



Applying Predictive Analytics (PA) to the Real-Time Management and Operation of Traffic Management Systems (TMSs)

Transportation Management Center (TMC) Pooled-Fund Study
Federal Highway Administration (FHWA)
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Speaker's Notes (1/44)

The TMC PFS is a group of public agencies and organizations who voluntarily pool funds each year and collaborate on projects to develop technical resources and advance activities to address the key challenges and issues they are collectively facing in support of improving performance, capabilities, and how they manage and operate their Traffic Management Systems (TMS) and Centers (TMC).

This presentation was developed as part of the TMC PFS project on Applying Predictive Analytics into the Real-time Management and Operation of Traffic Management System (TMSs).





Presentation Outline

| Topic | Slide(s) |
|---|----------|
| 1. PA within the broader context of analytics, artificial intelligence (AI), and TMS decisionmaking. | 3–17 |
| 2. PA maturity and the ways PA may improve real-time transportation systems management and operation. | 18–22 |
| 3. Issues to consider with integrating prediction into TMS. | 23–26 |
| 4. PA Readiness Checklist. | 27–32 |
| 5. Use cases and examples. | 33–39 |
| 6. Trends, implications, and resources. | 40–42 |





Speaker's Notes (2/44)

The presentation includes six sections:

1. Predictive analytics within the broader context of analytics, artificial intelligence, and TMS decisionmaking.
2. Predictive analytics maturity and how it may improve real-time transportation systems management and operation.
3. Issues to consider with integrating prediction into TMS.
4. Predictive analytics Readiness Checklist.
5. Use Cases and Examples.
6. Trends, Implications, and Resources.





What Are TMSs?

- Complex operational systems that combine field equipment, advanced communications and information technology, and software.
- Software that collects and synthesizes traffic data, integrates external systems, and enables command and control of intelligent transportation system field devices.



Speaker's Notes (3/44)

A TMS is a system that comprises a complex, integrated blend of hardware, software, processes, and people performing a range of functions and actions. TMSs are complex operational systems that deploy and use technology—such as field equipment, advanced communications, IT, and software tools. TMSs collect and synthesize traffic data, integrate external systems, and facilitate the command and control of intelligent transportation system (ITS) field devices. Further, TMSs are staffed with operators who actively manage and perform a range of functions and actions that facilitate improvements in the efficiency, safety, and predictability of travel in a surface transportation system.

Decision support provides operations personnel with processes and tools to assist them in making timely and effective decisions in a more consistent manner.





Prediction and Connection to TMSs

What is PA?

- Using data and models to predict what may happen in the future.
- Integrating PA tools and methods into active management and operation of TMSs to improve the safety and efficiency of surface transportation.
- Delivering prediction in the context of TMSs through decision support tools (DSTs).
- Recognizing the need to understand:
 - Issues to consider.
 - Requirements for integration.
 - Opportunities to use PA in the context of real-time management and operation of TMSs.



Speaker's Notes (4/44)

Predictive analytics is the use of data and models to predict what may happen in the future. More specifically, it entails the development of a model using historical data and the application of the model using current data to forecast potential events or outcomes. The purpose of this presentation is to provide information to support agencies who are considering the integration of predictive analytics tools and methods into the active management and operation of a traffic management system (TMS). Specifically, this presentation focuses on the issues to consider, possible requirements to integrate, and potential opportunities to use predictive analytics in the context of real-time management and operation of TMSs.

This presentation provides an overview of how predictive analytics may be considered in the management and operation of TMSs and traffic management centers (TMC) to aid in a range of decisionmaking. Prediction in the context of TMSs will be delivered through decision support tools (DST).





What Is Decision Support?

Decision support is a concept that involves:

- Improving the timeliness and effectiveness of decisionmaking.
- Using all the processes and tools that enable better, faster, and more consistent decisionmaking.





Speaker's Notes (5/44)

Decision support provides operations personnel with processes and tools to assist in making timely, effective, and more consistent decisions.



What Are DSTs?

- DSTs are offline or online tools that support a range of decisions.
- Offline DSTs are typically used to support planning:
 - Incident response plans.
 - Paper-based decision trees.
- Online DSTs are computer-based tools that support real-time traffic management and operational decisionmaking:
 - Real-time traffic analysis tools.
 - Lookup tables integrated into a TMS.





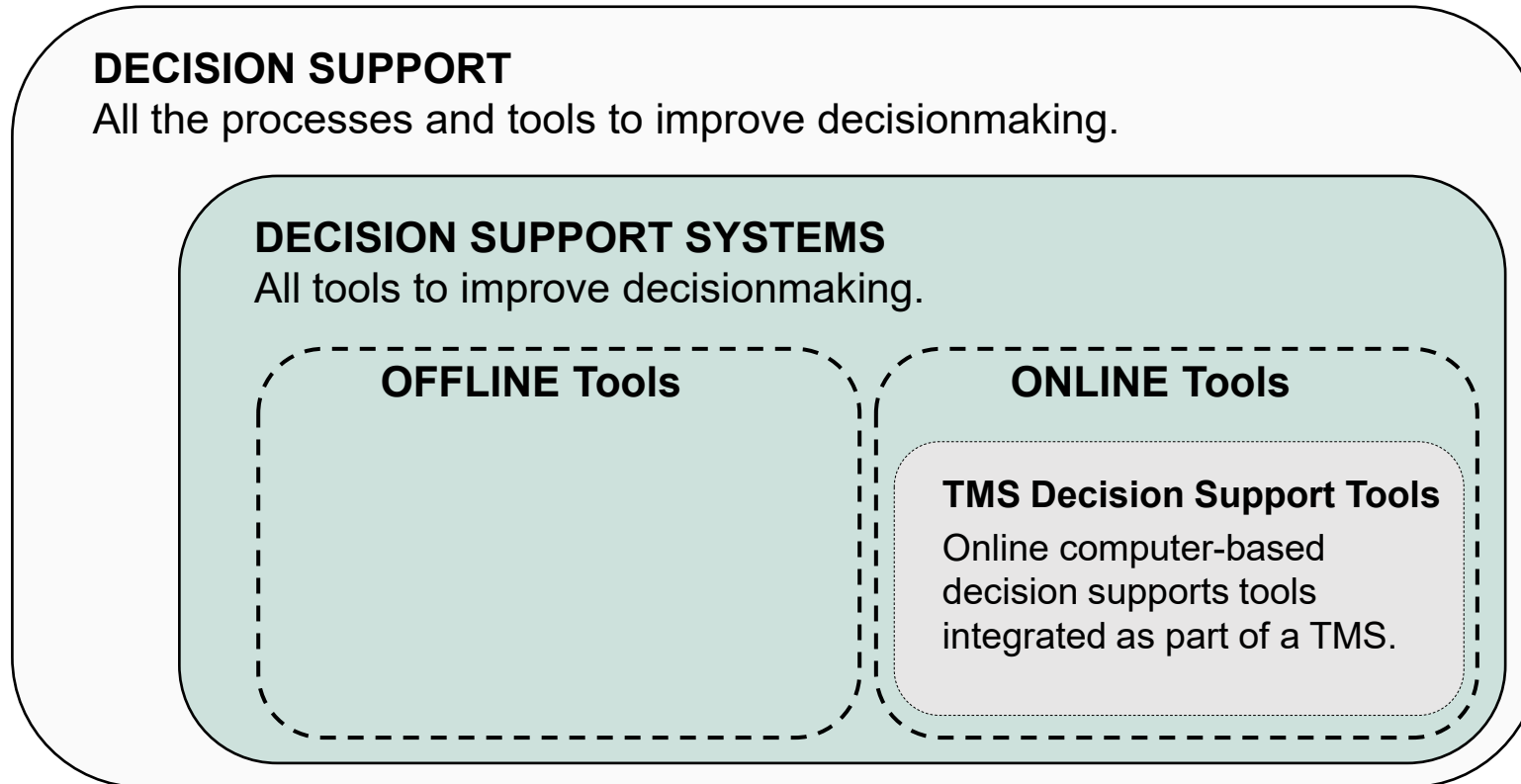
Speaker's Notes (6/44)

What are Decision Support Tools? They are online or offline tools that support decision-making. Offline DSTs typically support planning while online tools typically support real-time traffic management and operational decision-making.



How Are Offline and Online DSTs Used?

Offline and online DSTs are used to improve decisionmaking.



Source: FHWA.⁽¹⁾





Speaker's Notes (7/44)

This figure depicts a taxonomy of DSTs. Offline and online tools are subsets of decision support systems, which are a subset of decision support.





How Can DSTs Enhance TMSs?

DSTs enhance TMSs through the following means:

- Providing strong knowledge of the transportation system.
- Understanding agency policies and operational procedures.
- Applying policies and procedures in realtime based on changing conditions and different events.
- Processing a wide range of data and information.
- Anticipating effects of different operational strategies or plans.



