Use of Decisionmaking and Information Management Systems in Mainstreaming TSMO

Publication No. FHWA-HOP-21-044

March 2023

U.S. Department of Transportation
Federal Highway Administration

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HOP-21-044	**2. Government Accession No.**	**3 Recipient's Catalog No.**
4. Title and Subtitle Use of Decisionmaking and Information Management Systems in Mainstreaming TSMO		**5. Report Date** March 2023
		6. Performing Organization Code
7. Author(s) Emanuel Robinson, Valerie Orellana, Sana Wilder, Jocelyn Bauer, Pat Noyes, Kayce Georgi		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Leidos, 11251 Roger Bacon Drive, Reston, VA 20190 Westat, Inc., 1600 Research Blvd, Rockville, MD 20850 Pat Noyes & Associates, Boulder, CO 80302		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. DTFH61-16-D00053
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration 1200 New Jersey Ave., SE Washington, DC 20590		**13. Type of Report and Period Covered** White Paper, 2018 - 2020
		14. Sponsoring Agency Code HOP
15. Supplementary Notes Tracy Scriba, FHWA Task Order Contracting Officer's Representative		
16. Abstract This White Paper explores how decisionmaking, decision support systems (DSSs), and information management systems (IMSs) may be mechanisms for mainstreaming TSMO (transportation systems management and operations) within transportation agencies. The Paper provides examples of how these systems have been used to advance and integrate TSMO in major agency functions such as planning, operations, maintenance, asset management, and performance management.		
17. Key Words Mainstreaming, TSMO, transportation systems management and operations, infomation management systems, decisionmaking, decision support systems.	**18. Distribution Statement** No restrictions.	

19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 29	**22. Price**

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

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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 ACRONYMS AND ABBREVIATIONS

AMS	analysis, modeling, and simulation
ATDM	active transportation and demand management
DOT	department of transportation
DSS	decision support system
FHWA	Federal Highway Administration
GIS	geographic information system
ICE	Intersection Control Evaluation
ICM	integrated corridor management
IMS	information management systems
INVEST	Infrastructure Voluntary Evaluation Sustainability Tool
ITS	intelligent transportation systems
ITSDCAP	ITS Data Capture and Performance Management
SANDAG	San Diego Association of Governments
SHA	State Highway Administration
STARS	Statewide Traffic Analysis and Reporting System
TOAST	Traffic Operations Assessment Systems Tool
TSMO	transportation systems management and operations

1. INTRODUCTION

Transportation agencies use transportation systems management and operations (TSMO) to enhance the reliability and safety of their systems. There are numerous ways to support mainstreaming TSMO throughout transportation agencies and advancing TSMO as way of doing business. The Federal Highway Administration (FHWA) has developed a series of White Papers focused on mainstreaming TSMO through formal policies and processes, changes in agency culture, advances in decisionmaking and information management, and development of business cases for TSMO.

This White Paper discusses the decisionmaking tools and information management systems (IMSs) used by transportation agencies and how they can support mainstreaming TSMO efforts. Decisionmaking tools, such as decision support systems (DSSs), and IMSs facilitate more informed decisions, which enable transportation agencies to apply TSMO more effectively, thereby increasing its credibility and making it more likely to be mainstreamed. Although there are limited direct examples of DSSs and IMSs being used for mainstreaming TSMO within transportation agencies, this White Paper provides insights from related uses of these technologies for their potential use in mainstreaming TSMO.

DSSs and IMSs are related, and often a DSS includes an IMS component. An IMS evaluates, analyzes, and processes an organization's data to provide meaningful information. Typically, IMSs focus on making an organization's internal operations more efficient. A DSS is a system that supports effective decisionmaking and decisions in specific situations.

Background

The transportation sector is rapidly changing while increasing in complexity with respect to data, functions, and decisions. In addition, the workforce is changing and required skills are fluctuating. An organization is composed of personnel, infrastructure (including software), and activities. This White Paper focuses on the organizational aspects of decisionmaking, DSSs, and IMSs. These components are all interrelated within an organization's overall operation. Workers and executives have to manage the daily barrage of information to make decisions. Information related to these decisions and across different activities (knowledge) has to be stored and managed. As data and tasks become more complex and computing power more sophisticated, DSSs are developed to facilitate decisionmaking. Similarly, increased computing power and sophistication have led to the development and use of various IMSs that provide the backbone to DSSs and other software and are a resource for managing employee knowledge (especially in a time of increasing turnover and background training variability).

These three components (decisionmaking, DSSs, and IMSs) roughly coincide with the notion of people, processes, and infrastructure connected in any range of activities in an agency. TSMO cuts across the range of activities at an agency and is often at the cutting edge of computer systems and technology. Consequently, efforts to mainstream TSMO throughout an organization will often touch on each of these components, ranging from decisionmakers in an array of TSMO settings to utilizing DSS for TSMO applications and to relying on IMSs to organize the wealth of data brought in by TSMO activities.

Effective TSMO requires transportation staff from different disciplines to make decisions across a range of activities, including planning, operations, maintenance, and performance management. DSSs and IMSs backed by relevant data can be strategically applied in all these activities to increase the desired outcomes of TSMO for users of the transportation system. These successes increase the awareness and acceptance of TSMO, which promotes the integration of TSMO throughout an agency. The incorporation of TSMO or TSMO considerations into agency DSSs or IMSs helps connect TSMO to larger agency processes and decisionmaking. For example, including ITS and other operations-related assets within an asset management system helps to mainstream TSMO into a department of transportation's (DOT's) asset management activities. Below are four major areas where DSS and IMS can help integrate TSMO into decisionmaking:

- **Planning.** TSMO can be better integrated into the transportation planning process and other agency planning activities with information management tools and data that help agencies consider TSMO in connection with mobility and safety needs and solutions. This could be a geographic information system (GIS) tool that combines layers of data for congestion, safety, air quality, and other needs so that investment decisions involve a consideration of multiple factors. Additionally, access to high-quality system performance data allows planners and operators to determine the needs for TSMO strategies and evaluate TSMO strategy effectiveness. Data can also support the benefit-cost analysis of potential mobility solutions and help make the case for TSMO strategies.
- **Operations.** To effectively manage the efficient and safe flow of people and goods, transportation system operators must make tactical decisions on when, where, and how to use operations assets, such as ramp metering, dynamic message signs, dynamic lane use, signal timing regimes, and other system management levers. Many transportation management centers use DSSs to support or automate some of those decisions based on the current roadway situations and historical data. These systems help turn data (real-time and historical) into actionable information. The more effective these actions are, the more agencies will turn to TSMO to address transportation issues. As discussed in the next chapter, integrated corridor management (ICM) and active transportation and demand management (ATDM) often rely on DSS to support real-time management.
- **Maintenance and asset management.** Applying asset management processes, databases, and DSSs to TSMO assets improves asset reliability and uptime, which is necessary for effective TSMO strategies. As mentioned above, integration of TSMO assets with the management of other transportation assets helps mainstream TSMO.
- **Performance management.** The intelligent transportation systems (ITS) underlying many TSMO activities generate a lot of data that can be used in agency scorecards and performance management efforts. These data can help demonstrate the cost-effective use of resources and before-and-after effects of projects, such as TSMO, infrastructure improvements, safety countermeasures, and others. These data support overall agency performance management decisions.

