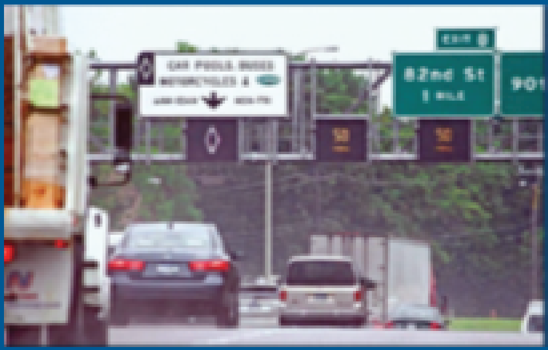
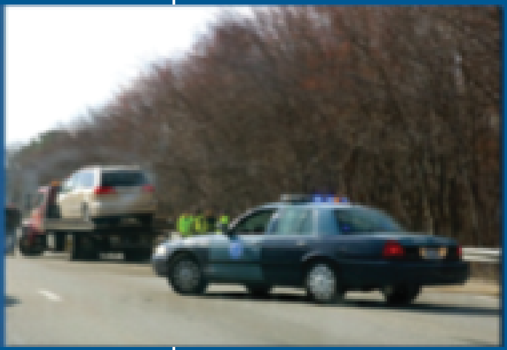
TRANSPORTATION RESEARCH

CIRCULAR

Number E-C218 December 2016

Advancing Freeway Operations Through Strategic Research





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TRANSPORTATION RESEARCH CIRCULAR E-C218

Advancing Freeway Operations Through Strategic Research

TRB Committee on Freeway Operations

December 2016

Transportation Research Board
500 Fifth Street, NW
Washington, D.C.
www.TRB.org

TRANSPORTATION RESEARCH CIRCULAR E-C218
ISSN 0097-8515

The **Transportation Research Board** is one of seven programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal.

The **Transportation Research Board** is distributing this E-Circular to make the information contained herein available for use by individual practitioners in state and local transportation agencies, researchers in academic institutions, and other members of the transportation research community. The information in this circular was taken directly from the submission of the authors. This document is not a report of the National Academies of Sciences, Engineering, and Medicine.

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Foreword

Margaret M. Steciuk
Margaret's Project Management

The name assigned to technology in the transportation industry has changed many times, from the creation of electronic fuel injection to popular systems such as Global Positioning Systems, found standard in many cars today. Technology has revolutionized the way people travel from place to place. Along with the vehicle industry's electronic revolution, we have witnessed an evolution in managing traffic flow, reducing crashes, controlling congestion through lane-access treatments, preferred access, active management of traffic, and improving incident response—all under the rubric of operations, which constantly has evolved as new tools have become available. From predictive software to electronic surveillance systems, operations have advanced rapidly in the past two decades.

This publication is a timely capture of the state of affairs in freeway operations and reflects on the known universe of tools, techniques, and trends in emerging technologies in freeway management. For practitioners, getting the word out on operations and on the tools and practices in place today is key to building roadways that will be more successfully managed in the future.

The planning and the operation of the transportation system often are two detached sets of activities with different requirements and different cultures. Management and operation of the transportation system typically involves a different set of practitioners than planning the system—one set of practitioners has a short-term or real-time focus, often with little consideration of how activities relate to regional transportation systems or to long-term goals and objectives. Transportation planners traditionally have relied upon long-range travel needs, goals for a region, and funding constraints, with little consideration of short-term operational issues. Transportation agencies, metropolitan planning organizations, and other stakeholders increasingly are recognizing the value of coordination and collaboration among planners and operators. Although they come from differing perspectives, transportation planning and operating agencies generally share the goal of enhancing system performance and can benefit from stronger linkages.

This publication will aid transportation planners and designers in understanding an operational point of view, and will provide the entire transportation community with an excellent explanation of current practices and gaps in knowledge from which to move forward with our ever-advancing technologies.

Acknowledgments

This e-circular has been developed steadily over the past few years through the leadership and assistance of many individuals, working groups, and committees. It is important to acknowledge the dedicated work of these individuals and groups who volunteered their valuable time, insights, and inspiration.

The TRB Freeway Operations Research Subcommittee, under its charge to develop and advance a research and technology transfer agenda to advance the state of the practice and state of the art in highway traffic operations, took the lead in spearheading the development of this e-circular.

The TRB Freeway Operations Committee provided overall leadership, guidance, and encouragement to the Research Subcommittee.

The development of the e-circular extended far beyond that of the Freeway Operations Committee. Other committees, subcommittees, task forces, and working groups that should be explicitly acknowledged for their role in assisting in the e-circular development include:

- Regional Transportation Systems Management and Operations Committee;
- Managed Lanes Committee;
- Traffic Control Devices Committee;
- Intelligent Transportation Systems Committee;
- Highway Capacity and Quality of Service Committee;
- Active Traffic Management Joint Subcommittee;
- Measuring and Quantifying Performance Task Force;
- Traffic Incident Management Network;
- High-Occupancy Vehicle–Managed Use Lanes Pooled Fund Study;
- Traffic Management Center Pooled Fund Study; and
- AASHTO Surface Transportation Systems Management and Operations Research Technical Working Group.

Many individuals contributed to the development of this e-circular. While it is impossible to provide an exhaustive list, there are a number that need to be specifically recognized for their contributions. Jon Obenberger, James Colyar, and Chris Poe were in many ways the inspiration and driving force behind this e-circular. Other individuals that deserve special acknowledgement include Matt Burt, Jimmy Chu, Chuck Fuhs, Qing He, Tom Jacobs, Jim Katsafanas, Lawrence Klein, Beverly Kuhn, Dawn LaFrance-Linden, Phil Masters, Kevin Miller, Lou Neudorff, David Noyce, Srikanth Panguluri, Eric Rensel, Bob Sheehan, Alex Skabardonis, Maggie Steciuk, and Yinhai Wang.

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Introduction

As an integral part of the surface transportation network, freeways are the backbone of a nation's roadway system and play an essential role in providing safe and efficient transportation services for commuting, commercial, and recreational movement of drivers, riders, and shippers. Freeways also serve as the major transportation infrastructure that facilitates government transportation needs (e.g., emergency service providers, first responders, military, and security) and assist quick responses to weather-related, natural disasters and human-caused emergencies.

Freeways in the United States have improved dramatically since they initially were built and have become more complex, with the implementation of intelligent transportation system (ITS) features such as advanced detection, surveillance, information dissemination, and telecommunications.

The overarching objective of freeway management programs is to minimize congestion and improve the safety of the traveling public. The Transportation Research Board (TRB) Freeway Operations Committee's Millennium Paper states that "freeway operations and management, in its broadest context, entails a program to combat congestion and its damaging effects: driver delay, inconvenience and frustration, reduced safety, and deteriorated air quality." The key to freeway management and operation is to keep freeway capacity and the vehicular demand on a freeway in balance. The most-effective way to combat congestion is to take action before traffic flow deteriorates and congestion forms. Ideally, agencies should consider comprehensive programs of operational improvements, active transportation management, and active demand management techniques on the freeway to prevent traffic flow from breaking down and congestion from forming. Even with the most severe examples, these programs can delay the onset of congestion and speed the recovery from it, therefore minimizing the inefficiencies that congestion causes.

PURPOSE

The purpose of this e-circular is to

- Leverage previous and ongoing research efforts related to freeway management and operations;
- Provide an opportunity to facilitate the interaction, sharing of information, and communication of successful practices to a broader audience in order to advance and improve upon the current state of the practice;
- Identify strategic focuses and directions for the TRB Freeway Operations Committee;
- Identify and potential areas of research for each strategic focus area for the Freeway Operations Committee to consider advancing as projects within the National Cooperative Highway Research Program; and
- Consider research that could be useful for other agencies (e.g., Federal Highway Administration and state departments of transportation), organizations (e.g., American Association of State Highway and Transportation Officials and the Institute of Transportation Engineers), research interests [e.g., Transportation Management Center Pooled Fund Study and High-Occupancy Vehicle (HOV) Pooled Fund Study], and academia.

ORGANIZATION

The Freeway Operations Committee has identified nine strategic focus areas and corresponding research projects for each area that need to be pursued in order to develop the resources and tools to address and overcome challenges and advance practice. The nine strategic focus areas include the following:

- Active traffic management (ATM);
- Integrated corridor management (ICM);
- Managed lanes;
- Traffic incident management (TIM);
- Performance data, monitoring, and management;
- Traffic management centers (TMCs);
- Detection and surveillance;
- Freeway traffic control devices (TCDs); and
- Connected and automated vehicles (CAVs).

While these focus areas are distinct, there is often overlap in strategies and needs between one or more focus area, such as between ATM and ICM systems and strategies or between performance data, monitoring, and management and TMCs.

Table 1 summarizes the volunteers who have been identified to lead and facilitate the development of materials that support each focus area. Without their leadership, this e-circular could not have been possible. In addition, Jim Katsafanas served an invaluable role as technical editor of the overall document, and Maggie Steciuk was instrumental in getting the document published through TRB.

TABLE 1 Volunteer Leads by Focus Areas

Focus Area	Lead	Support
ATM	Beverly Kuhn	TRB ATM Joint Subcommittee
ICM	Bob Sheehan, Chris Poe	TRB Regional Transportation Systems Management and Operations Committee
Managed lanes	Chuck Fuhs	TRB Managed Lanes Committee High-Occupancy Vehicle–Managed Use Lanes Pooled Fund Study
TIM	Eric Rensel	TIM Network
Performance data, monitoring, and management	Alex Skabardonis	TRB Measuring and Quantifying Performance Task Force (part of Regional Transportation Systems Management and Operations Committee)
TMCs	Jimmy Chu	TMC Pooled Fund Study
Detection and surveillance	Lawrence A. Klein	Yinhai Wang
Freeway TCDs	David Noyce	TRB Traffic Control Devices Committee
CAVs	Chris Poe, Jon Obenberger, Matt Burt, Dawn LaFrance-Linden	TRB ITS Committee

Active Traffic Management

STATE OF THE PRACTICE

Within the context of freeway operations, traffic management is defined as encompassing the monitoring of traffic conditions, deploying various strategies and adjustments based on changing conditions, and sharing information based on conditions to maximize the available capacity of the areawide roadway system. State and local transportation agencies across the United States deploy various strategies and technologies to assist with their traffic management approach. The strategies vary in degrees of integration, coordination, and technological sophistication. While agencies structure their traffic management programs to suit their geographic and institutional needs, they typically handle the following generally functionalities through a traffic management center (TMC) or centers:

- Perform monitoring. Monitor infrastructure in the TMC domain either visually or by field data equipment.
- Manage events. Events can be random, planned, or recurring. Management of these items, typically by an established process of verification, coordination, and implementation of response strategies, is a critical function.
- Provide services. Activities such as traveler information and service patrols fall into the service category. Other activities such as maintenance of intelligent transportation systems (ITS) devices may also fall into the services category.
- TMC support. These are activities that keep the TMC running and include items such as staffing, management, agency communications, and more.

In addition to those indicated above, some traffic management strategies have become fairly standard and common place with available expertise, technology, and systems such as traffic signal coordination, road weather information systems (RWIS), the display of travel times on dynamic message signs (DMS), and traffic incident management (TIM). A recent Federal Highway Administration (FHWA) State Operations Survey (*1*) reported the following strategy-specific results based on responses from 20 to 25 locations:

- The four most widely deployed operational strategies are travel time posting on DMS, traffic signals operating on a closed loop or central system, RWIS , and TIM. Their deployment rates are more than 90%, well over the other strategies.
- Real time traffic adaptive control signals, lane-usage controls [i.e., high-occupancy vehicle (HOV) lanes, managed lanes], electronic tolling, ramp metering, and lane-usage controls (reversible) have been adopted by 30% to 50% of responding states.
- Operational strategies such as lane usage controls (i.e., reversible, truck restricted), various types of managed lanes [i.e., dynamic toll, high-occupancy toll (HOT), bus-only shoulder lanes, temporary hard shoulder use during peak hours, priced dynamic shoulder use] are deployed by less than 30%.

Table 2 provides a high-level summary of the state of the practice across four of the most common traffic management strategies as a representative sample of the current trends in traffic management and emerging trends and approaches.

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Active traffic management (ATM) has emerged as the evolutionary offshoot of systems management and operational strategies bringing these philosophies together to manage facility conditions. ATM provides the ability to dynamically and proactively manage recurrent and nonrecurrent congestion on an entire facility based on real-time traffic conditions. Focusing on trip reliability, ATM strategies maximize the effectiveness and efficiency of a facility while increasing throughput and enhancing safety. ATM strategies rely on the use of integrated systems with new technology, including comprehensive sensor systems, real-time data analysis, and automated dynamic deployment to optimize system performance quickly and without the delay that occurs when operators must deploy operational strategies manually. When various ATM strategies are implemented in combination they can work to fully optimize the existing infrastructure and provide measurable benefits to the transportation network and the motoring public. Table 3 contains a listing of these technologically advanced operational strategies and provides brief descriptions of these strategies along with current U.S. deployments.

TABLE 2 Major Traffic Management Strategy Areas State of the Practice

Traffic Management Strategy Area	Current Trends	Emerging Trends and Approaches
Traffic signal management	Traffic signal timing performance is not regularly measured in connection to objectives, resulting in outdated timing patterns that do not reflect current traffic and pedestrian needs. Signal timing policies and practices tend not to be documented.	Adaptive signal control Transit signal priority Connected vehicle technology–data Multimodal intelligent traffic signal system
Traveler information	Websites, DMS, 511, and RWIS are the top distribution methods deployed by agencies to share traveler information with the public. Information type (pretrip versus en route) and content (travel times, weather, parking) has evolved significantly.	Comparative travel times (across modes and facilities) Connected vehicle technology Enable advanced traveler information systems (ATIS)
Managed lanes	Static–time-of-day lane controls HOV lanes	HOT lanes Active traffic management Intelligent network flow optimization
Incident management	TIM is an integral component of traffic management programs with well-established partnerships across agency lines.	Performance measures Quick clearance Response, emergency stating and communications, uniform management and evacuation

TABLE 3 Active Traffic Management Strategies (*2*)

ATM Operational Strategy	Description	Sample of Current U.S. Deployments
Adaptive ramp metering	The deployment of traffic signal(s) on ramps to dynamically control the rate at which vehicles enter a freeway facility. Can utilize traffic responsive or adaptive algorithms, dynamic bottleneck identification, automated incident detection, and integration with adjacent arterial traffic signal operations.	Los Angeles, Calif.; Portland, Ore.
Adaptive traffic signal control	The continuous monitoring of arterial traffic conditions and queuing at intersections and the dynamic adjustment of signal timing to optimize one or more operational objectives (such as minimizing overall delays).	New York
Dynamic junction control	Dynamically allocating lane access on mainline and ramp lanes in interchange areas where high traffic volumes are present and the relative demand on the mainline and ramps change throughout the day.	Los Angeles
Dynamic and contraflow lane reversal	The reversal of lanes to dynamically allocate the capacity of congested roads, thereby allowing capacity to better match traffic demand throughout the day.	Various
Dynamic lane use control	Dynamically closing or opening of individual traffic lanes as warranted and providing advance warning of the closure(s) (typically through dynamic lane control signs) to safely merge traffic into adjoining lanes.	Minneapolis, Minn.; Seattle, Wash.
Dynamic merge control	Dynamically managing the entry of vehicles into merge areas with a series of advisory messages (e.g., displayed on a DMS or lane control sign) approaching the merge point that prepare motorists for an upcoming merge and encouraging or directing a consistent merging behavior.	Northern Virginia
Dynamic shoulder lanes	The use of the shoulder as a travel lane(s) based on congestion levels during peak periods and in response to incidents or other conditions as warranted during non-peak periods.	Minneapolis; Chicago, Ill.
Dynamic speed limits	The adjustment of speed limits based on real-time traffic, roadway, and weather conditions. Dynamic speed limits can either be enforceable (regulatory) speed limits or recommended speed advisories, and they can be applied to an entire roadway segment or individual lanes.	Seattle; Minneapolis
Queue warning	The real-time display of warning messages (typically on dynamic message signs and possibly coupled with flashing lights) along a roadway to alert motorists that queues or significant slowdowns are ahead, thus reducing rear-end crashes and improving safety.	Seattle; Northern Virginia
Transit signal priority	The management of traffic signals by using sensors or probe vehicle technology to detect when a bus nears a signal controlled intersection, turning the traffic signals to green sooner or extending the green phase, thereby allowing the bus to pass through more quickly.	Various

EMERGING TRENDS OR DRIVERS OF CHANGE

Most urbanized areas around the world are facing serious mobility challenges, including an increase in travel demand, growth in congestion, a need to improve safety, and the reality of limited resources to address these challenges. While not a substitute for large-capacity expansion projects, ATM strategies can be cost-effective methods of prolonging the life and maximizing the efficiency of the infrastructure that can postpone the need for major expansion projects. They are also flexible enough to be implemented under temporary conditions in work zones and later be incorporated into the permanent operational infrastructure of a facility to extend the benefits to everyday operations.

The challenge in today's constrained transportation environment is that the implementing agency needs to have the ability to readily assess the potential benefits and costs of ATM for their region. They do not have the luxury of time or resources to develop a detailed simulation model or other similar complex assessment of ATM to support such a major investment decision. Furthermore, a diverse and sometimes conflicting assortment of issues must be addressed by agencies in their decision-making process. For ATM to be truly effective as part of the larger active transportation and demand management concept, these operational strategies need to move beyond reactive approaches to predictive and proactive approaches and work to the minimize the impacts of recurring and nonrecurring congestion in advance of breakdown.

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

Some recently completed, ongoing, and pending projects that aim to either provide additional knowledge about the emerging trends or to support the trends with innovating technologies include the following:

- FHWA: Develop *ATM Feasibility and Screening Guide.* This project will provide feasibility and screening guidance to transportation agencies to help identify the appropriate path forward with ATM suited to their regional needs and characteristics.
- NCHRP Project 03-114: Planning and Evaluating Active Traffic Management Strategies. This project will provide planning and evaluation guidance to transportation agencies, including the identification of appropriate performance goals and measures for planned projects, selecting the appropriate analysis tool or tools to evaluate the likely impacts of those projects, and planning for the collection of field performance data for use in trend analysis and performance-based planning.
- High-Occupancy Vehicles–Managed-Use Lanes Pulled Fund Study (HOV/MUL PFS), *Evaluation of International Applications of ATM Lane Control Signing for Use in the United States*. This report documents the evaluation of motorist comprehension of dynamic lane assignment (DLA) signing, potential modifications to the *Manual on Uniform Traffic Control Devices*, and additional research needed regarding signing for DLA.
- HOV/MUL PFS, *Design and Operations Elements of Dynamic Shoulder Use.* This report gives general guidance and direction on deploying dynamic shoulder use, including goals, objectives, the decision process, agency cooperation, and complementary operational strategies, along with critical design issues and specific guidance related to dynamic shoulder use, including

design standards, cross-section specifics, dynamic shoulder use treatment at interchanges, pavement design to support dynamic shoulder use, ITS elements, and design exceptions.