Speaker's Notes (8/44)

DSTs at TMSs support the functions, decisions, or actions that TMS operators carry out (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 begun transitioning from managing, controlling, or coordinating travel on one type of facility to supporting several facilities.



What Are the Benefits of TMSs Using DSTs?

- Improve decisionmaking (e.g., faster, fewer, more consistent decisions).
- Improve performance (e.g., reduce traffic disruptions).
- Evaluate and prioritize alternative responses.
- Monitor transportation network performance.
- Operate and manage TMS and a portion of a surface transportation network proactively.
- Automate selecting event response plans.





Speaker's Notes (9/44)

DSTs help operators make quick, consistent, and proven responses to events. This can enable new operators to respond in the same way that long-term expert operators respond. Because responses are based on expertise, real-time data, and agency policies and procedures, they are consistent and reliable, and they help improve transportation network performance for travelers.





What Are Common Types of DSTs?

Three common types include the following:

- Knowledge driven.
- Data driven.
- Model driven.





Speaker's Notes (10/44)

In general, TMSs use three types of DSTs: knowledge-driven DSTs, data-driven DSTs, and model-driven DSTs. The next few slides will review each type of DST.



What Are the Primary Characteristics of Knowledge-Driven DSTs?

- Provide specialized problem-solving by processing stored facts, rules, procedures, or knowledge.
- Emulate reasoning and expert decisionmaking behavior.
- Process facts and business rules instead of data—commonly known as rules-based systems or expert systems.

Example: Florida Department of Transportation's (FDOT) regional integrated corridor management system uses an expert rule engine to: ⁽²⁾

- *Make decisions based on predefined rules.*
- *Monitor conditions to decide when a response plan must be implemented, modified, or deactivated.*



Speaker's Notes (11/44)

Knowledge-driven DSTs provide specialized problem-solving expertise based on processing stored facts, rules, procedures, or similar forms of knowledge.

Knowledge-driven DSTs attempt to emulate human reasoning, but with more consistent results.

Expert systems are the best-known type of knowledge-driven DST. They use databases of knowledge generated by previous expert users and a system's business rules to emulate decision-making of an expert user of the system.

The primary characteristics of knowledge-driven DSTs include:

- Providing recommendations based on human knowledge.
- Applying a heuristic technique for problem solving. A heuristic is a practical or rule-of-thumb technique.



What Are the Primary Characteristics of Data-Driven DSTs?

- Process and analyze data to develop insights that support decisionmaking.
- Enable processing, manipulation, and visualization of large amounts of data.
- Depend on the quality of the data.
- Offer flexible analytical and reporting capabilities.
- Assist decisionmaker's interpretation of data patterns for predictions.

Example: PA and machine-learning algorithms that learn from historical data to identify patterns and make predictions based on multiple variables, such as time of day, weather, congestion, and average speeds.





Speaker's Notes (12/44)

Data-driven DSTs use data to aid in the decision-making process.

Data-driven DSTs use data from databases that can be queried. Data-driven DSTs enable processing and analysis of data to develop insights that support decision-making. Statistical analysis software is one of the most common types of data-driven DSTs.

The primary characteristics of data-driven DSTs include:

- Enable processing, manipulation, and visualization of large amounts of data.
- Depend on the quality of the data.
- Offer flexible analytical and reporting capabilities.
- Assist decision maker's interpretation of data patterns for predictions.



What Are the Primary Characteristics of Model-Driven DSTs?

- Simulate the behavior of a transportation network using mathematical models and simulation tools.
- Provide what-if analyses.
- Derive insights and provide forecasting and prediction capabilities.
- Use online or offline to support managing and operating TMS.

Example: Simulate the behavior of a transportation system using mathematical models and predict possible outcomes of actions to assess impact on travel time, environment and throughput.



Speaker's Notes (13/44)

Model-driven DSTs use mathematical models and simulation tools that express relationships among data elements or variables of interest for an analysis being conducted.

Model-driven DSTs simulate the behavior of a transportation system, or parts of the system, using different values for certain parameters.

The primary characteristics of model-driven DSTs are:

- Providing what-if analysis based on historical and assumed data.
- Leveraging algorithms and simulation and optimization tools to provide decision support.
- Using data and parameters provided by decision makers to help analyze a situation, but without intense amounts of data input.





DSTs Mapped to Decision Support Classifications

Table 1. DSTs mapped to decision support classifications.

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



Speaker's Notes (14/44)

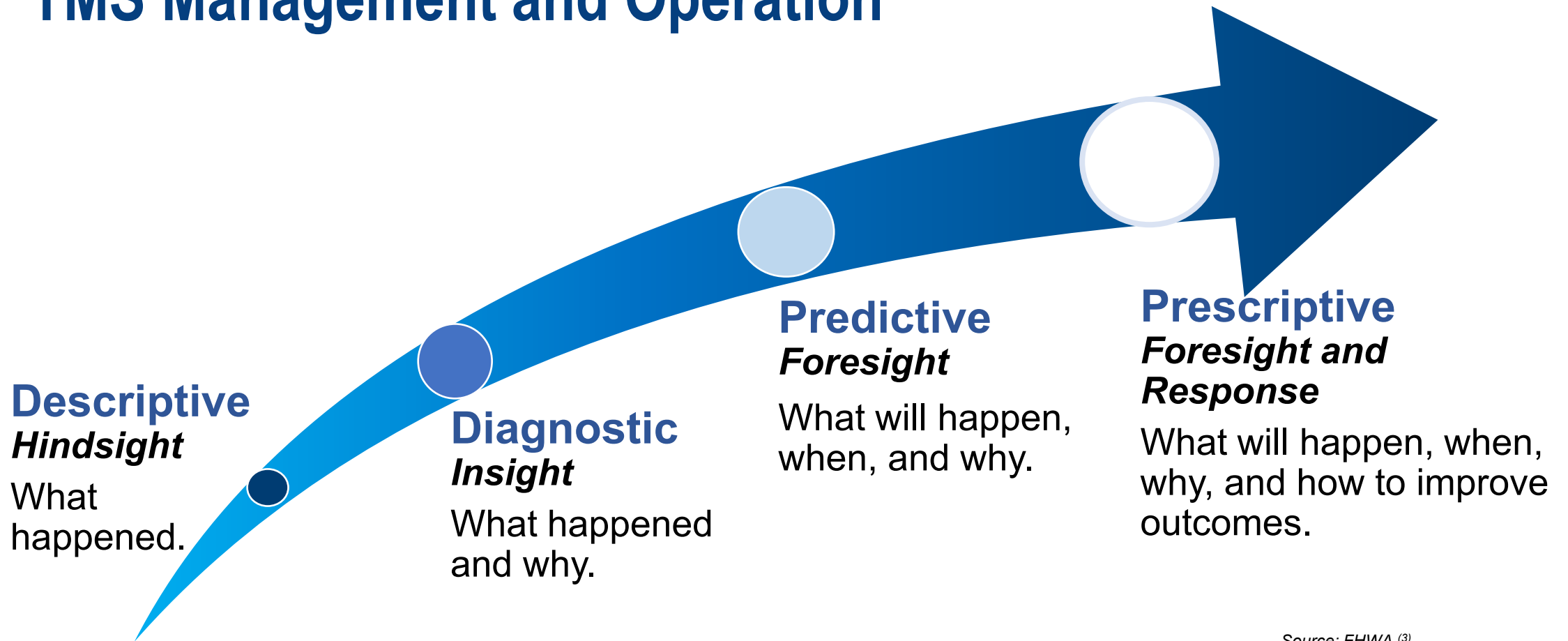
Examples of noncomputer-based, offline DSTs, illustrated in table above, are incident response plans and paper-based decision trees that can be printed and collated into reference information. Offline tools generally support decisions associated with short-term and long-term activities. Performance measurement dashboards that summarize or report data are an example of computer-based, offline DST.

In contrast, online DSTs are real time and computer based. Examples of computer-based, online DSTs include a range of traffic analysis tools. With greater access to data and computational capabilities, current knowledge-driven and noncomputer-based DSTs such as incident response plans may indeed evolve to be informed by data- and model-driven information such as origin-destination analyses and transplanted to a computer-based system. As DSTs shift towards data- and model-driven computer-based tools, the importance of computer-based DSTs grows, along with both their potential to improve the real-time decisionmaking of traffic operations personnel and to enhance the operational capabilities of TMSs.

Computer-based DSTs have the potential to process vast amounts of data, replicate the operational processes of an agency, and support the decisionmaking of TMSs or operators in TMCs. DSTs can aid operations personnel with monitoring and assessing conditions (e.g., environment, facility, and network), detecting and verifying incidents, and identifying and evaluating appropriate response strategies to planned and unplanned events. DSTs also can help agencies achieve more consistent decisionmaking between staff involved with managing traffic, TMC operations staff, and TMSs.



Analytics Maturity Path for Supporting Decisionmaking in TMS Management and Operation



Source: FHWA.⁽³⁾





Speaker's Notes (15/44)

Descriptive analytics offer hindsight. It uses simple statistical methods.