Objectives

This paper explores how decisionmaking, DSS, and IMS may be mechanisms to help integrate and mainstream TSMO within transportation agencies. Data, DSSs, IMSs, and the supported decisionmaking processes can enable or hinder mainstreaming TSMO within an integrated, collaborative organizational culture at transportation agencies. Agency culture impacts and is impacted by the data gathered, analysis performed, information managed, and decisionmaking processes (along with relevant DSSs) of the staff and leadership that comprise the organization.

This White Paper begins with an introduction in Chapter 1. Chapter 2 presents an overview of DSSs as tools to aid decisionmaking and connects this broader background to specific transportation agency uses of DSS. It also includes a discussion of the use of DSS with more advanced TSMO strategies (e.g., integrated corridor management, active transportation and demand management) and how those initiatives can help mainstream TSMO. Chapter 3 focuses on the broad area of IMSs, including the role of big data and their use among transportation agencies. Chapter 4 concludes the Paper with factors that agencies may find helpful to consider when looking to use IMSs and DSSs to support mainstreaming TSMO.

Intended Audience

This White Paper is written for transportation agencies—State DOTs and local and regional agencies who work in coordination with State DOTs—interested in mainstreaming and integrating TSMO into agency-wide activities. It is specifically aimed toward TSMO leaders, department heads, or functional unit leaders. It is intended to help agency personnel in multiple disciplines, not just TSMO and operations staff, understand ways TSMO can complement and integrate with their business practices. Information technology (IT) and data staff within transportation agencies can use this paper to understand their connections to mainstreaming TSMO.

Why Mainstream TSMO?

Transportation agencies have focused on the design, construction, and maintenance of transportation facilities. TSMO expands this focus by looking to operational improvements to existing facilities to maintain and restore system performance before adding physical capacity. Mainstreaming in the context of business processes is defined as "[P]roducts and services which are readily available to and appealing to the general public, as opposed to being of interest only to a very specific subset of the public." (Business Dictionary 2020) Mainstreaming TSMO makes management and operations strategies readily understood, considered, appealing, and available to the system users (public) as well as to agency leadership and staff, regardless of where they sit in the organization.

Typically, TSMO has been initiated in operations and maintenance business areas within transportation agencies, often evolving with ITS technologies and functions that involve ITS deployment programs and other operations (e.g., maintaining signal systems, and detecting and clearing incidents). Mainstreaming TSMO allows a broader range of strategies to be integrated throughout transportation departments and related agencies and organizations. Mainstreaming TSMO engages planners, designers, operators, and system users (public and private sector), and touches all aspects of mobility, including congestion, air quality, sustainability, safety, security, reliability, and related quality of life concerns. The goal of mainstreaming is to routinely consider TSMO strategies as solutions of equal substance with other options for improving transportation system performance and addressing transportation needs within a community or region.

2. DECISION SUPPORT SYSTEMS AND MAINSTREAMING TSMO

Organizations can implement efficient and consistent decisionmaking processes to assist decisionmakers at every level with managing the overwhelming amount of data and information they encounter daily. A variety of factors and biases can negatively affect individual decisionmaking, but the effective use of DSSs can allow transportation agencies to circumvent or eliminate these biases. This chapter provides examples of how organizations can use DSSs. The factors and biases that can impact individual decisionmaking are described in Chapter 5.

Decision Support Systems

There are tools that can provide support throughout the decisionmaking process. DSSs can help transportation agencies make decisions more efficiently and reduce the effect of human bias on decisionmaking. To support mainstreaming TSMO, DSSs can aid in planning, operations, maintenance and asset management, and performance management.

DSSs generally consist of three components: (1) the data/knowledge base, (2) the model (criteria and decision context), and (3) the interface. (Haettenscwhiler 1999, Marakas 1999) Most implementations neglect the context, which is also critical to how the DSS integrates with the organizational framework. (FHWA 2018) Decision support tools are also used at the leadership level to support cultural change.

DSSs are defined as computer-based information systems that support business or organizational activities and are fully computerized, human-powered, or a combination of both. (FHWA 2018) DSSs can also occur in a range of technology levels, from mechanical to digital. Within a transportation context, a traffic simulation model is an example of a tool that supports data analysis. Although a traffic model is not a "system," it produces information that supports the process of making decisions. A range of decision support tools is deployed within a transportation context and used to manage and control traffic as well as coordinate amongst staff members and outside stakeholders.

Applying DSSs in transportation, as stated by Lukasik et al. (2011), can support a variety of real-time traffic management activities, including:

- Traffic incident response strategy assessments.
- Online travel information systems.
- Predictive travel time calculations.
- Dynamic route guidance.
- Adaptive ramp metering using predictive traffic congestion algorithms.
- Intelligence-based transit DSS.
- Dynamic emergency vehicle routing.
- Emissions management.
- Urban and interurban congestion management.
- Security threat mitigation and large-scale evacuation management.

Transportation Agency Uses of Decision Support Systems

Numerous recent examples exist of DSS in transportation (specifically transportation management systems), though most do not have a direct link to mainstreaming TSMO. The research for this White Paper found decision support tools available at the national level to support the integration of TSMO into other functions of a DOT, which can support mainstreaming TSMO. Interviews with State DOTs for this paper also uncovered decision support tools specific to State DOTs that help them mainstream TSMO.

Table 1 provides a sample list of decision support tools available to all transportation agencies that can support mainstreaming TSMO within specific functional areas of a DOT.

Table 1. Sample decision support tools to support mainstreaming TSMO.