RESEARCH NEEDS AND AND OPPORTUNITIES

ATM operational strategies are rapidly gaining popularity across the United States and agencies are considering various approaches for deployment within congested corridors in an effort to address operational challenges. However, many unanswered questions exist with respect to ATM, including planning and evaluation, design and implementation, and operation and maintenance, which may be answered with further agency experience.

A list of potentially helpful research identified in a 2012 survey by the TRB Joint Subcommittee on ATM. Individual members of the subcommittee deem this research as potentially helpful based on the perspective of implementing agencies.

General

- What are the returns on investment and the benefits of ATM?

Planning, Evaluation, and Organization

- What research is needed related to the right measures of effectiveness and guidance?
- What is the proper performance measure to use for an ATM strategy and how does an agency measure it?
- How do specific performance metrics for ATM strategies fit into the overall active traffic demand management system?
- What are the safety analyses of ATM applications? Where might an agency introduce conflict?

Design, Implementation, and Deployment

- With respect to the ATM-related displays themselves, what is acceptable and effective?
- What are the best methods of showing lane control, particularly the need to show the merge points for system users?
- What are other graphical displays or the use of graphics in ATM displays?
- What are the safety aspects of speed differential? What are the separation treatment needs when a speed differential exists?

Operations, Maintenance, and Monitoring

- Speed management within this context—should it be set on actual conditions and how should an agency deal with variance?
- When considering advisory versus regulatory operations, is there a difference in effectiveness?
- What is the reaction of the drivers that has yet to be addressed? What is the stakeholder’s perspective of variable speed limits other ATM approaches?

- With respect to variable speed limits and ramp metering, what is the best approach for utilizing an algorithm and what is the intended objective of that algorithm?
- What is the best way to deal with enforcement with respect to variable speed limits?
- With respect to flow maximization, what is the goal of the algorithm and what is an agency trying to accomplish?

Integrated Corridor Management

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Integrated corridor management (ICM) is the coordinated management and operations of multiple transportation networks and cross-network connections comprising a corridor and the institutional coordination of those agencies and entities responsible for corridor mobility.

The goal of corridor integration is to bring the real-time operations and management of the surface transportation network into a unified whole, operating as "one" system in a manner that transcends institutional and jurisdictional boundaries. By using integrated data sets and information and seamless connections between corridor facilities and modes, transportation managers can be in a better position to take proactive actions and provide active guidance to travelers. In order to implement ICM, the transportation networks and systems would be well served through integration in three related ways:

- Institutional and organizational integration involves the collaboration between various agencies and jurisdictions (network owners) in support of ICM, including identification of shared operational objectives and aggregate performance measures and the distribution of specific operational responsibilities in a manner that transcends institutional boundaries.
- Operational integration may be viewed as the implementation of multiagency transportation management strategies, often in real time, that promote information sharing and cross-network coordination and operations among the various transportation networks in the corridor, and facilitate management of the total capacity and demand of the corridor.
- Technical integration provides the means by which information and system operations and control functions can be effectively shared and distributed among networks and their respective transportation management systems, and by which the impacts of operational decisions can be immediately viewed and evaluation by the affected agencies.

A corridor' is defined as a largely linear geographic band characterized by exiting and forecasted travel patterns involving both people and goods. The corridor includes the combination of various facilities and modes (e.g., limited access facility, surface arterials, transit rail, transit bus, and transportation services) that provide similar or complementary transportation functions. Additionally, the corridor includes cross-network connections that permit the individual networks to be readily accessible from each other.

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Institutional and Organizational Integration

ICM is built on the foundation of institutional and organization integration. An institutional framework for corridor operations allows for joint real-time performance-based decisions to be made by all parties responsible for transportation operations. There is no one institutional framework that defines ICM. The structure can be ad hoc or more formal depending on operational needs and objectives for the corridor. All parties must be committed to real-time joint operations driven by common needs and shared objectives. In addition, the roles and level of involvement may differ, but to be most effective, ICM would include all transportation resources. As a corridor is being considered for ICM, it is important that all agencies affecting the operation and maintenance of all networks participate.

Operational Integration

To manage a corridor in an integrated fashion requires the transportation operators to balance the load on the system. Load balancing addresses how traffic managers and travelers use the transportation networks in a corridor and involve actions that encourage the shifting of trips from one transportation mode to another mode, one route to another, or to another time in the day.

Operational approaches to balance the load on the system include data and information sharing, operational efficiency of networks and junctions, accommodating or promoting route and modal shifts, and managing capacity–demand relationship. These operational approaches are not mutually exclusive, contain multiple strategies with each approach, usually are prerequisites, and build toward capacity–demand management. For example, information sharing is essential to the success of the other approaches and promoting cross-network shifts may require capacity (operational) modifications to handle the additional users on alternative networks.

Technical Integration

Technical integration provides the means by which information and system operations and control functions can be effectively shared and distributed among networks and their respective transportation management systems, and by which the impacts of operational decisions can be immediately viewed and evaluated by the affected agencies. General areas of interest include field technology, command and control technology, technical protocols, standards, and real-time analytics.

The real-time analytics required for ICM goes far beyond what is typically required for more traditional types of transportation operations where single network management is the focus. An emerging analytical tool is a real-time, multimodal decision support system (RTMDSS). These systems are "information systems that support multimodal, transportation operational decision making in real time. An RTMDSS is an interactive, software-intensive system that gathers data from multiple relevant real-time data sources and knowledge bases. It uses this data, along with models, processes or analyses to implement context-specific actions and recommendations to assist managers in the process of collaboratively managing a multimodal transportation network to increase system efficiency and improve individual mobility, providing safe, reliable, and secure movement of goods and people" (*3*).

GAPS IN PRACTICE OR KNOWLEDGE

Data and Information Sharing

A fundamental element of integrated management is the need for improved situational awareness. Operators and travelers must have more comprehensive, accurate, and timely understanding of underlying operational conditions considering all networks in the corridor. Data and information sharing covers the provision of the systems current status or forecasted status for corridor operations and users, as well as the prediction of performance based on any action taken. In addition to the data exchange between local management agencies, information sharing with the traveler is of critical importance. One of the core tenets of the ICM is that travelers will utilize pre-trip and en-route corridor-level information to better inform and optimize their personal travel decisions. In fact, ICM depends on travelers altering their behavior to change route, mode, or time of departure.

Improve Operational Efficiency of Networks, Junctions, and Interfaces

Strategies to improve operational efficiency likely would be effective if they reduce travel times between modes and facilities, increase travelers' confidence, and improve reliability for corridor stakeholders. By improving the performance of one network and leveraging the performance of other routes and modes may or will improve the performance of the entire corridor. A better understanding of how to improve ICM operations through better integrating of transit, freight, and emergency services would be helpful.

Accommodate and Promote Network Shifts

Accommodating and promoting network and mode shifts allows operators to leverage the maturity of the first two approaches. ICM depends on travelers altering their behavior to change route, mode, or time of departure. Although it may not take a significant amount of network shift to improve the efficiency of different parts of the transportation network, corridor operators must be in a position to influence traveler response or apply network strategies for the benefit of the corridor performance.

Operators can provide general information and accommodate the travel shifts as they occur, or can go a step further and move towards corridor optimization by promoting specific traveler choices or actions that match corridor management response plans. More information would shed light on how to better accommodate traveler shifts both before and as they occur.

Capacity–Demand Management

Accommodating and promoting shifts among networks makes efficient use of any spare capacity within the corridor to better manage congestion and facilitate reliability, assuming available capacity on the adjacent networks and junctions is available. Therefore, to fully optimize the performance of the system, transportation managers will be required to modify the transportation capacity to meet the demand for the system—approaches that go beyond increases in roadway capacity.

RESEARCH NEEDS AND OPPORTUNITIES

The following potential research opportunities could improve the execution of active traffic management strategies by better defining approaches for institutional and organizational, operational, and technical integration.

Institutional and Organizational Integration

Research on the institutional organization best practices to create a successful ICM project could include the following:

- What are the core institutional elements that should be in place for an ICM initiative to be successful (such as shared goals objectives, agreements, and regional policies)?
- What factors are most critical to successfully organizing a local ICM partnership team?
- What is required to sustain ICM organizational and operational partnerships?
- What are the policy challenges for ICM (such as initial and long-term funding, data, automation, and transit operators)?
- What types of public and political marketing are needed?
- What institutional arrangements can support shared operations and maintenance of corridor assets?

Operational Integration

Research on the data needs for ICM operations and traveler information could include the following:

- What are the standard operating procedures and standard operating agreements for multimodal and multiagency data integration for real-time operations and management?
- What are the advantages and disadvantages of centralized versus distributed data models?
- What are the best practice models for using private-sector data?
- What are advantages of using data standards (e.g., Traffic Management Data Dictionary)?
- What are the issues with use of General Transit Feed Specification?
- What other shared data or multimodal information would be required to improve ICM?
- What type of information do travelers need to alter their behavior (are travel times, comparative travel times, or parking status enough to change behavior)?

Research on data modeling and visualization tools to support ICM planning and evaluation could include the following:

- What are best approaches to measure and calculate common corridor performance measures when considering multiple objectives from different organizations (such as vehicle miles traveled, vehicle hours traveled, person miles traveled, transit on-time performance, freight on-time performance, economic impacts, environmental impacts, and safety impacts)?
- What are techniques for visualization of multimodal, multiagency, and multiobjective performance monitoring?
- What are approaches to determine optimal data needs for ICM operational objectives?
- What are approaches to understand real-time changes in demand at the outer parts of the travel shed?

Research on transit, freight, and emergency services integration for better ICM operation could include the following:

- How can conditional-based transit priority be implemented to improve transit schedule and capacity?
- How to implement public and private-sector transit connection protection challenges?
- What are the approaches to develop and apply emergency vehicle "best route" to incidents and emergency response centers and challenges of integrating with corridor operations?
- What are the challenges of integrating destination parking information into real-time traveler information?
- What are the ICM challenges and opportunities for freight or heavy vehicle signal priority?
- How can freight or heavy vehicle rerouting be integrated into corridor optimization?
- What are business models for regional single multimodal fare payment–public transit and private-sector shared use?
- How can traffic signals be optimized for transit progression?
- How can ICM assist with incident management and response time requirements?
- How can ICM support integrating demand responsive mass transportation services?

Research on real-time and predictive traveler information for better ICM operation could include the following:

- What are the best practices to calculate full trip travel times (that is, representing the complete multimodal and multiroute trip)?
- How can dynamic toll and fare adjustments and credits be modeled?
- What are best practices to give dynamic route guidance to commuters?
- What are approaches to integrate messages and recommended actions from private-sector traveler applications?

Research on infrastructure capacity management for better ICM operation could include the following:

- What are the best practices for traffic signal coordination and optimization to achieve corridor performance objectives?
- What are the approaches to dynamically increase parking availability?
- How can dynamic lane or facility re-assignment (such as bus on shoulder, time of day, or dynamic transit-only lane) be used in ICM?
- How can ICM be used with dynamic adjustments to construction and maintenance roadway closures?
- What are the approaches to incentivize mode and route shift?
- How can dynamic toll and fare adjustments and credits be used to manage capacity?

Technical Integration

Research on the use of real-time decision support systems could include the following:

- What are the best practices for integrating traffic simulation into real-time decision support?
- What are effective artificial intelligence approaches?
- How can automated decision making be implemented and what are the human interfaces needed?
- What are the challenges with real-time prediction of traffic conditions and impacts of response plans?

Managed Lanes

STATE OF THE PRACTICE AND STATE OF THE ART

Lane management strategies cover three areas: price, vehicle eligibility, and access control. Strategies include dedicated high-occupancy vehicle (HOV) lanes, busways and bus rapid transit facilities, truck lane restrictions and bypass lanes, variably priced toll lanes and facilities, express lanes, peak period use of shoulders, priced queue jumps, and priced dynamic shoulder lanes. These strategies have been used individually to help regulate demand, reduce traffic turbulence, and utilize available and unused capacity. Tolled managed lanes are now operational in California, Texas, Minnesota, Colorado, Washington, Florida, Utah, Georgia, and Virginia. These facilities have a proven track record demonstrating the use of variable pricing as a means of controlling demand and maintaining performance while also providing free or discounted use for HOVs. The first-generation managed lane projects were largely HOV lanes, but often there was excess capacity available in the lane. The second-generation systems added tolled single-occupant vehicles and hybrids to become high-occupancy toll lanes, and to fill up the capacity voids. The third generation of projects has moved into managed lanes that better manage the demand–capacity balance and provide flexibility via pricing schemes, eligibility by time period, and access–egress. Many of these are multiple-lane treatments. Building upon the successes of these projects, managed-lane systems are now being incorporated into long-range transportation plans in many metropolitan areas across the United States.

GAPS IN PRACTICE OR KNOWLEDGE

While managed-lane networks or regional systems provide great opportunities to improve operations through data-driven management strategies, they also present the operating agencies with more difficult challenges. This is because operational strategies often need to be tailored for each corridor, and a goal of consistency in operation and design is difficult in this context. The Federal Highway Administration's (FHWA) Operations' Tolling and Pricing Program spurred the industry with innovation in managed lanes and other demand-driven pricing strategies through its Value Pricing Pilot Program, Express Lanes Demonstration Program, and other related efforts. These efforts have mostly since been mainstreamed by Moving Ahead for Progress in the 21st Century, but the lessons learned are applied elsewhere. The urban partnership agreements and congestion reduction demonstration programs of the past decade have greatly accelerated the learning curve through major investments in projects demonstrating state-of-the-industry technology and strategies. Industry leaders, including the Transportation Research Board Managed Lanes and Congestion Pricing Committees and the FHWA-sponsored HOV/Managed-Use Lane Pooled Fund Study (HOV/MUL PFS) have coordinated with the industry to investigate many aspects of managed-lane systems through research and pilot tests.

While these past efforts have helped with the learning curve with managed-lane networks, challenges remain regarding how to design and operate managed-lane systems and incorporate the more complex managed-lane programs into the overall transportation planning and operations of a region. Some of these challenges include the following:

- Developing strategies for variable pricing of multiple segments within a managed-lane system and effective means of conveying that information to drivers.
- Incorporating managed lanes into regional transportation planning and analysis methods (travel forecasting, benefit–cost, revenue generation) and integrated transportation systems. How do managed lanes impact the corridor?
- Strengthening institutional and organizational approaches and removing implementation barriers to managed lanes, including private- and public-sector partnerships, and legislative authority, particularly in regions where multiple agencies build, monitor, or operate pieces of the managed-lane network.
- Promoting the planning and design of managed-lane networks to provide for operational flexibility to promote safe and reliable performance (such as design for access–egress, driver information and signing, enforcement, and revenue collection).

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

Following are current and proposed national research and initiatives for managed lanes:

- FHWA's *Congestion Pricing Primer* series including the following titles:
  - *Congestion Pricing Overview*.
  - *Effective Approaches for Advancing Congestion Pricing in a Metropolitan Region*, intended to raise awareness among staff at metropolitan planning organizations and their partner agencies about the potential role of congestion pricing in supporting regional goals as well as the most-effective approaches for advancing congestion pricing strategies in a region.
  - *Congestion Pricing: Institutional Issues.*
  - *Economics: Pricing, Demand, and Economic Efficiency*.
  - *Non-Toll Pricing.*
  - *Technologies That Enable Congestion Pricing*.
  - *Technologies That Complement Congestion Pricing*.
  - *Transit and Congestion Pricing*.
  - *Income-Based Equity Impacts of Congestion Pricing*.
- FHWA's *Priced Managed Lane Guide* (2012) is a comprehensive source of collective experience gained from priced, managed lanes implemented in the United States from 1995 through 2012.
- *Guidebook for State, Regional, and Local Governments on Addressing Potential Equity Impacts of Road Pricing*, April 2013.
- *Design and Operations Elements of Dynamic Shoulder Use*, 2013.
- HOV/MUL PFS *Benefit/Cost Analysis of Value Pricing Projects*, 2011.
- *Synthesis of Current Variable Pricing Schemes in the United States*, 2013.
- *Evaluation of International Applications of Active Traffic Management Lane Control Signing for Use in the United States*, 2013.
- Miscellaneous documents from the HOV/MUL PFS.
- National Cooperative Highway Research Project (NCHRP) 15-49: An Implementation Guide updating content found in NCHRP 414 (1998).
- American Association of State Highway and Transportation Official's *HOV Guide*.

RESEARCH NEEDS AND OPPORTUNITIES

Potentially helpful research and opportunities identified by the Managed Lanes Research Subcommittee include the following:

Research

- Ingress–egress best practices (with focus on at-grade treatments for single and dual lanes).
- Separation treatments between concurrent managed lanes and adjacent general-purpose lanes, including application experience associated with use of traffic channelizers and delineators in managed-lane buffers.
- Tolling algorithms applied to managed lanes and effectiveness in managing demand.
- Comparative operational performance attributes for single- and multiple-lane managed-lane designs.
- Recent experiences in alternative delivery approaches for managed lanes, including design–build and public–private partnerships.
- Impacts of raising occupancy requirements when converting HOV lanes to HOT lanes.
- Traffic modeling and performance measurement criteria that take into account reliability and sustainability of options to meet future traffic growth when comparing managed-lane and general-purpose lane expansion options.

Demonstration Tests

- Demonstration tests of the latest automated occupancy enforcement technologies on projects.

Technology Transfer

- Periodic updates to the *Managed Lanes Implementation Guide* (when completed in 2015) with input from Managed Lanes and Congestion Pricing Research Subcommittees, HOV/MUL PFS, and NCHRP Panel 15-49.
- Applications of ATM on managed lanes to regulate speeds and manage queues.
- Real-time traffic demand management strategies to reduce or better manage peak demand for managed lanes and transit services.