- This is the type of analytics that are most frequently used within TMSs.
- It involves the analysis of data collected by TMS components to describe real-time, current state conditions, historic conditions (e.g., daily, weekly, monthly, quarterly, or yearly), and trends (changes temporally and spatially).





Speaker's Notes (15/44) – continued (1/5)

Diagnostic analytics offer insights. It is the process of using data to determine the causes of trends and correlations between variables.

- Diagnostic analytics helps organizations better understand the internal and external factors that affect outcomes.
- From a transportation perspective, diagnostic analytics may explore integrated data, to clarify whether the descriptive statistic suggest an anomaly rather than the natural variability in the data.
- Integration of data may inform how weather patterns or events, planned special events, holidays, shifts to telework, or workforce training or turnover affects operations.



Speaker's Notes (15/44) – continued (2/5)

- Diagnostic analytics are frequently performed using TMS subsystems to inform policies, processes, staffing, and management decisions, but also can be embedded within TMS subsystems to reduce TMS operator workload and the time required to monitor and assess transportation performance.
- For example, an advanced TMS could include subsystems with logic that makes prominent on a TMC monitor wall the CCTV feeds in closest proximity to road segments where diagnostic analytics identified an anomaly based on multiple criteria—such when traffic volume and speed from a sensor deviates by a temporal threshold, and event data from Waze shows reports of debris on roadway.
 - Note in this example, the anomaly detection employs diagnostic analytics; however, the translation of that detected anomaly to the logical action to display a camera is not diagnostic analytics, but rather a process rule.
 - Similarly, TMS software that proposes a set of candidate dynamic message signs and even message sets based on the operator's entry of incident location and other data is not employing diagnostic, predictive, or prescriptive analytics. Rather, it is applying logic rules based on proximity and directional logic.



Speaker's Notes (15/44) – continued (3/5)

Predictive analytics, the focus of this report, makes a significant leap beyond descriptive and diagnostic analytics, by developing and applying mathematical models to make statements about the future state of a system.

Mathematical modeling refers to the development process—that of creating a mathematical representation of a real-world scenario to make a prediction or provide insight. Simulation typically refers to the application of the mathematical model.

- Predictive analytics can be used to answer questions in real-time or for operations management, such as:
 - How long will the roadway be blocked for this crash?
 - Does this video show a vehicle traveling in the wrong direction?
 - How many, or which sensors may fail in the next three months?
- Prescriptive analytics proposes what will happen, when it may happen, and even why.





Speaker's Notes (15/44) – continued (4/5)

- In contrast, diagnostic analytics identifies what happened and why.
- In developing and applying the mathematical models to predict outcomes, traditional statistical methods such as regression or more advanced methods in the realm of machine learning and broader artificial intelligence may be employed.
 - The fidelity of the prediction depends on many factors, but at its core is a function of data quality (e.g., accuracy, completeness, reliability, relevance, and timeliness) and the model quality (e.g., robust, precise, descriptively realistic, accurate, generalized, and useful).



Speaker's Notes (15/44) – continued (5/5)

Prescriptive analytics, goes one step further from predictive analytics, to offer foresight and a response. This may include:

- Prescribing a real-time operational change;
- Prescribing a change in processes; or
- Enacting the change through automation with human in the loop to interrupt the automation.

Prescriptive systems may entail the simulation of multiple alternatives, refined to reach a proposed action.

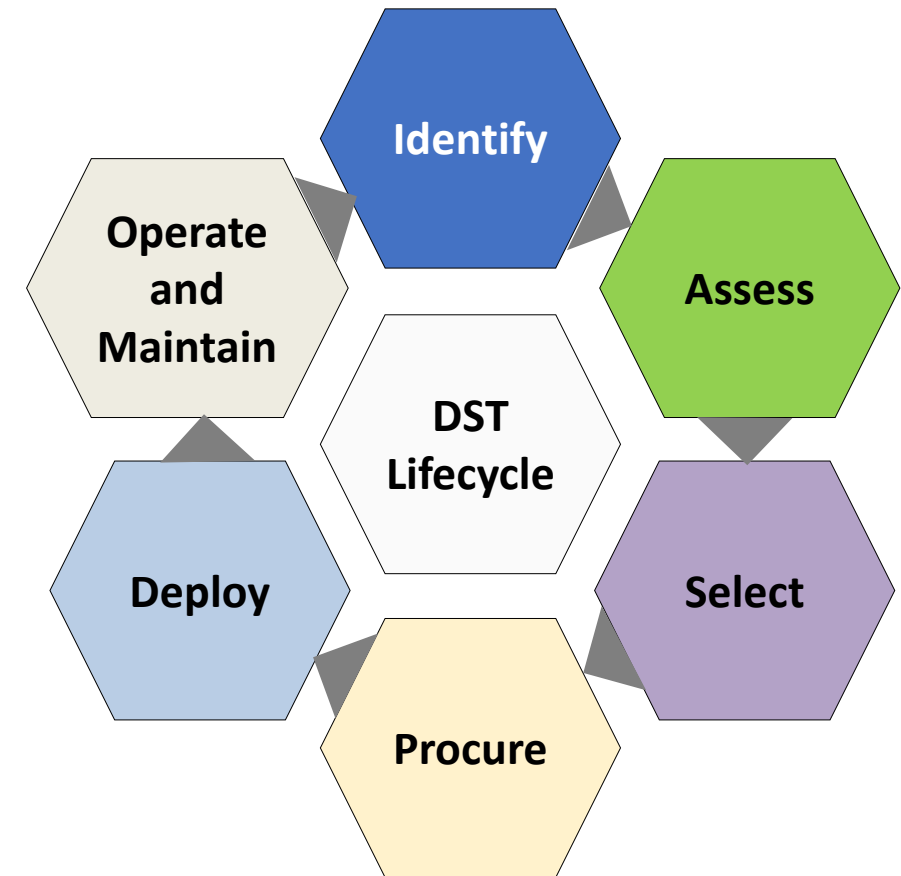
- Autonomous vehicles, such as Waymo or Cruise, employ neural network models (a class of flexible nonlinear regression and discriminant models, data reduction models, and nonlinear dynamical systems) make calculations in real-time that help the vehicle make similar decision as a human driver.
- Within a TMS, prescription analytics could be applied to improve dynamic tolling that optimizes mainline and managed lanes.



What Is a DST Lifecycle Framework?

The DST lifecycle includes:

- Identifying needs and requirements.
- Assessing needs.
- Selecting a DST.
- Procuring a DST.
- Deploying a DST.
- Operating and maintaining a DST.



Source: FHWA.⁽³⁾





Speaker's Notes (16/44)

A DST life cycle framework shows the steps in the life cycle of a DST. The framework is based on the state of the practice and the requirements for using a systems engineering process.

This life cycle framework can be used for many iterations of a DST used within a TMS. The next slides will cover each step of this framework.





What Issues Might an Agency Consider When Selecting and Procuring a DST?

- Has the agency analyzed tradeoffs between build, buy, and reuse?
- What are the agency's options for developing a custom DST?
- What are the agency's procurement processes and can the agency use existing contracts, or does the agency have staff who could develop a DST?
- How does the agency value reliability of an off-the-shelf product versus the flexibility of a custom product?
- Does the agency need a current practice or trade study to better understand available DST products?
- How closely do agency requirements match existing off-the-shelf products?
- What is the plan for developing procurement documents (e.g., request for proposal, direct purchase)?
- How will the agency select solutions or vendors to implement DST?





Speaker's Notes (17/44)

Agencies can consider these questions before deciding if development or implementation of a DST is needed. Also, an agency may have several options when planning procurement of a DST into a TMS. The options may be based on government (city, county, State) or agency policies.





Context for Integrating PA into TMS Management and Operations

- Effective traffic management requires both active traffic management and management of TMS, including subsystems and processes.
- Active traffic management provides dynamic and adaptive adjustments to current changes and future conditions.
- Active management of response levels may include static, reactive, responsive, and proactive.
- PA has the potential to improve responsiveness from static and reactive to responsive and proactive.