Functional Area	Decision Support Tool
Environment	FHWA offers a web-based tool, INVEST (Infrastructure Voluntary Evaluation Sustainability Tool), to support transportation agencies in assessing and evaluating projects and programs that are economically, socially, and environmentally sustainable. Agencies can evaluate TSMO investments within the operations and maintenance area of the tool. Agencies are rewarded within the tool for putting in place operational strategies, integrating TSMO into design, and monitoring progress toward specific goals. (https://www.sustainablehighways.org/)
Design	The Reliability by Design tool, developed as part of the second Strategic Highway Research Program, can help agencies determine how design strategies can improve travel-time reliability. It is a spreadsheet-based analysis tool that helps agencies estimate the effectiveness and comparative economic benefits of design treatments at specific locations. The tool is available for download. (http://www.trb.org/Main/Blurbs/169768.aspx)
Safety	The FHWA Intersection Control Evaluation (ICE) tool is a data-driven, performance-based framework that supports agencies in evaluating their intersection configuration and control options. It assists agencies in balancing operational, safety, and multimodal objectives. (https://safety.fhwa.dot.gov/intersection/ice/)
Planning	PlanWorks is a web resource that provides decision support in the areas of long-range planning, programming, corridor planning, and environmental review. Developed by FHWA, it offers a decision guide to support linking planning and operations. (https://fhwaapps.fhwa.dot.gov/planworks/Application/Show/7) In addition, TOPS-BC is a sketch-planning-level decision support tool developed by the FHWA Office of Operations. It is intended to provide support to transportation practitioners in benefit/cost analysis for a wide range of TSMO strategies. The tool was developed with the primary purpose of screening multiple TSMO strategies and for providing "order of magnitude" benefit/cost analysis estimates. (https://ops.fhwa.dot.gov/plan4ops/topsbctool/index.htm)

Several State DOTs have developed decision support tools to mainstream TSMO in construction management, planning, project development, and road maintenance. While mainstreaming

TSMO was typically not the primary purpose of the tools, they help connect several DOT functions to TSMO.

Florida DOT and university researchers developed a decision support tool to improve transportation management center operations and it helps to integrate TSMO with construction management decisions. Florida DOT, along with university researchers, fused traffic and event data collected by regional centers with private-sector, point detector, work zone, planning, weather, ramp metering, and managed lane toll pricing data (among others) to develop an integrated web-based tool called ITS Data Capture and Performance Management (ITSDCAP). (Hadi et al. 2015a, 2015b) The tool provides decision support for TMC operations, including assistance in construction management. This example demonstrates the integration of existing software and various streams of data (including operations, planning, and maintenance) to facilitate decisionmaking to connect TSMO and construction management decisions, leading to mainstreaming TSMO.

Similarly, Maryland DOT uses a host of advanced analysis, modeling, and simulation (AMS) tools that support various TSMO-oriented decisions as part of TSMO planning, alternatives analysis, engineering, and performance management. (Kim et al. 2017) Both AMS and ITSDCAP provide decision support through the prediction of incident impacts, calculation of the probability of breakdowns, and assistance in construction management. (Hadi et al. 2015a, Kim et al. 2017) AMS is capable of long-term travel demand planning and assessing active traffic and ICM, which mainstreams TSMO into planning decisions. Both AMS and ITSDCAP are comprehensive in their applicability. AMS is fast and can simulate large-scale transportation systems at less than 1/100 real-time. In Maryland, information about incidents, lane capacity, weather, and increased demand due to events provide the inputs to predict traffic conditions. Maryland DOT State Highway Administration (SHA) has used the AMS tools to screen alternatives, develop various operational scenarios, and develop TSMO strategies. Outcomes include better traffic monitoring, road closure predictions, and relevant notifications for travelers. (MDOT SHA 2017)

Ohio DOT developed the Traffic Operations Assessment Systems Tool (TOAST) "in an effort to make data-driven decisions and determine operationally sensitive corridors throughout the state." (Ohio DOT n.d.) This tool mainstreams TSMO within the planning process in Ohio and also integrates operations with safety and freight considerations. TOAST is an interactive spreadsheet in which routes are segmented into the State Priority System with breaks at the urban area boundaries, interchange center points, and road functional class changes. For each of the categories of travel time performance, bottlenecks, incident clearance, secondary crashes, safety performance, volume per lane, and freight corridors, TOAST normalizes the data ranges into values of 0-10 and then multiplies them by a weighting factor. TOAST calculates the total score for a route as a percent based on the score for each category divided by the total possible maximum score, wherein a higher percentage indicates better route performance and a lower percentage indicates a greater need for TSMO strategies. (Ohio DOT 2018a)

Not all DSSs require high-technology equipment or cutting-edge software. Colorado DOT developed an operations review element to its project development checklist to help facilitate decisionmaking. (Colorado DOT 2019) The areas of Colorado DOT maintenance, access management, operations, safety, and ITS combine into an inter-disciplinary approach to identify operational elements for consideration early in the project lifecycle. The TSMO evaluation has three parts: a safety assessment, an operations assessment, and an ITS assessment. The TSMO evaluation analyzes the project area and recommends improvements related to safety and mobility. This process has the potential to optimize decisionmaking while utilizing a low-cost approach.

Road weather management is a connection point for TSMO and maintenance and an opportunity to expand mainstreaming TSMO into road maintenance within DOTs. Some DOTs have developed and deployed programs that allow operators to plan for more appropriate signaling and signage to keep travelers informed. Wyoming DOT developed an application that allows maintenance personnel to report weather-related road conditions and make recommendations to transportation center-based staff. Michigan DOT combines multiple data sources into a system that generates real-time traveler alerts displayed on dynamic message signs. Although the systems are quite different, both improve operating conditions during poor weather conditions. (FHWA 2017) Utah's predictive system generates estimates of traffic conditions and gives operators the ability to deploy traffic signal timing plans that are most appropriate for those traffic conditions. (FHWA 2017, FHWA 2014)

Use of Decision Support Systems for Integrated Corridor Management

ICM is heavily reliant on IMS and decision support tools to operate successfully. ICM programs mainstream proactive, dynamic TSMO among multiple agencies and modes within a corridor. The data and systems required for ICM provide an opportunity to mainstream TSMO into several areas of a DOT, including coordination with other entities, planning, safety, IT, and asset management. Table 2 includes examples of ICM implementations.

Table 2. Examples of ICM Implementation.

