing a server's resource load helps ensure the organization optimizes performance and prevents downtime.

Software and API Updates

As with hardware updates, the process for updating the operating system, tools, software, APIs, and database software on the servers should be thoroughly tested. A back-out procedure should be developed in the event an upgrade does not go as planned.

Newer generations of DSTs are beginning to have self-evaluating capabilities. Additionally, agency staff should monitor and evaluate DSTs for the effectiveness of recommended responses and the utilization rates. If recommended responses run counter to the preset agreements and boundaries of a DST's logic, agency staff should review the DST for areas that need improvement. Depending on the type of DST(s) used, business rules or predictive models may need to be updated based on changes in the data or analysis of the DST operation.

Data Updates

Changes in the transportation network can occur frequently, depending on where the data originate (e.g., third-party data, detectors, and other TMSs). For the majority of TMSs, two types of data changes may occur: static and dynamic. Static data (e.g., roadway network and device location) do not change often; dynamic data (e.g., speed, volume, and occupancy) are constantly changing. The accuracy of static data used by a TMS can impact the operation of the DSTs. > Agencies may implement a defined update period to ensure changes can be made to all systems affected by data changes. Quarterly updates to the static data may be appropriate for traveler information systems, TMSs, and ICM programs.

New sources and types of data may become available as a TMS matures (e.g., additional field detectors, third-party data, CV data). When these sources become available, an analysis should be done to determine if these data will improve DST accuracy and reliability. Just because a new data source is available does not necessarily mean it should be integrated into the TMS and used by its DST(s).

USING AND MAINTAINING A DST: CASE STUDY

The Dallas Integrated Corridor Management (ICM) Demonstration Project case study illustrates some of the maintenance concepts discussed in this chapter and the potential impacts of not maintaining a DST. The US 75 ICM project was a collaborative effort led by Dallas Area Rapid Transit in collaboration with USDOT; the cities of Dallas, Plano, Richardson, and University Park; the town of Highland Park; the North Central Texas Council of Governments; North Texas Tollway Authority; and TxDOT. The Dallas ICM deployment focused on the four primary goals of any ICM: improving incident management, enabling intermodal travel decisions, increasing corridor throughput, and improving reliability of travel time (FHWA 2015).

The Dallas team used a variety of coordinated multimodal operational strategies to achieve these goals using DSTs, including the following:

- Use simulations to predict travel conditions for improved operational responses.
- Implement response plans interdependently among agencies.
- Divert traffic to strategic arterials and frontage roads with improved, event-specific response plans for traffic signal timing.

These strategies were implemented using a combination of two DSTs. The primary DST was a knowledge-driven DST that used a rules-based engine to produce potential response plans for incidents on US 75. The rules-based engine considered incident location, direction of travel, time of day, and congestion to select an initial response plan. Next, it evaluated conditions on detour routes, including available capacity on frontage roads and parallel arterials, and alternative modes, including light-rail transit. After making calculations, the rules-based engine selected potential response plans for the secondary, model-driven DST to evaluate.

The model-driven DST was used to simulate the various response plans and select the plan that provided the most overall benefit to the corridor. The model-driven DST used a simulation engine that employed a mesoscopic model to simulate the US-75 corridor.

Maintaining the knowledge-driven DST and the model-driven DST for the ICM program included monitoring the DSTs within the TMS computer hosting platform and ensuring the DSTs were online and receiving information. Additionally, data was collected from both DSTs for later evaluation of their performance. The stakeholder team met on a monthly basis to review the incidents that occurred, the response plans that were selected by the DSTs, and the impact of the responses provided. Adjustments were then made to the response plans and the rules engine if changes were determined necessary by the stakeholder committee.

The importance of maintenance was most evident with the model-driven DST. Due to funding issues, the model-driven DST's calibration was not maintained with new transportation network data as it became available. The model-driven DST was not recalibrated for a period of 2 yr, which caused the stakeholders to begin to question its output and reliability after the 2 yr of operation. Since the model was no longer calibrated to the current network, the stakeholders decided to retire the DST for the ICM program. This anecdote illustrates that a DST needs ongoing operations, maintenance, and recalibration to ensure the agency's investment receives its expected benefits over the life of the TMS.

ADDITIONAL RESOURCES

Agencies can reference the following resources to review processes for maintenance of software systems:

- ISO's (2006) ISO/IEC 14764: 2006 *Software Engineering—Software Life Cycle Processes—Maintenance*
- Smith's (2003) *Configuration Management for Transportation Management Systems: Final Report*
- Jackson, Gallagher, and Dorgan's (n.d.) "System Maintenance" web page from the Systems Engineering Book of Knowledge (SEBoK) website
- ISO's (2015) ISO/IEC/IEEE 15288:2015 *Systems and Software Engineering—System Life Cycle Processes*

DST MAINTENANCE CHECKLIST

After an agency has begun operations and monitoring of its DST, the agency should consider a DST maintenance process to ensure the DST is continuing to operate as expected. To help ensure they are prepared for maintaining the DST for its useful life, agencies should ask the following questions:

- Has the agency defined all DST maintenance activities?
- Does the agency have the monitoring tools in place to ensure DST(s) are operating correctly?
- Does the agency have a process for reporting issues with DST(s)?
- Does the agency have a process to manage changes to DST(s)?
- Does the agency have a process to manage enhancements and new releases?

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