Speaker's Notes (18/44)

Predictive Analytics in the context of TMS. Effective traffic management requires both active traffic management, which provides dynamic and adaptive adjustments to changing current and future conditions along with management of the TMS, including data, software, hardware, processes, and staff.(3) Active traffic management involves a cyclical process and framework to manage the performance of the transportation network, which includes:

- Monitoring system performance
- Assessing and predicting system performance
- Proposing dynamic actions
- Selecting and implementing the selected actions



Speaker's Notes (18/44) - continued

The levels of responsiveness in the active management framework context include:

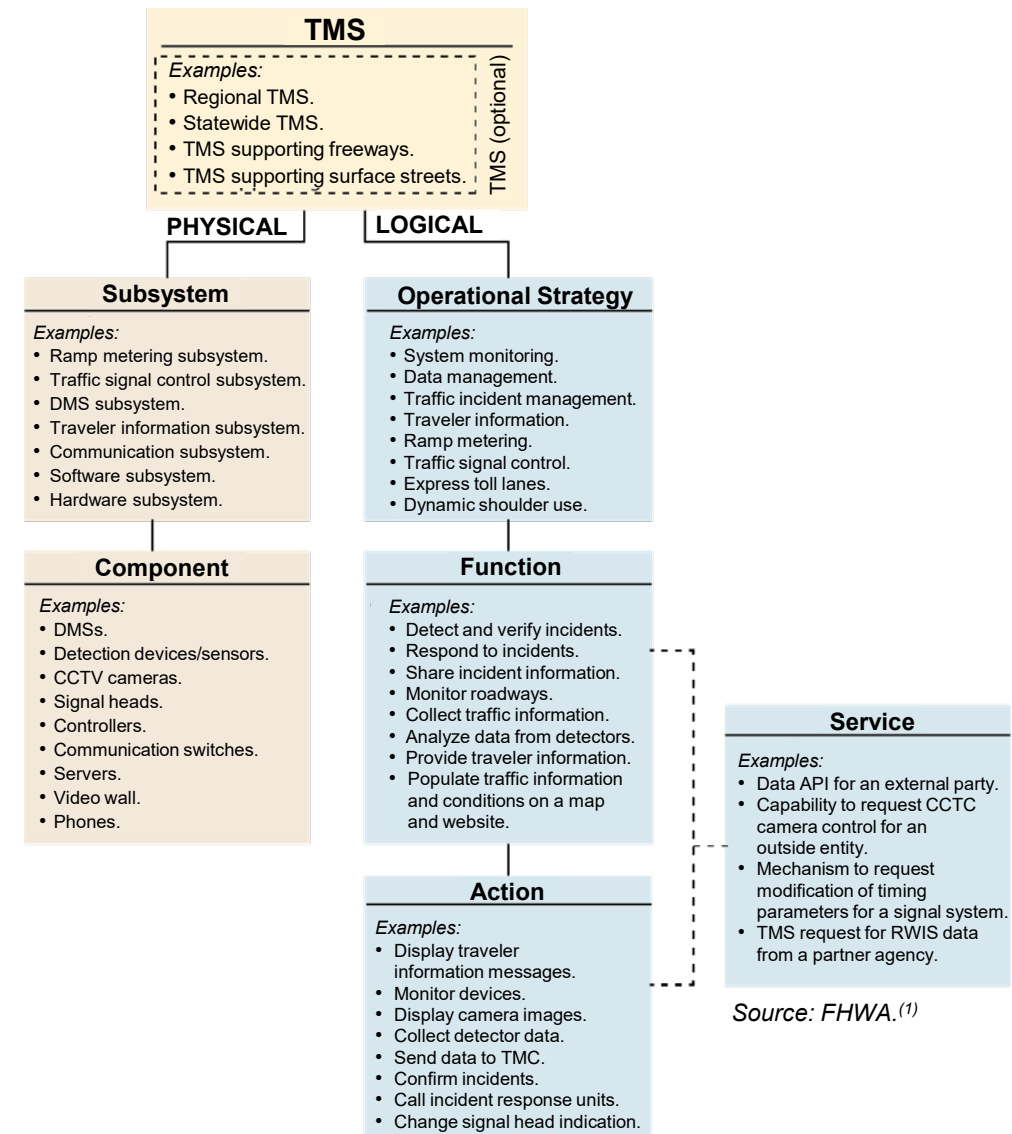
- **Static:** Responses to variations in conditions that are preset and updated based on the calendar.
- **Reactive:** Responses that occur when there are observed problems with the static plans requiring real-time monitoring.
- **Responsive:** Responses to variations in conditions that occur in real-time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

Predictive analytics has the potential to help traffic operators and managers by bringing efficiencies to the active management cycle and advance responsiveness from static and reactive to responsive and proactive. The application of predictive analytics could assist with the real-time formulation of proactive changes to the management and operation of different strategies or control plans.



How PA Could Support TMS

- PA can take place within TMS:
 - Closed-circuit television camera (CCTV) component.
 - Ramp metering subsystem.
- PA can support TMS logical elements such as the detect incident function.
- PA can inform offline and online DST.



Source: FHWA.⁽¹⁾





Speaker's Notes (19/44)

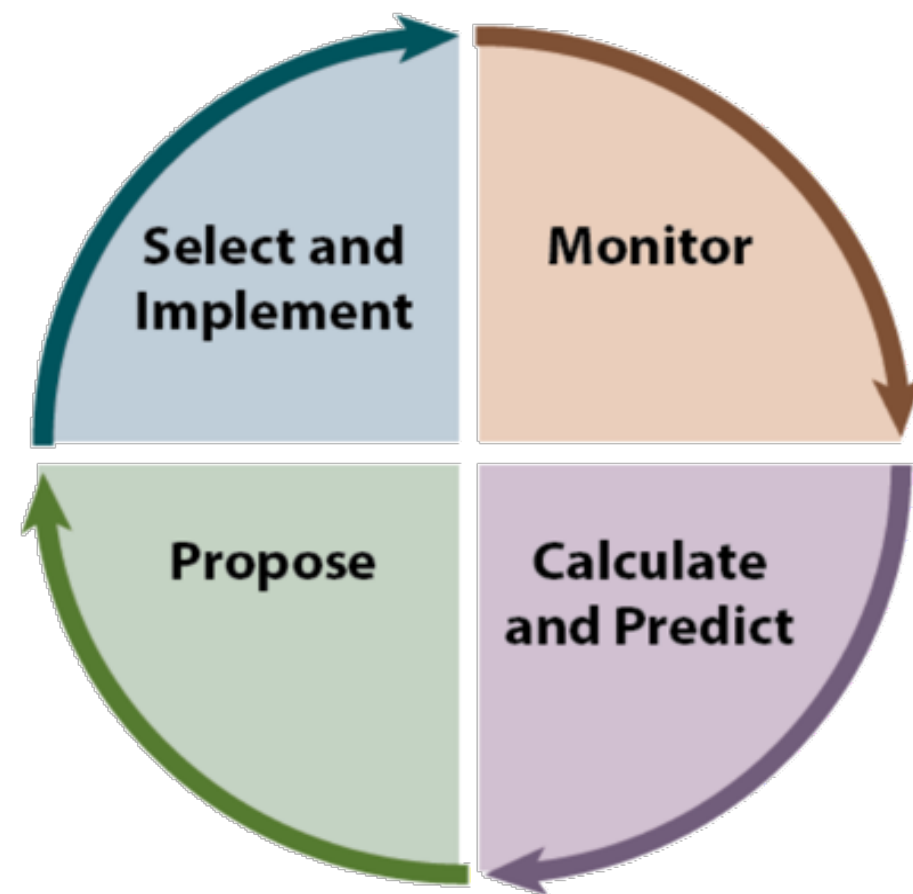
The data subsystem is a particularly important area to consider as agencies assess their current and future capacities needed for predictive analytics.

Subsystems comprise components and technology that carry out specific functions and actions, such as transmitting, processing, analyzing, interpreting, reporting, and archiving data.



PA in the Context of TMS Decisionmaking

- Descriptive and diagnostic analytics assist with monitoring the current condition of the transportation network.
- PA offer earlier insights regarding future outcomes to help operators formulate a response strategy.
- Prescriptive analytics will propose a response and, potentially, even offer insights as to the outcome of action or inaction.



Source: FHWA.⁽¹⁾



Speaker's Notes (20/44)

DST provides four primary functions to assist operators with decisionmaking:

- **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 to predict the future state of the network and increased risk of impactful events.
- **Propose:** Generate one or more response plans (i.e., sets of operational strategies, functions, and actions) to mitigate effects of the traffic event.
- **Select and implement:** Select and execute the response plan most likely to best improve performance.



Speaker's Notes (20/44) – continued (1/2)

Descriptive and diagnostic analytics offer great value within the monitoring phase of decisionmaking as well as in the calculate element that support prediction.

- Common descriptive analytical measures include counts (e.g., traffic volume, active incidents, customer complaints, active snowplows), averages (e.g., segment speed, travel time), and deviations from average or percentages (e.g., delay, travel time reliability, percentage of sensors online).
- Descriptive analytics provide insights into the historic and current state of the transportation system.
- They can support real-time decisionmaking when viewed by operators with expertise to interpret the data.
- For example, if the real-time traffic flow or average speed on a road segment declines, an operator may decide to access a CCTV feed in the proximity of the road segment.
- Conversely, historical descriptive analytics provide insights for policies, processes, staffing, and management decisions. For example, operators may use the percentage online data to prioritize sensor maintenance or choose to modify safety service patrol routes based on the spatial and temporal frequency of incidents.





Speaker's Notes (20/44) – continued (2/2)

When the volume and velocity of data are in the realm of big data, descriptive analytics may require “big data” techniques.