Agency	Example	How It Applies to Mainstreaming TSMO
Florida DOT	Florida DOT's approach to ICM includes developing a DSS, as well as tie-in to an information exchange network that allows stakeholders to view/edit events and equipment status and coordinate response plans. It is particularly important in managing traffic during the Interstate 4 (I-4) Ultimate Improvement Project by using arterials to mitigate traffic congestion. Florida DOT has also been developing dashboards to help move the agency toward the increased use of ICM, which has been a long-standing focus of the agency. (Florida DOT 2018)	The DSS and IMS in Florida DOT's ICM approach help mainstream TSMO across responder agencies and support decisionmaking during incidents and construction. Florida DOT is using data and performance measures to illustrate the importance of using ICM.
San Diego	San Diego has a long-standing and well-developed ICM system. The update to *San Diego Forward: The Regional Plan*, adopted in 2019 (SANDAG 2018), describes the anticipated completion of the next set of ICM Concept of Operations Reports. The reports would identify and expand on the ICM concept for up to three new corridors, in addition to existing I-15. These reports are a first step in establishing institutional and technical partnerships needed for successful collaboration in an ICM	The institutional and technical partnerships developed for ICM can help mainstream TSMO into corridor planning and operations. ICM is an area where the larger concept of TSMO could be integrated early on in ICM efforts and provide

Agency	Example	How It Applies to Mainstreaming TSMO
	environment. The San Diego Association of Governments is also currently coordinating with the California Department of Transportation (Caltrans) on the development of the next ICM concept by completing the I-805 South Corridor TSMO Plan.	opportunities for it to be mainstreamed as ICM is expanded.
Iowa DOTs	Iowa DOT is conducting ICM studies focused on a corridor around the Des Moines metropolitan area. (Iowa DOT 2018)	Iowa DOT's ICM initiatives are in the planning stage (at the time of this White Paper) but provide an opportunity to increase support and awareness for TSMO concepts within an agency and promote broader mainstreaming.
Maryland DOT	Maryland DOT plans to develop ICM capabilities in the Baltimore-Washington Corridor. Through the ICM Pilot Project, stakeholders from multiple functional areas within the DOT collaborated to develop a concept of operations, ICM AMS plan, and a deployment approach. The functions included planning, freeway operations, roadway operations, emergency responders, and information providers. (Mahapatra and Singleton 2016) The Maryland DOT SHA incorporated the recommendations of the pilot as a set of projects in the TSMO Master Plan. The agency has upgraded the signal infrastructure and has active projects to deploy ITS infrastructure and upgrade its advanced transportation management systems to implement these strategies. MDOT SHA is also transferring the lessons learned from the ICM Pilot to other corridors in the State through the TSMO Master Plan.	The ICM Pilot Project raised awareness of TSMO strategies among multiple functional areas and stakeholders, supporting the integration of TSMO. It also furthered TSMO planning within the agency.
Michigan DOT	Michigan DOT's TSMO program includes funding received in 2012 to implement ICM in three distinct corridors: I-75 in Oakland County, I-75 in Wayne County, and I-696 in Macomb County.	ICM strategies are part of the larger TSMO program, including connected and automated vehicles and active traffic management. (Miller, Juckes, and Adler 2018) ICM helps to build the TSMO program and increase its awareness within the agency. This may lead to increased mainstreaming.

Use of Data and Decision Support Tools for Active Transportation and Demand Management

ATDM strategies are part of the TSMO programs of transportation agencies and require the use of IMSs and some type of decision support tool due to the dynamic nature of ATDM. The data and systems required for ATDM provide an opportunity to mainstream TSMO into several areas of a DOT, including asset management, maintenance, IT, safety, and planning. Table 3 describes the use of ATDM in three States.

Table 3. Use of ATDM in Three States.

Agency	Example	How It Applies to Mainstreaming TSMO
Washington State DOT	Washington State DOT uses an ATDM strategy that includes overhead lane signs to provide motorists with advance notice of traffic conditions. The goal of the system is to reduce the likelihood of collision and improve traffic flow by using changeable messages signs with variable speed limits, symbols for driver direction, and warning messages related to congestions or crashes. The implementation began in 2010 as one of the first in the country and focused on sections of I-5, I-90, and State Route 520. Evaluation results showed a 14 percent decrease in weekend collisions attributed to unfamiliar drivers being given real-time information. (FHWA 2017)	The measurable success of a TSMO-related strategy, ATDM, validates the importance of TSMO in improving system performance, which can lead to greater emphasis on TSMO within an agency and incorporation within other divisions.
Ohio DOT	Ohio DOT uses data and maps of safety hot spots to determine where to place safety patrols. There is an effort underway to replace all advanced traffic management system modules and capture all traffic data flow in a new data warehouse, allowing for easier fusion of data. (Ohio DOT 2018b, 2017)	This is an example of the importance of IMS and use of big data to support decisionmaking for incident management. This supports the connection of TSMO and safety within the agency.
Tennessee DOT	Tennessee DOT received $100,000 from the State Transportation Innovation Councils Network in 2016 to develop a data analytics tool for its freeway service patrol (HELP trucks) dispatch decisionmaking. The project ties closely to the FHWA Every Day Counts trainings on incident management and data-driven safety analysis.[1]	This is also an example where TSMO and safety are linked through a decisionmaking tool. It also helps elevate the effectiveness of TSMO strategies, which may lead to greater mainstreaming through the DOT.