Traffic Incident Management

STATE OF THE PRACTICE

At the time the last research circular was published a new era in traffic incident management (TIM) was taking place. The National Unified Goal (NUG) for TIM was in draft form and it was finalized and released in 2007. With the release of the NUG a flurry of activity was initiated and led by coordination among members of the National Traffic Incident Management Coalition (NTIMC). The actions of the NTIMC, the Federal Highway Administration (FHWA), and the Transportation Research Board (TRB) have shaped the state of the practice that exists today.

According to the 2009 *Manual of Uniform Traffic Control Devices* (MUTCD) Chapter 6-I "a traffic incident is an emergency road user occurrence, a natural disaster, or other unplanned event that affects or impedes the normal flow of traffic." Causes include but are not limited to the following:

- Crashes;
- Vehicle breakdowns;
- Fires;
- Hazmat spills and leaks;
- Debris or other objects in roadway;
- Pavement or road structural failures;
- Roadway medical emergencies;
- Animals in or near roadway;
- Smoke, fog, dust, snow, ice, or stormwater on or across roadway; and
- Law enforcement activities.

Construction and maintenance work zones (CMWZ), planned special events (PSE), and controlled emergency evacuations (EEV) are not considered traffic incidents by this MUTCD definition. Other chapters of the MUTCD provide guidance for these activities. However, the same protocols, practices, and procedures used for TIM are fundamentally identical to and directly applicable to CMWZ, PSE, and EEV.

MUTCD Chapter 6-I classifies traffic incidents as minor (less than 30-min duration), intermediate (up to 2-h duration), and major (those lasting up to 24 h). Though the predominant focus has been on major incidents on freeways, many accidents also happen on arterial roads and streets where the same TIM practices apply. Regardless of the severity, extent, and location, traffic incidents cause immediate disruption, delay, and danger. Responders and involved parties are at high risk from errant vehicles approaching or passing through the incident zone. Aside from that, traffic incidents create congestion, which cost billions of dollars annually to the economy. Compounding the problem is the lack of coordination, cooperation, and communication among the various responder disciplines and agencies.

According to FHWA, TIM is "a planned and coordinated multidisciplinary process to detect, respond to, and clear traffic incidents so that traffic flow may be restored as safely and quickly as possible. Effective TIM reduces the duration and impacts of traffic incidents and improves the safety of motorists, crash victims, and emergency responders."

TIM is a relatively new concept. Though the issues had been addressed since the early 1990s it was not until the FHWA formed NTIMC in 2004 that it achieved a sustained, wide-based interest. The NTIMC, comprised of representatives from responder disciplines and other interested stakeholders, developed and promoted a number of initiatives such as the National Uniform Goal, Move-Over/Slow-Down laws, high-visibility vests, standard on-scene practices for all responders, and, most notably, the Traffic Incident Management Responder course. FHWA has also conducted a number of TIM informational workshops for responders and other officials around the nation, mostly in major metropolitan areas. The goal is to eventually train several hundred thousand responders. An online version of the course is in early development.

FHWA's Incident Management Program has recently sought the endorsement of professional organizations such as International Association of Chiefs of Police (IACP), International Association of Fire Chiefs (IAFC), American Association of State Highway and Transportation Officials (AASHTO), International Municipal Signal Association (IMSA), Institute of Traffic Engineers (ITE), American Public Works Association (APWA), I-95 Corridor Coalition, Cumberland Valley Volunteer Fire Fighters Association (CVVFFA),National Volunteer Firefighters Council (NVFC), National Association of Emergency Medical Technicians (NAEMT), and Towing and Recovery Association of America (TRAA). Several of the following organizations have issued their own TIM responder training or guides:

- Emergency Responders Safety Institute's Responder Safety website has a suite of free short courses.
- I-95 Corridor Coalition has a free virtual training course whereby participants can perform in the various roles.
- IACP has prepared an informational video
- TRAA incorporates TIM into its certification courses.
- APWA is revising the National Incident Management System Consortium's (NIMSC's) *Highway Incident Manual*. NIMSC is primarily fire service-oriented but asked APWA to update it with a public works–transportation perspective.
- The United States Fire Administration issued a revised Traffic Incident Management Systems Manual in 2012.
- The National Fire Protection Association's Technical Committee on Professional Qualifications for Traffic Incident Control Management is developing standards and guidelines for responders from all disciplines.
- International Association of Fire Fighters (IAFF) issued the *Best Practices for Emergency Vehicle and Roadway Operations Safety in the Emergency Services* in 2010 in collaboration with the Federal Emergency Management Agency (FEMA) and the U.S. Department of Justice.

The NTIMC was superseded in 2013 by a new Executive Leadership Group of top representatives from FHWA, AASHTO, IACP, and IAFC to determine overall policy, strategy and advocacy. Another independent group comprised of representatives from other disciplines and organizations, such as ITE, IMSA, ITS America, APWA, ATSSA, IAFF, NVFC, and TRAA have served in an advisory capacity. The National Committee on Uniform Traffic Control Devices (NUTCD) develops and recommends changes to the MUTCD including Chapter 6-I. The TIM network (http://timnetwork.org) collects and distributes best practice information as it becomes available.

In addition to the MUTCD 6-I, TIM is based on the concepts, protocols, and structure of the incident command system (ICS) used for all-hazards emergencies and planned events. Police and fire are well trained in ICS and most agencies use it for routine operations. The other responder disciplines, particularly emergency medical services (EMS) and public works–transportation, do not seem to have the same depth of content in their basic courses (IC100, 200, 700) or in their advanced courses (ICS 300 and 400). It is imperative that those responders who are normally involved in TIM situations are qualified in ICS.

EMERGING TRENDS OR DRIVERS OF CHANGE

TIM can be considered in four activity areas associated with emergency management. Mitigation activities are the efforts to reduce the impact of an incident on overall freeway operations. Preparedness involves efforts on the part of first responders to improve their response to and recovery from a freeway incident. Response efforts are the activities associated with the emergency response to a freeway incident. The recovery phase is the steps taken after an event has stabilized to get the freeway back to normal operations. Overlap between the phases does occur; however, the sections below identify the primary phase each effort takes place.

Mitigation

- Real-time performance measurement. Not only for planning future TIM, real-time monitoring of volumes and speeds is needed to proactively identify incidents and manage the response and recovery for the incidents.
- Secondary incidents. Efforts continue to minimize their occurrence and severity.

Preparedness

- Education and training. Transportation agencies must commit funding and staff time to training efforts around TIM. Ideally these efforts will include table-top and full-scale exercises.
- Interoperability and communications among first responders. While steadily improving, further advances are needed.
- ICS. Transportation agencies need to play an active role in training and adoption of ICS procedures for all staff.
- Functional classification policies and procedures. Development of official memorandums of understanding between varying levels of government within the same functional classification (for example between local and state law enforcement agencies or transportation agencies) is important in resource allocation and coordination during events impacting multiple jurisdictions.
- International practices and lessons. Innovative practices should be investigated, recognizing institutional and cultural differences.
- Clearinghouse of TIM experience. The NTIMC intends to develop an online reference site.

Response

- Interagency coordination. The key players are law enforcement, fire and rescue, EMS, public information services, towing and recovery, environmental protection (i.e., for hazmat), and transportation agencies, and they need to work together and communicate effectively
- Communication. Communication between varying levels of government within the same functional classification (for example between local and state law enforcement agencies or between local and state transportation agencies) is important in effective resource allocation and coordination.
- Software evolution. Development continues on preparing for and managing incidents. One prime area is the integration of CAD systems for emergency responders with traffic management center (TMC) software for freeway management.
- Information dissemination. Advanced traveler information systems (ATIS) are constantly improving for normal traffic operations, but incidents require especially quick and accurate pretrip information and in-vehicle information during travel. In addition to highway advisory radio and dynamic message signs, commercial AM and FM radio are aggressively utilized.

Recovery

Quick Clearance Policies and “Move It” laws. These have the goal of minimizing impact on the traveling public not involved in the incident and getting the freeway back to normal operation as effectively as possible.

GAPS IN PRACTICE OR KNOWLEDGE

Research and technology transfer areas are identified below. Many of the areas lie in synthesis of preferred practices in use across the nation and world.

Strategic

- Goal definition addressing at least safety and travel time. Creation of national models and guidelines. Relative importance of
    1. Ensuring responder safety (through reflective garments, positioning, and lighting);
    2. Rescue–triage of accident victims and stranded motorists;
    3. Traffic safety directions to approaching traffic; and
    4. Salvage of cargo and load. Much of this will likely be addressed in the effort to develop the NUG for TIM.
- Performance measurement with standard and commonly understood metrics, but applied in scale to the affected area, e.g., urban versus rural, flat land versus mountainous terrain.
- Organizational and institutional issues to integrate TIM with PSE management and management of evacuations and emergencies; refinement of intergovernmental agreements, including defined role of TMCs.
- Public outreach and education regarding Move It laws, prudent incident site behavior.

- TIM support in planning and design, including crash investigation sites and the need for a regional perspective.

Tactical

- Preplanned responses and assignments, including towing and recovery practices.
- Standard operating procedures covering vehicle positioning, lighting (on site and approach warning), high-visibility garments, crash investigation procedures and on-site role based on order of first-responder arrival. Needs to consider state law changes and NIMSC mandates.
- Routine use of on-site camera images (e.g., from cell phones and CCTV where available) to assist in triage assessment.
- Potential changes to the MUTCD in support of site management.
- Potentially greater authority for transportation agencies on site.
- Possible greater role of auto clubs (e.g., providing roving courtesy patrols). Consider other foreign practices as well.

Technical and Communications

- Evolution of traffic simulation and travel demand models covering
  1. Pre-planning scenarios,
  2. Real-time TIM (simulation and evaluation of multiple traffic management scenarios to manage the incident), and
  3. Post-incident evaluation. Includes detection links to measure volume and saturation flow rates on both freeways and arterials. Ideally, dispatchers or automatic systems would advise first responders on the quickest route to an incident site.
- Improved data fusion covering incident detection and impacts, including quick synthesis of cell phone calls. Is detector-based incident detection only applicable to tunnels? Travel time prediction under dynamic incident conditions.
- Media and content of traveler information and control strategies, including dynamic message signs (permanent and portable), ramp metering, and website information, plus television and radio. To what degree can approaching demand be managed?
- Detector and performance monitoring in support of TIM: technology, extent, communications, and data archiving; potential use of portable detection and cameras.
- Full integration of responder CAD and TMC software, plus cross-agency system architectures.
- In-vehicle information dissemination: new technology and best practices.
- Added risks, challenges and best responder practices for new hi-tech vehicles (e.g., high-voltage hybrid batteries, front and side airbags, reinforced steel cages).
- Quick clearance devices, such as collapsible trailers easily moved to the incident site by motorcycle.
- Further advances and integration of on-site responder communications.
- Capacity reductions due to “rubber-neckers” (both travel directions) and potential mitigation.

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

Following are projects that indicate recently created resources, current research, and proposed research for managing travel for incident management:

- NCHRP Project 20-7, Task 173: Measuring and Communicating the Effects of Traffic Incident Management Improvements. This project has developed a summary of best practice for measuring and communicating the effects of incident management programs. The summary has been published as NCHRP Research Results Digest 289 in 2004.
- NCHRP Project 20-07, Task 215: Statewide Incident Reporting System. This study laid the groundwork for a business and technology plan to meet the requirements of Statewide Incident Reporting Systems in SAFETEA-LU. The report was completed and distributed to the AASHTO Highway Subcommittee on Systems Operations and Management in 2006.
- NCHRP Project 20-07, Task 239: Identification and Delineation of Incident Management and Multi-Agency Emergency Response Functions. This study will identify and delineate incident management–emergency response functions that should be the focus of future training efforts and job responsibilities.
- NCHRP Project 20-07, Task 221: Traffic Incident Management + Program for Worker Safety. The AASHTO Standing Committee on Highways will summarize research findings and approaches related to TIM worker safety and develop a set of recommendations to improve worker safety to be adopted nationally. The revised report has been received and publication is pending.
- The I-95 Corridor has developed a Quick Clearance Tool Kit to help initiating or improving Quick Clearance programs and activities that builds off a best practices report they issued in 2003.
- FWHA developed a *Simplified Guide to the Incident Command System for Transportation Professionals* and is a training course is available through the National Highway Institute.
- FHWA developed a *Primer for Making the Connections: Advancing Traffic Incident Management in Transportation Planning*.
- FHWA published the final report on *Focus States Initiative: Traffic Incident Management Performance Measures*. Eleven states participated in this FHWA initiative to identify appropriate measures of performance for TIM programs.
- The FHWA Joint Program Office is analyzing additional ways that ITS can be applied to support enhanced response to incident scenes by adapting traditional intelligent transportation system freeway and traffic management systems.
- FHWA published the *Service Patrol Handbook* in November 2008.
- FHWA published the *Traffic Incident Management Handbook* in January 2010.
- NTIMC established the TIM Network (http://timnetwork.org) in October 2010.
- FHWA developed TIM performance measurement knowledge base tool and TIM self-assessment tool to be used by state and regional program managers to assess their achievement of a successful multiagency program to manage traffic incidents effectively and safely.
- FHWA developed SHRP 2 national TIM responder training program.
- FHWA published *Field Operations Guide for Safety/Service Patrols* in December 2009.
- FHWA published *Best Practices in TIM* in December 2010 and *Analysis, Modeling, and Simulation for Traffic Incident Management Applications* in July 2012.

RESEARCH NEEDS AND OPPORTUNITIES

All of the areas discussed in the previous section deserve further research and refinement and are defined in four categories as follows:

- Operational needs such as incentivizing, strategic recovery, dynamic routing, and psychological impacts;
- Technological needs such as advanced recovery, connected response, and distributed systems;
- Programmatic needs such as public works, rural considerations, more integration between the National Incident Management System and TIM and better TRB and department of transportation alignment on TIM research needs; and
- Administrative needs such as logistics integration, sector analytics, and an Interstate highway police authority.

However, advancing the practice is the responsibility of all practitioners, researchers, and leaders involved with the subject. At the 93rd Annual Meeting of the Transportation Research Board in January 2014, an expert panel and 50 others debated what the next generation of TIM topics could be. There are six topics that the group discussed that are part of next-generation TIM. The following issues would benefit from having primary research tracks that could provide opportunities to link to broad transportation system management and operations (TSM&O) topics:

- TIM and freight. Freight reliability plays a tremendous role in the health and well-being of our nation. When traffic incidents affect the movement of freight it limits the ability to achieve economic goals and drives the cost of living up.
- The psychology of incident response. Management techniques have been employed for years to help emergency responders deal with stress related to their jobs. Specific research on how psychological mindsets of responders affect incident response will help improve scene safety and reduce the risk of secondary crashes.
- TIM and big data. Using advanced analytics and complete data sets that represent multiple data points, the understanding of how TIM affects congestion will be improved and understood.
- TIM and the insurance industry. To improve how incidents are cleared and the philosophy by which incidents are targeted for avoidance a partnership with the insurance industry is necessary.
- TIM and connected and autonomous vehicles. While future technology is touted as reducing the number of crashes on the roadway, when crashes occur they could be more severe. Investment is needed to understand how connected vehicles will impact emergency responders.
- Making the connection to 911 centers. Event notification is a key component of reducing incident duration and yet in many cases this group of emergency responders is not included in TIM teams or as part of TIM coordination.

To achieve the areas of progress that has been defined in this chapter, several leading areas of research that have been developed. The outcome of these areas of research could lead to other projects that address specific more specific areas. However, these projects will likely define the issues and could lead directly to implementation in some cases.

TIM Training

The SHRP 2 L32 suite of products has been a great success of the SHRP 2 program; however, if the need and progression are not reinforced, reviewed, or improved, the full benefit may not be realized. As lessons learned and awareness of the saturation level of the SHRP 2 TIM training is quantified, a new project could potentially benefit the next generation of TIM training. With the construction of dedicated TIM training facilities now occurring across the nation, the depth of topic investigation and the overall number of topics themselves would have to be increased. This project would ideally accomplish three goals:

- Conduct more intensive sampling of areas where TIM training is and is not being conducted for more broad operational and policy awareness.
- Identify future TIM training needs along with the establishment of horizon years when the training will be required or a linkage with capability maturity.
- Develop a framework for TIM training calibration based on SHRP 2 implementation.

Optimal Visibility

Previous efforts attempted to examine the optimal visibility conditions for TIM including personal protective equipment (PPE) and vehicles. This project could benefit from building on that work and being more inclusive of highway construction and maintenance workers as well as having specific emphasis on visibility of vehicles at the end of a queue approaching a crash scene.

Quantitative Benefits of TIM

This project could consist of a national assessment that can effectively capture a snapshot of what the benefit of consistent TIM would allow. The resulting research document would hypothesize how quantified TIM (as part of a broad TSM&O approach) benefits would become part of the transportation funding allocation model whereby transportation agencies would need to achieve annual benchmarks to achieve 100% funding eligibility in designated categories.

TIM as Part of Total Network Management

Total network management that includes arterials, integrated corridor management (ICM), and other TSM&O principles could consider how TIM can be implemented at both the strategic and tactical levels more effectively. This work could help the TIM discipline look forward to true multimodal and multiple transportation facility ownership models that includes an advanced understanding of how TIM impacts quality-of-life outcomes.

TIM and Freight

A greater depth of understanding regarding the economic impact of TIM strategies and the daily impact that is quantified would be greatly beneficial. Work that evaluates the entire supply chain model and the downstream effects that are caused by positive and negative TIM practices would potentially be useful.

Decision Support for TIM

Understanding the psychology that is involved with decisions on response will help drive technological innovation in the future. Although TIM will always rely upon people to be fully effective, the development of decision-support technology can help simplify decisions that need to be made. For the next generation of software that is deployed in TMCs, public safety access point dispatch centers, etc., the availability of historical information that can help predict outcomes will rely on the experience of individuals that can be built into business case rules. This work could also benefit from an analysis of the role that big data can and should play in TIM.

Progressing the Relationships between Transportation and Public Safety

Building on both the NUG for TIM as well as the National Road Map for TIM established in the 2012 Transportation and Public Safety Summit, more work that is about bringing together agencies from a technological standpoint would be informative. Linking TMCs and public safety dispatch centers exists only in concentrated areas. This project could examine the barriers that prevent full integration of data between agencies from an information technology perspective and suggest ways to overcome the barriers.

Insurance Industry Partnerships

It would appear as though a relationship between the insurance industry and the TIM community would make sense because they both have similar goals of reduced incidents. This project would be most helpful if it were to examine the insurance industry and identify ways that TIM can be considered when developing policies and procedures. Also, an emphasis on the development of a partnership framework that could provide outreach for TIM, TIM research funding possibilities, and other cost offsetting opportunities would also be helpful.