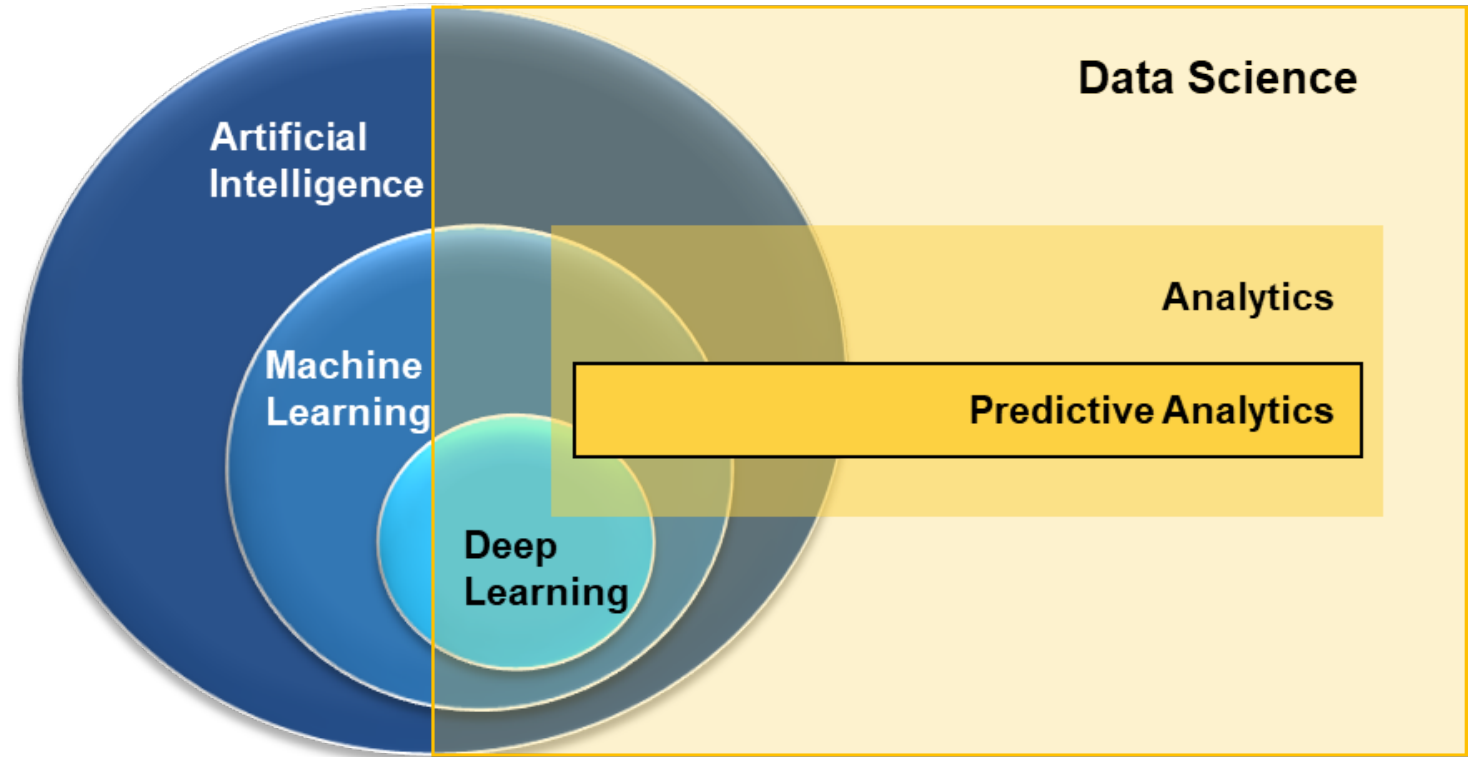
There are applications of predictive analytics associated with the calculate and predict and there is potential to support the proposed phases of decisionmaking.

The most common types of predictive models currently supporting TMS decisionmaking are smart edge devices that process video to detect incidents, congestion, or wrong-way driving. These devices apply machine learning



PA in the Context of Future TMS Capabilities

- Identify needs and requirements for integrating PA into TMS management.
- Select DST to enable PA integration:
 - Knowledge driven.
 - Data driven.
 - Model driven.



Source: FHWA.⁽³⁾



Speaker's Notes (21/44)

Predictive analytics is one class of analytics. These analytics are typically employed within the field of data science, which begins with understanding business needs, collection of data and using statistics, scientific computing, scientific methods, processes, algorithms, and systems to extract or extrapolate knowledge and insights from noisy, structured, and unstructured data.

Prediction in the context of TMSs will be delivered through decision support tools (DST). DSTs use knowledge, data, and methods through offline or online interactions. Offline interactions may be computer or noncomputer based.

Knowledge-driven DSTs provide specialized problem-solving expertise based on the processing of stored facts, rules, procedures, or similar forms of knowledge. They attempt to emulate human reasoning, but with more consistent results. Expert systems are the best known type.

Data-driven DSTs use data to aid in the decision-making process. Data-driven DSTs use data from databases which can be queried and enables processing and analysis of data to develop insights that support decision-making. Statistical analysis software is one of the most common types of DSTs.





Speaker's Notes (21/44) - continued

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.



AI and Machine Learning Techniques for Supporting Prediction in TMSs

- **Classification—Good Fit:**
 - Image detection.
 - Object recognition.
 - Text recognition.
 - Language translation.
 - Sound recognition.
- **Generate new data—Good Fit:**
 - Text generation.
 - Image generation.
 - Video generation.
- **Regression—Fair Fit:**
 - The compositional nature of the world.
 - The pattern of patterns (spatial and temporal).
 - The many techniques in images and speech.
 - The limited techniques for categorical variables, e.g., predict the income of an individual based on their sex, age, nationality, academic degree, family size, etc.



Speaker's Notes (22/44)

Machine learning, a subset of AI, focuses on building methods that “learn” based on experience or data. Machine learning can use mathematical models such as regression, classification, clustering, and natural language processing. Machine-learning algorithms may include supervised learning, wherein a model learns to predict human-given labels; unsupervised learning, which does not require labels; and reinforcement learning, wherein the model does not require labels and autonomously strives to optimize. Again, data with greater volumes, varieties, velocities, and veracities are key to robust machine-learning models. Moreover, machine learning supports a range of analytics, including prediction.

Deep learning is a subset of machine-learning algorithms that use a brain-like logical structure of algorithms called artificial neural networks, which capture nonlinear patterns in data. Neural network models of the past had failed due to lack of data with sufficient volume, variety, velocity, and veracity, as well as due to lack of computing power. With the growth in the volume, variety, velocity, and veracity of data and the growth in cloud computing power, deep-learning techniques have been successful in the areas of vision (image classification), text, audio, and video.





Issues To Be Considered in Assessing the Options to Add Prediction into Decisions Made to Support TMSs

- Data and data-management issues.
- Human resources and institutional issues.
- Implementation and maintenance issues.



Speaker's Notes (23/44)

Several key considerations are involved in the planning for the adoption and use of predictive analytics in a TMS. The more significant range of issues to consider in the pursuit of predictive analytics is organized across the following three categories:

- Data and data management—Predictive analytics typically requires data and unique computing capabilities. Agencies adhering to data management policies and practices may find their data and computational tools insufficient for the use of predictive analytics in traffic management decisionmaking. For example, most agencies do not store their CCTV camera video beyond a limited duration, if at all. Thus, the opportunity to develop machine-learning models may be limited. Predictive analytics that rely on smaller event datasets that make use of regression models may still be viable.





Speaker's Notes (23/44) - continued

- Human resources and institutional considerations—Predictive analytics in a TMS may represent a shift from reactive decisionmaking to more future-oriented, proactive decisionmaking for TMC operators and managers. Using real-time information from the TMS, TMC operators and managers currently make decisions based on descriptive and diagnostic analytics, experience, and intuition. The introduction of predictive analytics into traffic management may influence how traffic management staff use and trust data. Other considerations include managers' and operators' workflows, tasks, technology interfaces, and organization policies and practices.
- Implementation and maintenance considerations—Predictive analytics from the modeling perspective is not static. Rather, predictive analytics models should be routinely reassessed, retuned, or even rebuilt as travel behaviors and patterns; event types, locations, and frequencies; data sources and quality; and even weather events change.



Considerations: Data and Data Management

- Understand what data are available, their quality—completeness, timeliness, accuracy, consistency, validity, integrity.
- Use sufficient data labeling for PA model development using machine learning or deep learning.
- Employ modern data management principles when using big data PA, such as:
 - Use of cloud services for scalability, flexibility, and cost-effectiveness.
 - Distributed computing to support efficient and timely real-time analytics.
 - Decentralized data governance.
 - Decoupled hardware and software.