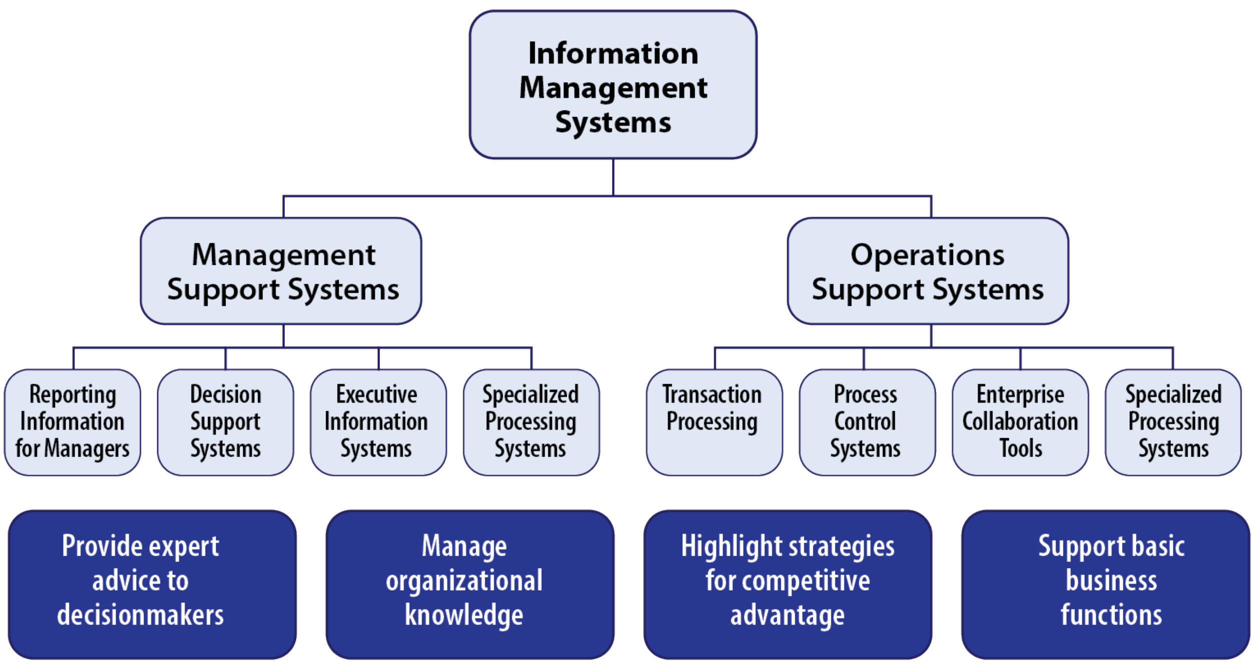
[1] More information on Every Day Counts is available at https://highways.dot.gov/federal-lands/programs-tribal/partners-resources/every-day-counts, last accessed March 28, 2023.

3. INFORMATION MANAGEMENT SYSTEMS AND MAINSTREAMING TSMO

IMSs allow organizations to collect, organize, store, analyze, and report data. They are used with DSSs or alone to support TSMO. DSSs often have a processing module that makes recommendations to the user. The effective use of IMSs is key to planning operational improvements and assessing their potential or actual effects. This chapter describes general use of IMSs in business and industry, typical data sources, the use of data, and current transportation agency uses of IMS. It also provides ideas for agencies related to mainstreaming TSMO, including the role of integrating an IMS with other agency systems, agency infrastructure, and the overall context important to successfully mainstreaming TSMO with the use of IT-related tools.

General Approaches

There are many types of IMSs that play key roles in business and industry. Information systems in business organizations can often be grouped under one of two broader categories—operations support systems (support of business operations) or management support systems (support of managerial decisionmaking). (Al-Mamary, Shamsuddin, and Aiati 2014) Figure 1 provides a conceptual diagram of the distinct type of operations and management support systems.



Source: Adapted from O'Brien and Marakas 2007

Figure 1. Diagram. Operations and management classifications of information systems.

Management decisions tend to be longer term and strategic. IMSs will support these functions in a variety of ways, including reporting that presents tailored information for managers to make appropriate decisions and inputs to DSSs, executive-level information systems, and specialized processes. Similarly, there are business operations that need support, such as transaction processing, process control systems, enterprise collaboration tools, and specialized processing systems. These two pathways combine to provide expert advice to decisionmakers, to manage organizational knowledge (including transmitting knowledge from retiring staff to new staff and training), to highlight strategies to be used for competitive advantages, and to support basic business (usually short-term or daily) functions.

In addition, there are four types of analytics solutions in the information management area, which all build on one another and can lead to improved performance: (IBM Software 2013, James 2017)

- **Descriptive.** Data and business intelligence are used to ask questions about things that *have* happened.
- **Diagnostic.** Data are compared to assess what might be wrong (i.e., questions related to what *might* be happening that is not correct).
- **Predictive.** Statistical models are used to focus on questions related to what *could* happen given possible scenarios (including if nothing changes).
- **Prescriptive.** Optimization and simulation are used to derive answers to questions related to what *should* be done.

There are other ways to conceptualize or categorize IMSs, but this structure provides a useful framework for the current discussion about TSMO efforts.

Transportation Agency Uses of Information Management Systems and Big Data

Transportation agencies have developed a variety of uses of IMS, including manipulating and mining ever-increasing large data sources. The use of large data sets creates new possibilities for agencies to enhance TSMO. Transportation organizations have a vast amount of data available to them, but it is not always clear how the data are used and how different data sets relate to one another. Within the private transportation sector, data are used to analyze traveler preferences and habits on a macro and micro scale, optimize capacity and pricing, and predict maintenance needs. These benefits can be translated to public sector transportation agencies as well. (IBM Big Data and Analytics 2014) These data can be used to show the potential or actual benefits of TSMO strategies, leading to greater consideration in planning alternatives analysis and helping TSMO projects compete for funding.

Transportation agencies use traveler data to respond to needs in real-time. Floating travel data are collected by Bluetooth®-enabled mobile phones, global positioning system devices, and other technology used at the customer level. Using this information in addition to trip information, transportation agencies can immediately map areas of traffic congestion, incidents and lane closures, and modes experiencing substantial delays. This knowledge elicits immediate response as well, such as rerouting given by dynamic signage, changes in pricing of toll lanes, signal timing adjustments, and alerts to media and traveler information systems.

Eventually, real-time responses become historical data that, when analyzed, provide means to evaluate how the operational changes mitigated issues. This continuous analysis of solutions strengthens traffic system models and heightens reliability. The wealth of historical travel data also enables system analysts to make predictions. Using multiple historical variables, such as weather, traffic, time of day, and destinations, transportation system analysts can make adjustments prior to real-time data collection. (Buckley and Lightman 2014)

Transportation studies using big data can describe the larger features of transportation systems and also unique user experiences because outputs (e.g., destinations, speeds, and times) are not inferred. These measures can inform operational and physical changes, including those of road design and maintenance needs. (Sweet, Harrison, Buckley, and Kanaroglou 2016)

In addition to big data, transportation agencies use IMSs for a variety of purposes, most notably to advance TSMO in transportation planning and identify operational needs (table 4). DOTs have integrated their systems with other preexisting systems, established interoperability with other agencies, used software and researchers to build data frames, and established IT policies. Artificial intelligence capabilities of next generation IMSs are also a natural evolution of managing information and big data in service of planning and operational needs.