Performance Data, Monitoring, and Management

STATE OF THE PRACTICE AND STATE OF THE ART

The use of performance measures in transportation planning and investment decision-making processes of public agencies has increased significantly over the past few years. Several activities and documents have been developed addressing performance measures, including:

- *National Cooperative Highway Research Program (NCHRP) Synthesis 311*: *Performance Measures of Operational Effectiveness for Highway Segments and System*. This synthesis examines the use of performance measures for the monitoring and operational management of highway segments and systems. More than 70 performance measures were identified.
- *Transportation Management System Performance Monitoring, Evaluation and Reporting Handbook*. This handbook developed by the Traffic Management Center (TMC) Pooled Fund Study (PFS) provides transportation officials with a basic background and best practices for monitoring, evaluating, and reporting system performance.
- NCHRP Project 3-68, *Web Document 97*: *Guide to Effective Freeway Performance Measurement*. This guidebook identifies measures for several categories (e.g., freeway safety, operational efficiency, ride quality, environmental, customer satisfaction), and examines the effective use of performance measures in freeway operations and in meeting the needs of a variety of stakeholders.
- The Federal Highway Administration Mobility Monitoring Program tracks and reports traffic congestion and travel reliability for over 100 metropolitan areas annually. Starting in 2011, performance measures are reported for 328 corridors nationwide based on data from mobile sources.
- Methodology to Measure and Quantify TMC Benefits. This PFS mapped performance measures for mobility and safety to typical TMC functions and presented methods to measure and quantify benefits in traffic operations due to the implementation of TMCs and the systems, infrastructure, and functions associated with their operation.
- Several agencies have developed procedures for performance measurement, monitoring, and reporting, and real-time archival data systems. The FHWA Operations website (http://www.ops.fhwa.dot.gov/perf_measurement/example_programs.htm) includes several links and reports on performance measurement.

GAPS IN PRACTICE OR KNOWLEDGE

The potentially helpful research for freeway performance monitoring, evaluation, and reporting have become more critical as the emphasis of real-time traffic management and the use of technology are more prevalent. Gaps in the practice and research exist in the following areas:

- Moving Ahead for Progress in the 21st Century (MAP-21) placed increased emphasis on performance management within the federal aid highway program and transit programs, and requires use of performance-based approaches in statewide, metropolitan, and nonmetropolitan transportation planning. Identification of best practices to address performance measures on highway operations as required by MAP-21 and development of a roadmap to guide transportation agencies to meet the requirements would be useful.

- The U.S. Department of Transportation (DOT) Integrated Corridor Management (ICM) Program focuses on the coordinated management and operations of multiple transportation networks and cross-network connections comprising a corridor and the institutional coordination of those agencies and entities responsible for corridor mobility. Therefore, the performance measures selected to assess the corridor existing conditions and alternative strategies would be helpful if they represented the corridor–region as a whole, and were also useful for the individual modes and facilities.
- Experiences from the ICM program and other corridor studies indicate that terminology and definitions of performance measures are often inconsistent among jurisdictions. Also, the selected performance measures are not directly related to the project objectives. This creates difficulties in understanding the impacts of selected strategies on the performance measures across jurisdictions and may prevent the implementation of new strategies. Guidance for identifying and selecting the performance measures that reflect project objectives of the project, and are consistent and understood by decision makers, users, and other stakeholders would be beneficial.
- Active transportation and demand management (ATDM) involves the proactive management of freeway facilities. This requires prediction of freeway performance and implementation of appropriate mitigation strategies. The methodology for prediction of traffic performance measures should be based on a combination of continually collected field data and modeling tools. The model predictions would be stored, and when the evaluation period approaches, field measurements are taken and compared to the original model predictions. By periodically recalibrating the model using the field data, the model's predictive accuracy can be improved over time and can be used to produce more improved predictions of traffic performance.
- Several ATDM and dynamic mobility applications (DMA) strategies require the definition and estimation of performance measures from field data and modeling tools. Examples include performance metrics to assess the safety and mobility impacts of speed harmonization and queue warning.
- Data requirements and alternatives for data collection could be beneficial, including data for estimation and monitoring of performance measures including traffic data, incident data, weather data, and construction and maintenance schedules. Also beneficial would be guidance on the sources of data by ownership (public versus private data), and technologies (from fixed surveillance infrastructure—sensors, vehicle probes, social media, and crowdsourcing data).
- Connected vehicle (CV) technology brings new opportunities and challenges in system management and performance measurement. The performance measurement from CV data depends on the penetration rates of CV and technology characteristics (sampling protocol, communications means, and latency), as well as operating conditions. Guidance would be beneficial on how the CV data will be utilized alone and in combination with other sources to provide reliable estimates of performance measures.
- Many agencies lack the resources to collect field data for performance measurement and monitoring. These data-poor agencies could benefit from guidance on best practices for performance measurement including the use of sample survey data, *Highway Capacity Manual*

type analysis, and simulation tools. If simulation models are used, procedures would have to be in place to derive the performance measures from the model outputs.

- Performance reporting carried out with a performance measurement and monitoring program that includes comprehensive reporting methods for data about the transportation network to be translated into useful information for the system operators, users, and other stakeholders would be helpful. Examples include summary reports, graphs, and dashboards across space and time scales to assist users in understanding the magnitude and trends in the data and operational performance. Information on data accuracy and precision can be included to help explain the reliability of the measures.
- Reporting reliability. The performance of freeway facilities on a selected analysis time period is not fixed but varies due to changes in traffic demand, incident occurrence, adverse weather, special events, work zones, and other factors. An accurate measurement of traffic performance would include reliability metrics to provide a complete understanding of the facility operating conditions (e.g., typical metrics from travel time distribution—average, standard deviation, 95th percentile).

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

Efforts have been made to identify effective performance measures and methods on performance monitoring, evaluation, and reporting. The following are representative projects that are recently completed or are currently underway in this focus area:

- *Performance Based Planning and Programming Guidebook*, FHWA, September 2013. The guidebook has been designed to help state DOTs, metropolitan planning organizations (MPOs), regional transportation planning organizations, transit agencies, and other partner organizations understand the key elements of a performance-based planning and programming process and the relationship of these elements within existing planning and programming processes. The guidebook highlights effective practices to help transportation agencies in moving toward a performance-based approach to planning and programming for MAP-21.
- NCHRP Project 03-114: Planning and Evaluating Active Traffic Management Strategies. This project will provide planning and evaluation guidance to transportation agencies, including the identification of appropriate performance goals and measures for planned projects, and planning for the collection of field performance data for use in trend analysis and performance-based planning.
- Estimate Benefits of Crowed-Sourced Data from Social Media. This PFS explores the opportunity of TMCs to utilize crowdsourced data from available mobile applications and to develop measures to assess their impact on TMC operations.
- Strategic Highway Research Program 2 Reliability Program. Several projects developed and tested procedures for defining and estimating performance measures for freeway travel time reliability. Methodologies were developed for incorporating reliability analysis into the 2010 *Highway Capacity Manual*. FHWA Operations site has several reports on congestion and reliability (http://www.ops.fhwa.dot.gov/perf_measurement/reliability_reports.htm)
- Data capture and management program. This U.S. DOT activity aims to enable the active acquisition and systematic provision of integrated, multisource data to enhance current operational practices and transform surface transportation systems management. A research data

exchange depository has been established that will include real-time and archived data, probe data from field tests, and data from research projects including simulations.

- U.S. DOT ICM Program. As part of the ICM effort, a set of key national corridor performance measures have been defined consistently applied across multiple ICM sites. Algorithms have been developed and applied at the pioneer ICM sites to calculate national measures of corridor performance (delay, travel time reliability, and throughput) from simulation model outputs.
- Several agencies are developing on-line reporting tools to facilitate the reporting of performance measures. This includes archival data systems (Oregon, California, Maryland, Florida, and Virginia), and reporting including summary reports, animations and dashboards.

RESEARCH NEEDS AND OPPORTUNITIES

Research and technology transfer opportunities to address potentially helpful research and gaps include the following:

Research

- Reliability metrics that are incorporated in the reporting of performance measurement. Data and methodology requirements that are used to obtain reliability metrics. Planning estimates on the expected impacts of certain mobility strategies on reliability.
- Improved methods for sensor data error checking, imputation of missing values, and data fusion from multiple sources. Ways to determine the error in performance estimates as a function of detector failures. Also, acceptance testing criteria for private-sector data for use in performance measurement.
- Methods for estimating performance measures from CV data.
- A methodology for predicting performance measures from field data and analytical tools, as part of a decision-support system in the TMC.
- Methods that are defined and developed for calculating certain mobility and safety related performance measures for ATDM and DMA strategies from modeling–simulation outputs.
- Techniques for analysis of data from traveler's mobile devices (big data) to obtain performance measures. Assessments of the usability of the data for obtaining additional information not typically gathered through conventional approaches (e.g., origin–destination information and trip chaining).
- New measures that apply to multimodal systems and specific situations (e.g., evacuations and emergencies).
- Procedures that are developed and defined for performance measures for freight traffic.
- A synthesis of state and MPO multimodal programming as part of MAP-21 with a focus on how goals and performance measures are used in a multimodal context for the programming of transportation projects.
- Guidance on the personnel resources and level of effort required to establish and maintain a comprehensive performance measurement, monitoring and reporting program.
- Procedures for calculating nonobservable performance measures (e.g., fuel consumption, air pollution) from commonly field-measured metrics.

Demonstration Project or Operational Tests

- A field test to determine the advantages and limitations of alternative data collection methods for calculation of performance measures that can be also accomplished by analyzing data from existing freeway systems at selected metropolitan areas in the United States.

Training

- Staff training on performance measures, data collection and analysis, and presentation techniques.

Traffic Management Centers

STATE OF THE PRACTICE AND STATE OF THE ART

Traffic (or transportation) management centers (TMCs) are a key tool that is needed by public agencies to monitor and report on roadway and travel conditions, coordinate with local interests in response to changing conditions, and proactively manage and control traffic to mitigate the impacts of congestion and improve the reliability of travel. TMCs also play a critical role in coordinating, supporting, and sharing information on roadway and travel conditions that are needed by a variety of different interests to provide a variety of emergency services to the traveling public. TMCs are a key technical and institutional hub bringing together the various jurisdictions, modal interests, and service providers to focus on the common goal of optimizing the performance of the surface transportation system.

TMCs require dedicated management and staff with specialized skills and training, rely on advanced technologies, require dedicated operating and capital funding, face complex institutional issues in coordinating with service providers in response to incidents, and functions within a time-critical environment—a culture drastically different from what most agencies are accustomed to. These demands and constraints present challenges that agencies face on a daily basis without the benefit of having the necessary resources, experience, skills, and training. These are challenges that agencies continually face which impacts their ability to efficiently and effectively manage and operate TMCs.

Meeting challenges and customers' expectations requires pursuing a wide variety of both proven and innovative strategies to realize the full potential of the investment that they have, and will continue to make, in TMCs. Investment will allow agencies to proactively manage and control traffic in a manner that optimizes the performance and investment in the surface transportation system. Investments that allow TMCs to improve the safety, mobility, and productivity of travel will also foster economic growth and development. To deal with limited resources and the increasing complexity involved in managing and operating TMCs, practitioners need access to technical guidance, best practices, training, innovative techniques and technologies, and fact-based tools to assist them in improving the performance and their services.

GAPS IN PRACTICE OR KNOWLEDGE

TMCs have made tremendous progress for the past three decades. But because of their critical role in the operation of a freeway management system, it is essential that the TMCs continuously monitor and address the new emerging technical trends and challenges. TMCs would be most beneficial if they advance and improve upon the current state of the practice related to management, operation, and performance. The following issues fill gaps in practice and knowledge would likely develop the resources and tools for agencies to address and overcome the challenges that they will be facing in the future.

Improving Day-to-Day Operations

The effective and efficient management and operation of a TMC directly influences its performance, its ability to mitigate the impacts of congestion, and the performance of the roadways it manages. The management and operation of a TMC relies on the availability of staff with the appropriate skills, support resources, and tools to perform the tasks, activities, and functions. This requires managers to be able to estimate, schedule, procure, and manage the staff, resources, and tools that are either available or required to operate a TMC. Some of these tools may include agency or TMC policies, procedures, protocol, operational strategies, control plans, training manuals, staff estimating and scheduling software, and other resources that staff need to successfully perform their assigned duties and tasks. Recommended practices and guidance does not exist to assist practitioners on how to develop, train, hire, or contract for staff or support services that are necessary to support the continued management and operation of TMCs.

Enhancing Business Management of TMCs

TMCs require a commitment from local agencies to provide the capital, operating, and maintenance funds that are required to implement, manage and operate a TMC. Often agencies pursue the deployment of TMCs without (*a*) providing the proper business foundation to support the justification of the initial or continued expenditure of funds; (*b*) integrating the potential benefit of the TMC into the strategic and program plans of an agency or region; (*c*) estimating the future impact a TMC may have on the performance of the surface transportation system; and (*d*) quantifying the resources required to effectively manage the operation and evolution of a TMC.

Agencies are faced with continuously managing evolution based on the desire to expand its functionality, electronically share information with stakeholders, replace technologies, expand the area of coverage, and meet the continuously changing needs the many stakeholders of the TMC in a region. Effective and efficient business management of TMCs requires corresponding business plans, management systems, monitoring, evaluation, and reports on performance. This also requires that these plans, processes, and performance of the TMC are integrated into the appropriate strategic plans, programming, asset management, performance monitoring, and reports within an agency and region.

Guidance, lessons learned, and best practices will likely provide agencies and practitioners with the needed directions and resources to improve the collaboration, coordination, and planning between public agencies to enhance the business planning, management, resource allocation decisions, performance monitoring, and reporting on performance of TMC and its influence on other business processes within an agency and region. Recommended practices, guidance, and business planning tools do not exist or have not been developed to assist practitioners on the business planning and management of TMCs.

Developing TMCs and Managing Their Evolution

The planning, design, implementation, and how the evolution of a TMC is managed will likely influence its reliability, effectiveness, efficiency, and operational resources. Often agencies pursue the deployment of TMCs without providing the proper foundation to support the planning, design, implementation, operation, and maintenance of the facilities throughout their life cycles;

the justification of the continued expansion and evolution of their systems; the integration of the potential benefit of the TMC into the strategic and operations plans of an agency or region; or estimation of the future impact a TMC may have on the performance of the surface transportation system. Transportation operating agencies are faced continuously with managing the evolution based on the desire to expand its functionality, share information electronically with stakeholders, replace technologies, expand the area of coverage, and meet the continuously changing needs that many TMC stakeholders in a region. Improved collaboration and coordination between agencies would enhance the planning, design, management, and decisions that are made throughout the life cycle of a TMC.

Recommended practices, guidance, and tools to assist practitioners in developing and advancing the activities related to the key phases of the life cycle of a TMC and in managing its evolution have been limited.

Developing and Delivering Roadway and Travel Condition Information

The delivery of en-route roadway and travel condition information is critical for TMCs to be able to effectively manage and control traffic. TMCs play the primary role in collecting, developing, and delivering en-route information to the traveling public. The ability to effectively and efficiently deliver information to motorists will allow agencies to manage travel in response to changing roadway and traffic conditions. This capability will allow agencies to open or close lanes of traffic, restrict use of certain lanes to specific types of vehicles, close sections of roadway, suggest alternative routes, display travel time information, inform motorists of actions that may be required to take, and conditions they may encounter if they continue on this roadway.

Developing, Training, Hiring, and Contracting for Staff and Services

One of the most important components that influence the operation of a TMC is the availability of qualified staff. TMCs require dedicated management and staff with the specialized knowledge, skills, ability, and training to efficiently and effectively perform the necessary tasks and deliver the vital services and functions. Recommended practices and guidance do not exist to assist practitioners on how to develop, train, hire, or contract for staff or support services that are necessary to support the continued management and operation of TMCs. Nationally, to date, activities that have been pursued have been limited.

Knowledge Transfer

This focus area is intended to provide a more efficient use of resources; facilitate sharing of resources developed and technological and institutional experiences gained; assist in knowledge management with compiling and warehousing information; support technology transfer on innovative applications; and coordinate with national coalitions and organizations with TMC–TMS interests.

RESEARCH NEEDS AND OPPORTUNITIES

The following are areas of potentially helpful research for TMCs.

Day-to-Day Operations

Future initiatives that may be pursued that build off of and expand upon previous efforts include:

- Predicting traffic and roadway conditions;
- Collecting, processing, archiving, and using data for operations;
- Data archiving subsystem—concept of operations, requirements, and design; and
- Data quality and requirements.

Business Management

Future projects that may be pursued that build off of and expand upon previous efforts include:

- TMC business planning software;
- TMC multiyear program plans;
- TMC asset management;
- Formatting and sharing operations data for transportation planning; and
- Tolling and other pricing operations in TMCs.

Developing and Managing TMCs

Future projects that may be pursued that build off of and expand upon previous efforts include:

- TMC building and control center design handbook;
- Multistate and mega region TMC coordination;
- Tool to support regional and multisystem configuration management;
- Open source advanced traffic management system software licensing and development;
- Automation of TMC functions; and
- Cloud computing, data fusion, and data management.

Roadway and Travel Conditions Information

This focus area would emphasize research, development of technical guidance, and filed operational tests as related to:

1. Procedures, methods, techniques, ad tools to support and improve collecting, processing, developing, and delivering roadway and travel condition information;
2. Human factors and driver behavior associated with information display and dissemination;
3. Policy, institutional, and operational issues; and

4. Technologies, information requirements, and resources required to proactively manage traffic in real-time in response to changing conditions.

Future research projects would build off those efforts as well as explore issues related to the following:

- Procedures and requirements for providing road conditions and travel time information;
- Methods for TMCs to develop and distribute predictive travel time information;
- How to display travel times across regions;
- Best practice in private sectors information dissemination; and
- Diversity of sources, coverage, types, and quantity of data.

Staffing

Future projects that may be pursued include the following:

- Knowledge needs assessment and workshops for TMC owners, managers, and staff;
- Training program template and opportunities for TMC staff;
- TMC operator certification program development and implementation; and
- Two-year college programs for TMC operators and technicians.

Knowledge Transfer

Potential projects within this focus area would focus on facilitating peer-to-peer information sharing and exchanges, enhancing knowledge management and information warehousing, and developing innovative training and technology transfer techniques and activities to raise the awareness and advance traffic management and control practices. Such a project includes the *TMC Marketing Handbook and Toolbox*.