Speaker's Notes (24/44)

Predictive analytics typically requires data and unique computing capabilities. Agencies adhering to data management policies and practices may find their data and computational tools insufficient for the use of predictive analytics in traffic management decisionmaking. For example, most agencies do not store their CCTV camera video beyond a limited duration, if at all. Thus, the opportunity to develop machine-learning models may be limited. Predictive analytics that rely on smaller event datasets that make use of regression models may still be viable.

Data integrity also refers to the safety of data with regard to regulatory compliance.



Considerations: Human Resource and Institutional

- TMC operators and TMS managers' focus is on systems management and operations:
 - Tradeoffs in building agency-internal PA capacity and using external expertise (vendor, university, consultant, and others).
 - Significant turnover in agency staff and staff knowledgebase may challenge the agency's ability to understand PA, develop PA models, and maintain them.
- Institutional data or intelligent technology practices and policies.
- Institutional culture to embrace new tools and practices.
- Interactions between the PA information; the delivery interface; and human knowledge, reasoning, and decisionmaking will determine whether the PA will be adopted.





Speaker's Notes (25/44)

Because humans are the mediators of the information within a TMC, it is important to understand how their work and the design of their environment impacts the implementation and use of predictive analytics.





Considerations: Implementation and Maintenance

Table 2. Comparison of PA implementation approaches.

| Implementation Features for PA | On-premise or Cloud with Traditional Devices | On-premise or Cloud with Predictive Devices | Cloud Native with Predictive Devices | Cloud Vendor Software-as-a-Service |
|---|--|---|--------------------------------------|------------------------------------|
| Cost | L | H | M | M* |
| Real-time functionality (e.g., ability to conduct analytics) | L | M | H | H |
| Expertise for managing system that supports real-time prediction | L | L | L | M |
| Resiliency (e.g., cyber, natural disaster, staff change) | H/L | H/L | M/H | M/H |
| Flexibility (e.g., peak demand, data growth, new models) | L | L | H | H |
| Institutional fit with traditional TMS culture | H | M | L | L |
| Ownership and analytics transparency | H | M | L | L |
| Delivery speed and up-time (e.g., data access by vendors and users) | L | L | H | H |





Speaker's Notes (26/44)

This table provides a generalized comparison of various implementation approaches to predictive analytics for TMSs across features such as cost, ownership, and resiliency. Each approach offers advantages and disadvantages along a continuum of implementation features for predictive analytics.





Readiness Assessment To Integrate PA in TMSs

Areas that require readiness assessment include:

- Policy.
- System.
- Data.
- Acquisition.
- Maintenance.



Speaker's Notes (27/44)

The readiness checklist is intended—after some initial work has been completed—to confirm the need for predictive analytics capability and a corresponding DST. The needs assessment effort should come first and be foremost. FHWA report Decision Support Methods and Tools for Traffic Management Systems specifies a five-step process for identifying needs for a DST as follows:

1. Identify stakeholder and DST goals, making sure to include end users as well as those with institutional, operational, or technical responsibility.
2. Elicit and document user and system needs through outreach mechanisms such as workshops and interviews and use the interactions to also educate stakeholders.
3. Reconcile, validate, and prioritize stated needs to resolve conflicts or close gaps and thereby deliver a unified, prioritized vision of DST needs.
4. Verify whether the system is feasible and necessary, delineating what may or may not be addressed.
5. Define project scope, budget, and time constraints.





Policy Readiness

- Does your agency have a policy for the cloud and cloud services? If it has one, what does it entail?
- Does your agency have an open data policy? If so, what does it entail? Might it limit what data can be used by predictive models?
- Does your agency have policies regarding how analytics will be used to inform decisions and specific types of actions? If so, what types of decisions and actions are explained?
- How are data and analytics actively managed in the TMS?
- What policy or cultural barriers may limit governing and managing data and analytics in your agency?





Speaker's Notes (28/44)

Policy readiness refers to the practices, governance structures, and procedures associated with data and analytics. Some of the key questions and considerations for policy readiness are as shown on the slide.





System Readiness

- Do you have a place to store large amounts of data?
- Do you have computing power or a graphics processing unit (GPU) to read and process large amounts of data quickly?
- Is there power or communications bandwidth (roadside fiber) or both available for traditional and edge sensors, and will smart edge sensor communications be supported?
- Is the advanced transportation management system (ATMS) able to support data volumes for building, training, and iterating models? If no, consider cloud service analytics and PA in the loop.





Speaker's Notes (29/44)

System readiness refers to the components necessary for predictive analytics, such as data systems, sensors, communications, and cloud infrastructure. Some of the key questions and considerations for system readiness include:



Data Readiness

- Are there issues with storing specific types of data?
- Does your agency have sufficiently high resolution, disaggregated data?
- Does your agency have multiple years of data?
- What percentage of data are labeled, and what is the quality of the labeling?
- Is there ground truth data?
- Does your agency have ancillary data to create labels?
- Does your agency store raw, unprocessed or unaltered data?
- Are data representative of the entire area of interest, e.g., are data more reliable in one area versus another?





Speaker's Notes (30/44)

Data readiness refers to data collection, quality, storage, and analytic capacity for big data and predictive analytics. Some of the key questions and considerations for data readiness include:



Acquisition Readiness

- Is your agency able to purchase cloud services?
- Have you defined the capabilities, rather than processes, for acquisition?
- Has your agency considered what data is “owned,” and how the data it can be shared?
- Do the agencies’ procurement methods support monthly service charges (e.g., Cloud) which may vary?
- Will the current or evolving PA requirements exceed the capabilities of the TMSs computing hardware (servers)?
- Is your agency able to outsource data analytics (e.g., consultant support)?





Speaker's Notes (31/44)

Acquisition readiness refers to the processes and practices needed to support the procurement of tools, data, and technologies that support predictive analytics. Some of the key questions and considerations for acquisition readiness include:





Maintenance Readiness

- Is there a replacement strategy for TMS devices which may need to be replaced to meet requirements for using PA?
- Is there a plan, resources, or both in place for continuous data preparation and maintenance?
- Will protocols or automation be put in place to detect when your prediction models need to be retrained?
- Will the agency have the resources to monitor, evaluate, and manage the use of predictive models?





Speaker's Notes (32/44)

Incorporating predictive analytics into TMS will require ongoing maintenance of hardware, data, staff, and the predictive models themselves. Some agencies have incorporated real-time descriptive and diagnostic analytics using big data. A summary of maintenance readiness questions drawn from broader industries that have more mature predictive analytics pipelines are presented on this slide.



Potential PA Use Cases Within the TMS

- Traffic incident management (TIM).
- Road weather management.
- Ramp metering.
- Variable speed limit (VSL).



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Speaker's Notes (33/44)

Predictive analytics could support some of the most common operational strategies in a TMS—through every phase of the traffic incident timeline (detect, verify, respond, and return to normal traffic flow) and in coordination with TSMO strategies such as part-time shoulder use, ramp metering, variable speed limits (VSLs), traveler information, and road weather management. The following slides give examples of the strategies' use.



PA Maturity: TIM

- Most real-time PA for TIM in the research or proof-of-concept stage:
 - Models have yet to estimate real-time, network-wide impact, severity, or duration of incidents that match expert judgment.
 - Models can predict the incident hotspots, but these predictions generally do not exceed expert judgment.
 - Vendor products detect slow downs, incidents, stalled vehicles, and other events by processing camera sensor images.
 - Some products are integrated with ATMS using an API.
- Tremendous value in TIM from descriptive and diagnostic analytics.



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Speaker's Notes (34/44)

The TIM process consists of five phases: incident detection, verification, response, clearance, and recovery. Descriptive and diagnostic analytics can accelerate detection and verification functions and actions. Predictive analytics embedded within online DSTs may support clearance and recovery functions and actions. Predictive analytics that proposes high-risk road segments based on demand, road weather, and other factors also may support offline decisions associated with safety service patrol positioning.

In the context of predictive analytics and the ability to estimate in realtime networkwide impact, severity, and duration, few models have yet to provide predictions that match expert judgment. Likewise, the application of predictive analytics to estimate the frequency and locations of crashes based on demand and weather conditions also is in the research and testing phase.



PA Maturity: Road Weather Management

- Real-time PA for road weather management are at the research or proof of concept stage:
 - Potential for improved pavement status over a 1-h, 4-h, 1-d, and 1-w horizon by roads with more detailed segments.
 - Potential to support route, materials/treatment use, or staffing optimization.
 - The Integrated Modeling for Road Condition Prediction (IMRCP) system offers an example of PA research.⁽⁴⁾
- IMRCP provides tremendous value from available descriptive and diagnostic analytics:
 - Maintenance decision support systems use heuristics based on traditional PA.
 - Real-time detection of weather-affected roadways.