Table 4. Examples of Agency Use of Information Management Systems and Big Data.

Agency and Decisionmaking Area	Example
Washington Data DOT Supports TSMO-related decisions in planning and performance management.	Washington State DOT has a Corridor Sketch database that it uses to identify locations within the 300 corridors on the transportation system having the greatest likelihood of congestion issues. Washington State DOT Regions use this database to enter their needs. Database development was led by the Planning Division within Washington State DOT and has helped the agency focus on TSMO strategies as the first line of investment. This database is used for Washington State DOT's integrated scoping process, which provides a more comprehensive approach for project scoping and is an example of mainstreaming TSMO efforts. In partnership with the STAR Laboratory at the University of Washington, Washington State DOT helped develop and use the Digital Roadway Interactive Visualization and Evaluation Network (DRIVENet), an online platform for data sharing, integration, visualization, and analysis. This was developed to integrate the data silos within Washington State DOT and support effective decisionmaking. Processed data from DRIVENet are used to develop Washington State DOT's Gray Notebook. (Washington State DOT 2018)
Maryland DOT SHA Supports TSMO-related decisions in performance management, planning, and operations.	Maryland DOT SHA, like many other DOTs, rely on partnerships with academic, research, and private institutions for big data analysis and data warehouse development; these partners play a role in data management and determination of measures and targets. For example, Maryland DOT SHA has a partnership with the University of Maryland and actively collaborates on platforms like the Regional Integrated Transportation Information System, a situational awareness, data archiving, and analytics platform.
Texas DOT Supports TSMO-related decisions in planning and performance management.	Texas DOT, as well as other DOTs, use commercial, off-the-shelf technology for analysis and reporting, and in-house staff to do the data science work to tailor it to their needs. Texas DOT has branded its system (Statewide Traffic Analysis and Reporting System (STARS)) but uses commercially available software to forecast, map, and visualize data, including TSMO-related data. (Knowles and Carrizales 2014) Texas DOT's IMS

Agency and Decisionmaking Area	Example
	has moved beyond TSMO into business management (which may be important in mainstreaming TSMO efforts, where TSMO can potentially be used to support various business and reporting functions throughout the agency). (Texas DOT 2018)
Wisconsin DOT Supports TSMO-related decisions in planning.	Advances in software systems and data integration provide opportunity to streamline the TSMO planning process for many entities, including the Wisconsin DOT. Wisconsin DOT has made advances in software systems and data integration that enable streamlining of the TSMO planning process. Chief among these is the spatial database now in place for all ITS and ITSNet inventory and GIS tools, applications, and mapping. (Wisconsin DOT 2014)
Florida DOT Supports TSMO-related decisions in project development.	Florida DOT is focusing on governance and standards as a part of its IT strategy. Within several district offices, two transportation management centers, a central office, a private highway enterprise, and non-IT central office groups, standardization is encouraged so that projects can draw from and be applicable to all users.
Iowa DOT Supports TSMO-related decisions in planning.	An example of IMS informing planning and project prioritization is the ICE-OPS tool at Iowa DOT, which establishes specific criteria to assess sections of the transportation system with operational and safety concerns. This information is then combined with a specific, data-driven process to identify and prioritize transportation improvement projects as a part of its 5-year plan. The tools for this process are in development. (Iowa DOT 2018)
Ohio DOT Supports TSMO-related decisions in planning.	Ohio DOT shares transportation and systems data via a web-based tool, TOAST. It plans to expand this to include more data and assist other program areas with planning and prioritization of projects.
Pennsylvania DOT Supports TSMO-related decisions in planning and operations.	Pennsylvania DOT created One Map, which is software that overlays transportation data onto a map. (Pennsylvania DOT 2018) It supports TSMO planning decisions about the types of operations tactics to use and locations (e.g., placement of ramp meters and other ITS assets). It includes crash data and identifies where to best spend a limited budget.

Asset management systems are a core part of a transportation agency's functions and provide opportunities to mainstream TSMO through the integration of ITS and traffic signals in asset management systems. Table 5 includes examples of asset management systems in transportation, noting the role of IMS and potential for use in mainstreaming TSMO.

Table 5. Examples of TSMO and Asset Management Systems

Agency	Example
Arizona DOT	Arizona DOT undertook several initiatives to improve its business practices related to asset management (and in general). Core to these initiatives was an integrated information system that would facilitate the implementation of improvements. It would allow agency staff to assemble and analyze data from multiple sources, including from asset management and TSMO. (Arizona DOT 2017)
Nevada DOT	Nevada DOT developed a data warehouse linked to interactive dashboards with maps and advanced analytics for data within the pavement management system. TSMO-related measures were incorporated within a single asset management platform and used some of the DSS principles. This demonstrates the cross-sector usage of data that can be an advantage to mainstreaming TSMO.

4. CONSIDERATIONS FOR MAINSTREAMING TSMO

Factors and Biases Affecting Decisionmaking

Several factors and common decisionmaking biases can influence individual decisionmaking and impact TSMO. These decisionmaking biases and other factors lead to the need for additional supportive software, such as DSSs and IMSs. These biases and factors affecting decisionmaking are not specific to personnel in transportation agencies and can occur in any setting. Managing these decisionmaking biases can lead to better decisions that apply TSMO more effectively, increasing its credibility and making it more likely to be mainstreamed.

Decisionmaking is a complicated process with a myriad of potential influences to consider. These influences can affect the decisions of individual staff, including those who are in leadership positions and drive overall organizational strategies. In an evaluation of different managerial decisionmaking processes, Omarli (2017) determined that factors affecting the administrative decisionmaking processes were personal, environmental, and psychological. The growing amount of data and fluid environment that TSMO decisionmakers are in can make TSMO decisionmaking prone to some of these factors.