Detection and Surveillance

STATE OF THE PRACTICE

Inductive loop detectors are still the most utilized type of sensor in traffic management systems (*4*). They are commonly deployed as single loops at discrete locations to measure traffic volume and lane occupancy. Other traffic flow parameters such as density and speed must be inferred from algorithms that interpret or analyze the measured data (*5–8*). Algorithms for detecting the onset of congestion and incidents are also typically based on these single-loop measurements (*9*). Although such algorithms have been developed and implemented at a variety of locations, none work perfectly as a trade-off is required among the sensitivity parameters that control incident detection probability, detection time, and false alarm probability. To measure traffic speed and vehicle length, inductive loops are sometimes configured as dual loops (or speed traps). A dual-loop detector is formed by two consecutive single-loop detectors placed several meters apart. Although dual-loop detectors are ideal for collecting speed and vehicle length data, there are too few of them on our current freeway systems to meet current traffic management needs.

The increasing use of cell phones by motorists has made telephone reports a common method of incident detection. Operators at a traffic management center (TMC) use visual surveillance from field-located cameras to verify incidents when these are available. Dispatched law enforcement, other emergency service personnel, service patrols, or tow truck operators also support the incident verification function. Microwave radar sensors, video detection systems with pan, tilt, and zoom cameras, and combinations thereof are now commonly utilized for vehicle counting and speed measurement and for traffic signal actuation or signal timing. They also find application in automatic incident detection on freeways. License plate readers (LPRs) or automatic number plate readers are used on highways for tolling applications such as reading license plates of vehicles with missing or expired toll tags and for origin–destination measurements. These LPRs are available in fixed configuration for installation on roadside infrastructure, and in mobile configuration for installation on vehicles. Both fixed and mobile LPRs are extensively used for public safety, homeland security, and traffic signal violation enforcement applications.

Gantry-mounted laser curtains are used for high-accuracy vehicle classification in tolling applications. LPRs are at times used in work zones for enhancing work zone safety. Microwave Doppler radars, installed inside traffic barrels, are used for detecting speed for work zone safety purposes. Microwave Doppler radar speed detectors are also used on rural curves, with accompanying dynamically flashing LED chevrons, to reduce single-vehicle lane departure incidents. Microwave side-fire frequency modulated continuous wave radars and inductive loops are used on ramps.

STATE OF THE ART

The state of the art in detection and surveillance replaces traditional single-loop detectors with sensors that provide additional types of data such as queue detection, travel time measurement, and vehicle tracking through the detection zone. State-of-the-art systems take advantage not only of the newer detection technologies, but also of magnetometers, acoustic sensors, infrared sensors, Bluetooth-based travel time data collection systems, and laser radar sensors to monitor the infrastructure both longitudinally and sectionally and to classify vehicles for tolling applications. Several manufacturers offer sensors that utilize multiple technologies such as video and microwave radar, video and acoustic, infrared and ultrasound, and an infrared, ultrasound and microwave Doppler combination. Lower-cost thermal imaging cameras exist for improved vehicle detection under low-light conditions. Fog alert sensors and specialized pedestrian and cyclist warning sensors are also available. Media access control (MAC) address matching found in mobile electronic devices merges infrastructure-based point-detection techniques with cellular-based geo-location and GPS, and moves toward incorporation of data and information from the Connected Vehicle Program. Connected vehicle safety applications are designed to increase situational awareness and reduce or eliminate crashes through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) data exchanges that support driver advisories, driver warnings, and vehicle and infrastructure controls. Improvements in positioning, computing, and detection technologies also have the potential to update and improve upon incident and congestion detection algorithms and freeway system control strategies that are utilized in active transportation and demand management strategies. Some TMCs utilize computerized algorithms that identify locations where significant congestion exists and trigger the video system to display images from the appropriate video camera. This makes it easier for operators to identify congestion-prone locations and reduces the delay in incident response. More recently, the private sector has been gathering and supplying crowd-sourcing data to public agencies. These data are obtained from massive numbers of willing highway users of mobile devices.

EMERGING TRENDS OR DRIVERS OF CHANGE

In present practice, traffic detection and surveillance devices are typically available at discrete points in a freeway corridor. The deployed traffic sensors, mostly single-inductive loops, have limited data collection capabilities. Vehicle occupancy sensors are in development that can detect the number of people in a car and thus be a valuable adjunct to high-occupancy vehicle (HOV) lane and variable-price tolling operations.

Point sensors, surveillance video cameras, mobile and fixed Bluetooth sensors (*10–12*), GPS-equipped probe vehicles, and automatic vehicle identification systems can be integrated to create a more-powerful detection and surveillance system. The vehicle tracking feature of state-of-the-art detection systems enables data collection that aids in individual trip route planning and in providing origin–destination pairs for forecasting future improvements to the roadway network. Evaluations of modern over-roadway sensors show that they provide an alternative to inductive loop detectors. When properly installed, the traffic flow parameters measured with these sensors satisfy the accuracy requirements of many current freeway and surface street applications. While these new sensors have gradually replaced the aged inductive loops, their detection capabilities have not been fully utilized. For example, a video detection system, though capable of providing additional types of traffic data as compared to loops, is simply used as a substitute for inductive loops because most control devices merely accept data available from loop detectors. Thus, the additional video sensor information such as queue detection and vehicle tracking are ignored in this case.

The cost of large-scale detection and surveillance is one of the biggest impediments to agencies implementing state-of-the-art traffic management systems. Identifying cost-effective sensors and utilizing the full detection capabilities of these sensors are important in practice. However, this may be a difficult task because (*a*) practitioners and designers typically do not have training in modern detection technologies and (*b*) there is not a single resource nationally that will aid them in developing the full range of skills needed to design and implement a detection and surveillance system.

GAPS IN PRACTICE OR KNOWLEDGE

Federal Highway Administration's *Traffic Detector Handbook*: *Summary of Vehicle Detection and Surveillance Technologies Used in Intelligent Transportation Systems Handbook* and *Sensor Technologies and Data Requirements for ITS* are valuable tools that enable understanding of the strengths and weaknesses of various sensor technologies and applications. However, additional documentation that describes the requirements and the best practices for designing and implementing the detection and surveillance component in a traffic management system would be helpful.

There is also a gap in the knowledge of the true maintenance costs and therefore the overall life-cycle costs of all detection methods. Although much has been written on installation costs of traditional and alternate detection technologies, little has been documented about the ongoing maintenance costs of the technologies. Some states, such as California, are becoming more aware of this issue and are developing systems to track sensor maintenance costs.

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

While there is no current national initiative addressing detection and surveillance issues, the U.S. Department of Transportation Connected Vehicle Program does contain elements that rely on vehicle detection. The Connected Vehicle Program is concerned with the development and deployment of a fully connected transportation system. Two of the program components that utilize detection to impact freeway operations include the following:

- Active traffic demand management (ATDM) exploits market-ready technologies and innovative operational approaches for managing traffic congestion within the existing infrastructure. The vision for ATDM research is to allow transportation agencies to increase traffic flow, improve travel time reliability, and optimize available capacity throughout the transportation network.
- V2V safety initiatives aim to reduce incidents by utilizing 5.9-GHz direct short-range communication (DSRC) technology for blind spot and lane change warning, forward collision warning, electronic emergency brake light activation, intersection movement assist, do-not-pass warning, and control loss warning.

Additional information about these initiatives is found in the next section, Research Needs and Opportunities.

RESEARCH NEEDS AND OPPORTUNITIES

The following are potential research topics that could address the gaps in detection and surveillance.

Research

- FHWA last completed and published an update to its *Traffic Detector Handbook* in 2006. A complete revision of this handbook—incorporating advances in detection, surveillance, and safety made possible by sensors that incorporate multiple technologies, new magnetometer designs, low-cost thermal imaging cameras, initiatives such as the Connected Vehicle Program, and the increased availability of cell phone and GPS data to locate vehicles and generate travel times using MAC address matching—is overdue.
- Self-directed learning tool for traffic detection and surveillance. This study project could develop a self-directed learning tool for practitioners to study traffic detection and surveillance theories, detection system design principles, and the merits and applications of commercially available traffic sensors and other strategies such as those that use GPS-based vehicle location devices.
- Performance monitoring using point detection data and the probe vehicle trajectory data collected from GPS and cellular-based geo-location systems. This study could develop a new algorithm for highway performance measurement using both point detection data and probe vehicle trajectory data collected from GPS and cellular-based geo-location systems.
- Continued development of the Connected Vehicle Program to communicate with surrounding vehicles using 5.9 GHz DSRC technology. Safety applications to be tested include:
  - Blind spot warning–lane change warning to alert drivers when they try to change lanes if there is a car in the blind spot or an overtaking vehicle;
  - Forward collision warning to alert drivers if they fail to brake when a vehicle in their path is stopped or traveling slower;
  - Electronic emergency brake lights to notify drivers when a vehicle that they can't see ahead of them is braking hard for some reason;
  - Intersection movement assist to warn the driver when it is not safe to enter an intersection, for example when something is blocking a driver's view of opposing traffic;
  - Do-not-pass warning to alert drivers if they attempt to change lanes and pass when there is a vehicle in the opposing lane within the passing zone; and
  - Control loss warning to alert drivers when a nearby vehicle has lost control.
- With the continued increase in coverage provided by motorist's GPS-equipped cell phones, an examination of the future of point sensors on freeways and other limited access highways is timely. While continued use of the point detectors for traffic signal control appears needed in the future, it is not as clear that mass deployment of these sensors may be required to detect incidents or slow moving traffic conditions.
- Adaptive ramp metering will become more important to freeway traffic management as traffic demand increases and freeways and arterials are more tightly coupled via integrated corridor management. Current sensors on ramps are point detectors. Therefore, multiple sensors of this type are required to dynamically measure ramp queue length and gaps on through lanes. Video and radar sensors also have the potential to provide these measures. However, research

would be helpful if it identified enhancements to these sensors to make them practical as ramp sensors for adaptive ramp metering.

Demonstration Project or Operational Tests

- Large-scale metro-area test of application of cell phone data to provide travel times to commuters and other travelers.
- Methods and tools for large scale data analyses and informed decisions.
- Continued testing of V2V and V2I equipment and algorithms designed to warn drivers of potential hazards with incorporation of newer sensor technologies to enhance infrastructure-based vehicle detection and surveillance.
- Above-ground sensors are beginning to be used for freeway ATDM for detection of shockwave propagation and queue warning. Display of queue warning messages are often TMC operator controlled, but at other times are produced autonomously by the sensors themselves. Wider demonstration and operational tests would be helpful in testing and validating the performance and effectiveness of such sensors for these applications and to establish specifications and benchmarks for their requirements.
- LPRs have been used for several years in European countries, such as the Netherlands, to help smooth and harmonize speed to obtain maximum capacity. Demonstration of the technology on U.S. highways would allow this method to be used for ATDM applications.

Technology Transfer

- Best practices for designing and implementing a cost-effective system for traffic detection and surveillance. This study would collect success stories from transportation agencies in cost-effective design and implementation of traffic detection and surveillance systems and summarize them in a final project report.
- Detection and surveillance system cost database. Much has been reported on installation costs for detection technologies but little has been documented about the ongoing maintenance costs. This database would collect and document the installation as well as on-going maintenance costs of traditional and alternate detection technologies.
- Continued exploration, application, and incorporation of sensor and data fusion techniques from homeland defense applications to traffic management to aid in developing a more complete and accurate picture of the traffic situation at hand and in data mining (*13*, *14*).
- Best practices to utilize crowd-sourced data and user-device derived data, such as from tracking user devices equipped with GPS, cellular radio, or Bluetooth, would be useful if they were documented with case studies and procedures so unfamiliar agencies can quickly adapt these tools.
- Validated and centrally documented accuracy, deployment procedure, and cost of work zone sensors such as speed barrels and other portable sensors would be useful if documented and disseminated.

Freeway Traffic Control Devices

STATE OF THE PRACTICE

A traffic control device (TCD) is defined as "all signs, signals, markings, and other devices used to regulate, warn, or guide traffic, placed on, over, or adjacent to a street, highway, pedestrian facility, bikeway, or private road open to public travel by authority of a public agency or official having jurisdiction" (*15*). TCDs are used to "notify road users of regulations and provide warning and guidance needed for the uniform and efficient operation of all elements of the traffic stream in a manner intended to minimize the occurrences of crashes" (*15*). In the context of freeways, TCDs used to control freeway mainline or ingress and egress traffic are a subset of the array of TCDs described in the *Manual for Uniform Traffic Control Devices* (MUTCD) and are considered freeway TCDs hereafter. Current and future freeway operations and management strategies, such as active traffic management (ATM), managed lanes, and traffic incident management, are critically dependent on TCDs to effectively communicate these strategies to users of the freeway system.

TCDs are most often categorized into the areas of signs, markings, and signals. Signs and markings are two most widely used freeway TCDs, while traffic signals and other new and innovative TCDs are becoming more common freeway applications. Signs are used to regulate traffic flow, warn road users in advance of unexpected roadway conditions, and provide traveling guidance. Signs can be placed along the side of the freeway, over the travel lanes with adequate vertical clearance, or an emerging practice of replicating the sign using pavement marking on the travel lanes (i.e., horizontal signing). Signs have traditionally been fixed in place and static, but technology advances and introduced new and innovative applications of dynamic signing. For the purposes of providing prevailing information, such as time-limited shoulder usage, variable speed limits, time dependent toll rates, and travel time dynamics, various forms of fully or partially changeable message signs are used. Commonly used freeway signs include:

- Regulation signs: stop and yield signs at on-ramp entrances, speed limit signs, various plaques, lane designation signs, wrong way signs, signs to prohibit certain vehicle types, signs to indicate legal use of shoulder, weight limit signs, high-occupancy vehicle control signs, reversible lane control signs, and toll message signs.
- Warning signs: signs for changes in horizontal alignment, vertical alignment, cross-section or road surface conditions, chevron, truck rollover signs, advanced traffic control signs, merge signs, lane ends signs, added lane signs, road narrows signs, low clearance signs, and freeway ends signs.
- Guidance signs: route signs, exit signs, interchange signs, weigh station signing, reference location signs, rest and scenic area signs, tourist information and welcome center signs, and recreational and cultural interest area signs.

Markings on freeways are primarily used for channelization and lane control. Pavement markings are used to delineate lane and freeway boundaries and neutral (gore) areas. Word and symbol markings are used to indicate preferential lanes such as high occupancy vehicle lanes and electronic toll collection (ETC) lanes. Symbol markings can also serve as horizontal signing when used to indicate route information. Delineators are used to improve drivers' perceptions of changing alignments such as curves. Rumble strip markings are commonly installed on freeway shoulders to alter drivers from leaving travel lanes inattentively through vibration and sound.

In freeway applications, traffic signals are used for lane-use control, ramp entrances, toll plazas, and other emerging areas of ATM. Ramp meters are the most common use of signals in freeway operations designed to control ingress traffic volumes. At toll plazas, lane-use control signals and warning beacons are typically installed to assist drivers in choosing the proper ETC lanes.

Temporary traffic control (TTC) devices are also commonly used on freeways to channelize traffics around work zones or traffic incident scenes, providing separations and protections to road users, first responders, and people within the temporary traffic control zones. Typical TTC devices on freeways include but are not limited to advanced warning signs, channelizing devices, and operation control.

TCDs visually, and in some cases haptically, convey information to roadway users. Therefore, the conspicuity, sizing, legibility of graphic or text, and placement of a TCD are crucial to effectively convey a message or meaning. The high speed and dynamic nature of freeways significantly increases the need for effective TCD applications.

STATE OF THE ART

The current version of the MUTCD is intended to represent the state of the art in traffic control, including freeway traffic control devices. Nevertheless, new TCD concepts and products are emerging rapidly, often to accommodate the new dynamic strategies being employed on freeways. Innovations include enhanced TCD appearance (such as conspicuity or legibility), more responsive–active–dynamic controls, and new ways of communication between road users and TCDs.

Several examples can be cited to define the state of the art in selected areas of TCD applications. Many of these TCDs are not formally adopted by the MUTCD and therefore are considered experimental in their application and use. Nevertheless, new and innovative uses of pavement markings are used to improve communication with the road user and reinforce the intended message and desired behavior. For example, elongated pavement markings and elongated horizontal signs have been implemented to complement roadside or overhead signs. Improvements in TCD marking materials (e.g., paints, plastics, tapes) increase conspicuity and legibility, especially at night. Although still experimental, fluorescent pavement markings using energy-trapping materials are being employed in both Europe and the United States. Internal and external illumination, such as solar-powered in-pavement marker (IPM) systems, has been used to provide enhanced nighttime visibility of markings to overcome limitations in retroreflective properties. Dynamic signs have been introduced to support current applications of ATM and variable speed limit control. Many other innovations can also be found in the areas of signs and signals.

Emerging areas in freeway operations have also redefined the state of the art in TCDs. ATM, managed lanes, and traffic incident management are three of several operational and control innovations that have required and implemented new TCD applications to communicate the desired operations.

EMERGING TRENDS OR DRIVERS OF CHANGE

Emerging trends in freeway operations revolve around innovative use of dynamic controls to maximize the efficiency of existing infrastructure and to optimize the short-term control of lanes and incidents. All of these emerging trends require new and innovative ways of communicating these strategies to road users. TCDs will continue to provide this communication conduit.

Advances in intelligent transportation systems (ITS) technologies and the emergence of vehicle-to-infrastructure (V2I) and vehicle-to-vehicle communication (V2V) will likely revolutionize the type and form of TCDs used. Connected and autonomous vehicles technologies will require the development of a virtual TCD system that may no longer require a comprehensive roadside infrastructure.