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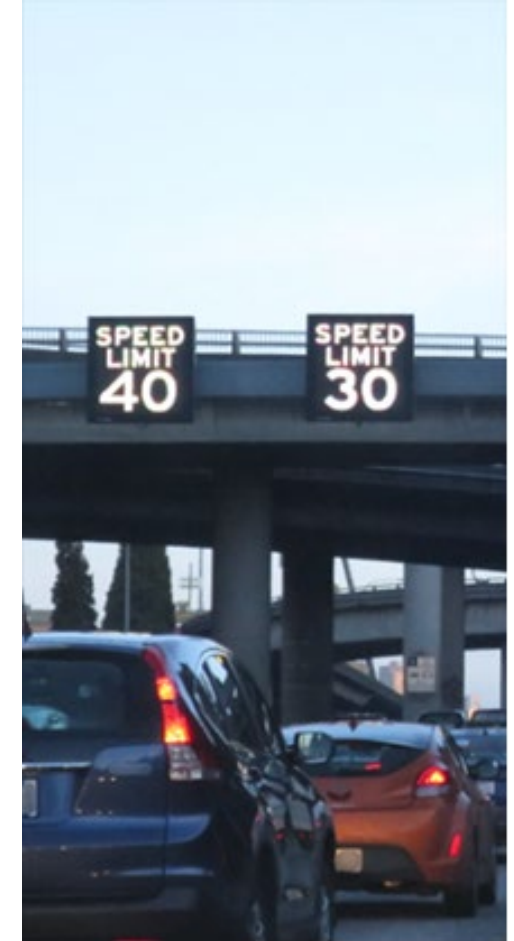
Speaker's Notes (35/44)

Use of the IMRCP tool suggests that the IMRCP road weather data and weather forecast may be useful and inform maintenance decision support systems without providing an interface to incorporate data directly into the management and operations of specific operational strategies or other traffic management decisions.



PA Maturity: Ramp Metering and VSL Speed Limit

- Real-time PA for ramp metering and VSL in research stage:
 - PA will require improved lane-specific volume and speed data, potentially from connected vehicles.
 - PA will require focused simulation, field, and human factors testing.
 - While VSL in practice is rule based, researchers explored other methods: fuzzy-logic, analysis, and control-theory-based strategies.
- Fuzzy logic and predictive models (e.g., simulation) are used to develop ramp metering algorithms.



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Speaker's Notes (36/44)

Ramp metering could benefit from algorithmic advances in real-time, dynamic operations, but the predictive potential would require improved lane-specific volume and speed data. Still, even though traffic-responsive algorithms have applied machine-learning techniques in simulated test platforms, the levels of programming complexity, certain challenging training procedures, and demanding data requirements have precluded such algorithms' real-world application.

While no real-world application of advanced predictive techniques in ramp metering exists, improved heuristic-based metering processes based on descriptive analytics do exist. As an example, the Washington State Department of Transportation (WSDOT) uses real-time descriptive analytics for adaptive ramp metering, implementing a fuzzy logic ramp metering algorithm on 126 ramps in the Greater Seattle area in 1999.





Examples of Using Prediction in TMS

- Predicting incident duration.
- Predicting queue length.
- Predicting traffic flow.
- Predicting weather.





Speaker's Notes (37/44)

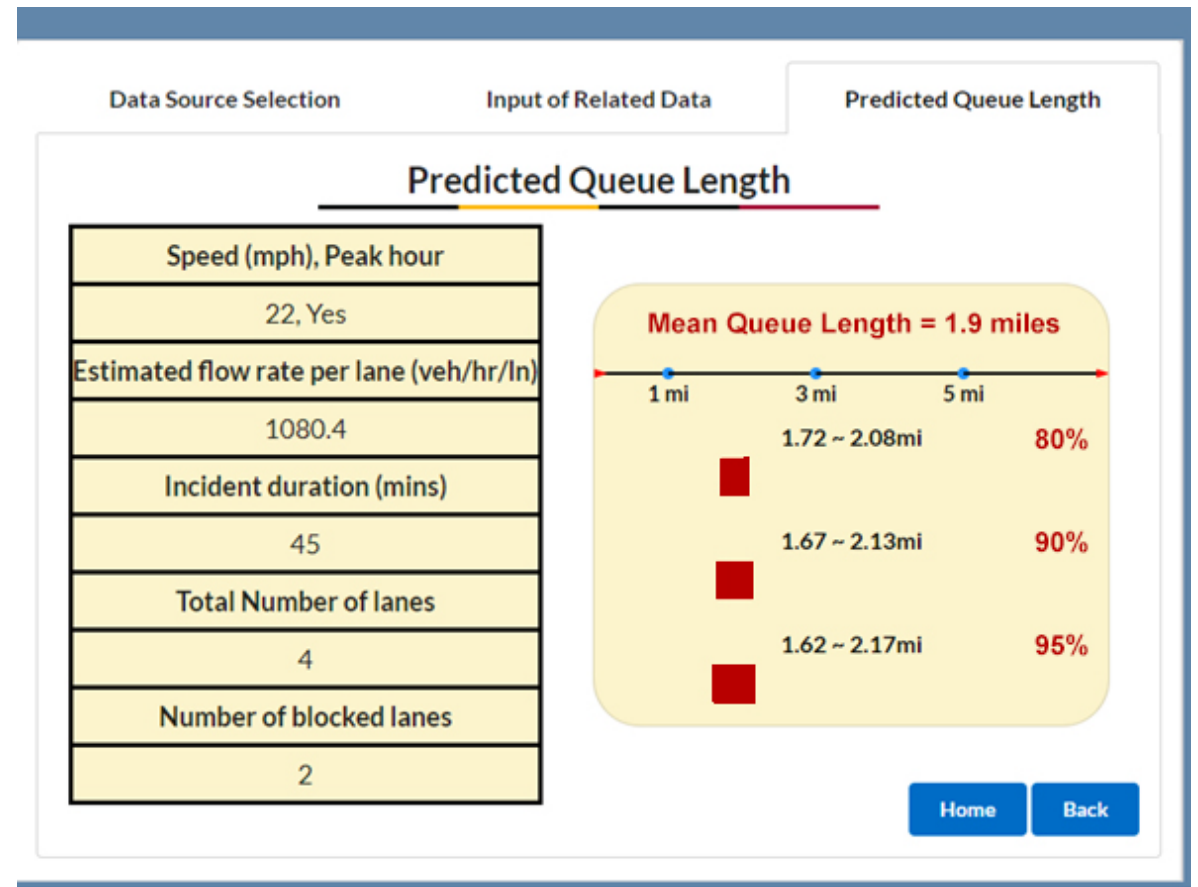
Prediction can be used in TMS to predict incident duration, queue length, traffic flows and weather to help support operator decisionmaking about specific actions such as deploying resources or updating CMSs.



Predicting Incident Duration and Queue Length

Maryland Department of Transportation, Coordinated Highways Action Response Team program:⁽⁵⁾

- Applies traditional PA (regression modeling).
- Predicts incident duration in 30-min bins.
- Predicts likely queue length.
- Shows significantly greater value once it is integrated within the TMS.



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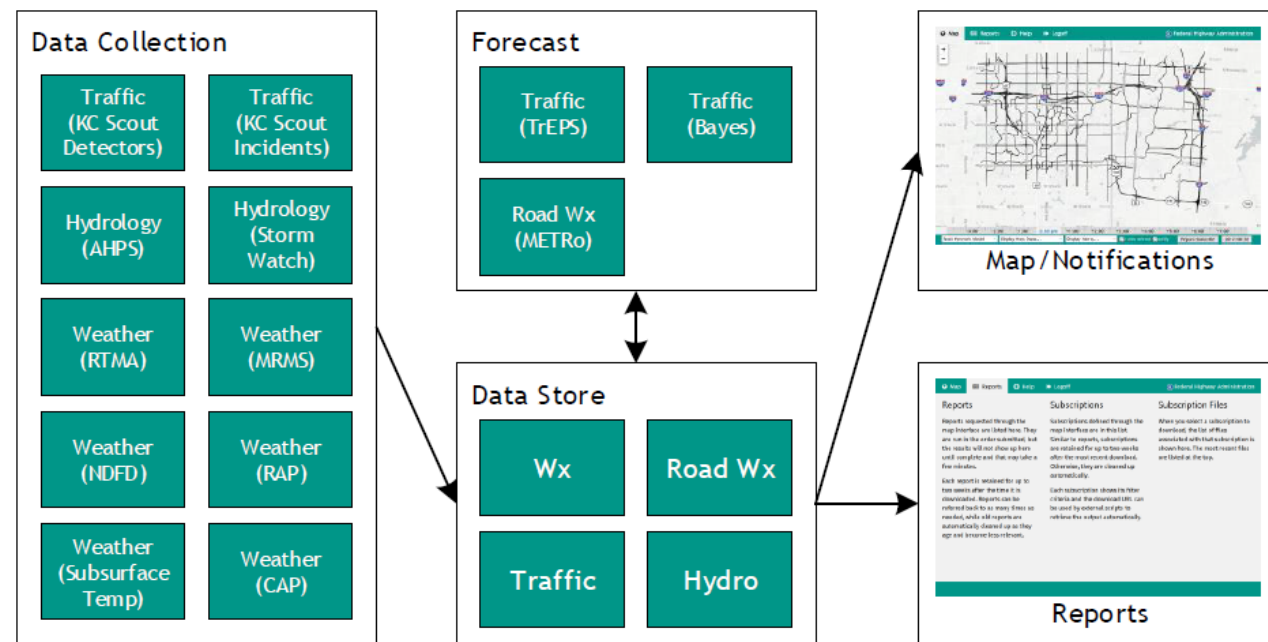
Speaker's Notes (38/44)

The MDOT Coordinated Highways Action Response Team (CHART) program, through a collaboration with the University of Maryland, developed a prototype to predict incident clearance times within four-time ranges: under 30 minutes, 30–60 minutes, 61–120 minutes, or more than 120 minutes in 2019 based on multiple years of historic crash data from their ATMS. One of the key challenges limiting the use of this predictive capability is that the UI is not integrated with the CHART ATMS. Consequently, the tool requires operators to manually enter information (e.g., vehicle counts, county, number of responders, and number of lanes closed) that could readily be pulled from the operators' ATMS.