There are four common biases that can affect decisionmaking in everyday tasks and are quite common in organizations:

- **Framing.** A common decisionmaking bias involves people reacting differently to information depending on its phrasing, context, or "framing" (Tversky and Kahneman 1981). This bias can have profound impacts on organizational change efforts. A strategy to mitigate this bias is to change labeling/logos (which is why organizations will often spend time/resources on marketing refreshes), colors, or codes to indicate clearly that the context has changed (e.g., from normal operations to emergency operations or from one organizational structure to another). In addition, one should be aware of how information is presented and whether it may be framed in a negative or positive way, especially when making a business case to leadership to support TSMO efforts.
- **Confirmation bias.** People often favor or seek out information that confirms a prior hypothesis or belief, leading to confirmation bias. (Wason 1968) This bias can affect leadership when there is the tendency to focus more on data that support an initial approach or only listen to opinions that support their plans. Instead, an alternative decisionmaking process or a properly deployed framework (with appropriate metrics and reporting support) could be to sample the full range of both negative and positive possibilities rather than just the positive ones.
- **Anchoring.** Individuals have the tendency to rely on the first piece or limited pieces of information when planning or forming an estimate; this is known as anchoring (Ariely 2008,Tversky and Kahneman 1973). This bias often manifests itself in operational situations where the first incoming field reports (e.g., of evacuation times on a roadway) will drive estimates or the more salient images will affect planning. To mitigate this bias, one should be careful about weighting early or limited information and should generate alternative or counterfactual options. Another option is to constantly refine estimates as data become more reliable over time. (FHWA 2018) An ideal framework and reporting set of tools for management would iteratively adjust estimates

as new data come in and present options across the full range to combat the tendency to overweight one part of the spectrum based on early estimates.

- **Groupthink.** A bias that is particularly salient in more hierarchical and structured organizations is the concept of groupthink, as demonstrated by the famous Asch experiments (1951). It is defined as a desire for harmony, often at the expense of optimal solutions. Subordinates or peers may follow along with sub-optimal approaches so that the team or organization can "get along." When leading a change effort or in a position of authority, one can combat this bias by: (1) encouraging objections consistently and publicly, (2) not indicating preference for a particular choice or approach until after the team has provided their opinions, (3) asking designated members to play "devil's advocate," and (4) regularly evaluating previous patterns to determine if there has been a standard approach that is regularly repeating (i.e., a "rut"). Transportation agencies are hierarchical and structured, so groupthink is a potential problem. If an agency wants to avoid some of the pitfalls of groupthink, then making it clear that alternative opinions and truth will be rewarded can help to increase the comfort level and improve information sharing, which is often restricted when groupthink is endemic. This can be accomplished by welcoming the identification of what is not working well so that it can be addressed.

Observations in Using Information Management Systems and Decision Support Systems for Mainstreaming TSMO

As noted in the introduction, there are no known examples of DSSs and IMSs specifically for mainstreaming TSMO; however, as discussed in the previous sections, many of these systems were integrated into larger systems and enabled data sharing, which facilitates mainstreaming TSMO. In addition, IMSs and DSSs possibly could be tailored for mainstreaming TSMO purposes (e.g., using big data to augment business intelligence decisions that rely on an enterprise-level DSS to make a business case for TSMO).

There are several general considerations and lessons learned for IMSs and DSSs that can support mainstreaming TSMO:

- **User needs.** It is vital for a DSS or IMS to support the needs of the users and accommodate their knowledge, skills, abilities, and goals of activities. Any software used to mainstream TSMO efforts should be developed with the user at the center. With DSS, one should also be mindful of the points along the decisionmaking pathway where biases and errors tend to be most prevalent in most users. This will become critical as DSS software is brought on that can help agencies mainstream TSMO, especially when that means interacting with staff who do not fully understand or appreciate TSMO.
- **Data fusion, integration, interoperability, and quality.** Several examples noted the integration of disparate databases or connecting systems, both intra- and inter-agency (the latter is of particular importance within the ICM context). Agencies can consider ways to standardize data variables (and any data collection instruments) and structures across units to the extent possible as well as develop plans for integrating databases, performing data fusion (which entails a further step of replacing or reducing the data), and ensuring interoperability. This effort will allow for lower costs for developing and integrating both an IMS and a DSS. It will also facilitate planning, operating, management, staffing, and other investment decisions that take into account data related to operations as well as

other data types. The completeness, accuracy, reliability, and fidelity of the data are important for supporting whatever decisions are made (as well as the accuracy of those options developed through analysis or provided to decisionmakers).

- **Software flexibility and usability.** To facilitate use, software needs to be useable and appealing, as well as allow for multiple users with different goals to interact with it to meet their needs. Allowing users the ability to tailor or modify reports to suit each user's (or unit's) needs is also important. For example, Pennsylvania DOT mentioned a district executive scorecard that has different performance measures that are easily pulled based on the needs of executives and other users, with tailorable output. (Pennsylvania DOT 2018) This flexibility will allow for more widespread use, adoption, and integration into the normal DOT workflows, which will go a long way in mainstreaming TSMO.
- **Maintenance and evolution.** The costs of maintaining a DSS/IMS or updating/upgrading both systems as data and information change are often overlooked in planning. Ideally, both the DSS and IMS would be capable of supporting the integration of modular components that can be updated easily.
- **Monitoring and evaluating performance.** Another often-overlooked aspect of DSS and IMS is the ability to monitor their performance and evaluate that performance against a benchmark to assess the value added. That information would be helpful in making the business case for mainstreaming TSMO in any organization.
- **Planning.** As noted by several DOTs, the software development and integration process was also part of the IT planning process (including budgeting) and policies. Early involvement of TSMO will allow it to be integrated into the core components and plans of any DSS and IMS (see the Wisconsin DOT example in table 4). Systems or tools, such as Ohio DOT's TOAST, allow TSMO to be more readily and consistently considered in the transportation planning process.
- **Partnerships.** Several examples noted in the previous sections highlighted the importance of forming partnerships with local universities, vendors, and other non-transportation agencies that may be of benefit. Efforts to mainstream TSMO will also likely benefit from leveraging these partnerships in the context of IMS and DSS.
- **Culture.** Software (e.g., for DSS and IMS) is not developed or integrated in a vacuum. The organizational culture and structure provide a base for how that software is to be used. Software can have TSMO's needs as a central component, indicating TSMO is central within an agency. Conversely, software that is developed with an eye toward integrating TSMO throughout the agency may help to drive a change in culture that supports mainstreaming TSMO.

These lessons learned and discussion points are meant to provide several topics for consideration in an agency's efforts using DSS and IMS to support efforts to mainstream TSMO.

5. REFERENCES

Al-Mamary, Y.H., A. Shamsuddin, and N. Aziati. 2014. The Role of Different Types of Information Systems in Business Organizations: A Review." *International Journal of Research* 1, no. 7.

Ariely, D. 2008. *Predictably Irrational: The Hidden Forces That Shape Our Decisions*. New York, NY: Harper Collins.