GAPS IN PRACTICE OR KNOWLEDGE

Newly developed freeway TCDs, especially those associated with ATM strategies, have been implemented in various forms developing a new body of understanding and lessons learned. From a general point of view, challenges may rise from the following:

- Implementation. A challenge in implementing newly developed freeway TCDs is the lack of standards and guidelines. The MUTCD does not address the design and implementation of new and innovative devices, which likely gives practitioners difficulties in finding an approved starting point. In addition to existing studies that provide data support to guideline development (*16*), investigations could enrich the case pool. Beyond the lack of guidance, the installation of new TCDs might confound the existing infrastructure, e.g., adding to the complexity of existing traffic control environment or requiring reconstruction of the installation site for system integration.
- Effectiveness. Driver perception and comprehension are always a fundamental concern when evaluating the effectiveness of TCDs. LED message boards are widely used to display dynamic information. Unlike static signs whose size, font, color, retroreflectivity, height, and placement are well studied for optimal conspicuity within their functional ranges, LED-based signing would still benefit from investigation, especially in adverse weather conditions (e.g., snow, ice). Similarly, the visibility and legibility of elongated pavement marking signs under high-speed freeway conditions are not fully understood.
- Reliability. New and adaptive devices might be physically or logically unreliable. Power supply requirements and evolving electronic circuits makes these devices more vulnerable to failure, and raises the concern of protection as well as the need for countermeasures when devices are physically disabled. In addition, some dynamic devices provide real-time information often without sufficient and valid real-time traffic data. As noticed by the community of ITS, errors are inevitable in real-time traffic data. When erroneous data are fed to these dynamic devices, misleading information or guidance can be generated and defeat the purpose of effective active traffic control. The situation can become more challenging given that there is also latency in data transmission and computation.
- Expense. Some new devices consume more energy than their traditional counterpart and the cost of manufacturing, installations, operation and maintenance are all significantly higher.

- Maintenance. Unlike static TCDs, dynamic devices are more difficult to maintain and replace. An unfortunate example is from Minnesota Department of Transportation (DOT) that is facing the challenge of finding maintenance service for its smart lanes as the company providing the message boards dissolved (*17*).

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

Below are some recently completed, ongoing, or proposed projects that aim to either provide additional knowledge about the emerging trends or to support the trends with innovating technologies:

- State DOTs through a TCD Pooled Fund Study (PFS) is conducting research related to improving road user communication through elongated pavement marking signs placed adjacent to the same post-mounted sign. The project is evaluating the conspicuity, legibility, and effectiveness of symbolized pavement markings that are elongated (horizontal) versions of regulatory and warning post-mounted signs. New regulatory and warning signs related to such things as toll collection, merging, and weaving are also being evaluated as part of the TCD PFS program.
- National Cooperative Highway Research Program (NCHRP) Synthesis 20-05/Topic 38-13: Applications of Illuminated, Active, In-Pavement Marker Systems. This project documented the state of IPM technology and the experiences from IPM practices. (Now published as *NCHRP Synthesis of Highway Practice 380: Applications of Illuminated, Active, In-Pavement Marker Systems*.)
- NCHRP project 03-114: Operational and Reliability Impacts of Active Traffic Management Strategies. One of the objectives of this project is to review existing studies on operational and reliability impacts of ATM strategies, and corresponding life-cycle costs, resource requirements, and institutional and management challenges with operating and maintaining ATM strategies and making the study data easily accessible.
- University Transportation Center (UTC) project 2013-009S: Dynamic Traffic Control Interventions for Enhanced Mobility and Economic Competitiveness. This research is intended to develop efficient methods that dynamically evaluate the effectiveness of ATM techniques and their application on freeway facilities.
- Connected Vehicle–Infrastructure UTC (CVC-UTC) Project: Prototyping and Evaluating a Smartphone Dynamic Message Sign Application in The CVI-UTC Testbed. This project will produce a product that extends the spatial and temporal influencing areas of DMS by integrated them into the vehicle–infrastructure platform.
- The University of Michigan's Transportation Research Institute and federal and state transportation departments have plans to equip a percentage of Ann Arbor's driving population with V2V and V2I technology (*18*).
- The Smart Highway project in the Netherlands is bringing together the aesthetic, environmental, and functional aspects of highways to serve the roadway user in an energy saving and responsive manner (*19*).

RESEARCH NEEDS AND OPPORTUNITIES

A review of other strategic focus areas in this e-circular will find TCD research a key component of many. For example, the ATM chapter identifies several potentially helpful areas of research pertaining to ATM-related traffic control displays, TCD display graphics, and changeable lane markings. The ICM chapter identifies needs to better communicate dynamic route guidance to road users. Traffic incident management research areas include dissemination methods of real-time information and so on. All new and innovative freeway operational strategies will require supporting advances in TCDs to effectively communicate the desired information to road users. Corresponding to the above gaps in practice and knowledge, combined with the TCD areas identified throughout this document, several potential areas of research are highlighted below. The research is intended to be high order and high priority, with the potential to develop a number of specific research efforts under each:

- What is the most appropriate and effective methodology for presenting dynamic information to road users under high-speed freeway conditions?
- How do changes in speed affect the methodologies selected?
- What communication mechanism(s) assure the greatest road user compliance?
- What is the best method for identifying and delineating dynamic lane control?
- How can pavement marking dynamically support changes in freeway operations and lane control?
- What are the most effective and safest methods for communicating real-time information to road users through in-vehicle or personal communication devices?
- What is the reliability and durability of new TCDs and develop countermeasures for device failures?
- What is the sensitivity of dynamic TCDs to erroneous data and hacking?
- What is the appropriate migration from physical TCD’s to virtual TCDs?
- What are the best methodologies and impact of nighttime illumination of signs and markings?
- What are the gaps between new and emerging freeway operations techniques and available communication tools like TCDs?

Impact of Connected and Automated Vehicles on Freeway Management

STATE OF THE PRACTICE

Connected and automated vehicles (CAVs) can have a profound impact on freeway traffic management, including freeway traffic operations and the ability of agencies to manage travel on freeway facilities. Due to the fast changing nature of CAV technology, identifying the potential impacts and the resources agencies may require to integrate this technology into how they operate and manage traffic on freeways will be an iterative and on-going process. Documenting these challenges and research areas will likely enable researchers, the private sector, and practitioner communities to successfully navigate the implementation of CAV technology. Through this approach, agencies can maximize the potential benefits of CAV, both to the public and the freeway traffic management community.

Connected vehicles are those in which wireless technologies are used to "connect" vehicles to each other (vehicle to vehicle, or V2V), to infrastructure (vehicle to infrastructure, or V2I), and/or other elements such as pedestrians (vehicle to other, or V2X). Drivers are still in control with connected vehicles but are given assistance through in-vehicle recommendations, warning, and alerts.

Automated vehicles are those in which at least some (in the case of "driverless" vehicles, all) aspects of the safety-critical control functions (e.g., steering, throttle, or braking) occur without direct driver input. Automated vehicles may be autonomous, that is, use only vehicle sensors and high-resolution mapping, or may be connected, that is, use communications systems such as connected vehicle technology, in which vehicles can communicate wirelessly with each other and roadside infrastructure.

It has been hypothesized that the combination of connected and automated vehicle technologies, or connected automation, will yield greater benefits than connected or automated vehicles singularly. CAVs offer agencies the opportunity to consider the potential benefits of collecting, compiling, and integrating the data generated by these vehicles into the day-to-day operation of the systems used by agencies to manage and control traffic on freeway facilities and to share information on traffic and travel conditions with other stakeholders.

EMERGING TRENDS OR DRIVERS OF CHANGE

As CAV technologies transition out of research and development into testing and implementation, the transportation sector is expected to undergo transformative changes. The impact of CAVs on freeway traffic management is an emergent area of research and, as such, there is no 'state of the practice' or 'state of the art' as there are for the other research areas in this document.

At the July 2015 TRB Automated Vehicle Symposium (AVS) breakout session, "Impact of Connected and Automated Vehicles on Traffic Management Systems and Operational Strategies," wide-ranging discussions occurred regarding potential research areas, including CAVs and those related to managing and operating travel on freeways. Based on those discussions, it has been determined that research on the implications that CAV technology may have for freeway travel, and the possible integration of CAV data into the day-to-day management and operation of traffic on freeways by Traffic Management Centers (TMCs) and Active Traffic Management (ATM) would be helpful. There are issues raised by the introduction of CAV technology and issues are often inter-related and difficult to isolate.

Future Automated Vehicle Symposiums and related conferences provide important opportunities for the TRB Freeway Operations Committee (FOC) to continue sharing perspectives and draw input from stakeholders. They also provide opportunities to develop linkages between this committee's CAV freeway operations research interests and those of the broader CAV community. Further development of the potential research areas would have to be supported through the FOC partnering with the American Association of State Highway Transportation Officials (AASHTO) Transportation System Management and Operations (TSMO) technical committee working group, and the AASHTO Connected Vehicle and Research working groups. Alignment of FOC CAV research efforts with the TRB Regional Transportation Systems Management and Operations (RTSMO) Committee will also be important. Additional strategic initiatives of interest are the National Cooperative Highway Research Program (NCHRP) Project 20-102 series of CAV research projects, as well as the near-final Next Generation TSMO Research Framework and its prospective agenda.

GAPS IN PRACTICE OR KNOWLEDGE

Institutional Readiness

TMC personnel are not equipped with the knowledge, skills, tools, or resources to develop, implement, and operate highly technical Integrated Corridor Management (ICM) and ATM applications. Similarly, there is a lack of institutional readiness for collecting, saving, and converting CAV data into actionable information for TMC operational use, sharing information with these vehicles, or sharing this information with other stakeholders.

Data

- **Requirements**: The data, functions, capabilities, tools, and ITS infrastructure needed to integrate the sharing of data with CAVs into the systems responsible for monitoring and facilitating the day-to-day management and operation of travel on freeways have not been identified. It will also depend on defining how the ITS infrastructure and TMCs can share information with CAVs and other stakeholders.
- **Collection:** In order for TMCs to collect high-volume, multi-source data, a national framework that defines the process involved with the collection and sharing of data with CAVs, creates standards, and offers guidance would be beneficial as would tools to support these functions..
- **Aggregation and Storage:** Legacy systems in the current TMC environment may not be equipped to collect, aggregate, store, use, and share high-volume, multisource data to realize the benefits of newly available CAV data.

Planning

Review of current methodologies, tools, and practices would help determine how CAV technology can be integrated to realize improvements in various agency functions (planning, design, maintenance, and more).

Roadway Maintenance

Vehicle manufacturers are offering options which assist with prevention of lane departure. These systems rely on the availability of accurate and well-maintained lane markings, as will fully autonomous and driverless vehicles. The condition of the roadway infrastructure (e.g., lane markings, potholes) may disrupt the functioning of these types of systems and vehicles. The trend over the past 20 years has been to delay maintenance until roadway degradation has reached a critical point. State departments of transportation are the agencies that allocate funds for efficient maintenance of roadways.

Resources

There are limited resources (including time) available for public agencies to consider the integration of CAV technology into how traffic is managed and controlled on freeways. Public agencies would benefit from the basic resources, tools, and guidance for determining our data needs including through the process of collection, compilation, analysis and dissemination capabilities. A Capability Maturity Model assessment to determine framework for maturity across the five levels may be helpful as well.

CAV Penetration

How long it will be until CAVs become ubiquitous is unknown. Transportation agencies need to determine how to progressively align their practices and infrastructure to accommodate this paradigm shift. Important questions to answer include: What is the critical mass for use of Basic Safety Messages (BSMs) and sharing of data within TMC operations? What is the length of transition period and the effort required for implementation?

Capabilities of TMCs and Public Sector

If the sharing of data between individual vehicles provides travelers with additional information on the performance of the roadway, what information will TMCs need to provide to individual vehicles in the future? What information, control strategies and capabilities will TMCs need to effectively share information with CAVs to improve the performance (e.g., safety, mobility) of travel on freeways (e.g., varying speed limits to enhance throughput)?

Will TMCs of the future incorporate or could they rely on data from vehicles as sensors? This would require V2I communications, standards for messages to share data with CAVs and roadside units (RSUs), deployed RSUs with necessary capabilities, and the ability for systems to manage the collection, storing, sharing, and pulling of data into the traffic management system—all of which are still in research and development.

Will vehicles rely on their internal sensors to provide local conditions to maintain safe operation to prevent collisions, and safe travel speeds?

Will vehicle imaging systems provide visual reference data to the TMC? For what purposes?

Demonstrating Benefits

An agency must have demonstrated benefits to deploy systems.

- The penetration rate of CAVs is not known**.** What level of CAV penetration is sufficient to show a benefit to use for freeway operations?
- Traffic management benefits are difficult to quantify with a limited number of vehicles.
- Field studies are difficult to devise with a low concentration of vehicles within a time necessary to demonstrate benefits.
- Information and guidance are needed for public agencies to assess the potential for RSUs collecting and sharing data with CAVs and how that could augment or replace data collected through existing methods. Additional information is needed for public agencies to assess the costs associated with developing, deploying, maintaining, and operating RSUs and the supporting telecommunications infrastructure to share data through these devices.

Areas in Which Additional Knowledge Would Be Especially Beneficial

- A synthesis study would be a helpful way to summarize the CAV research being conducted by the U.S. Department of Transportation, CV Pooled Fund Study (PFS), NCHRP, AASHTO, universities, states, and others to provide a benchmark on the current state of the practice to better allow these agencies to coordinate their research activities amongst each other.
- Use of CAV data more proactively to meet traffic management needs (e.g., dynamic routing/ managing demand to maximize capacity, predicting traffic jams, etc.)
- What role will the Original Equipment Manufacturers (OEMs) play in the evolution of CAV technologies? Are there performance standards that are consistent and promote safety?
- How long will it take the market penetration to get to the point where the paradigm drastically shifts? What do the CAV stakeholders and agencies need within that timeframe? What do we need to do in the meantime (national standards, etc.)? What is the transition period and how will it play out?

Possible Financing Challenges

- How can we incentivize or monetize the safety that we think the consumer deserves?
- Pricing and data possibilities: modal balance and seamless transfers between modes, focus on first and last mode and all of this within the ICM environment? For dynamic pricing on a toll facility, can you vary pricing on a managed lane and transit to get better modal split? Can it be done through connectivity?
- Will public-private partnerships have a role? Will there be coordination with private partners to implement CAV freeway operations strategies?

Undefined Functionality and Design

- What is it that we want to do in terms of freeway operations, and can those be supported by what the vehicles are currently able to do? We need to consider that the messages are limited in many cases.
- What level of automation should agencies design and build for?
- Consistency is needed. Messages displayed to driver must be same in vehicle and infrastructure; agencies must have confidence in CAVs behavior.
- The hierarchy of applications is undefined. Conflicts in information or commands to driver and vehicle must be resolved. Safety is the first priority, but what follows? Mobility, environment, or convenience?

CURRENT AND PROPOSED NATIONAL RESEARCH AND INITIATIVES

Following are examples of current and proposed national research and initiatives for CAVs and freeway traffic management:

- CDS Program *Integrating Emerging Data into Operational Practice* Study (underway).
- Intelligent Transportation Systems Joint Program Office (ITS JPO) Connected Vehicle Dynamic Mobility Applications (DMA) Program, particularly DMA bundles relevant to freeway operations such as *Intelligent Network Flow Optimization (INFLO)* (http://www.its.dot.gov/dma/bundle/inflo_plan.htm).
- ITS JPO *Automated Vehicles Research Program* (http://www.its.dot.gov/automated_vehicle/index.htm).
- ITS JPO *Connected Vehicle Pilots Deployment Program* (http://www.its.dot.gov/pilots/index.htm).
- AASHTO/ITS JPO *National Connected Vehicle Field Infrastructure Footprint Analysis Final Report*, 2014 (http://ntl.bts.gov/lib/52000/52600/52602/FHWA-JPO-14-125_v2.pdf).
- AASHTO/ITS JPO Near-Term *V2I Transition and Phasing Analysis Connected Vehicle Application Prioritization Tool* (underway).
- Federal Highway Administration (FHWA) Office of Operations *Impacts of Technology Advancements on Transportation Management Center Operations*, 2013 (http://ops.fhwa.dot.gov/publications/fhwahop13008/fhwahop13008.pdf).
- FHWA Office of Operations *Advanced Traveler Information System (ATIS) 2.0*, (underway).
- FHWA Office of Policy *Connected Vehicle Impacts on Transportation Planning* (underway).
- NCHRP 20-24(98) *Draft Connected/Automated Vehicle Research Roadmap* for AASHTO (http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-24(98)_RoadmapTopics_Final.pdf).
- Connected Vehicle Pooled Fund Study *Traffic Management Centers in a Connected Vehicle Environment*, 2013 (http://www.cts.virginia.edu/wp-content/uploads/2014/05/Task4._Recommendations_122313_-_FINAL.pdf).

RESEARCH NEEDS AND OPPORTUNITIES

The following are potential areas of research for the following areas for CAV:

TMC Roles and Organizational Capability

- How will CAVs change current TMC functions?
- Will the TMC need to take on additional roles?
  - Incident management
  - Operation of toll or managed lanes
  - Coordination and dissemination of real-time, multimodal travel information
  - Assets management, including monitoring critical assets (facility management centers)
- How will CAVs impact the work load on TMCs? (Now TMCs are reactive; in the future, proactive.)
- How to incrementally advance legacy systems and organizational capability to meet high-volume, multisource CAV data requirements? What tools and information do agencies need to determine when to deploy RSUs and what infrastructure is needed to enable TMCs to share information and allow data collected at these devices into the operation of the system?

Personnel and Training

- Skill sets for operators in TMCs—knowledge, skills, and abilities (KSAs)—have changed over time to be less technical. What does this mean for the future?
- Are TMC personnel properly trained in analysis techniques that make best use of CAV data for meeting TMC operational needs?
- Will TMC personnel need additional knowledge and skills to be able to operate highly technical CAV applications?
- Will TMC personnel need to know data analysis techniques to make best use of the data?
- What are the workforce and infrastructure needs (in-house, contracted)?

Business Models

- What are the institutional implications of the complexity introduced by CAV technology and data to the capacity of TMCs?
- What incremental organizational and business model strategies can public agencies like TMCs use to adapt to new requirements?
- Given that state and regional agencies are often operating under financial and staffing stresses, how will the changes brought by CAV technology be managed?

Data Collection

- What type of CAVs generated and transmitted data should be collected to support the management, operation, and assessment of the performance of TMCs and different operational strategies? That is, BSM, Part 1, or other?

- What standards are needed for applications?
  - *Traffic Management Data Dictionary* (TMDD) and other standards today
  - Defining networks segments or using latitude and longitude
  - Mapping standards
- What are the data requirements? Do they vary by application?
  - Data Format
    - Data type (data elements, message formats)
    - Granularity (second by second, every minute, etc.)
    - Frequency of capture (how often TMC collects data from source)
  - Data Source
    - Value of mobile device, crowdsourced traveler, and/or infrastructure data
  - Scale
    - Geographic scale (agency, metropolitan area, statewide, national)

Data Analysis and Use

- What CAV-generated and transmitted data is appropriate to integrate into the algorithms used to manage and use traffic management strategies (e.g., ramp metering)?
- What data from CAVs might be of value to agencies managing and using different traffic management and operating strategies on freeways or surface streets?
- What infrastructure data (roadside equipment) is needed to optimize operational strategies?
- What mobile device related data might be of value to TMCs managing and using different traffic management and operational strategies on freeways or surface streets?
- Will the collection and use of CAVs generated and transmitted data allow agencies to expand their area of coverage for performance monitoring and use of different operational strategies?
- What research and guidance is needed to enable CAVs generated and transmitted data to be integrated into traffic analysis tools to support the evaluation of the use of different ATM operational strategies?
- How might CAVs (and drivers) respond to information shared by TMCs related to different traffic management strategies (e.g., regulatory, warning, advisory)?