Predicting Traffic Flow and Weather

- IMRCP model applies traditional PA (regression modeling), machine learning, and simulation.⁽⁴⁾
- The model is not integrated within the TMS.
- The model is based on two winters of data.
- The speed prediction model showed great deviations from ground truth.
- Data sources and services require consistent monitoring to assure a high quality of service, due to the distributed nature of the system.



Source: FHWA.⁽⁵⁾

AHPs = Advanced Hydrologic Prediction Service; CAP = common alerting protocol; MRMS = multiradar/multisensor System; NDFD = National Digital Forecast Database; RAP = rapid refresh; RTMA = real-time mesoscale analysis; Wx = weather.





Speaker's Notes (39/44)

As part of the FHWA-funded Integrated Modeling for Road Condition Prediction (IMRCP) project, the Kansas City Scout Traffic Management Center (KC Scout) deployed a system based on the Traffic Estimation and Prediction System (TrEPS) platform.



Trends and Implications for PA in TMS

- Trends that will make predictive analytics more accessible and usable:
 - TMSs are being rearchitected to become more modular.
 - Big data vendors are beginning to offer predictive analytics as a service.
 - Cloud service providers are developing tools that simplify model development and use.
 - Big data are becoming more accessible and improving in quality.
- Agencies may get ready for predictive analytics by considering the following:
 - Supporting a process and policy shift to proactive strategies.
 - Exploring traditional PA.
 - Shifting toward modern data management.
 - Exploring big data first through descriptive and diagnostic analytics.
 - Considering multiagency or multistate data sharing.
 - Considering open-source tools and code.
 - Focusing on human-centered decision needs.



Speaker's Notes (40/44)

There are a few trends that will make predictive analytics more accessible and usable for transportation operations within the next decade, if not sooner. These trends include:

- Transportation agencies continue to modify the structure and architecture of their TMSs to become more modular. These changes offer the potential for agencies to make incremental changes to the capabilities of their TMS. These capabilities may allow agencies to explore the potential to incorporate the use of predictive analytics to support how agencies use operational strategies, control plans, or operate a TMS.
- Agencies may have the ability to purchase or lease software and other products which can access and use proprietary, “black box” predictive and prescriptive capabilities. While these “black box” systems have significant transparency challenges and may deliver the prediction as an API to the data subsystem, testing maturing and collaboration among agencies harks of the potential to validate the prediction, if not the model. An example of this approach is The Eastern Transportation Coalition data marketplace, which includes data validation processes and reports for vendor data.
- Cloud service providers are developing tools that make the process of developing and applying predictive analytics far simpler, a form of plug-and-play capabilities. Thus, even with very little expertise, agencies may be able to apply machine and deep learning algorithms to develop a predictive model. While this is an opportunity, it must be tempered by diligence on how the model, or algorithm, will be implemented within the TMS software subsystem and whether the model needs to “live” within the cloud environment due to the need for specific cloud functions.





Speaker's Notes (40/44) – continued (1/3)

Similarly, agencies can prepare to use predictive analytics in the future by considering the following:

- **Supporting TMSs to proactively manage and control traffic.** By moving towards proactive management and operation of their TMS and the use of operational strategies, agencies will position the culture, policies, and procedures to support the adoption of predictive analytics in the future.
- **Exploring opportunities to consider developing simpler predictive analytics.** By applying data to develop regression or clustering models, the agency can grow its understanding of statistical methods and confidence with predictive model development and refinement processes.





Speaker's Notes (40/44) – continued (2/3)

- **Embrace modern management practices for data systems.** When focusing on real-time operations using multiple emerging data sources, data systems design needs to be flexible and self-adjusting, support distributed storage and processing, decouple hardware and software, distribute data governance, and support broad data access and use. Core to modern practices for data systems is the ETL method for data storage. Implementing these and other modern management facets for data systems may lead agencies to consider cloud storage, management, software, and analytics services.
- **Understand your data from the lens of descriptive and diagnostic analytics before pursuing predictive analytics.** Predictive analytics is the third level in analytics advances, requiring mastery of descriptive and diagnostic analytics prior to its exploitation and confident use. An agency pursuing predictive analytics must first have confidence and mastery of descriptive and diagnostic analytics with the intended data, whether that mastery is through in-house, contracted, or vendor offerings. As described in chapter 2, descriptive and diagnostics analytics align with the monitoring and calculation stages for active traffic management.



Speaker's Notes (40/44) – continued (3/3)

- **Consider multiagency or multistate data sharing to facilitate model development.** Given the data requirements for predictive model development—particularly the need for a very large volume of well-labeled data—coupled with the cost of supporting such systems, multistate collaboration on archived data sharing may prove a viable pathway to develop and test predictive models among agencies with a common predictive need. For example agencies may want to develop a model similar to that developed by the MDOT to predict incident duration and queue length. Once models meet a specific confidence threshold, they can be implemented and tailored for each agency's operations and decision thresholds specific to deployment of resources and DMS messaging.(41)
- **Consider open-source tools and code.** There are many reasons for turning to open-source tools and code. Having open-source or agency-owned software and DSTs affords agencies the opportunity to manage and make changes when applicable. The ability to modify the software and supporting APIs in support of the operational strategies agencies may use, provides the opportunity for them to make changes in the future.





Resources and Additional Information on Other TMS Practices

- TMS portal.⁽⁶⁾
- TMC PFS website.⁽⁷⁾
- “Traffic Analysis Tools” website.⁽⁸⁾
- *Predictive Analytics for Traffic Management Systems.*⁽³⁾
- *Decision Support Methods and Tools for TMSs.*⁽⁹⁾





Speaker's Notes (41/44)

Resources and Additional Information on Other TMS Practices include:

1. NOCoE's TMS Portal.
2. TMC PFS website.
3. FHWA's Traffic Analysis Tools Website.
4. Predictive Analytics for Traffic Management Systems (FHWA Report).
5. Decision Support Methods and Tools for TMSs (FHWA Report).





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2. FDOT. 2023. “FDOT D5 Regional Integrated Corridor Management System” (web page). <https://teo.fdot.gov/architecture/architectures/d5/html/projects/projarch66.html>, last accessed February 11, 2024.
3. FHWA. 2023. *Predictive Analytics for Traffic Management Systems*. Report No. FHWA-HRT-24-091. Washington, D.C.: FHWA.
4. FHWA. 2020. *Integrated Modeling for Road Condition Prediction*. Report No. FHWA-JPO-18-631. Washington D.C.: Federal Highway Administration. <https://www.scholars.northwestern.edu/en/publications/integrated-modeling-for-road-condition-prediction-fhwa-jpo-18-631>, last accessed April 8, 2024.
5. MDOT. 2017. *Development of a Traffic Management Decision Support Tool For Freeway Incident Traffic Management (FITM) Plan Deployment*. Report No. MD-17- SHA/UM/4-19. https://www.roads.maryland.gov/OPR_Research/MD-17-SHA-UM-4-19_FITM_REPORT.pdf, last accessed February 11, 2024.



Speaker's Notes (42/44)

References include:

1. Florida DOT's "FDOT D5 Regional Integrated Corridor Management System" web page
2. FHWA's Integrated Modeling for Road Condition Prediction – Phase 3 Evaluation Report.
3. Maryland DOT's Development of a Traffic Management Decision Support Tool For Freeway Incident Traffic Management (Fitm) Plan Deployment Report
4. National Operations Center of Excellence "Traffic Management Systems and Centers" web page
5. FHWA's "TMC Pooled-Fund Study" web page
6. FHWA's "Traffic Analysis Tools" web page.



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Speaker's Notes (43/44)

Additional references include:

1. FHWA's Predictive Analytics for Traffic Management Systems Report
2. FHWA's Decision Support Methods and Tools for TMSs Report





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Speaker's Notes (44/44)

None.