Arizona DOT. 2017. *Transportation Asset Management Case Studies- Data Integration: The Arizona Experience*. Washington, D.C.: FHWA.

Asch, S.E. 1951. "Effects of group pressure on the modification and distortion of judgments," in H. Guetzkow (ed.), *Groups, leadership and men*, ed. H. Guetzkow (Pittsburgh, Pennsylvania: Carnegie Press), 177–190.

Buckley, S., and D. Lightman. 2014. "Ready or Not, Big Data is Coming to a City (Transportation Agency) Near You." Paper No. 15-5156. *TRB 94th Annual Meeting Compendium of Papers*.

Business Dictionary. 2020. *What is mainstream? Definition and meaning*. WebFinance Inc.

Colorado Department of Transportation. 2018. "Project Operations Evaluation." (web page). https://www.codot.gov/programs/operations/tsmo-evaluation, last accessed February 13, 2023.

FHWA. 2014. *Implementation of a Weather Responsive Traffic Estimation and Prediction System (TrEPS) for Signal Timing at Utah DOT*. Report No. FHWA-JPO-14-140. Washington, DC: FHWA.

FHWA. 2017. *Transportation Systems Management and Operations in Action*. Report No. FHWA-HOP-17-025. Washington, DC: FHWA.

FHWA. 2018. *Human Factors Guidelines for Transportation Management Centers (TMCs)*. Report No. FHWA-HRT-16-060. Washington, D.C.: FHWA.

Hadi, M., Y. Xiao, M. Ackert, M. Plass, and E. Birriel. 2015a. "Developing Decision Support Tools for Florida's Traffic Management Centers," *TR News,* 297.

Hadi, M., Y. Xiao, T. Wang, M.S. Iqbal, A. Massahi, J. Jia, and H. Fartash. 2015b. *Decision Support Systems for Transportation System Management and Operations (TSM&O)*. Tallahassee, FL: Florida DOT.

Haettenschweiler, P. 1999. *New user-friendly concept of decision support. Good decisions in business, politics and society*. Zurich: VDF Hochschulverlag AG.

IBM Big Data and Analytics. 2014. *Big data and analytics in travel and transportation*. Somers, NY: IBM Corporation.

IBM Software. 2013. *Descriptive, Predictive, Prescriptive: Tranforming Asset and Facilities Management with Analytics*. Somers, NY: IBM Corporation.

Iowa DOT. 2018. Phone interview.

James, P.P. 2017. "Role of Management Information System in Business and Industry." *International Journal of Humanities and Social Science Invention* 6, no. 7.

Kim, W., H. Kim, M. Won, and G.-L. Chang. 2017. *Development of a Traffic Management Decision Support Tool for Freeway Incident Traffic Management (FITM) Plan Deployment*. Baltimore, MD: Maryland DOTSHA.

Knowles, B., and M. Carrizales. 2014. *Statewide Traffic Analysis and Reporting System (STARS II).* TexasDOT, Transportation Planning Conference.

Lukasik, D., B. Churchill, J. Golob, T. Malone, and E. Hubbard. 2011. *Assessment of Emerging Opportunities for Real-Time, Multimodal Decision Support Systems in Transportation Operations*. Report No. FHWA-JPO-10-058 . Washington, D.C.: U.S. DOT, Intelligent Transportation System Joint Program Office, Research and Innovative Technology Administration.

Mahapatra, S., and E. Singleton. 2016. "Baltimore-Washington Integrated Corridor Management Pilot Project." Presentation to at the Intelligent Transportation System Maryland Annual Meeting, Linthicum Heights, MD, September 21–22.

Marakas, G. 1999. *Decision Support Systems in the 21st Century*. New York: Prentice Hall.

MDOT SHA. 2017. *Deploying Advanced Technology Infrastructure for Transportation Systems Management and Operations in Maryland: US 1 Innovative Technology Deployment Corridor*. Application for an Advanced Transportation and Congestion Management Technologies Deployment grant through FHWA.

Miller, K., M. Juckes, and J. Adler. 2018. *Decision Support Systems for the Next Generation Advanced Traffic Management System*. Intelligent Transportation System Detroit.

O'Brien, J., and G. Marakas. 2007. *Management Information Systems*. McGraw-Hill.

Ohio DOT. n.d. "Traffic Operations Assessment Systems Tool (TOAST)." (web page). https://www.transportation.ohio.gov/working/data-tools/resources/toast, last accessed February 13, 2023.

Ohio DOT. 2018a. *Traffic Operations Assessment Systems Tool.* Spreadsheet. https://www.transportation.ohio.gov/static/Working/data-tools/toast/2018/TOAST%20FY18.xlsm, last accessed February 22, 2023.

Ohio DOT. 2018b. Phone interview.

Omarli, S. 2017. "Which Factors Have an Impact on Managerial Decision-Making Process? An Integrated Framework." *Essays in Economics and Business Studies*. János Tibor Karlovitz, ed. ISBN 978-80-89691-42-5. DOI:10.18427/iri-2017-0068.

Pennsylvania DOT. 2018. Phone interview.

SANDAG (San Diego Association of Govenrments). 2018. *San Diego Forward: The 2019-2050 Regional Plan*. Fact Sheet. http://www.sandiegonaacp.org/wp-content/uploads/2018/07/SANDAG-SD-Forward-Regional_Plan_Factsheet.pdf, last accessed February 13, 2023.

Sweet, M., C. Harrison, S. Buckley, and P. Kanaroglou. 2016. "Big Data in Transportation Program Management: Findings and Interpretations from the City of Toronto." Presented at the Transportation Reasearch Board 2016 Annual Meeting, Washington, DC.

Tennessee DOT. 2019. Phone interview and email correspondence.

Texas DOT. 2018. Phone interview.

Tversky, A., and D. Kahneman. 1973. "Availability: A heuristic for judging frequency and probability." *Cognitive Psychology* 5, no. 2: 207–232.

Tversky, A., and D. Kahneman. 1981. "The Framing of Decisions and the Psychology of Choice." *Science* 211, no. 4481: 453–458.

Wason, P. 1968. "Reasoning about a rule." *The Quarterly Journal of Experimental Psychology* 20, no. 3: 273–281.

Wisconsin DOT. 2014. *Transportation Systems Management & Operations Infrastructure Plan: State of the State Report.* Madison, WI: Wisconsin DOT.

Washington State DOT. 2018. Phone interview.

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March 2023
FHWA-HOP-21-044