Planning

- How to take advantage of emerging next-generation data management, analytics, and high-performance computing to convert data to actionable information?
  - What analysis tools will the TMCs require for big data?
  - What computing power will the TMCs require for big data?
  - Do TMCs need autonomous, or semiautonomous, functions to deal with data processing and decision-making?
- What infrastructure and strategies do TMCs need to collect the data?
  - What are the infrastructure requirements to collect data from multiple sources?
  - Who builds and operates the collection tools?

- What data (e.g., loops, video detectors) and other sources of information could agencies eliminate collecting or replacing if they collect and use connected vehicle generated and transmitted data?
- What V2I communications, standards for messages to share data with CAVs and RSUs, deployed RSU's with necessary capabilities, and ability for systems to manage the collection, storing, sharing, and pulling of data into the traffic management system and local control?
- Where and what type of roadside devices, infrastructure and telecommunications capabilities do TMCs needed to transmit and receive collected connected vehicle data?
- What advances in traffic flow theory and application could be expected upon implementation of CAV? How will this affect the TMC's ability to manage system flow and enhance system operations reliability?
- What messages and driver interfaces should be transmitted to automated vehicles to support their compliance with the operation of ATM operational strategies? For example, ATM strives for "anticipatory" or "proactive" control, but drivers do not comply without reason.

Resources

- Are there other markets we are looking at that we aren't doing so yet? Other sectors of our economy or industry? Other areas of the industry that have gone through automation evolution? How do we do that where we get some benefit out it?
- Will the collection and use of CAVs generated and transmitted data allow agencies to lower their costs to manage and use ATM operational strategies compared to using traditional sources of data?
- What series of investments bring the best value?
- What's the value proposition?
  - Which data, under what conditions is, of value?
  - What are the concepts of operation associated with uses?
  - When and how is CAV data a better investment than alternatives (e.g., more infrastructure-based detection, purchasing probe data, etc.)?

CAV Penetration

- What is critical mass or penetration of CAVs producing probe data with additional vehicle data?
  - What is the use of penetration in the applications of the TMC context?
  - When can CAV penetration replace sensors and detectors?
  - When can CAV penetration replace dynamic message signs (DMS)?
  - When do the TMCs champion deployment of direct short range communication (DSRC) technology? Only for safety benefits? What about mobility benefits?
- ATM as a specialized TMC function with dynamic mobility applications (DMAs):
  - What is it that we want to do in terms of ATM, and can those be supported by what the vehicles are currently able to do? The messages are limited in many cases, and can we do what we want to do? Keep it simple and look at use cases for a traffic management strategy.

– What messages on traffic and roadway conditions can be used to facilitate driver and V2V information sharing and decisions (e.g., driver route choice, lane use, etc.) and performance?

– Predicting traffic congestion before it happens (how can CAV data help)?

Areas of Potential Research and Areas of Emphasis

SUMMARY OF AREAS OF POTENTIAL RESEARCH

Table 4 shows a compilation of all areas of potential research for each focus area. The focus areas have been broken down into subtopic areas to further categorize the areas of research. Overall, 109 areas are identified.

POTENTIAL AREAS OF EMPHASIS

At the TRB Freeway Operations Committee midyear meeting held June 22–26, 2014 in Irvine, California, the research subcommittee developed areas of emphasis for its potential research. Subcommittee members and friends who participated in the subcommittee meeting were also asked to consider the importance of these different research areas.

In 2015, a team (including Srikanth Panguluri, Lou Neudorf, and Qing He) led by the research subcommittee cochairs James Colyar and Chris Poe prepared an online research survey and broadly distributed the survey to the entire TRB Freeway Operations Committee members and friends list, along with other traffic operations-related committees and groups. The survey was completed before the research areas for connected and automated vehicles (CAVs) (Chapter 10) had been compiled, thus the CAV areas of research were not included. The survey was distributed in April 2015. A total of 36 responses were received, including 15 from government agencies, six from industry, and 13 from universities (two respondents skipped this question). Of the 36 respondents, the majority of responses (25) were received from the members or friends of the Freeway Operations Committee.

The online survey included 28 areas of potential research, narrowed down from the initial 101. The narrowing was primarily based on input at the 2014 midyear meeting, along with combining the areas of research that had significant overlapping purposes and were of ongoing or recently published research on those topics. For this reason, the wording of some of the research areas in the online survey were slightly different than the wording of the research areas identified previously in Table 4. In addition, the process of refinement ensured that the top 28 areas represented interests of all the areas. For example, three areas of potential research from each of the eigth subject areas were included in the final list of potential research areas for the on-line survey.

Table 5 shows the subject areas of the potentially helpful research included in the online survey.

This list will likely be instrumental for the Freeway Operations Committee, and the Transportation Systems Management and Operations (TSM&O) research community broadly, in deciding which research topics to pursue. It is envisioned that this list be revisited every few years to confirm important research areas of the Committee.

In addition, the online survey also asked the responders about the importance of four TSM&O research themes that were developed by the American Association of State Highway Transportation Officials Subcommittee on TSM&O Research Working Group in collaboration with the TRB Regional TSM&O and Freeway Operations Committees and the National Operations Center of Excellence (NOCoE). Table 6 shows the survey results of these research themes.

TABLE 4 Overall Areas of Potential Research

Subtopic Area	ID No.	Research Area Description
Active Traffic Management		
General	ATM-1	What are the returns on investment and the benefits of ATM?
Planning, evaluation, and organization	ATM-2	What research is needed related to the right measures of effectiveness and guidance?
	ATM-3	What is the proper performance measure to use for an ATM strategy and how does an agency measure it?
	ATM-4	How do specific performance metrics for ATM strategies fit into the overall ATDM system?
	ATM-5	What are the safety analyses of ATM applications? Where might an agency be introducing conflict?
Design, implementation, and deployment	ATM-6	With respect to the ATM-related displays themselves, what is acceptable and effective?
	ATM-7	What are the best methods of showing lane control, particularly the need to show the merge points for system users?
	ATM-8	What are other graphical displays and/or the use of graphics in ATM displays?
	ATM-9	What are the safety aspects of speed differential? What are the separation treatment needs when a speed differential exists?
Operations, maintenance, and monitoring	ATM-10	Speed management within this context: should it be set on actual conditions and how should an agency deal with variance?
	ATM-11	When considering advisory versus regulatory operations, is there a difference in effectiveness?
	ATM-12	What is the reaction of the drivers that has yet to be addressed? What is the stakeholder's perspective of variable speed limits other ATM approaches?
	ATM-13	With respect to variable speed limits and ramp metering, what is the best approach for utilizing an algorithm and what is the intended objective of that algorithm?
	ATM-14	What is the best way to deal with enforcement with respect to variable speed limits?
	ATM-15	With respect to flow maximization, what is the goal of the algorithm and what is an agency trying to accomplish?
Integrated Corridor Management		
Institutional and organizational integration	ICM-1	Institutional organization best practices to create a successful ICM project. Questions to be answered include: • What are the core institutional elements that should be in place for an ICM initiative to be successful (e.g., shared goals objectives, agreements, and regional policies)? • What factors are most critical to successfully organizing a local ICM partnership team? • What is required to sustain ICM organizational and operational partnerships? • What are the policy challenges for ICM (e.g., initial and long-term funding, data, automation, and transit operators)? • What types of public and political marketing are needed? • What institutional arrangements can support shared operations and maintenance of corridor assets?

NOTE: ID = identification; no. = number; ATM = active traffic management; ATDM = active transportation and demand management; ICM = integrated corridor management.

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TABLE 4 (*continued*) Overall Areas of Potential Research

Subtopic Area	ID No.	Research Area Description
Integrated Corridor Management		
Data and information sharing	ICM-2	Data needs for ICM operations and traveler information. Questions to be answered include: • What are the standard operating procedures and standard operating agreements for multimodal and multiagency data integration for real-time operations and management? • What are the advantages and disadvantages of centralized versus distributed data models? • What are the best practice models for using private-sector data? • What are advantages of using data standards (e.g., *Traffic Management Data Dictionary*)? • What are the issues with use of general transit feed specification? • What other shared data or multimodal information would be required to improve ICM? • What type of information do travelers need to alter their behavior (e.g., are travel times, comparative travel times, or parking status enough to change behavior)?
	ICM-3	Data modeling and visualization tools to support ICM planning and evaluation. Questions to be answered include: • What are best approaches to measure and calculate common corridor performance measures when considering multiple objectives from different organizations (e.g., vehicle-miles traveled, person miles traveled, vehicle hours traveled, transit on-time performance, freight on-time performance, economic impacts, environmental impacts, and safety impacts)? • What are techniques for visualization of multimodal, multiagency, and multiobjective performance monitoring? • What are approaches to determine optimal data needs for ICM operational objectives? • What are approaches to understand real-time changes in demand at the outer parts of the travel shed?
Improve operational efficiency	ICM-4	Transit, freight, and emergency services integration for better ICM operation. Questions to be answered include: • How can conditional-based transit priority be implemented to improve transit schedule and capacity? • How to implement public and private-sector transit connection protection challenges? • What are the approaches to develop and apply emergency vehicle best route to incidents and emergency response centers and challenges of integrating with corridor operations? • What are the challenges of integrating destination parking information into real-time traveler information? • What are the ICM challenges and opportunities for freight or heavy vehicle signal priority? • How can freight or heavy vehicle rerouting be integrated into corridor optimization? • What are business models for regional single multimodal fare payment—public transit and private-sector shared use? • How can traffic signals be optimized for transit progression? • How can ICM assist with incident management and response time requirements? • How can ICM support integrating demand responsive mass transportation services?

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TABLE 4 (*continued*) Overall Areas of Potential Research

Subtopic Area	ID No.	Research Area Description
Integrated Corridor Management		
Promote network shifts	ICM-5	Real-time and predictive traveler information for better ICM operation. Questions to be answered include: • What are the best practices to calculate full trip travel times (that is, representing the complete multimodal and multiroute trip)? • How can dynamic toll and fare adjustments–credits be modeled? • What are best practices to give dynamic route guidance to commuters? • What are approaches to integrate messages and recommended actions from private-sector traveler applications?
Capacity–demand management	ICM-6	Infrastructure capacity management for better ICM operation. Questions to be answered include: • What are the best practices for traffic signal coordination and optimization to achieve corridor performance objectives? • What are the approaches to dynamically increase parking availability? • How can dynamic lane or facility reassignment (e.g., bus on shoulder, time-of-day, or dynamic transit only lane) be used in ICM? • How can ICM be used with dynamic adjustments to construction and maintenance roadway closures? • What are the approaches to incentivize mode and route shift? • How can dynamic toll and fare adjustments–credits be used to manage capacity?
Technical integration	ICM-7	Use of real-time decision support systems. Questions to be answered include: • What are the best practices for integrating traffic simulation into real-time decision support? • What are effective artificial intelligence approaches? • How can automated decision making be implemented and what are the human interfaces needed? • What are the challenges with real-time prediction of traffic conditions and impacts of response plans?
Managed Lanes		
Research	ML-1	Ingress–egress best practices (with focus on at-grade treatments for single and dual lanes).
	ML-2	Separation treatments between concurrent MLs and adjacent general purpose lanes, including application experience associated with use of traffic channelizers–delineators in ML buffers.
	ML-3	Tolling algorithms applied to MLs, and effectiveness in managing demand.
	ML-4	Comparative operational performance attributes for single- and multiple-lane ML designs.
	ML-5	Recent experiences in alternative delivery approaches for MLs, including design–build and public–private partnerships.
	ML-6	Impacts of raising occupancy requirements when converting HOV lanes to HOT lanes.
	ML-7	Traffic modeling and performance measurement criteria that take into account reliability and sustainability of options to meet future traffic growth when comparing managed lane and general purpose lane expansion options.
Demonstration test	ML-8	Demonstration tests of the latest automated occupancy enforcement technologies on projects.

NOTE: ML = managed lanes; HOV = high-occupancy vehicle; HOT = high-occupancy toll.

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TABLE 4 (*continued*) **Overall Areas of Potential Research**

Subtopic Area	ID No.	Research Area Description
Managed Lanes		
Technology transfer	ML-9	Periodic updates to the *Managed Lanes Implementation Guide* (when completed in 2015) with input from Managed Lanes and Congestion Pricing Research Subcommittees, HOV/MUL PFS, and NCHRP Panel 15-49.
	ML-10	Applications of ATM on MLs to regulate speeds and manage queues.
	ML-11	Real-time TDM strategies to reduce or better manage peak demand for MLs and transit services.
Traffic Incident Management		
TIM training	TIM-1	As lessons learned and awareness of the saturation level of the SHRP 2 TIM training is quantified, a new project should be initiated to develop the next generation of TIM training. With the construction of dedicated TIM training facilities now occurring across the nation, the depth of topic investigation and the overall number of topics themselves will need to be increased. This project should accomplish three goals: (1) conduct more intensive sampling of areas where TIM training is and is not being conducted for more broad operational and policy awareness; (2) identify future TIM training needs along with the establishment of horizon years when the training will be required or a linkage with capability maturity; and (3) develop a framework for TIM training calibration based on SHRP 2 implementation.
Optimal Visibility	TIM-2	Previous efforts attempted to examine what the optimal visibility conditions are for TIM including PPE and vehicles. This research should build on that work and be more inclusive of highway construction and maintenance workers as well as specific emphasis on visibility of vehicles at the end of a queue approaching a crash scene.
Quantitative benefits of TIM	TIM-3	This project should consist of a national assessment that can effectively capture a snapshot of what the benefit of consistent TIM would allow. The resulting research document should hypothesize how quantified TIM (as part of a broad TSM&O approach) benefits would become part of the transportation funding allocation model whereby transportation agencies would need to achieve annual benchmarks to achieve 100% funding eligibility in designated categories.
TIM as part of total network management	TIM-4	This project should consist of a national assessment that can effectively capture a snapshot of what the benefit of consistent TIM would allow. The resulting research document should hypothesize how quantified TIM (as part of a broad TSM&O approach) benefits would become part of the transportation funding allocation model whereby transportation agencies would need to achieve annual benchmarks to achieve 100% funding eligibility in designated categories.
TIM and freight	TIM-5	A greater depth of understanding is needed regarding the economic impact of TIM strategies and the daily impact that is quantified. Work should be done to evaluate the entire supply chain model and the downstream effects that are caused by positive and negative TIM practices.
Decision support for TIM	TIM-6	Understanding the psychology that is involved with decisions on response will help drive technological innovation in the future. Although TIM will always rely upon people to be fully effective, the development of decision support technology can help simplify decisions that need to be made. For the next generation of software that is deployed in TMCs, public safety access-point dispatch centers, etc., the availability of historical information that can help predict outcomes will rely on the experience of individuals that can be built into business case rules. This work should also include an analysis of the role that big data can and should play in TIM.

NOTE: MUL = managed-use lanes; PFS = pooled fund study; NCHRP = National Cooperative Highway Research Program; TDM = transportation demand management; TIM = traffic incident management; SHRP 2 = Second Strategic Highway Research Program; TSM&O = Transportation Systems Management and Operations; PPE = personal protective equipment.

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TABLE 4 (*continued*) Overall Areas of Potential Research

Subtopic Area	ID No.	Research Area Description
Traffic Incident Management		
Progressing the relationships between transportation and public safety	TIM-7	Building on both the National Unified Goal for TIM as well as the National Road Map for TIM established in the 2012 Transportation and Public Safety Summit, more work is needed on bringing together agencies from a technological standpoint. Linking TMCs and public safety dispatch centers exists only in concentrated areas. This project should examine the barriers that prevent full integration of data between agencies from an IT perspective and suggest ways to overcome the barriers.
Insurance industry partnerships	TIM-8	It would appear as though a relationship between the insurance industry and the TIM community would make sense because they both have similar goals of reduced incidents. This project should examine the insurance industry and identify ways that TIM can be considered when developing policies and procedures. Also, an emphasis should be placed on the development of a partnership framework that could provide outreach for TIM, TIM research funding possibilities, and other cost offsetting opportunities.
Performance Data, Monitoring, and Management		
Research	PM-1	Incorporate reliability metrics in the reporting of PM. Identify data and methodology requirements to obtain reliability metrics. Provide planning estimates on the expected impacts of certain mobility strategies on reliability.
	PM-2	Develop improved methods for sensor data error checking, imputation of missing values, and data fusion from multiple sources. Determine the error in performance estimates as a function of detector failures. Also, develop acceptance testing criteria for private-sector data for use in PM.
	PM-3	Develop methods for estimating PMs from CV data.
	PM-4	Develop a methodology for predicting PMs from field data and analytical tools, as part of a decision-support system in the TMC.
	PM-5	Define and develop methods for calculating certain mobility and safety-related PMs for ATDM and DMA strategies from modeling–simulation outputs.
Research	PM-6	Develop techniques for analysis of data from traveler’s mobile devices (big data) to obtain PMs. Assess the usability of the data for obtaining additional information not typically gathered through conventional approaches (e.g., origin–destination information, trip chaining).
	PM-7	Propose new measures that apply to multimodal systems and specific situations (e.g., evacuations and emergencies).
	PM-8	Define and develop procedures for PMs for freight traffic.
	PM-9	Prepare a synthesis to provide a review of state and MPO multimodal programming as part of MAP-21 with a focus on how goals and PMs are used in a multimodal context for the programming of transportation projects.
	PM-10	Provide guidance on the personnel resources and level of effort required to establish and maintain a comprehensive PM, monitoring, and reporting program.
	PM-11	Define procedures for calculating nonobservable PMs (e.g., fuel consumption, air pollution) from common field-measured metrics.

NOTE: PM = performance measurement; CV = connected vehicle; DMA = dynamic mobility applications; MPO = metropolitan planning organization; MAP-21 = Moving Ahead for Progress in the 21st Century Act.

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TABLE 4 (*continued*) **Overall Areas of Potential Research**

Subtopic Area	ID No.	Research Area Description
Performance Data, Monitoring, and Management		
Demonstration project	PM-12	Conduct a field test to determine the advantages and limitations of alternative data collection methods for calculation of PMs. This can be also accomplished by analyzing data from existing freeway systems at selected metropolitan areas in the United States.
Training	PM-13	Provide staff training on PMs, data collection and analysis, and presentation techniques.
Traffic Management Centers		
Day-to-day operations	TMC-1	Predicting traffic and roadway conditions.
	TMC-2	Collecting, processing, archiving, and using data for operations.
	TMC-3	Data archiving subsystem: concept of operations, requirements, and design.
	TMC-4	Data quality and requirements.
Enhancing TMC business management	TMC-5	TMC business planning software.
	TMC-6	TMC multiyear program plans.
	TMC-7	TMC asset management.
	TMC-8	Formatting and sharing operations data for transportation planning.
	TMC-9	Toll and other pricing operations in TMCs.
Developing TMCs and managing their evolution	TMC-10	*TMC Building and Control Center Design Handbook.*
	TMC-11	Multistate and megaregion TMC coordination.
	TMC-12	Tool to support regional and multisystem configuration management.
	TMC-13	Open-source ATMS software licensing and development.
	TMC-14	Automation of TMC functions.
	TMC-15	Cloud computing, data fusion and data management.
Developing and delivering roadway and travel condition information	TMC-16	Driver behavior in response to the disseminated information (e.g., travel time, travel time at diversion points on a freeway system, impact of displaying travel times for alternative routes).
	TMC-17	Procedures and requirements for providing road conditions and travel time information.
	TMC-18	Methods for TMCs to develop and distribute predictive travel time information.
	TMC-19	How to display travel times across regions.
	TMC-20	Best practice in private sectors information dissemination.
	TMC-21	Diversity of sources, coverage, types, and quantity of data.
Developing, training, hiring, and contracting staff and services	TMC-22	Knowledge needs assessment and workshops for TMC owners, managers, and staff.
	TMC-23	Training program template and opportunities for TMC staff.
	TMC-24	TMC operator certification program development and implementation.
	TMC-25	Recommended 2-year college program for TMC operators and technicians.

NOTE: TMC = traffic management center; ATMS = advanced traffic management systems.

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TABLE 4 (*continued*) Overall Areas of Potential Research

Subtopic Area	ID No.	Research Area Description
Detection and Surveillance		
Knowledge transfer	TMC-26	*TMC Marketing Handbook and Toolbox.*
Research	DS-1	FHWA last completed and published an update to its *Traffic Detector Handbook* in 2006. A complete revision of this handbook is overdue to incorporate advances in detection, surveillance, and safety made possible by sensors that incorporate multiple technologies, new magnetometer designs, low-cost thermal imaging cameras, initiatives such as the CV Program, and the increased availability of cell phone and GPS data to locate vehicles and generate travel times using MAC address matching.
Research	DS-2	Self-directed learning tool for traffic DS. This study project develops a self-directed learning tool for practitioners to study traffic DS theories, detection system design principles, and the merits and applications of commercially available traffic sensors and other strategies such as those that use GPS-based vehicle location devices.
	DS-3	Performance monitoring using point detection data and the probe vehicle trajectory data collected from GPS and cellular-based geolocation systems. This study develops a new algorithm for highway PM using both point detection data and probe vehicle trajectory data collected from GPS and cellular-based geo-location systems.
	DS-4	Continued development of the CV Program to communicate with surrounding vehicles using 5.9-GHz DSRC technology.
	DS-5	With the continued increase in coverage provided by motorist's GPS-equipped cell phones, an examination of the future of point sensors on freeways and other limited access highways is timely. While continued use of the point detectors for traffic signal control appears needed in the future, it is not as clear that mass deployment of these sensors may be required to detect incidents or slow-moving traffic conditions.
	DS-6	Adaptive ramp metering will become more important to freeway traffic management as traffic demand increases and freeways and arterials are more tightly coupled via ICM. Current sensors on ramps are point detectors. Therefore, multiple sensors of this type are required to dynamically measure ramp queue length and gaps on through lanes. Video and radar sensors also have the potential to provide these measures. However, research is required to identify enhancements to these sensors to make them practical as ramp sensors for adaptive ramp metering.
Demonstration project or operational tests	DS-7	Large-scale metro-area test of application of cell phone data to provide travel times to commuters and other travelers.
	DS-8	Methods and tools for large-scale data analyses and informed decisions.
	DS-9	Continued testing of V2V and V2I equipment and algorithms designed to warn drivers of potential hazards with incorporation of newer sensor technologies to enhance infrastructure-based vehicle DS.
	DS-10	Above-ground sensors are beginning to be used for freeway ATDM for detection of shockwave propagation and queue warning. Display of queue warning messages are often TMC-operator controlled, but at other times are produced autonomously by the sensors themselves. Wider demonstration and operational tests are needed to test and validate the performance and effectiveness of such sensors for these applications and to establish specifications and benchmarks for their requirements.

NOTE: MAC = media access control; DSRC = direct short-range communication; V2V = vehicle-to-vehicle; V2I = vehicle-to-infrastructure.

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TABLE 4 (*continued*) Overall Areas of Potential Research

Subtopic Area	ID No.	Research Area Description
Detection and Surveillance		
Demonstration project or operational tests	DS-11	LPRs have been used for several years in European countries, such as the Netherlands, to help smooth and harmonize speed to obtain maximum capacity. Demonstration of the technology on U.S. highways is needed to begin exploiting this method for ATDM applications.
Technology transfer	DS-12	Best practices for designing and implementing a cost-effective system for traffic DS. This study would collect success stories from transportation agencies in cost-effective design and implementation of traffic DS systems and summarize them in a final project report.
	DS-13	DS system cost database. Much has been reported on installation costs for detection technologies but little has been documented about the ongoing maintenance costs. This database would collect and document the installation as well as on-going maintenance costs of traditional and alternate detection technologies.
	DS-14	Continued exploration, application, and incorporation of sensor and data fusion techniques from homeland defense applications to traffic management to aid in developing a more complete and accurate picture of the traffic situation at hand and in data mining (*13*, *15*).
	DS-15	Best practices to utilize crowd-sourced data and user-device derived data, such as from tracking user devices equipped with GPS, cellular radio, or Bluetooth, needs to be documented with case studies and procedures so unfamiliar agencies can quickly adapt these tools.
	DS-16	Validated and centrally documented accuracy, deployment procedure, and cost of work zone sensors such as speed barrels and other portable sensors needs to be documented and disseminated.
Freeway Traffic Control Devices		
General research	TCD-1	What is the most-appropriate and -effective methodology for presenting dynamic information to road users under high-speed freeway conditions? How do changes in speed affect the methodologies selected?
	TCD-2	What communication mechanism(s) assure the greatest road user compliance?
	TCD-3	What is the best method for identifying and delineating dynamic lane control?
	TCD-4	How can pavement marking dynamically support changes in freeway operations and lane control?
	TCD-5	What are the most-effective and safest methods for communicating real-time information to road users through in-vehicle or personal communication devices?
	TCD-6	Determine the reliability and durability of new TCDs and develop countermeasures for device failures.
	TCD-7	Determine the sensitivity of dynamic TCDs to erroneous data and hacking.
	TCD-8	Determine the appropriate migration from physical TCDs to virtual TCDs.
General research	TCD-9	Identify the best methodologies and impact of nighttime illumination of signs and markings.
	TCD-10	Identify gaps between new and emerging freeway operations techniques and available communication tools (such as TCDs).

NOTE: DS = detection and surveillance; LPRs = license plate readers; TCD = traffic control device.

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TABLE 4 (*continued*) Overall Areas of Potential Research

Subtopic Area	ID No.	Research Area Description
Connected and Automated Vehicles		
Institutional readiness	CAV-1	TMC roles and organizational capability questions to be answered include: • How will CAVs change current TMC functions? • Will the TMC need to take on additional roles? • How will CAVs impact the work load on TMCs? (Now TMCs are reactive; in the future, proactive.) • How to incrementally advance legacy systems and organizational capability to meet high-volume, multisource CAV data requirements? What tools and information do agencies need to determine when to deploy RSUs and what infrastructure is needed to enable TMCs to share information and allow data collected at these devices into the operation of the system?
	CAV-2	Personnel and training questions to be answered include: • TMC skill sets for TMCs—KSAs for operators in the TMC have changed over time, become less technical; what does this mean for the future? • Are TMC personnel properly trained in analysis techniques that make best use of CAV data for meeting TMC operational needs? • Will TMC personnel need additional knowledge and skills to be able to operate highly technical CAV applications? • Will TMC personnel need to know data analysis techniques to make best use of the data? • What are the workforce and infrastructure needs (in house, contracted)?
Institutional readiness	CAV-3	Business model questions to be answered include: • What are the institutional implications of the complexity introduced by CAV technology and data to the capacity of TMCs? • What incremental organizational and business model strategies can public agencies like TMCs use to adapt to new requirements? • Given that state and regional agencies are often operating under financial and staffing stresses, how will the changes brought by CAV technology be managed? • What type of CAV-generated and -transmitted data should be collected to support the management, operation, and assessment of the performance of TMCs and different operational strategies (e.g., BSM, Part 1, other)?

NOTE: CAV = connected and automated vehicle; RSU = roadside units; KSAs = knowledge, skills, and abilities; BSM = basic safety message.

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TABLE 4 (*continued*) Overall Areas of Potential Research

Subtopic Area	ID No.	Research Area Description
Connected and Automated Vehicles		
Data	CAV-4	Data collection questions to be answered include: • What type of CAV-generated and -transmitted data should be collected to support the management, operation, and assessment of the performance of TMCs and different operational strategies (e.g., BSM, Part 1, other)? • What standards are needed for applications? • What are the data requirements? Do they vary by application?
	CAV-5	Data analysis and use questions to be answered include: • What CAV-generated and -transmitted data is appropriate to integrate into the algorithms used to manage and use traffic management strategies (e.g., ramp metering)? • What data from CAVs might be of value to agencies managing and using different traffic management and operating strategies on freeways or surface streets? • What infrastructure data (roadside equipment) is needed to optimize operational strategies? • What mobile device related data might be of value to TMCs managing and using different traffic management and operational strategies on freeways or surface streets? • Will the collection and use of CAV-generated and -transmitted data allow agencies to expand their area of coverage for performance monitoring and use of different operational strategies? • What research and guidance is needed to enable CAV-generated and -transmitted data to be integrated into traffic analysis tools to support the evaluation of the use of different ATM operational strategies? • How might CAVs (and drivers) respond to information shared by TMCs related to different traffic management strategies (e.g., regulatory, warning, advisory)?
Planning	CAV-6	Questions to be answered include: • How to take advantage of emerging next-generation data management, analytics, and high-performance computing to convert data to actionable information? • What infrastructure and strategies do TMCs need to collect the data? • What data (e.g., loops, video detectors) and other sources of information could agencies eliminate collecting or replacing if they collect and use CAV-generated and -transmitted data? • What V2I communications, standards for messages to share data with CAVs and RSUs, deployed RSUs with necessary capabilities, and ability for systems to manage the collection, storing, sharing, and pulling of data into the traffic management system and local control?

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TABLE 4 (*continued*) Overall Areas of Potential Research

Subtopic Area	ID No.	Research Area Description
Connected and Automated Vehicles		
Planning	CAV-6	• Where and what type of roadside devices, infrastructure, and telecommunications capabilities do TMCs needed to transmit and receive collected CV data? • What advances in traffic flow theory and application could be expected upon implementation of CAV? How will this affect the TMC's ability to manage system flow and enhance system operations reliability? • What messages and driver interfaces should be transmitted to automated vehicles to support their compliance with the operation of ATM operational strategies? For example, ATM strives for "anticipatory" or "proactive" control, but drivers do not comply without reason. • Are there other markets we are looking at that we aren't doing so yet? Other sectors of our economy or industry? Other areas of the industry that have gone through automation evolution? How do we do that where we get some benefit?
Resources	CAV-7	Questions to be answered include: • Are there other markets that we aren't looking at yet, such as other sectors of our economy or industry? Other areas of the industry that have gone through automation evolution? How do we do that where we get some benefit? • Will the collection and use of CAV-generated and -transmitted data allow agencies to lower their costs to manage and use ATM operational strategies compared to using traditional sources of data? • What series of investments bring the best value? • What's the value proposition?
CAV penetration	CAV-8	Questions to be answered include: • What is critical mass–penetration of CAVs producing probe data with additional vehicle data? • ATM as a specialized TMC function with DMAs?

TABLE 5 Potential Areas of Research

Potential Areas of Research	Subject Area
Defining, collecting data, and evaluating relevant performance measures for ATM applications.	ATM
Effectively and safely communicating real-time information to road users through in-vehicle or personal communication devices.	TCD
Developing and utilizing decision support technology and big data to enable more responsive TIM.	TIM
Develop methods for obtaining and predicting performance measures from field and other data sources (e.g., mobile devices, big data) and analytical tools, as part of a decision-support system in the TMC.	PM/TMC
Conducting safety analyses of ATM applications, and the safety trade-offs relative to enhanced mobility.	ATM
Driver behavior in response to the real-time travel time information disseminated from TMCs including travel time displays at diversion points, and the impact of displaying travel times for alternative routes and modes.	TMC
Transportation and enforcement agencies, and public perspectives on dynamic speed limits and other ATM applications.	ATM
Opportunities and challenges for incorporating real-time decision-support systems into ICM.	ICM
Data- and information-sharing needs for ICM operations and traveler information, including types of information required and processes for sharing and managing data between multiple transportation agencies.	ICM
Develop methods for identifying and estimating performance measures from CV data.	PM
Continued testing of V2V and V2I equipment and algorithms designed to warn drivers of potential hazards with incorporation of newer sensor technologies to enhance infrastructure-based vehicle detection and surveillance.	DS
Determine the most-appropriate and -effective methodology for presenting dynamic information (e.g., travel times, speed limits–advisories, lane assignment, ML information) to road users under high-speed freeway conditions.	TCD
Improved methods to monitor highway sensor data error checking, data fusion from multiple sources, and acceptance testing criteria for private-sector data.	PM
Methods for TMCs to develop and distribute predictive traveler information.	TMC
National assessment to quantify the benefits of TIM.	TIM
Best methods for identifying, displaying, and delineating dynamic lane control and dynamic speed displays.	TCD
Opportunities and challenges for integrating transit, freight, and emergency services into ICM operations.	ICM
Regulating speeds, lane assignment, and managing queues on ML facilities using ATM applications.	ML
Real-time active demand management strategies to manage peak demand on ML facilities and transit services.	ML
Identify the potential future of cloud computing, data fusion, and data management at TMCs and their operations.	TMC

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TABLE 5 (*continued*) Potential Areas of Research

Potential Areas of Research	Subject Area
Examining the future of point sensors on freeways for traffic monitoring and management; planning, maintenance, and public–private partnership implications for agencies.	DS
Data modeling, simulation, and visualization tools to support ICM planning and evaluation.	ICM
Tools and other analysis techniques for comparing operational performance attributes for single- and multiple-lane ML designs.	ML
Dynamically support changes in freeway operations and lane control using advanced pavement marking and delineation techniques.	TCD
Examination of the benefits, enabling policies and procedures, and challenges for closer partnerships between the insurance industry and TIM community.	TIM
Development of a DS system cost database, which will include the types of information provided, and the installation as well as ongoing maintenance costs of traditional and alternate detection technologies.	DS
Impacts of changing occupancy requirements when converting HOV lanes to HOT lanes.	ML
Application and incorporation of sensor and data fusion techniques from homeland defense applications to traffic management to aid in developing a more complete and accurate situational awareness of traffic conditions.	DS

TABLE 6 TSM&O Research Themes

Research Themes
Workforce development for TSM&O. The increasing demand for TSM&O carries with it an equivalent need for development, maintenance, and expansion of the planning, engineering, operations, and maintenance workforce required to support TSM&O projects and initiatives. Research to address a wide variety of TSM&O workforce development issues such as attracting individuals to careers in TSM&O, retraining existing employees in other disciplines for TSM&O positions, retention of employees, career paths, training, and education would be beneficial.
TSM&O and decision support systems (DSS). Big data and its implications for analytical tools and systems are significantly influencing and enabling TSM&O within broader corporate and programmatic contexts. Transportation agencies are evolving and integrating asset management, operations management, and performance management plans and systems. Additional technologies and operating strategies (e.g., ATM and ICM) are evolving that require greater awareness of existing and future operating conditions. More holistic technological and institutional models for DSS in private industry are being imagined towards transportation agencies—particularly for TSM&O program and service development and management. Concerted research to accelerate the efficient integration of these business management systems within transportation agencies, and to establish next generation technology and business models for TSM&O-oriented DSS would be useful.

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TABLE 6 (*continued*) **TSM&O Research Themes**

Research Themes
Vehicle technology impacts to fleet operations and associated impacts to TSM&O. CV and CAV technologies have the potential to significantly impact the operation of public and private vehicle fleets such as transit, long- and short-haul commercial freight, taxis (including new shared-mobility services such as Uber), etc. Some auto manufacturers are also beginning to research shared-mobility services in the space between taxis (or single riders) and transit buses (multiple riders). These would be vehicles larger than taxis but smaller than buses that operate in a real-time demand mode with no specific route. There are also rapidly emerging developments in motive technologies and energy sources for personal vehicles and transit, as well as microscale innovations in personal mobility (e.g., electric bicycles) that are likely to dramatically affect the operation and management of the transportation network and associated vehicle and traveler services. Research to determine the impact of these type of connected–automated fleet operations on freeway management systems, arterial management systems, parking management systems, and emergency transportation operations would be helpful.
TSM&O for Sustainability & Resilience. Freight mobility and global economic competitiveness have focused TSM&O on the challenges of metropolitan, intercity, and inter-regional connectivity and reliability. TSM&O is also a vital strategy to address objectives of livability and sustainability within urban spaces and community centers. Enhancing and optimizing national transportation system resilience and advancing sustainability demands a structured recognition of this continuum of operational settings—from the continental scale of global connectivity (macro-operations) to the neighborhood scale of community connectedness (micro-operations). Research to clearly define this scaled context for TSM&O, and to understandably and measurably correlate TSM&O to the national policy priorities of sustainability and resilience would be beneficial. Several emerging research initiatives would complement this opportunity; including those related to smart connected communities, megaregional transportation operations, TSM&O aspects of logistics management, and others.

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